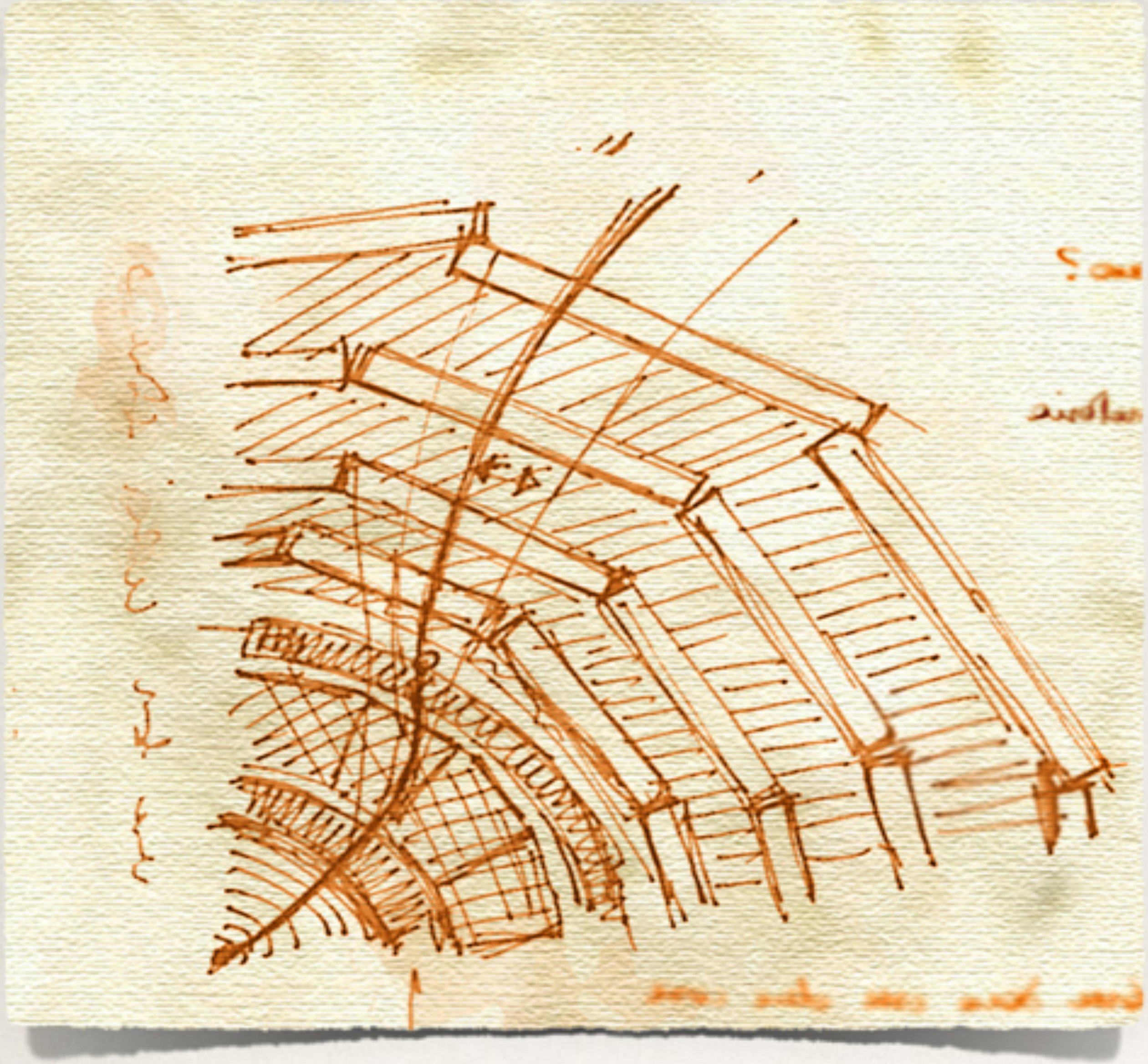


XI Escola do CBPF

Curso de Pós-Graduação

Notas de Aula

A Física dos Detectores de Partículas

Dr Arthur M. Moraes - CBPF

(web-page: http://cern.ch/amoraes)

21 de Julho de 2017

Introdução

Programa do Curso:

Aula 1: De Rutherford ao LHC: Desenvolvimento dos detectores ao longo da história da física das partículas elementares. (2ªf. 17/07)

Aula 2: Interações das partículas com a matéria. (3ªf. 18/07)

Aula 3: Detectando partículas carregadas & neutras. (5ªf. 20/07)

Aula 4: Cintiladores: detectando partículas via luminescência. (6ªf. 21/07)

Aula 5: Detectores de semicondutores: medidas de alta precisão. (2ªf. 24/07)

