太陽フレア中性子の生成過程

(≅ ガンマ線(π^0)の生成過程
≅ 高エネルギーイオンの寿命)

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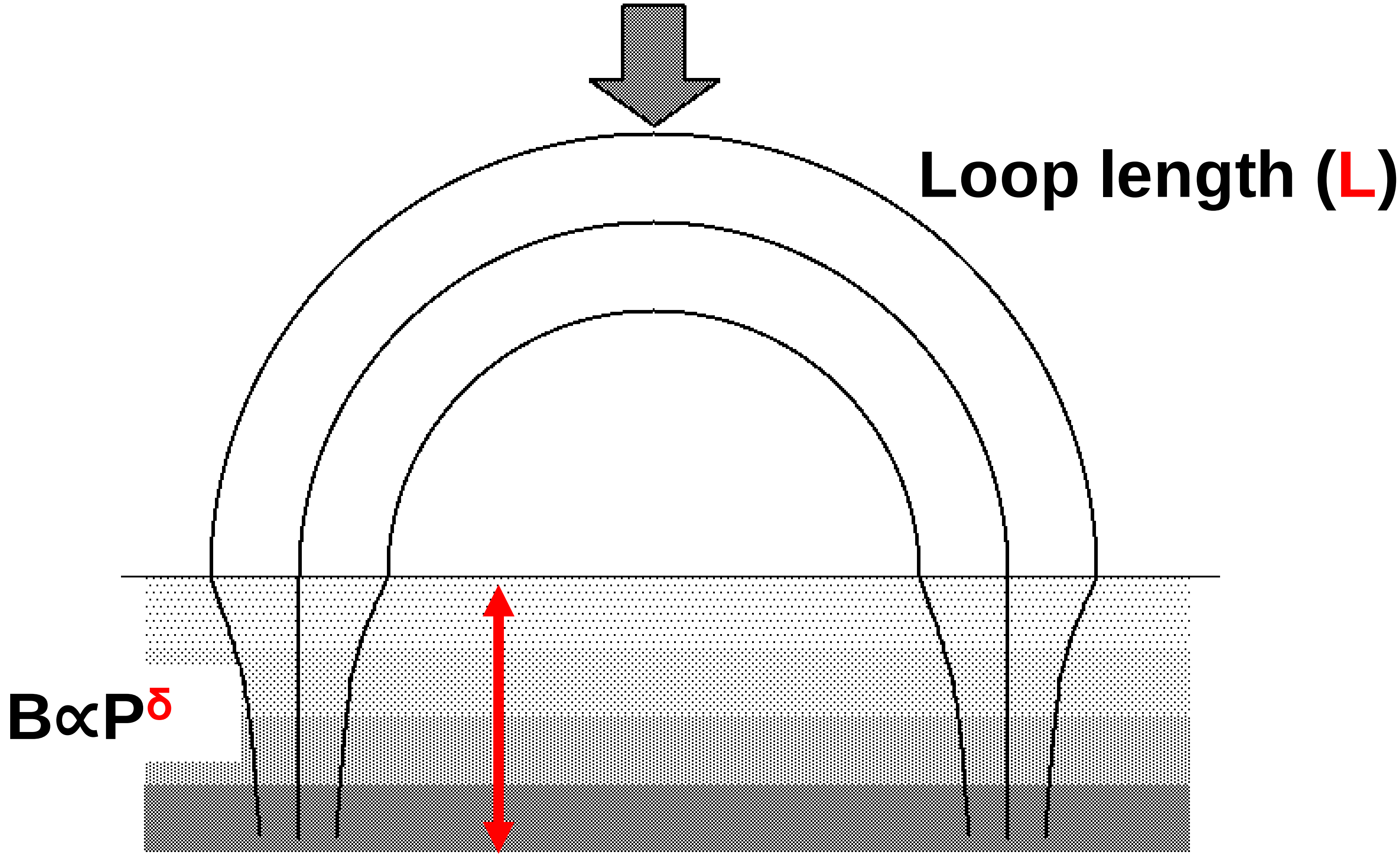
基本的に
R.J.Murphy, et al., ApJ Suppl,, 168, 167-194, 2007
の前半部分の reviewをします

Referencesと outline

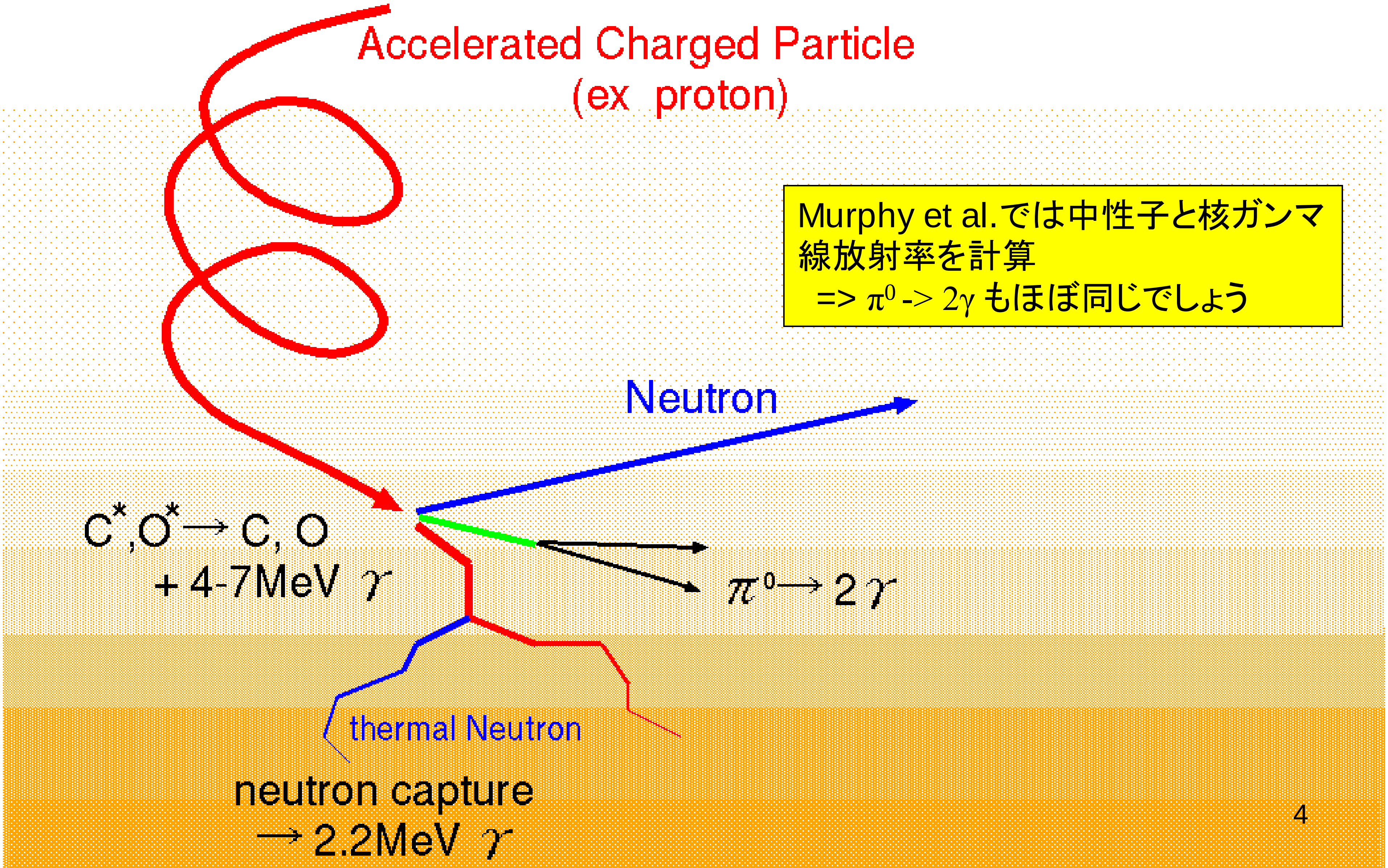
1. R.J.Murphy, et al. (2007)
   – フレアループにトラップされたイオンの運動を追跡し、foot pointでの nuclear interaction率（核ガンマと中性子生成）を計算
2. Hua et al., ApJS, 140, 563-579 (2002)
   – nuclear interactionの cross sectionと kinematicsはここを参照
3. Murphy et al., ApJS, 63, 721-748 (1987)
   – Hua model中の p-p interactionはここを参照

Injection of accelerated ions
(E^{-s}, a(t), α/p ratio)

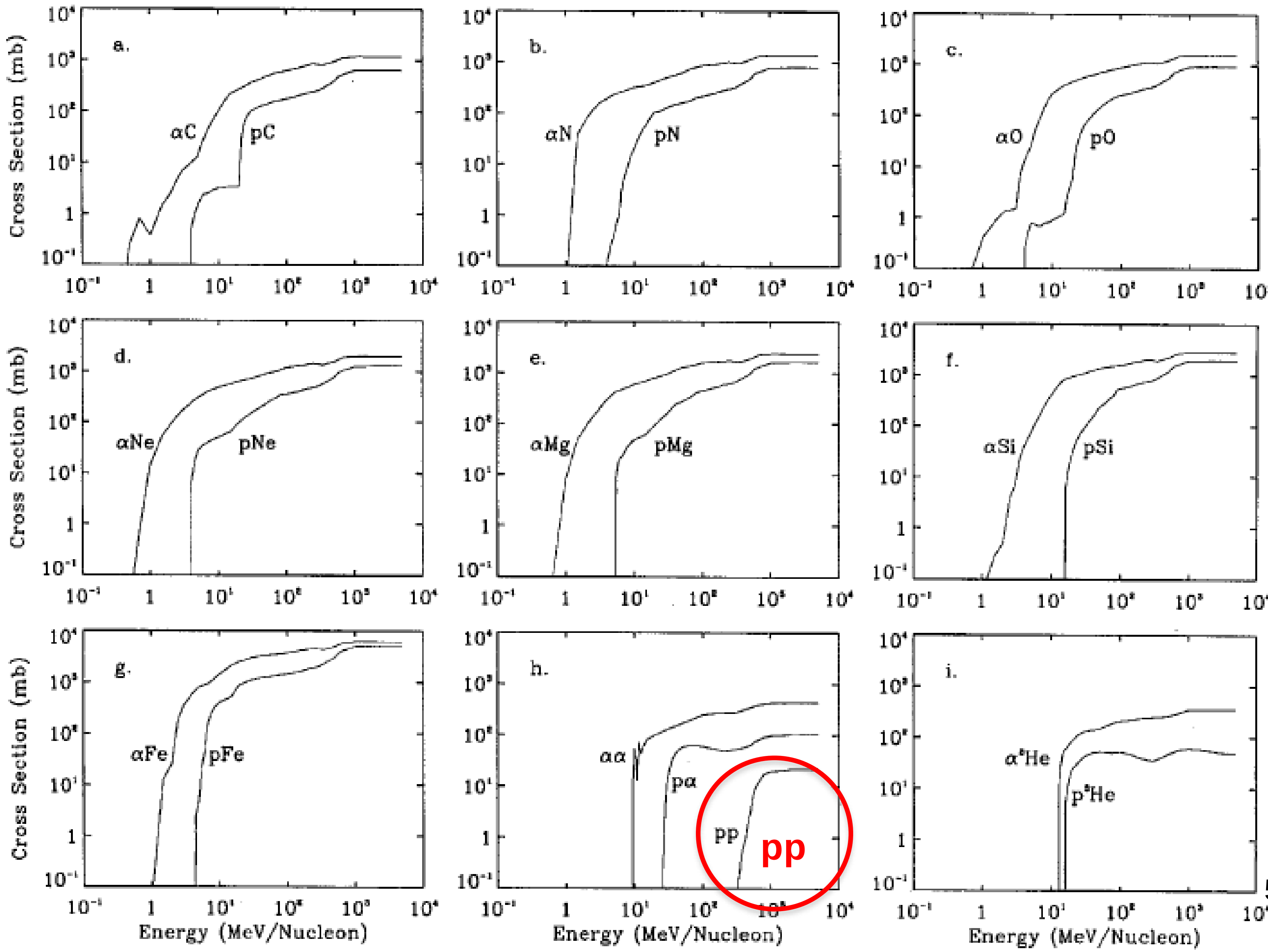


Solar atmosphere model (composition, density)

Neutral Particle Emission



neutron production cross sections (ref [2])



contribution to the total neutron yield (ref [2])

統計加速（Bessel関数型）の場合　　　ショック加速（べき関数型）の場合

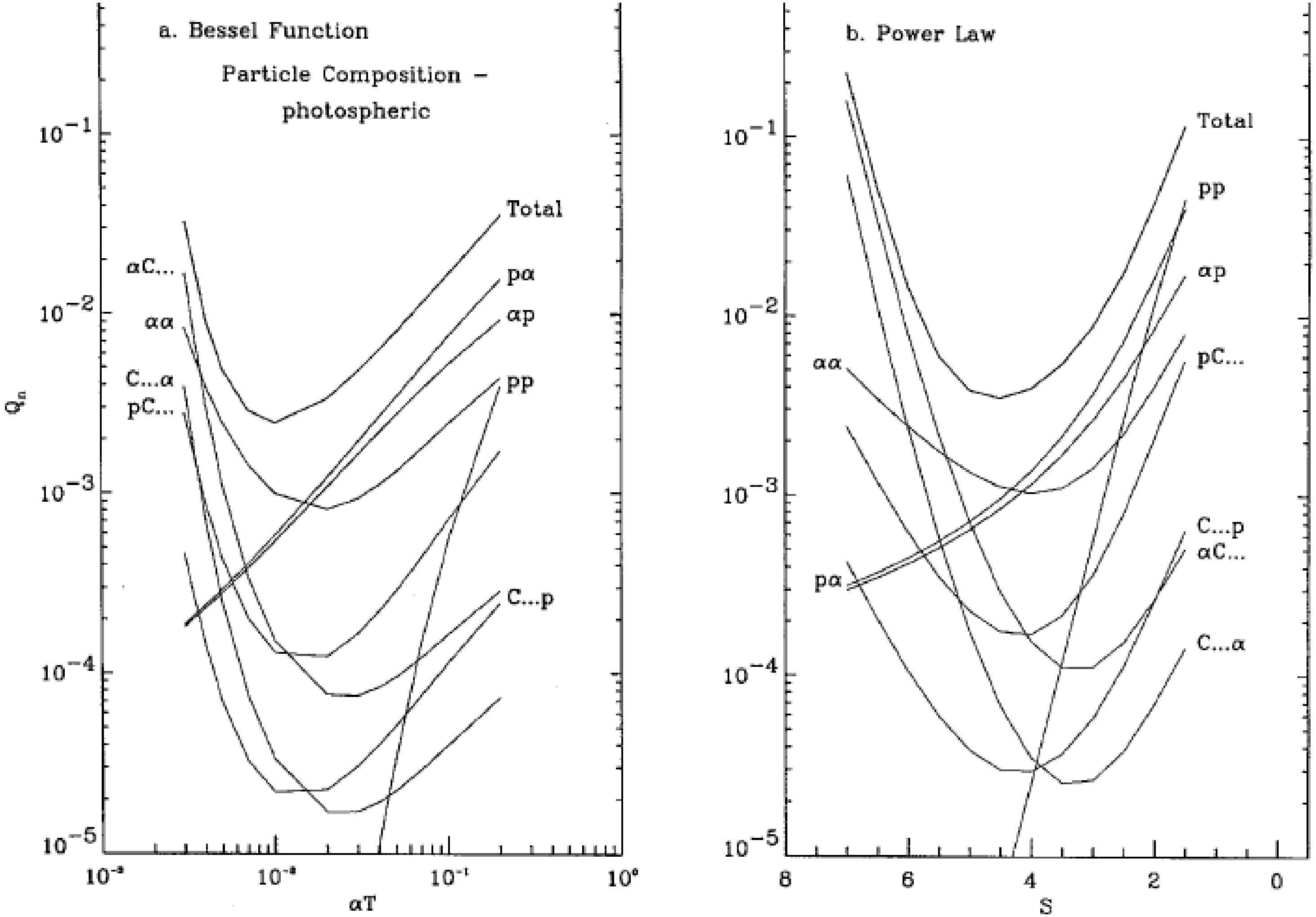
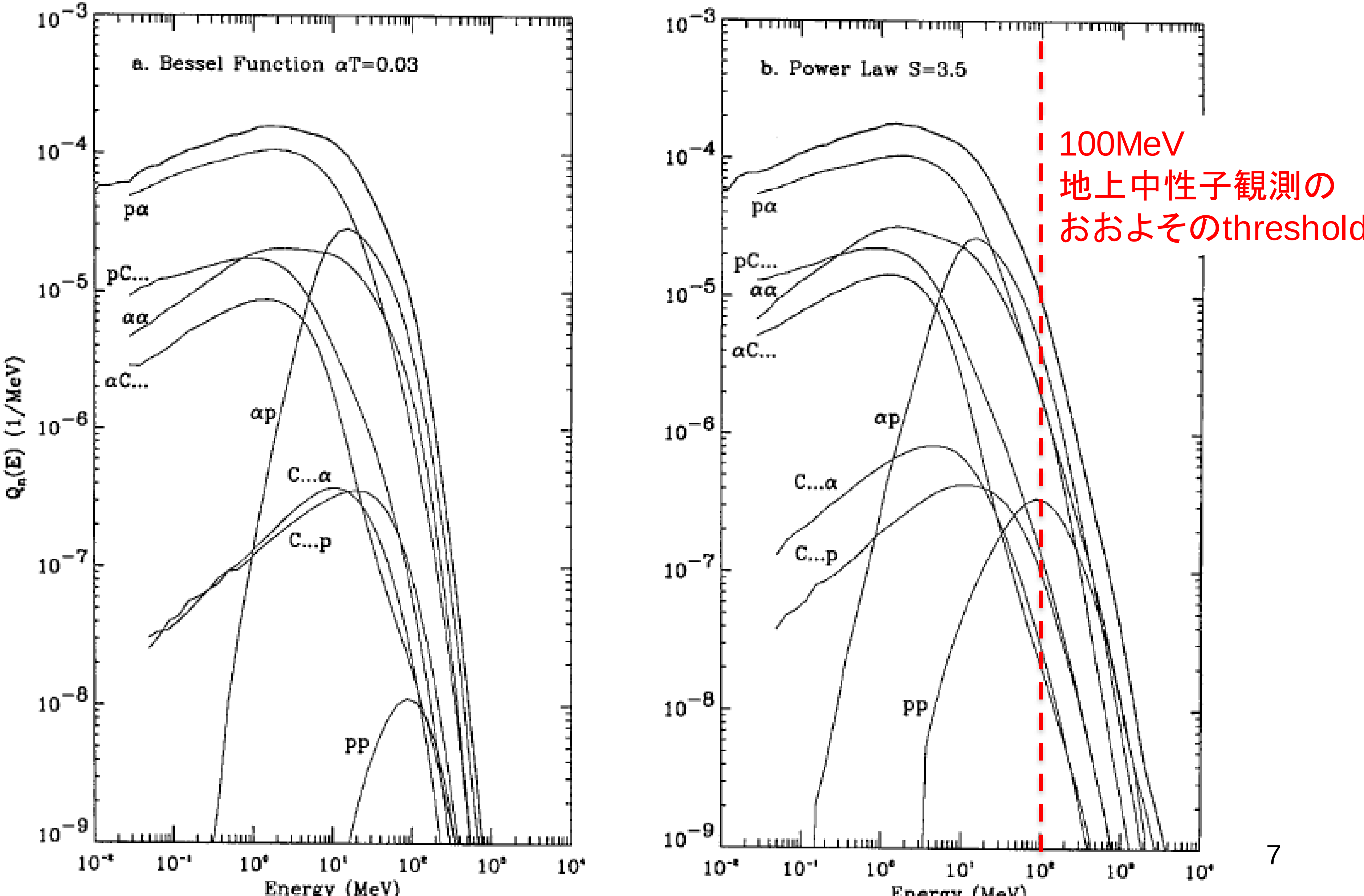


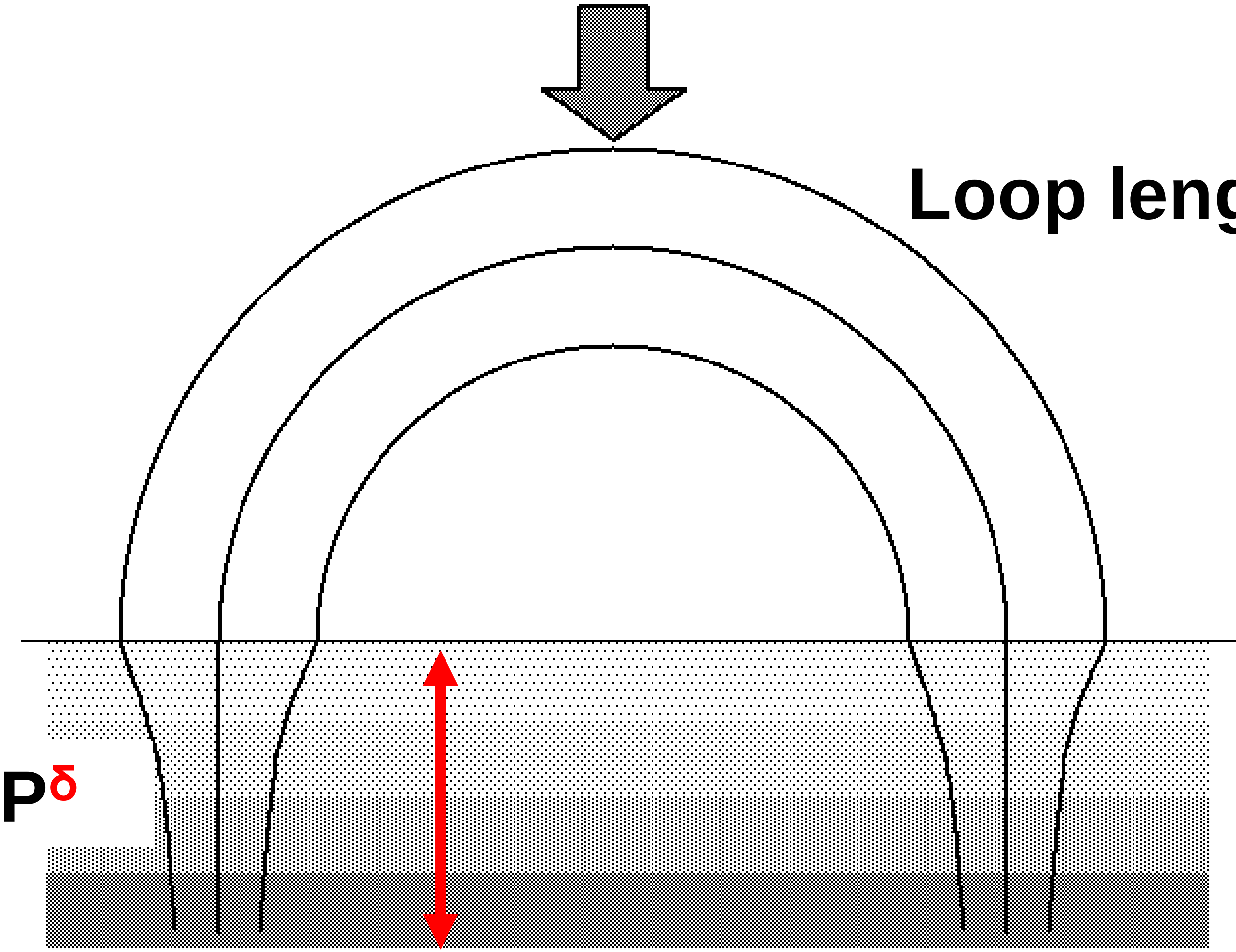
FIG. 4.—Thick target neutron yield Q_n for various reactions as a function of accelerated ion spectra, assuming (*a*) a second-order Bessel function spectrum, $N(E) \approx K_2[(12p/mc\alpha T)^{1/2}]$, expected from stochastic Fermi acceleration, and (*b*) a power-law spectrum, $N(E) \approx E^{-S}$, expected from shock acceleration, normalized for $N_p(> 30\ \mathrm{MeV}) = 1$, and assuming solar photospheric abundances for both the accelerated ions and ambient medium (Table 2).