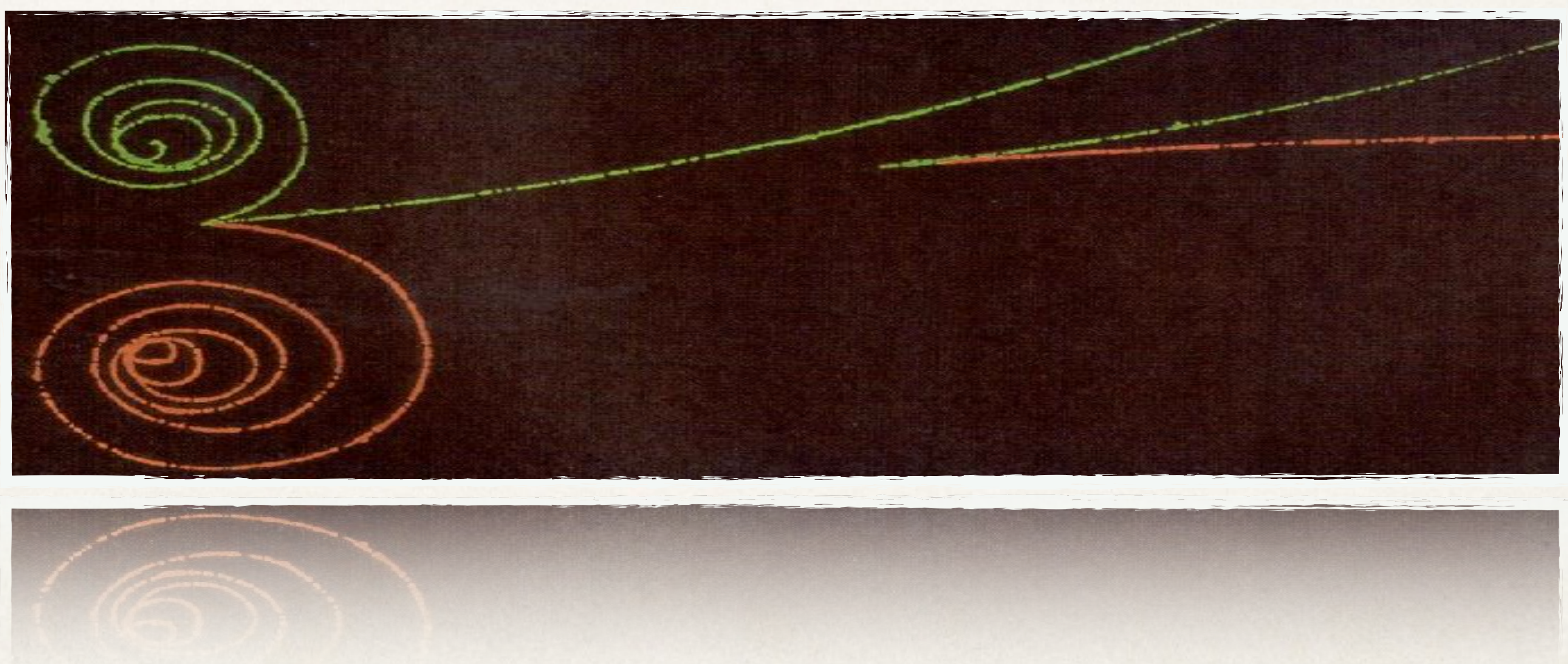
Aula 6: Detectores de gás: medindo partículas em grandes volumes. (3ªf. 25/07)

Aula 7: Calorímetros: eletromagnéticos & hadrônicos. (5ªf. 27/07)

Aula 8: Exemplos de aplicações dos detectores em várias áreas. (6ªf. 28/07)

Aula 4

Interações de partículas neutras com a matéria



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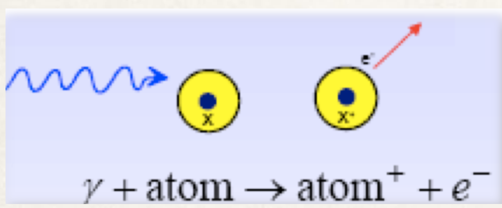
Interação de fótons com matéria

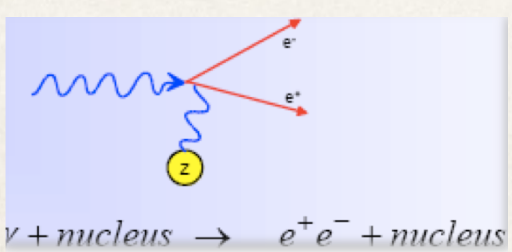
Característica das interações de fótons com a matéria: ***uma interação simples remove o fóton do feixe!***

causas: ***absorção total*** ou ***espalhamento***

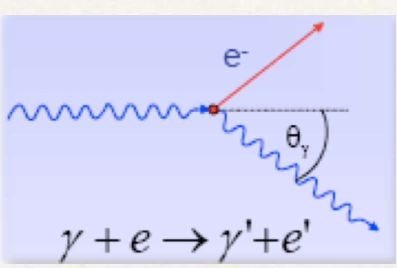
Efeito fotoelétrico

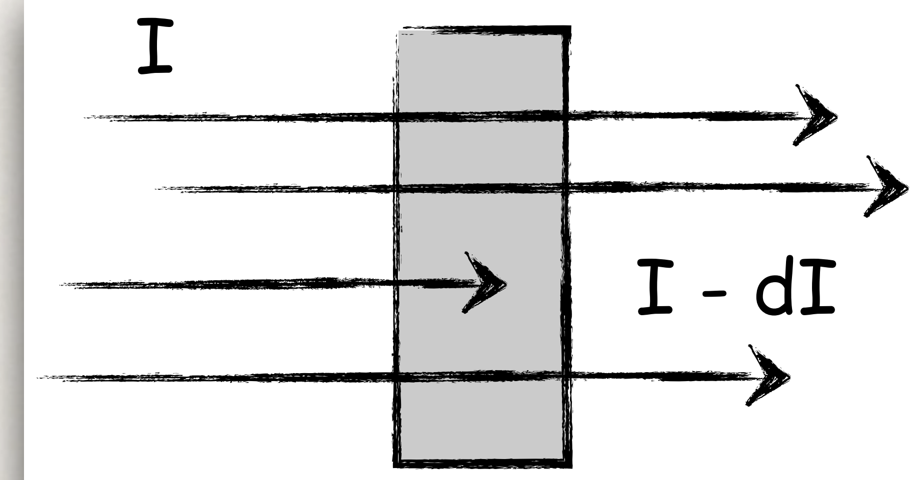


Produção de pares e^+e^-



Espalhamento Compton





$$dI = -\mu\, I\, dx$$

[μ : absorption coefficient]

depends on E, Z, ρ

➤ Beer-Lambert law:

$$I(x) = I_0 e^{-\mu x}$$

with $\lambda = 1/\mu = 1/n\sigma$

[mean free path]

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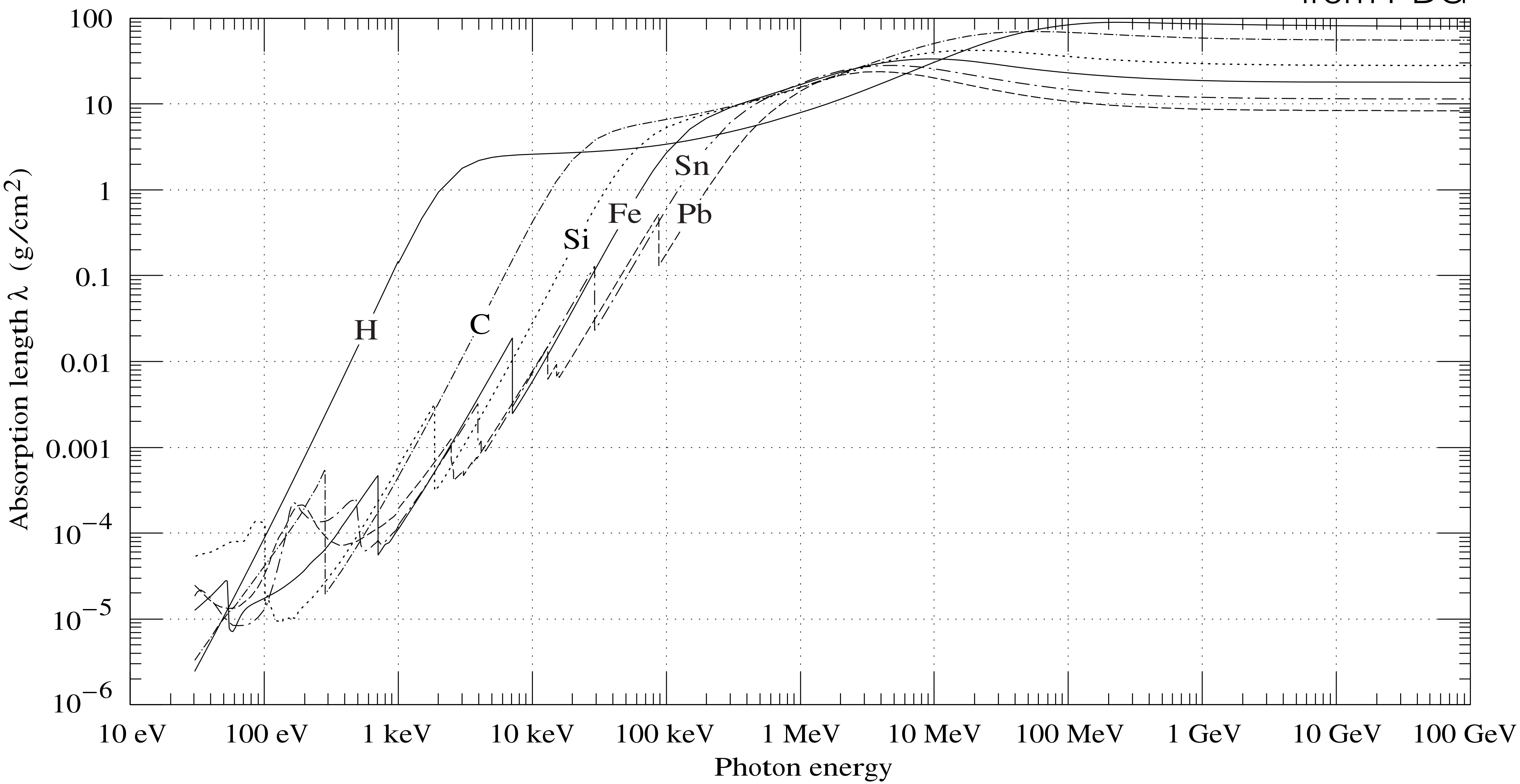
Interação de fótons com matéria