contribution in spectrum (ref [2])



ここから Murphy et al.の計算結果

Injection of accelerated ions
(E^{-s}, $a(t)$, α/p ratio)



Loop length (L)

$B \propto P^{\delta}$

Solar atmosphere
model (composition, density)

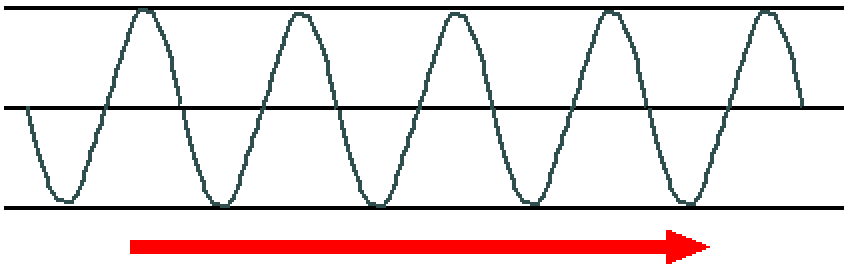
Parameters determining neutral emission

TABLE 1
PARAMETERS

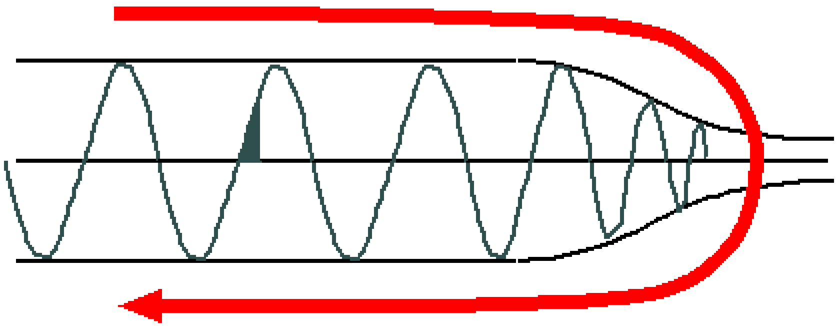
Type	Parameter
Acceleration	Power-law index, s
	Acceleration release time history, $a_{\text{ion}}(t)$
	Accelerated-particle composition
Physical	Level of PAS, λ
	Magnetic convergence, δ
	Loop half-length, L_c
	Ambient composition
	Atmospheric density and temperature model, $n(h)$ and $T(h)$
	Flare heliocentric angle, θ_{obs}

Cross section of gamma-ray and neutron yields

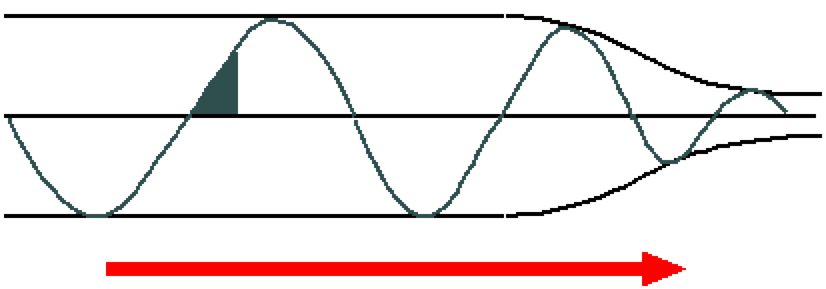
Magnetic Mirroring



Charged particle in a uniform magnetic field

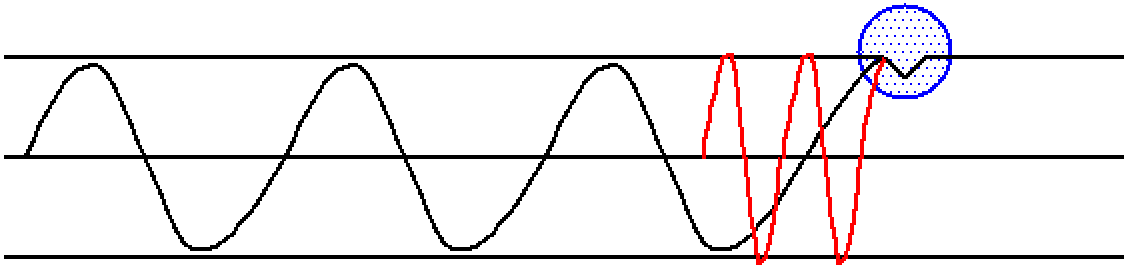


Charged particle in a converging magnetic field (Mirroring)
Mirrored particle never escapes from the loop.



Charged particle with a large pitch angle (cosθ) can penetrate deep in the converging field （loss cone）

(Pitch Angle Scattering) PAS



Pitch angle can change randomly.

Λ : mean free path required for an arbitrary initial angular distribution to relax to an isotropic distribution (energy independent)

λ : level of PAS, Λ/(L/2)

λ= ∞; no scattering

λ= 20; saturated

Composition

impulsive flare accelerated-ion abundances **defined** by Ramaty et al.

TABLE 2

AMBIENT AND ACCELERATED-ION COMPOSITIONS

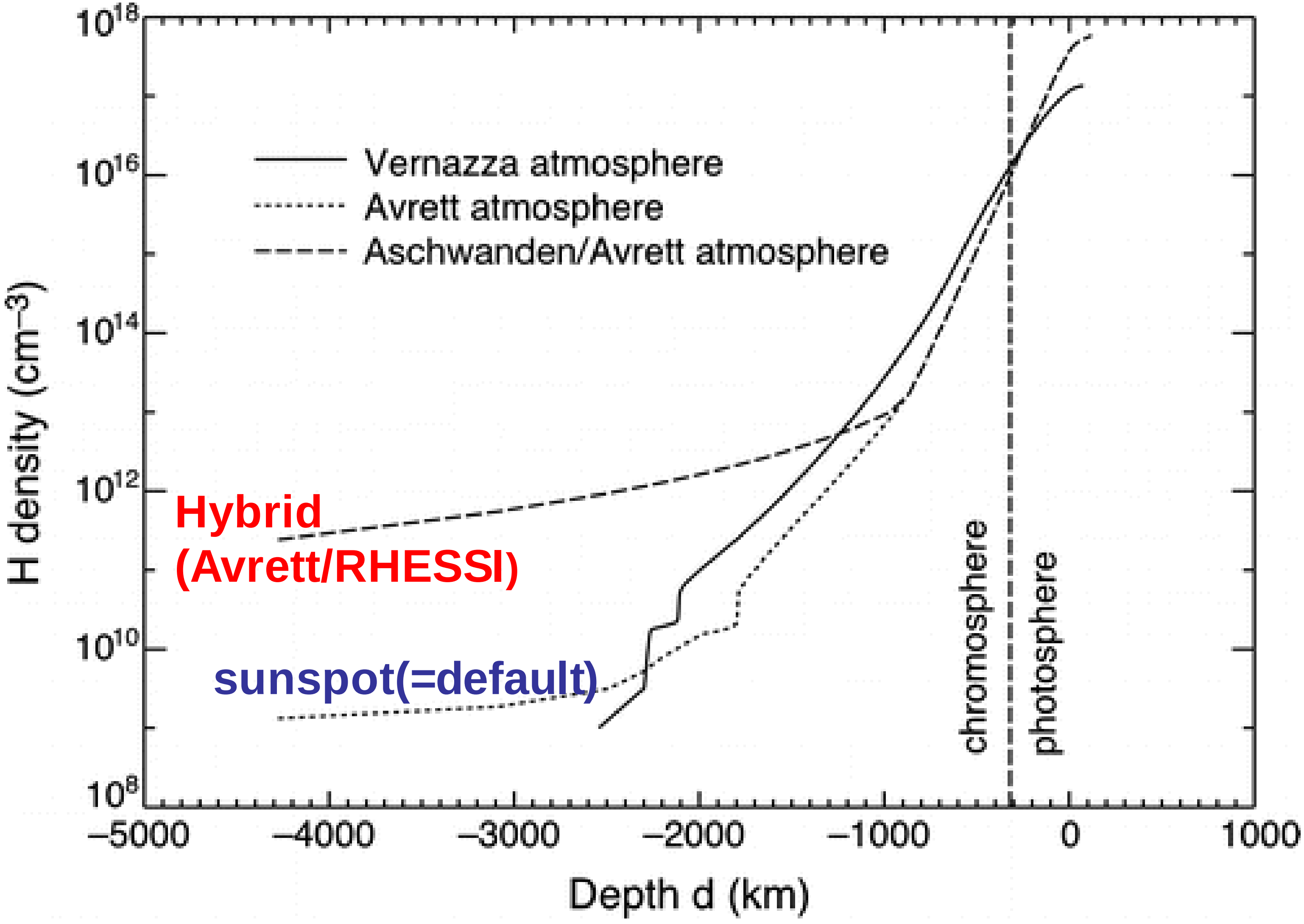
Element	Ambient	Accelerated
H	1.0	1.0
^{3}He	3.0×10^{-5}	0.5
^{4}He	0.1	0.5
C	2.96×10^{-4}	4.65×10^{-3}
N	7.90×10^{-5}	1.24×10^{-3}
O	6.37×10^{-4}	1.00×10^{-2}
Ne	1.59×10^{-4}	4.55×10^{-3}
Mg	1.25×10^{-4}	5.89×10^{-3}
Al	1.00×10^{-5}	1.57×10^{-4}
Si	9.68×10^{-5}	4.55×10^{-3}
S	2.03×10^{-5}	9.56×10^{-4}
Ca	6.75×10^{-6}	1.06×10^{-4}
Fe	8.54×10^{-5}	1.34×10^{-2}

$\alpha/p = 0.1$ or 0.5

$\alpha/O = 50$

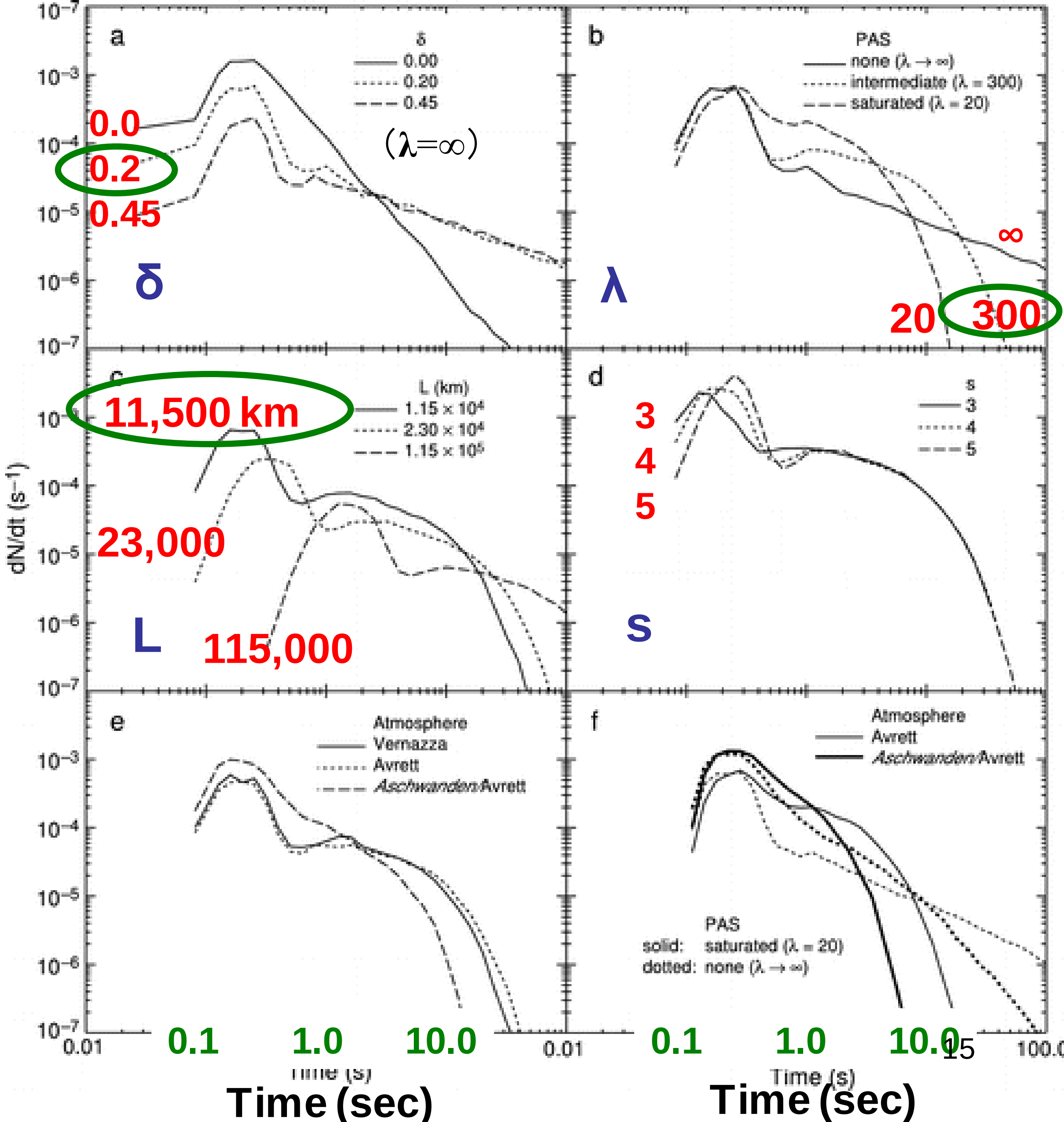
$^3He/^4He = 1$

Solar Atmosphere Model



Basic Processes

Nuclear interaction rate time history



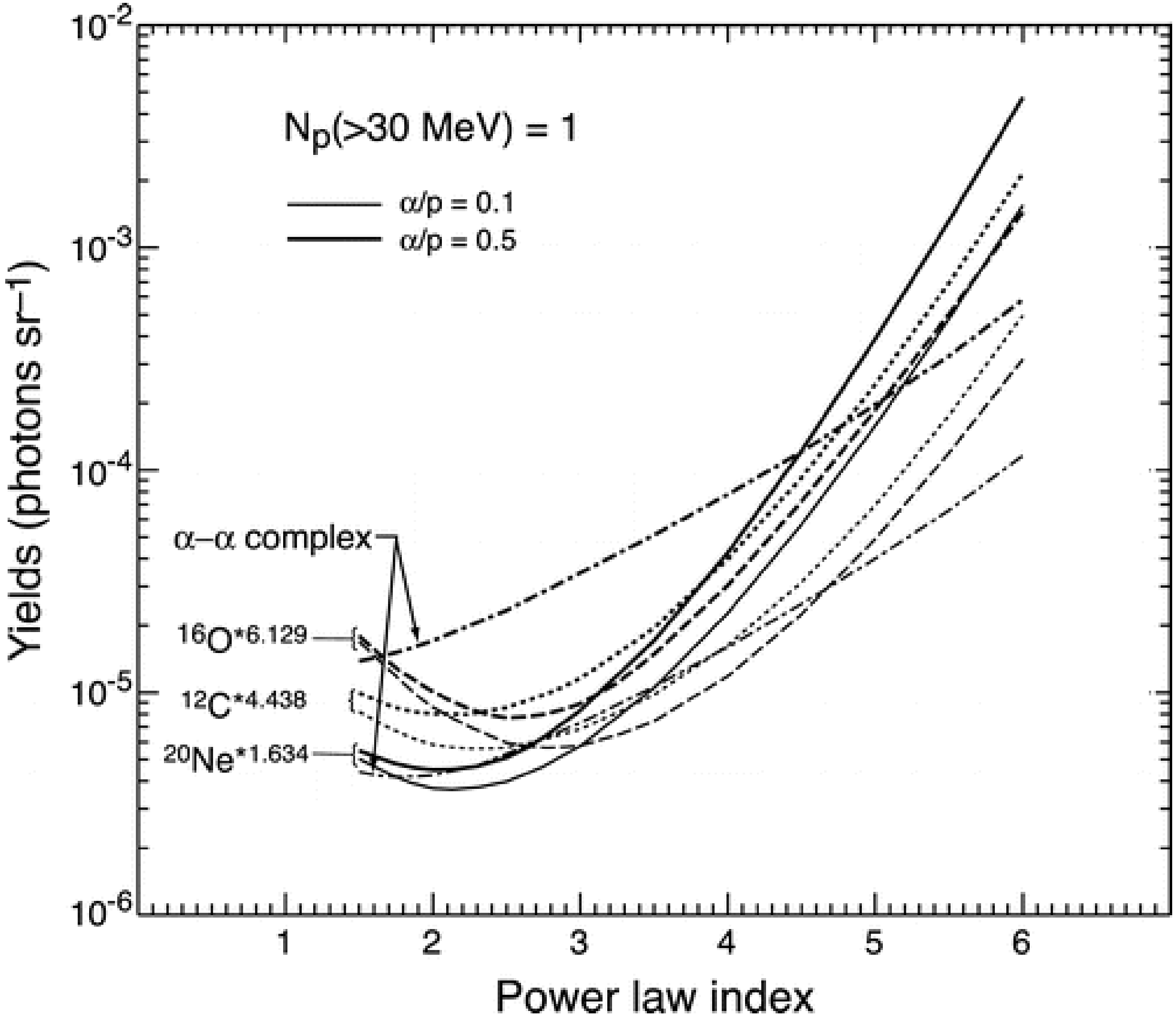
a(t) ; instantaneous
α/p = 0.5
s=4
λ=300
δ=0.2
L = 11,500km

まとめ

- Murphy et al.が フレアループ内での高エネルギーイオンの運動を追跡し、foot pointでの nuclear interaction rateを計算した
- 簡単なループモデルで、様々なparameterをふり、rateの time profileを計算
- PAS=∞（散乱しない場合）を除き、rateは 100秒程度で急激に減衰
- 継続的injectionがない限り、フレア中の高エネルギー粒子の寿命は100秒程度

Backup

Gamma-line yield (time integrated)