from PDG



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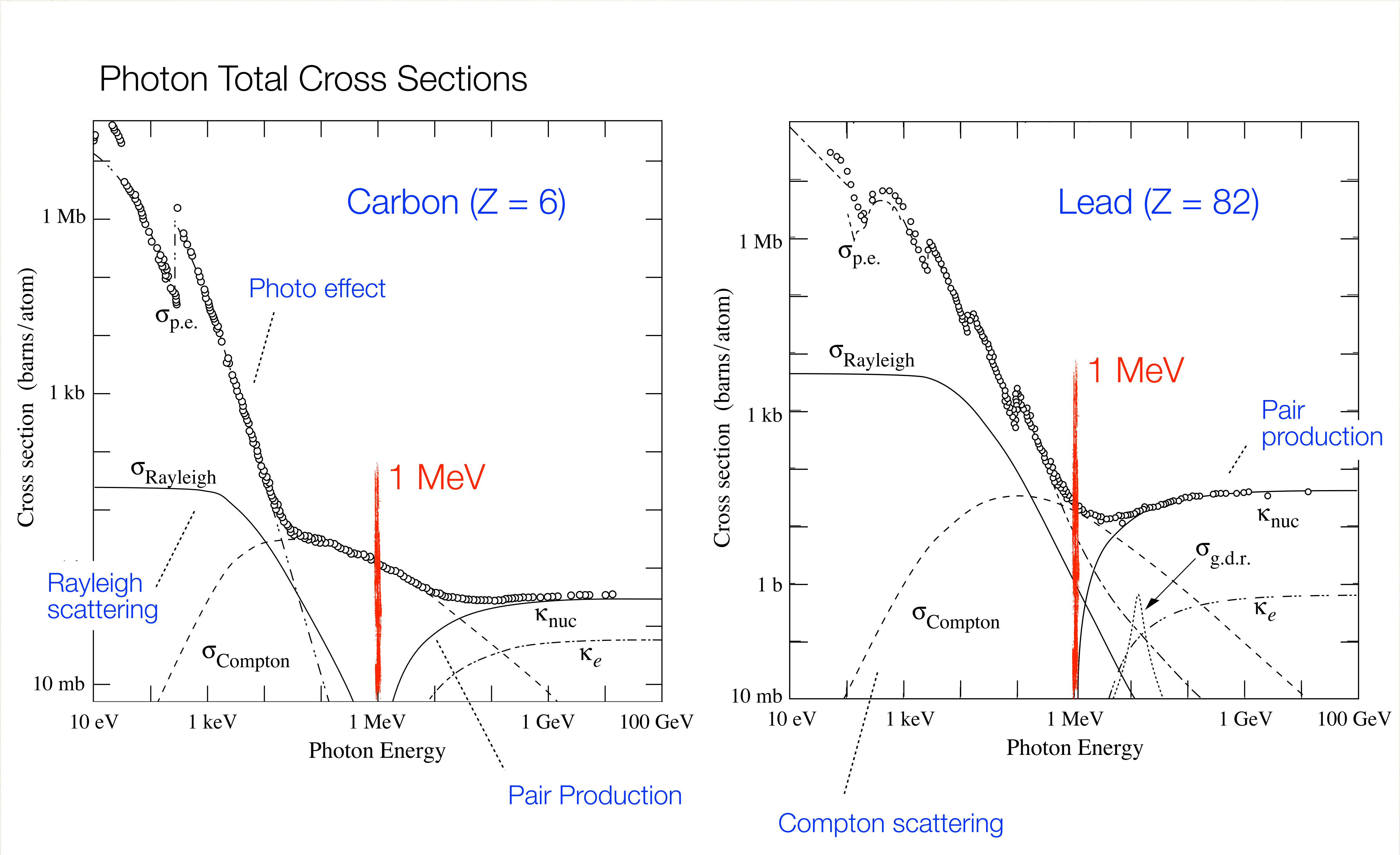
Interação de fótons com matéria