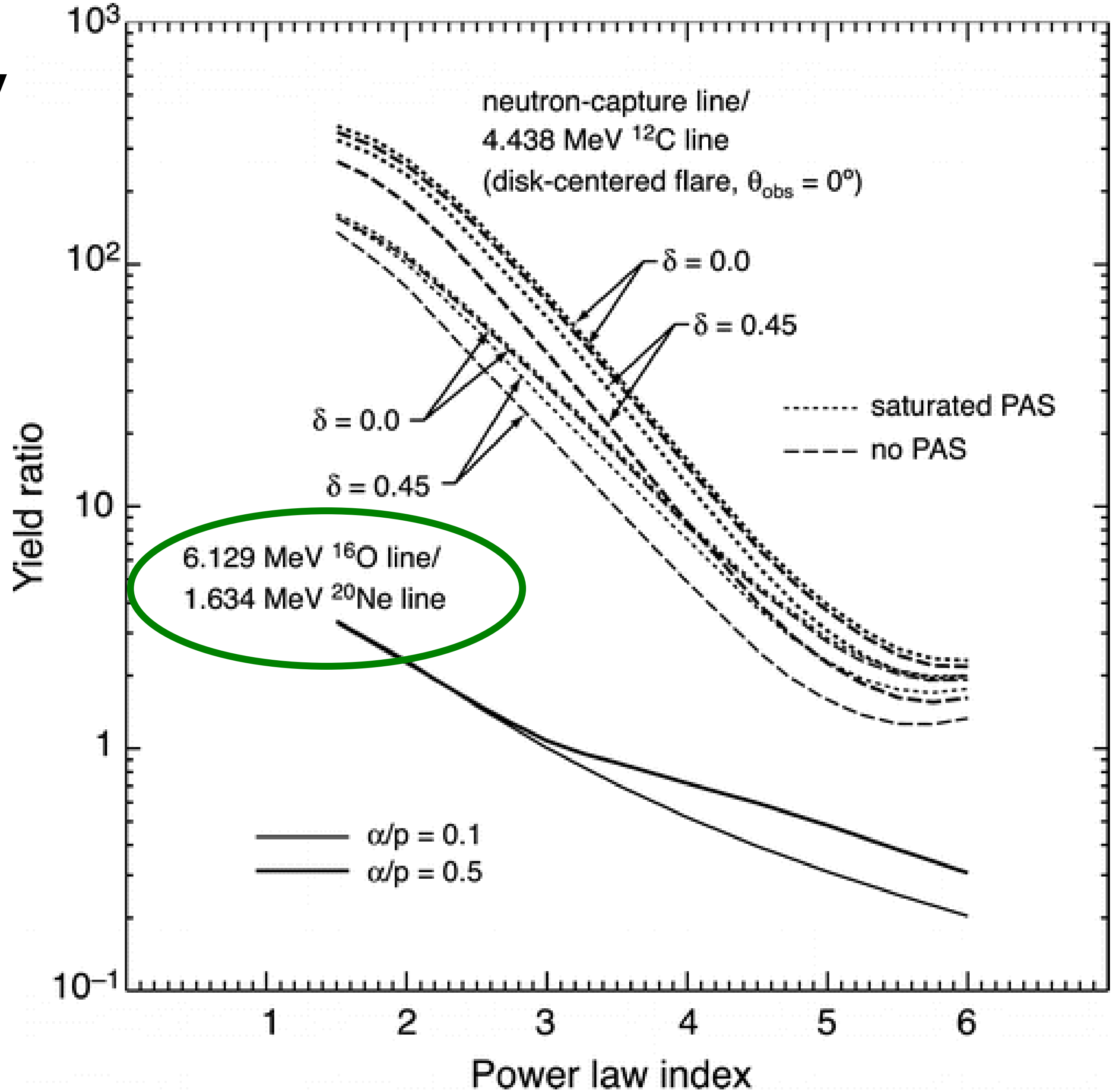
ATTENTION TO NORMALIZATION

Independent from the physical parameters

α- αcomplex α+ He → ^{7}Be*, ^{7}Li* → 0.478, 0.429 MeVγ

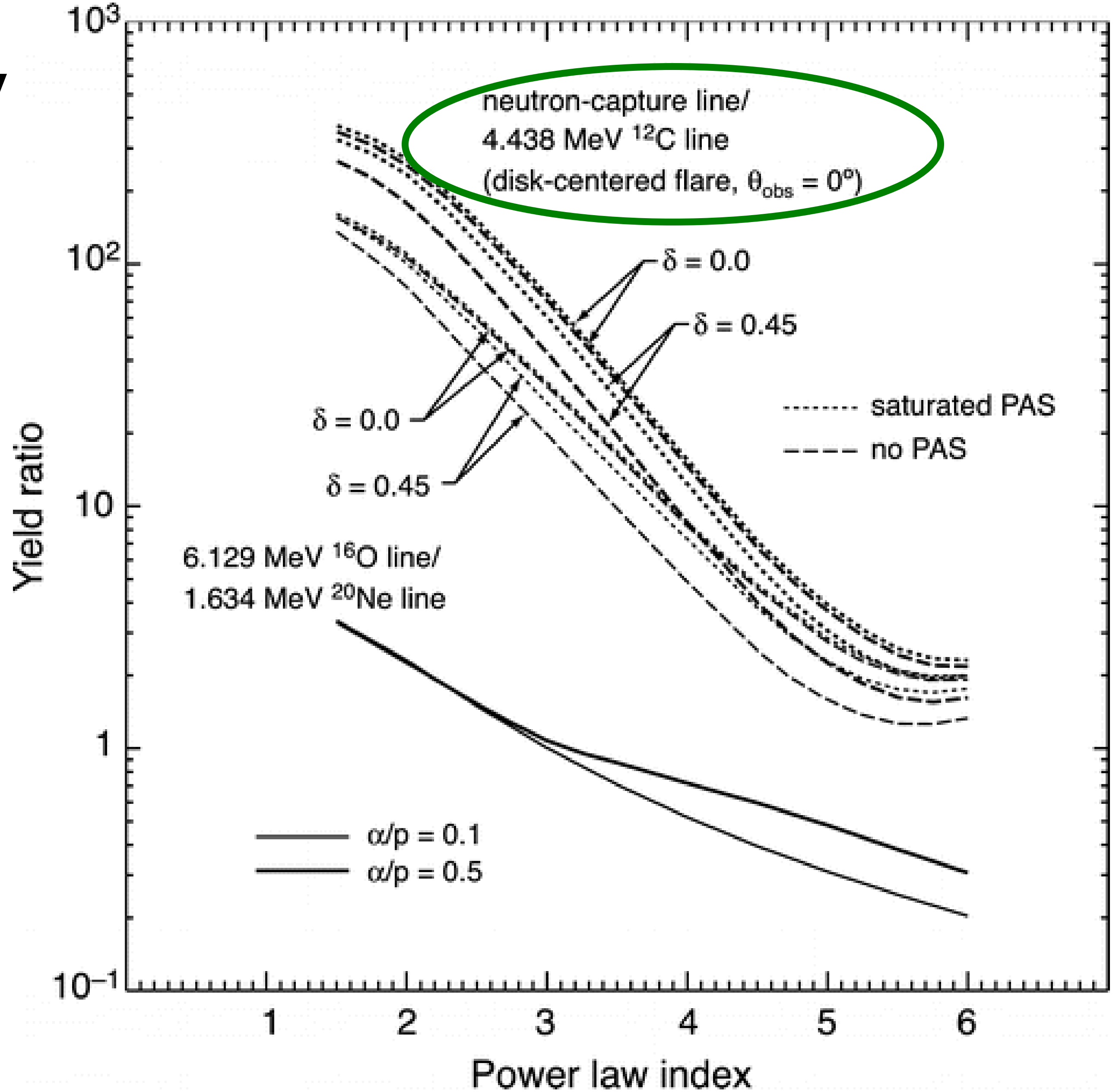
Power index dependence is different from line to line. -> RATIO??

Gamma-ray yield ratio



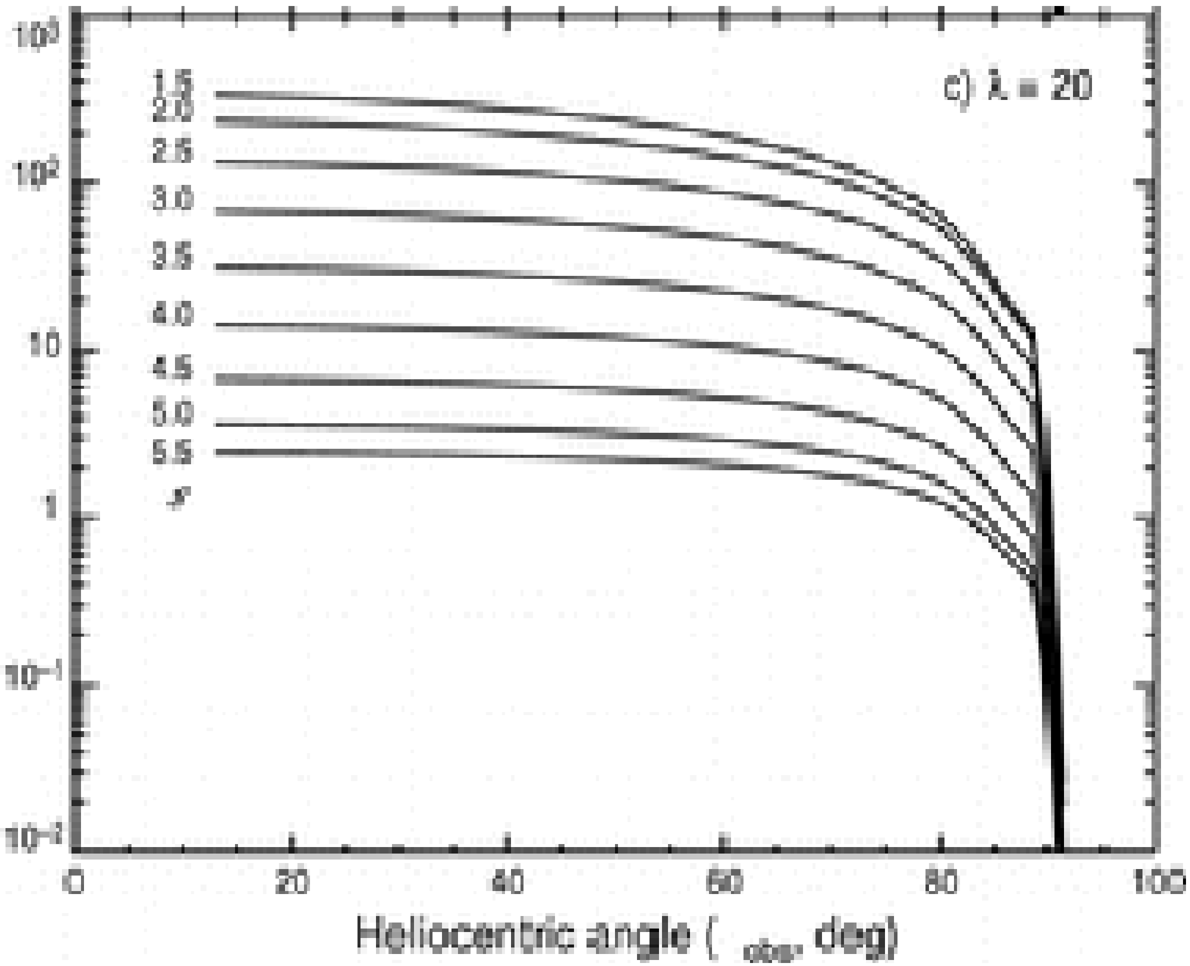
Gamma-line ratios are good estimator for the accelerated ion power index.

Gamma-ray yield ratio

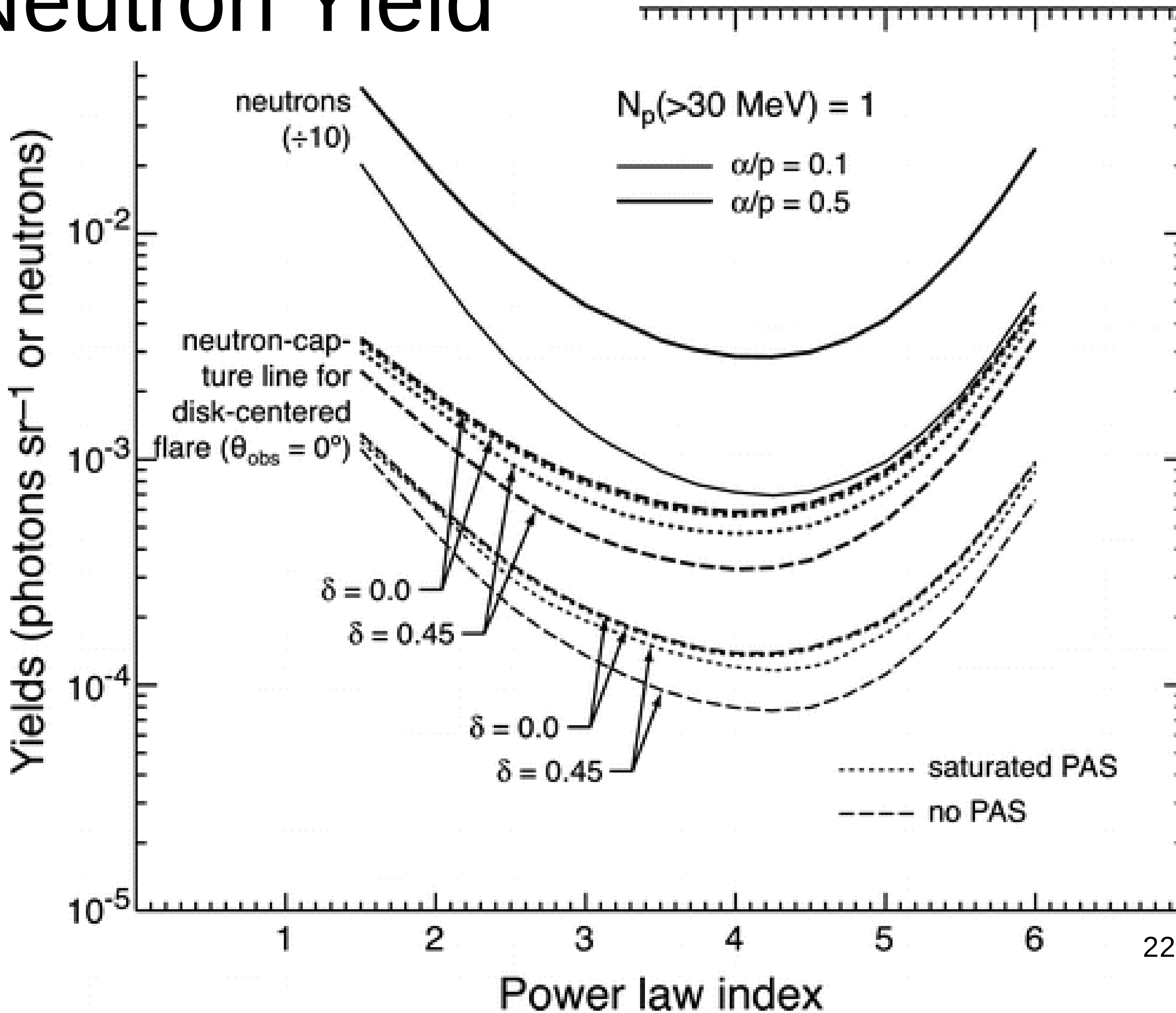


Gamma-line ratios are good estimator for the accelerated ion power index.

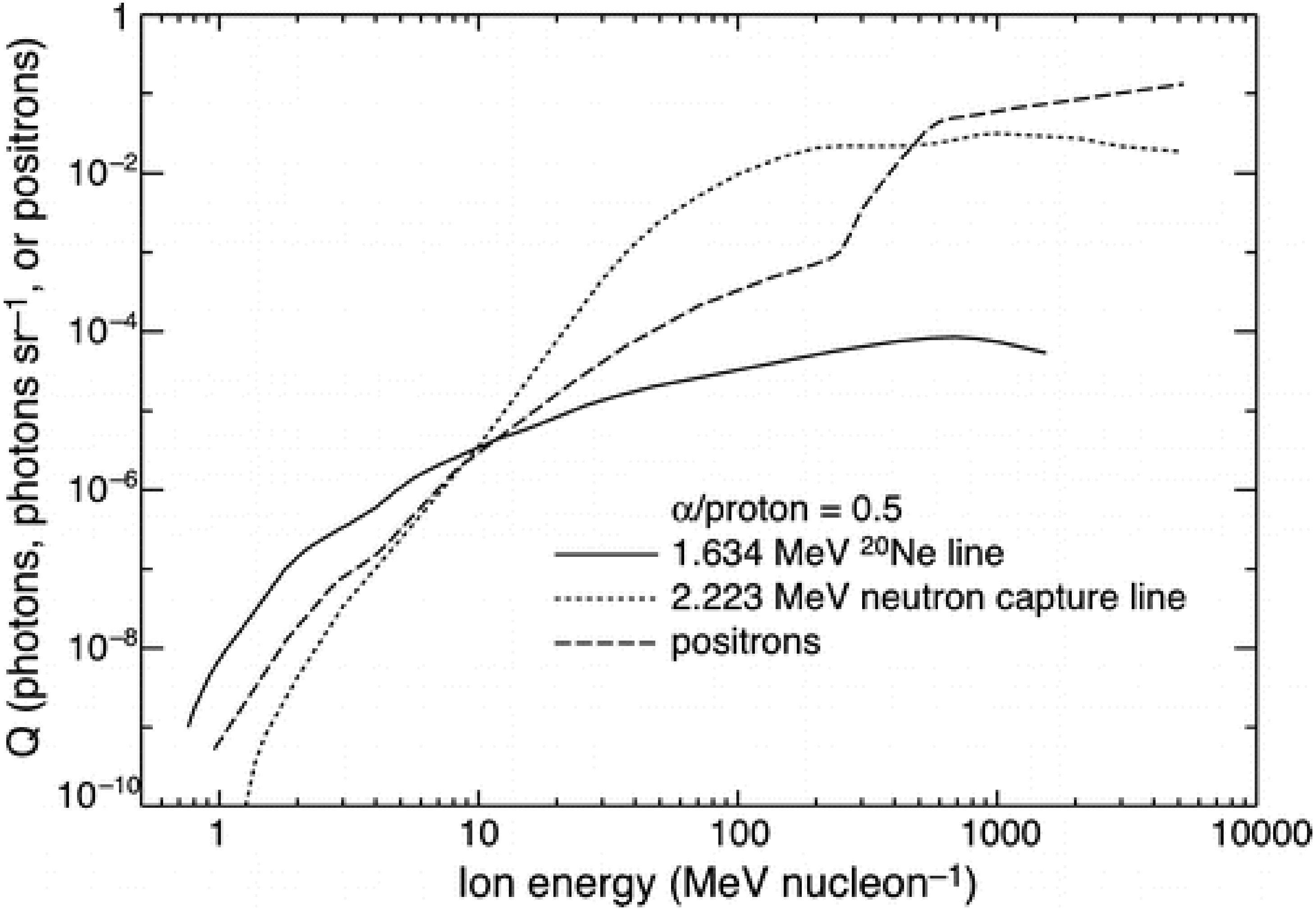
2.223 MeV/4.438MeV(C) ratio heliocentric angle dependence



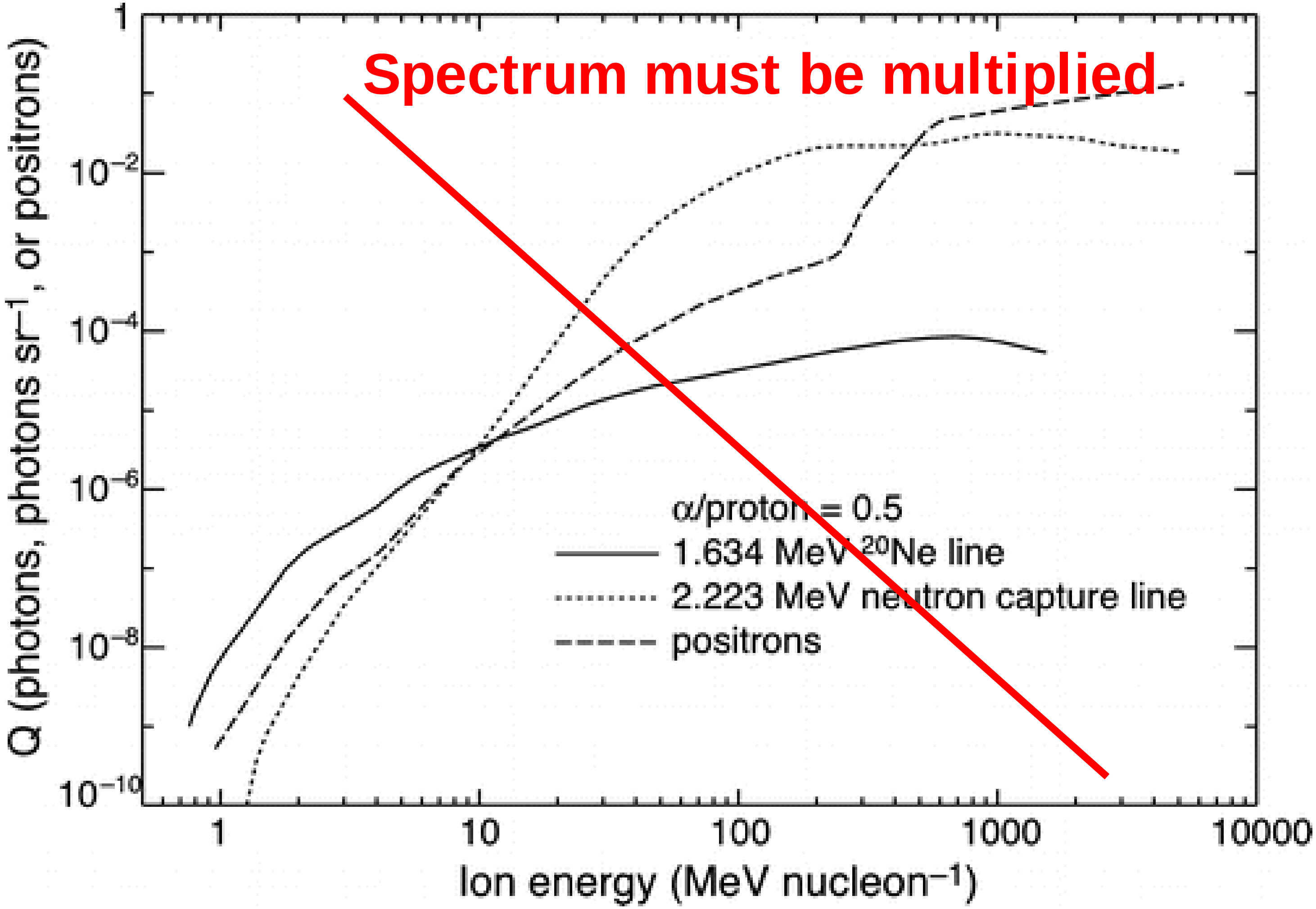
Neutron Yield



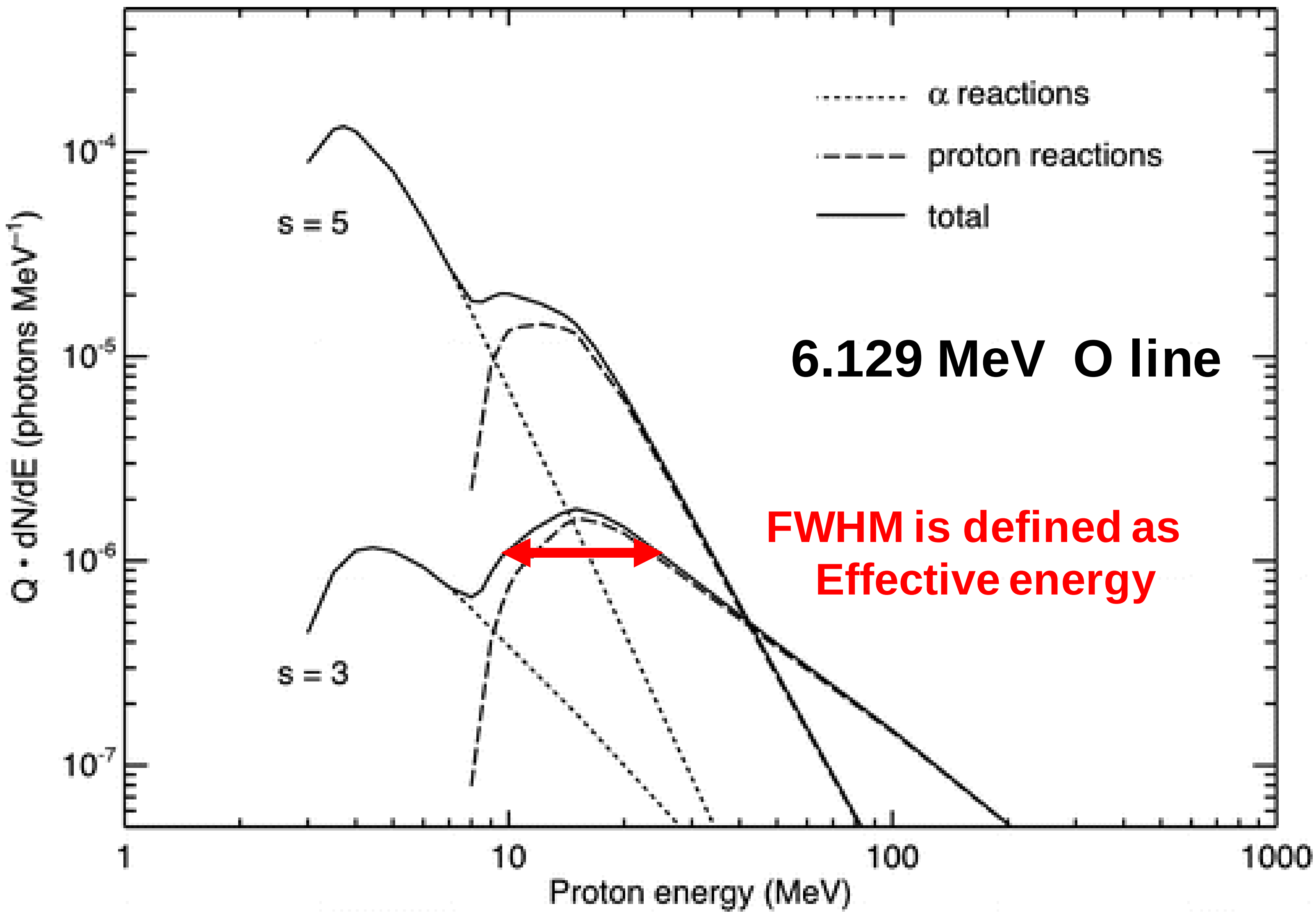
Effective Energy (1)