Interação de fótons: efeito fotoelétrico

Energy of
outgoing electron:

$$E_e = h\nu - I_b$$

Photon energy

Binding energy
[strongly Z dependent]

Typical energy dependence:

$$\sigma_{\mathrm{ph}} = 2\pi r_e^2\, \alpha^4\, Z^5\, (mc^2)/E_\gamma$$

[for $E_\gamma \gg mc^2$]

$$\sigma_{\mathrm{ph}} = \alpha\pi\, a_{\mathrm{B}}\, Z^5\, (I_0/E_\gamma)^{7/2}$$

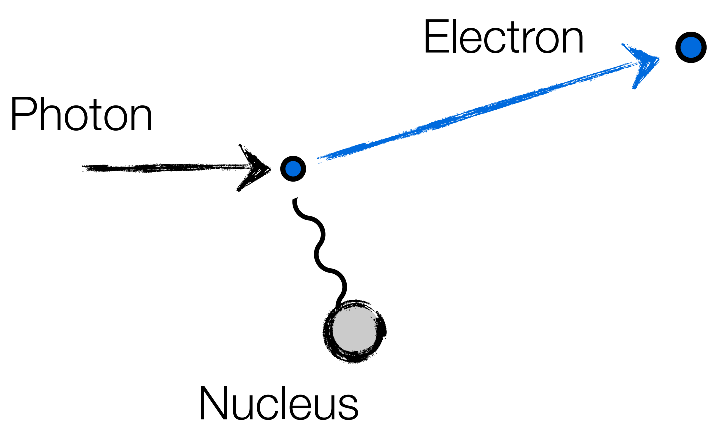
[for $I_0 \ll E_\gamma \ll mc^2$]

Example values:

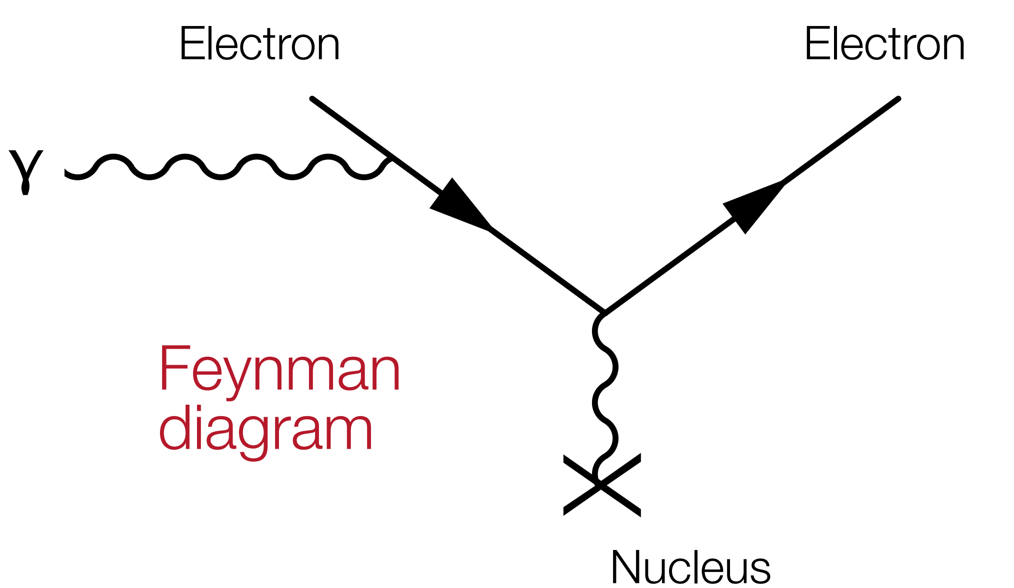
$a_B = 0.53 \cdot 10^{-10}$ m; I_0 =13.6 eV; α =1/137; 1 b = 10^{-24} m
use E_γ = 100 keV