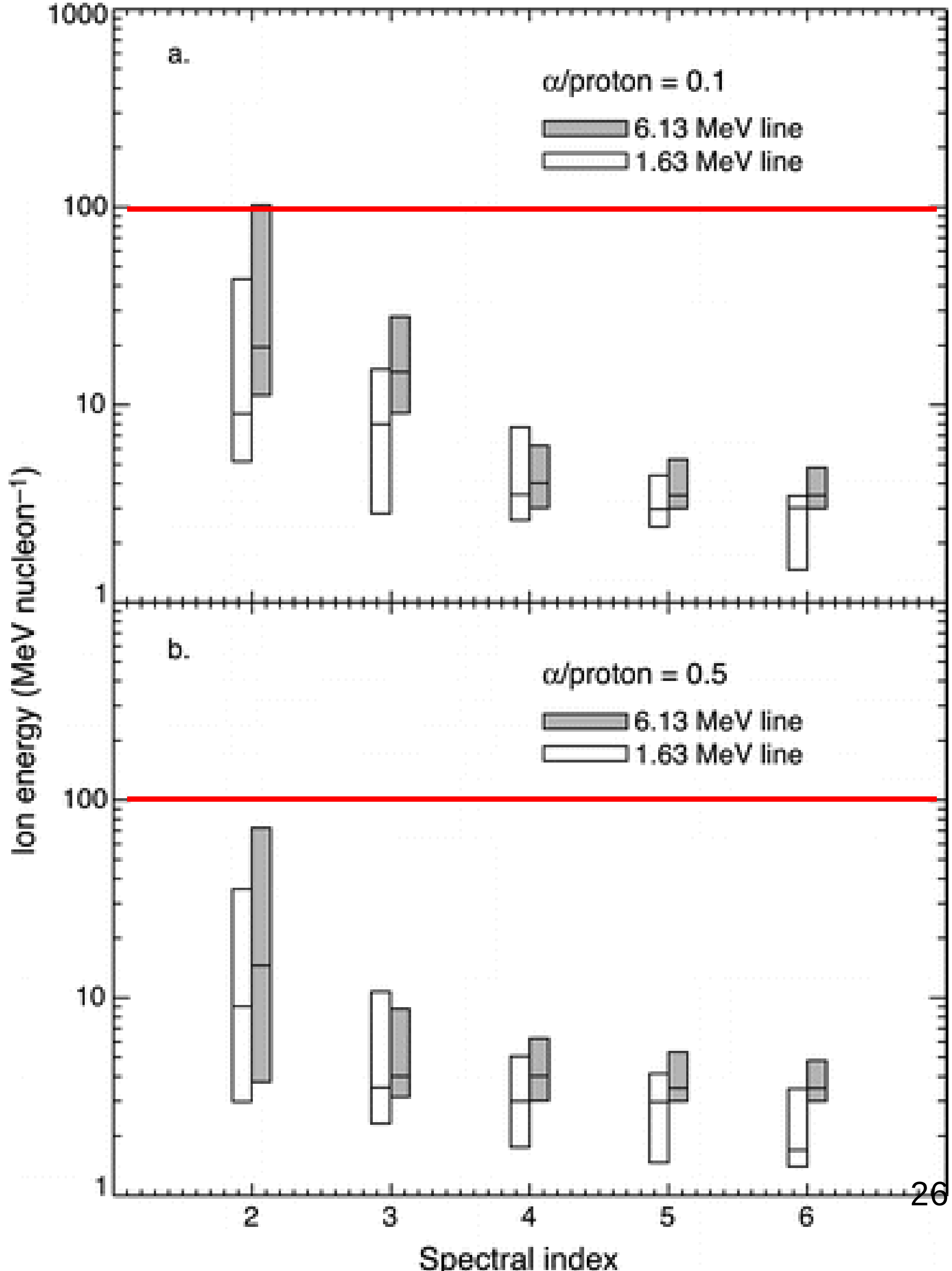
Effective Energy (1)



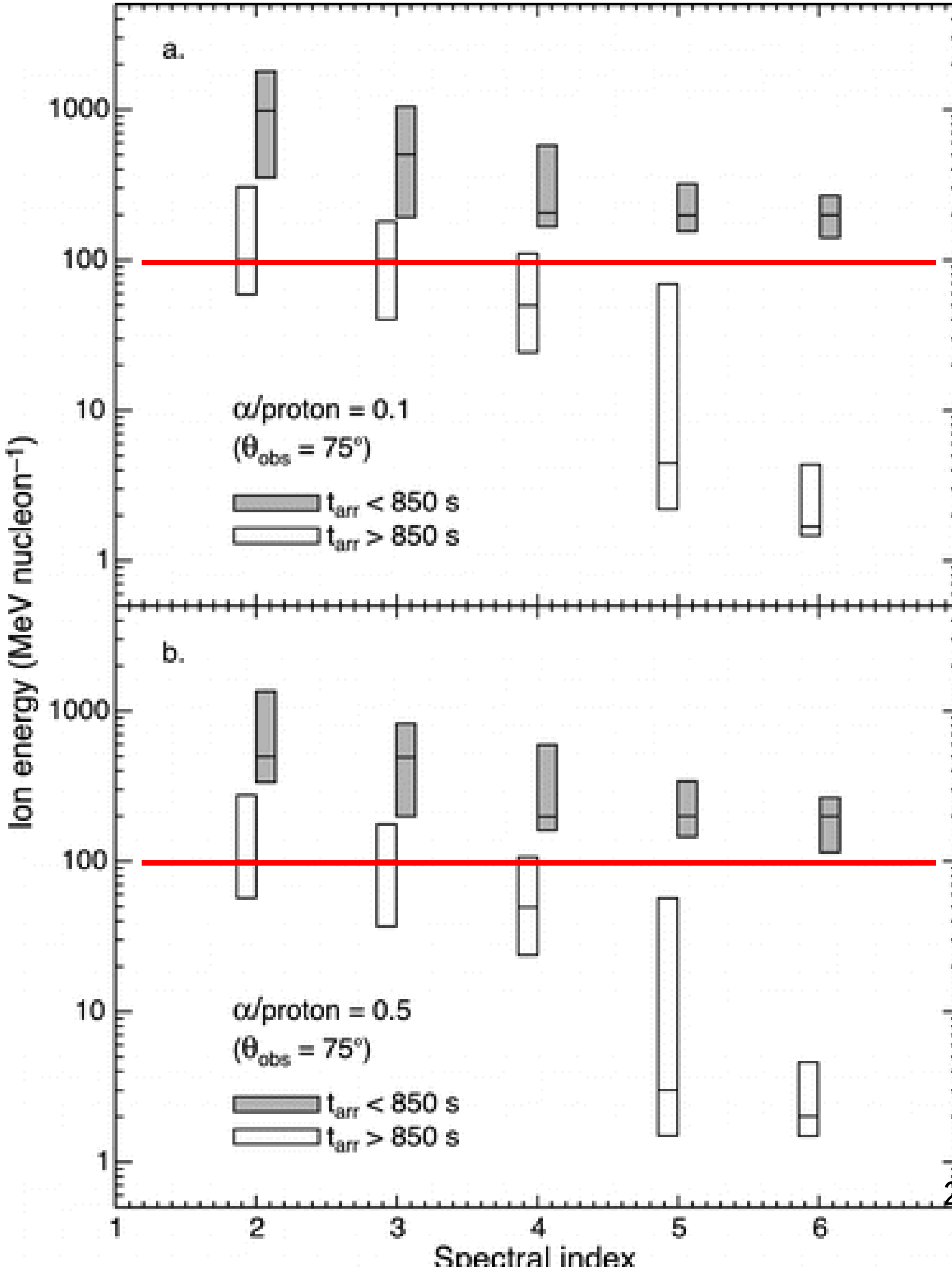
Effective Energy (2)



Effective Energy (3) (gamma-line)



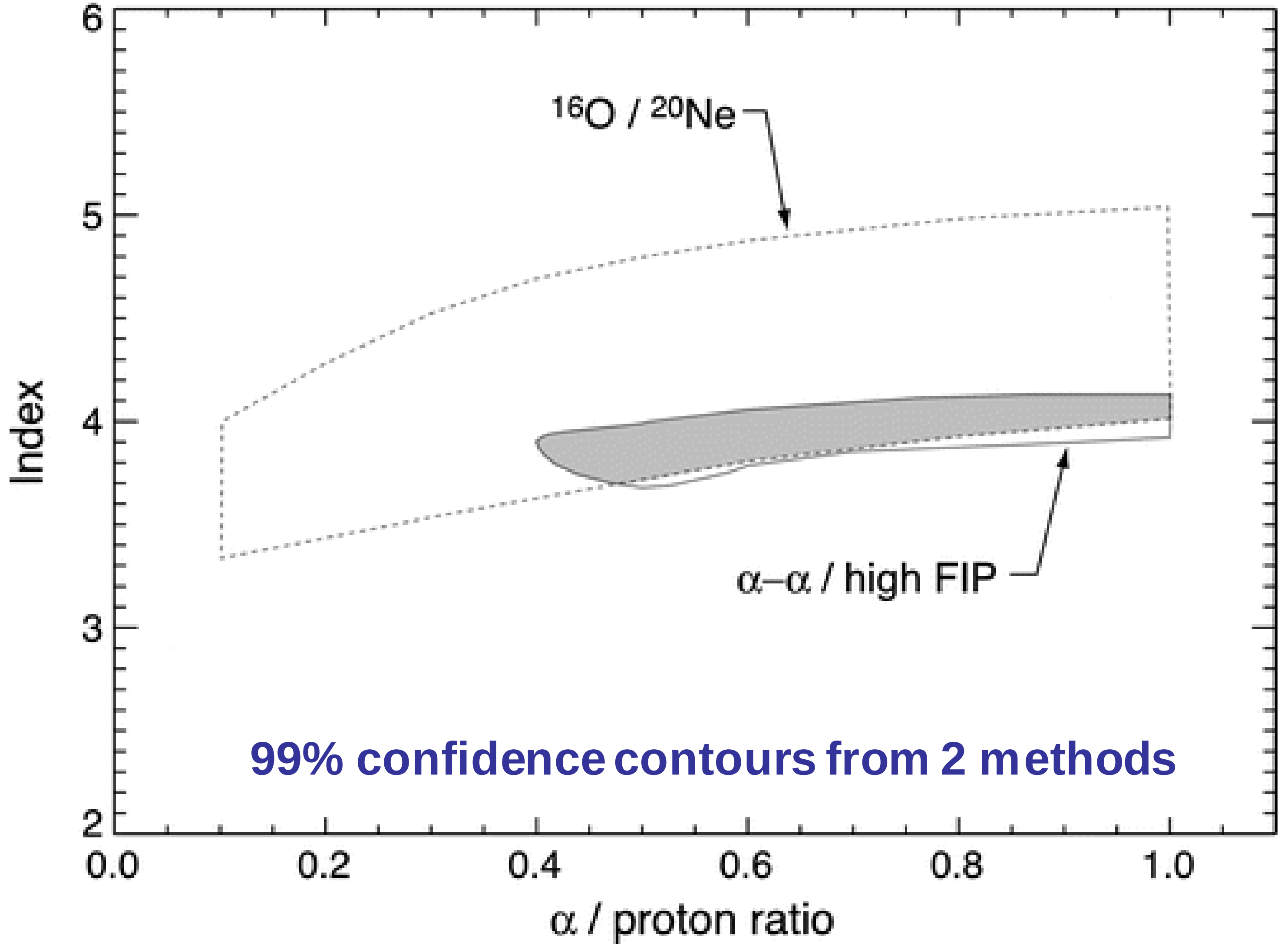
Effective Energy (4) (neutron)



Application to the June 4 1991 event

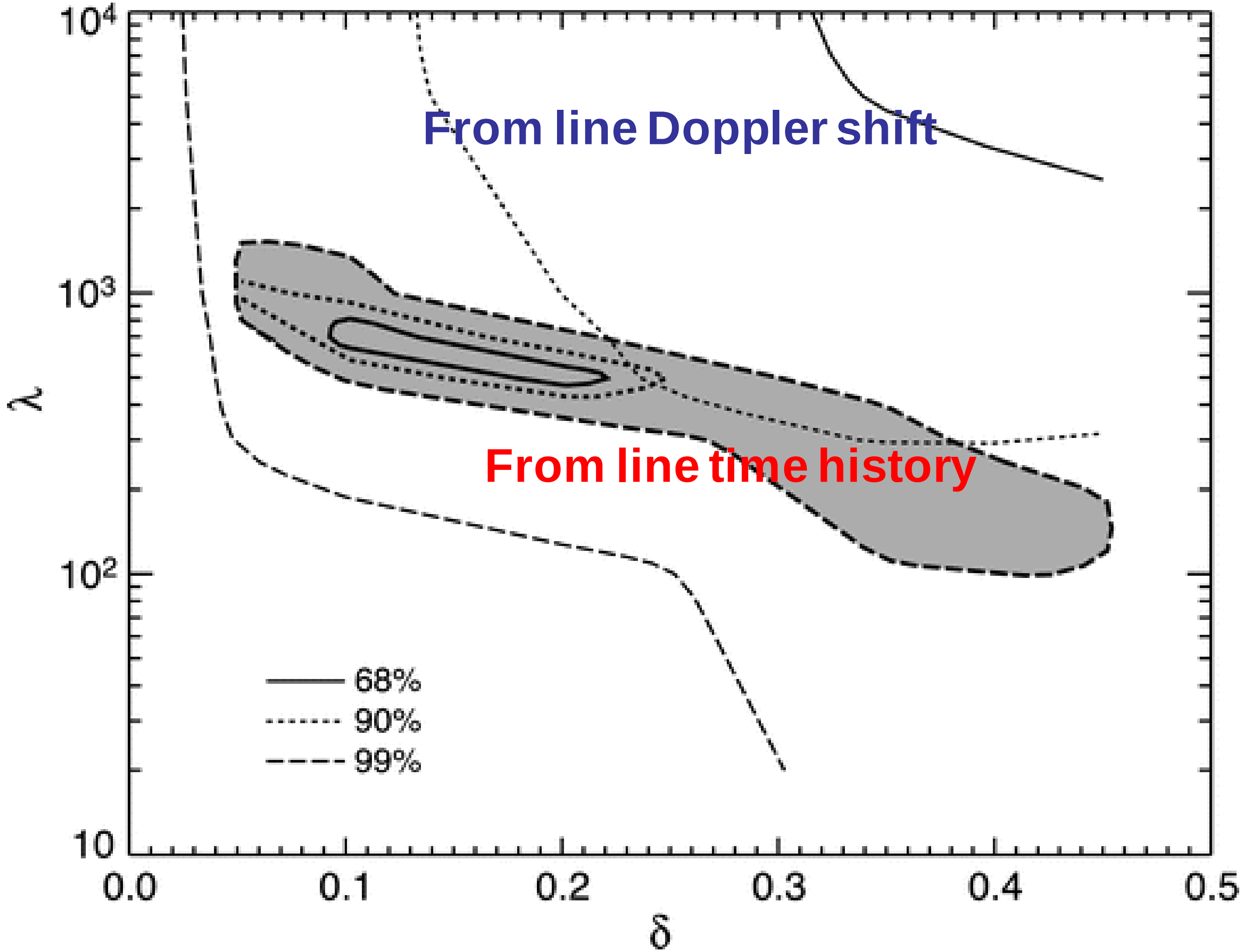
- From optical observation, L=11,500, 34,500 or 65,000 km (combination of the foot point)
- Power index,α/p ratio are obtained from O/Ne ratio and α-α complex/C ratio

Index vs. α/p ratio



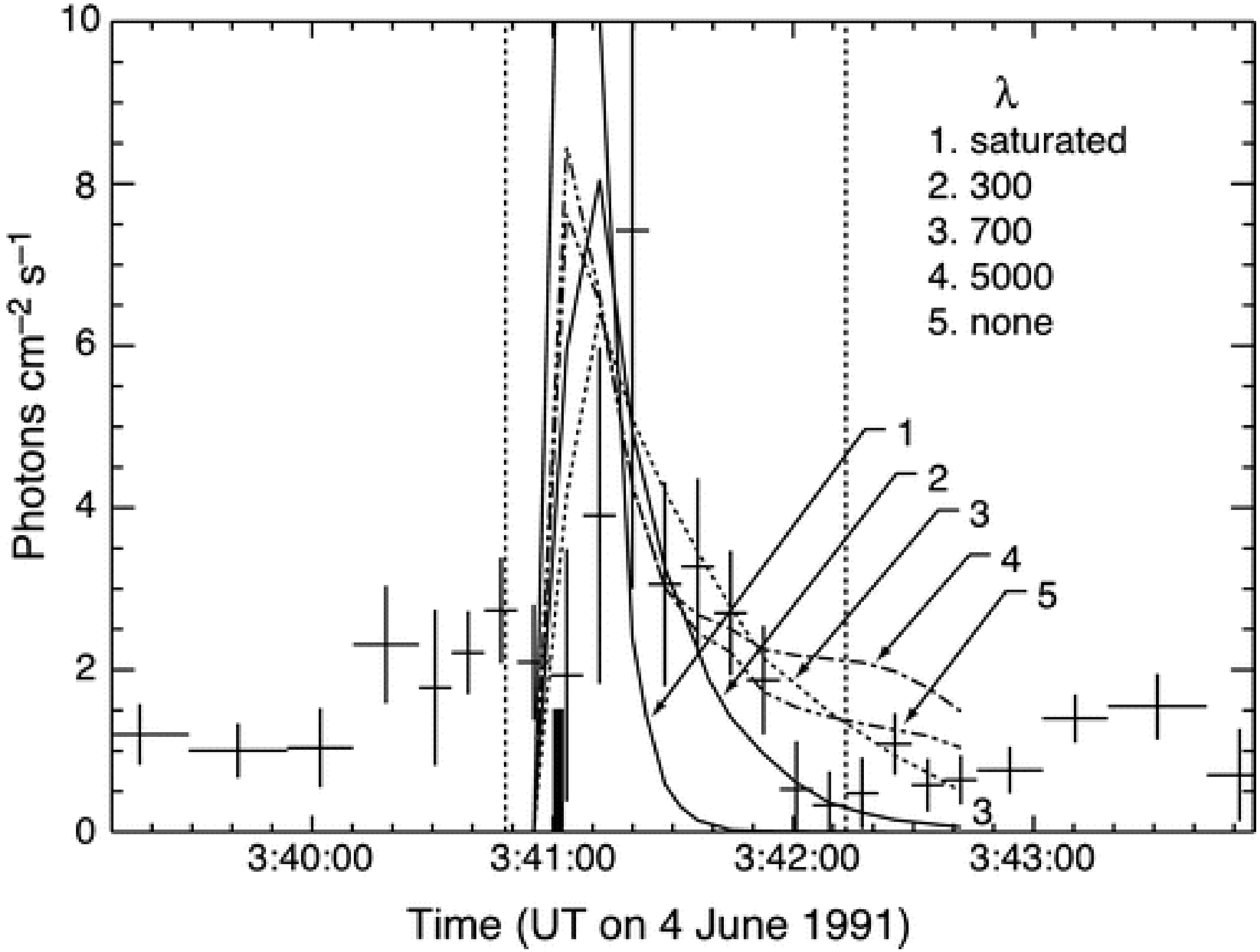
99% confidence contours from 2 methods

δ- λ(physical paramters)



a(t) ; instantaneous

Prompt γtime history

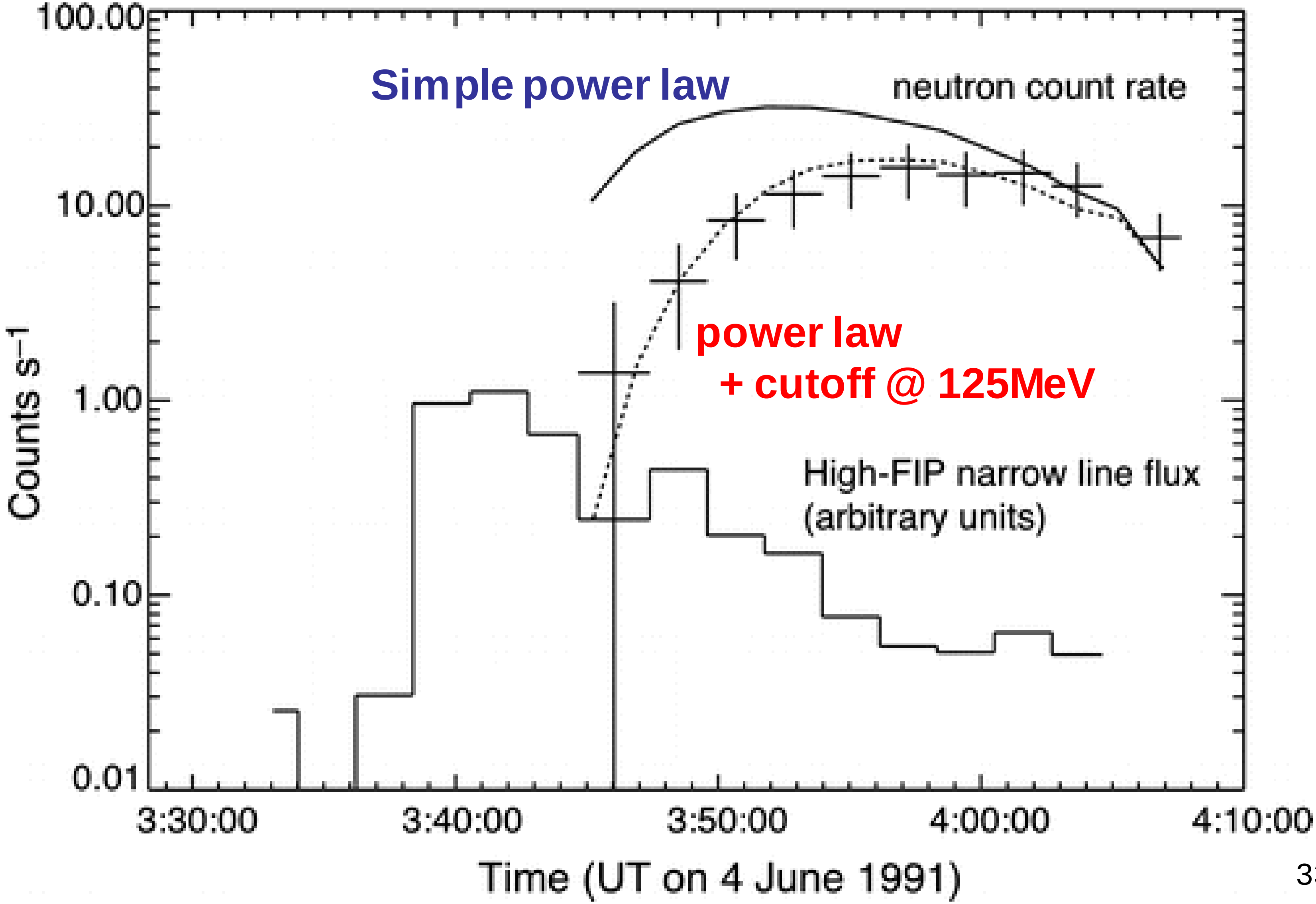


a(t) ; instantaneous

Neutron profile

- Using all the parameters determined, neutron profile observed by OSSE at >23MeV is compared with model.

Neutron profile (space)



Summary

- Self-consistent method using updated cross section is developed.
- Success requires measurements that cover a wide range of the observables…
- The method is applied for an event.
- Neutron observations are important for >100MeV.

additional

Neutron Yield (2)