➛ σ_{ph}(Fe) = 29 barn
σ_{ph}(Pb) = 5000 barn

Naive picture



γ + atom ➛ e^- + atom$^+$



Feynman diagram

Interação de fótons: efeito fotoelétrico

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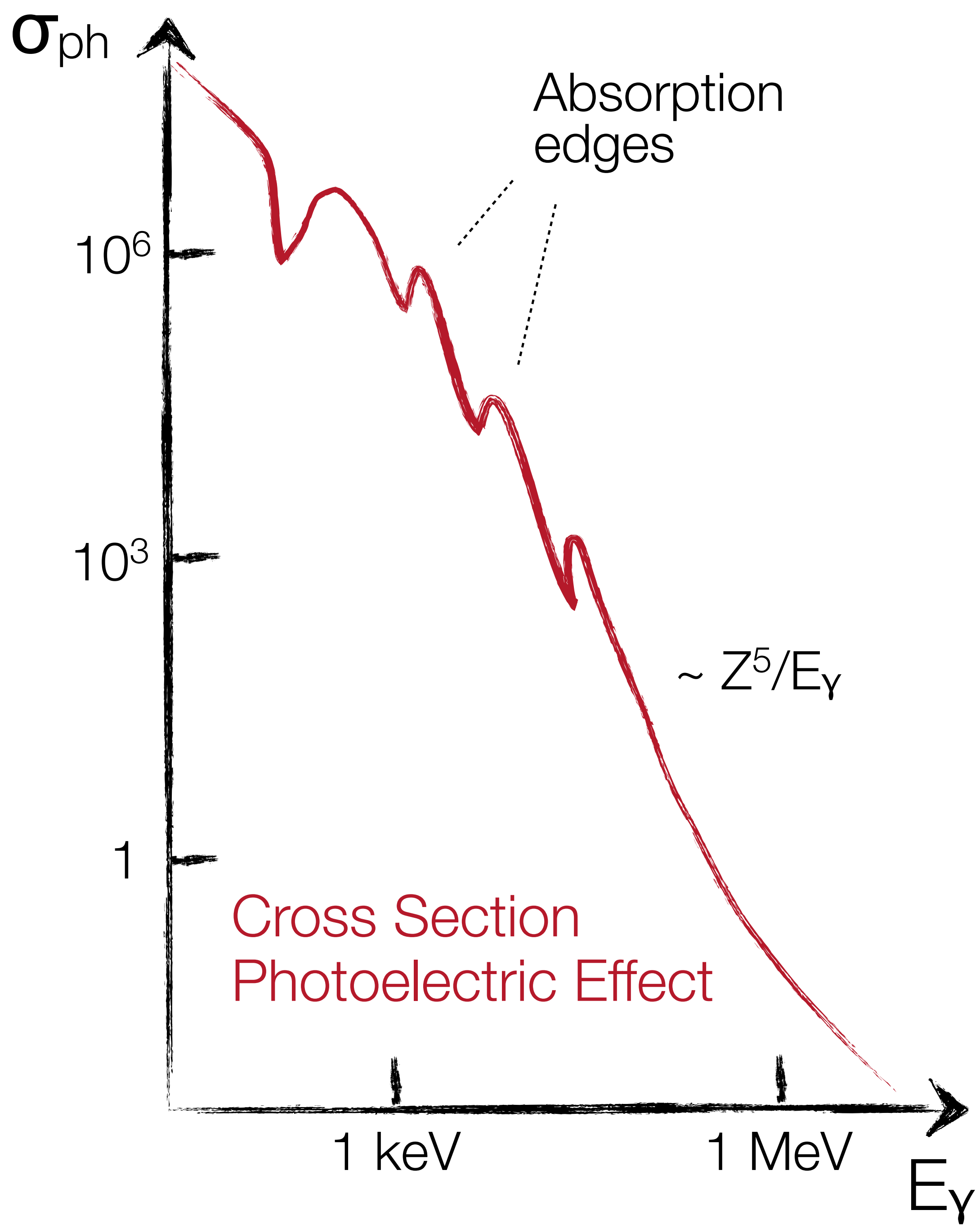

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Interação de fótons: espalhamento Compton

Energy of outgoing photon:

γ-Angle w.r.t. direction of incoming photon

$$E'_\gamma = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2}(1 - \cos\theta)}$$

Simple 4-vector algebra;
[Ansatz: $p_4^2 = (p_1^2 + p_2^2 - p_3^2)$]

Kinetic energy of outgoing electron:

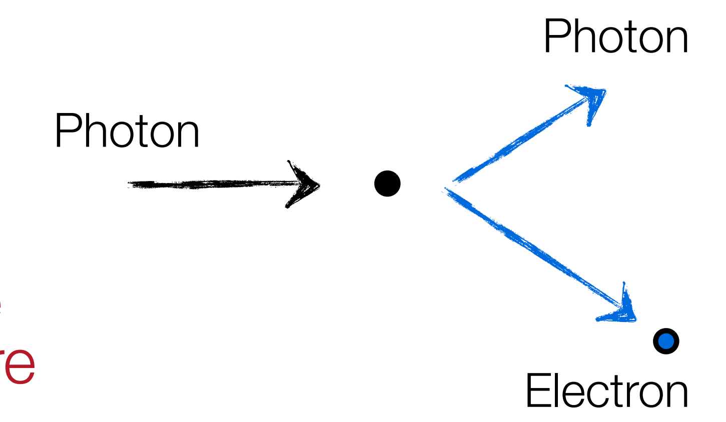
$$T_e = \frac{\frac{E_\gamma^2}{m_e c^2}(1 - \cos\theta)}{1 + \frac{E_\gamma}{m_e c^2}(1 - \cos\theta)}$$

Forward Scattering: $E_\gamma = E_\gamma'$; $T_e = 0$

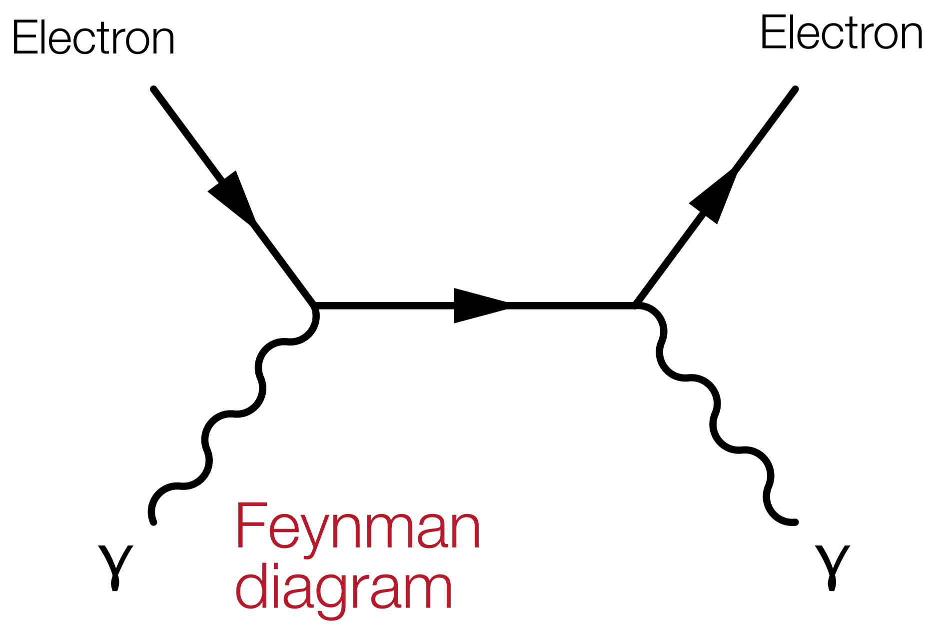
Backward Scattering: $E_\gamma' = \frac{1}{2} mc^2 (1 + mc^2/2E_\gamma)^{-1}$

$T_e = E_\gamma (1 + mc^2/2E_\gamma)^{-1}$

Naive picture



$$\gamma + e^- \rightarrow (\gamma)' + (e^-)'$$



Feynman diagram

Interação de fótons: espalhamento Compton

Cross Section:
[use QED ...]

$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2}\frac{1}{[1+\gamma(1-\cos\theta)]^2}\cdot\ \ldots$$

$$\ldots\cdot\left(1+\cos^2\theta+\frac{\gamma^2(1-\cos\theta)^2}{1+\gamma^2(1-\cos\theta)}\right)$$

[Klein-Nishina Formula]

Substitution/integration yields:

$$\frac{d\sigma}{dT_e} = \ldots \qquad \sigma_C = \ldots$$

Small photon energies [$E_\gamma \ll m_e c^2$]:

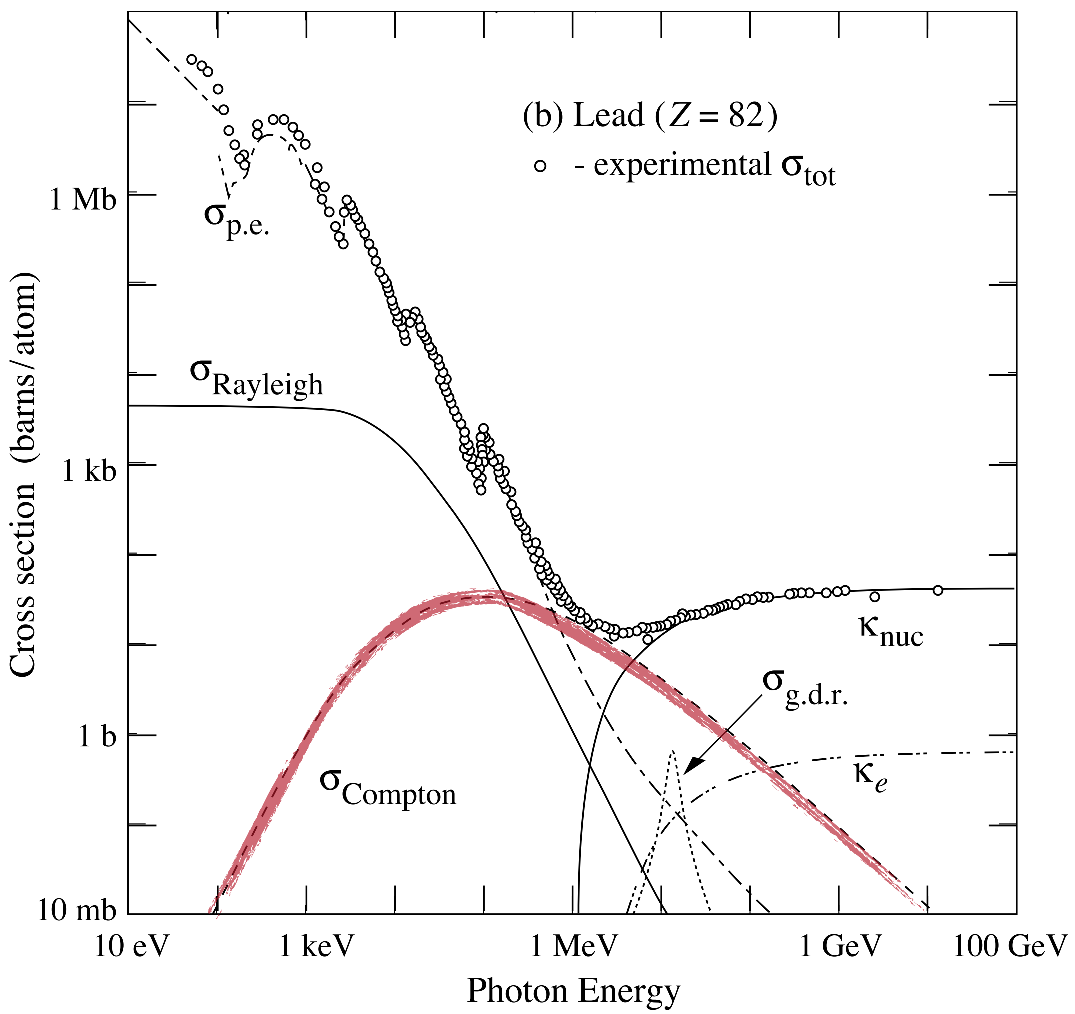
$\sigma_C = \sigma_{th}\,(1 - 2E_\gamma/mc^2)$

[with $\sigma_{th} = 8\pi/3\ r_e^2 = 0.66$ barn]

Thomson cross Section

Large photon energies: $\sigma_C \propto (\ln E_\gamma)/E_\gamma$
[$E_\gamma \gg m_e c^2$]

Photon Total Cross Sections



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Interação de fótons: produção de pares

Energy threshold:

$$E_\gamma \geq 2m_e c^2 (1 + m_e/m_n)$$

2 x electron mass

Kinetic energy
transferred to nucleus

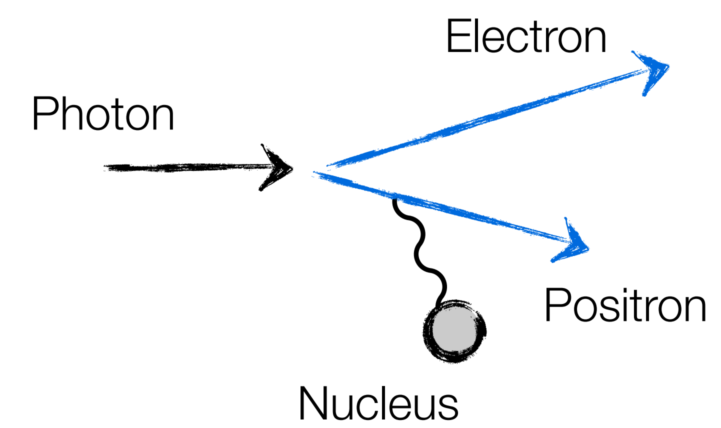
Cross Section:

Rises above threshold, but reaches saturation for large E_γ [screening effect] ...

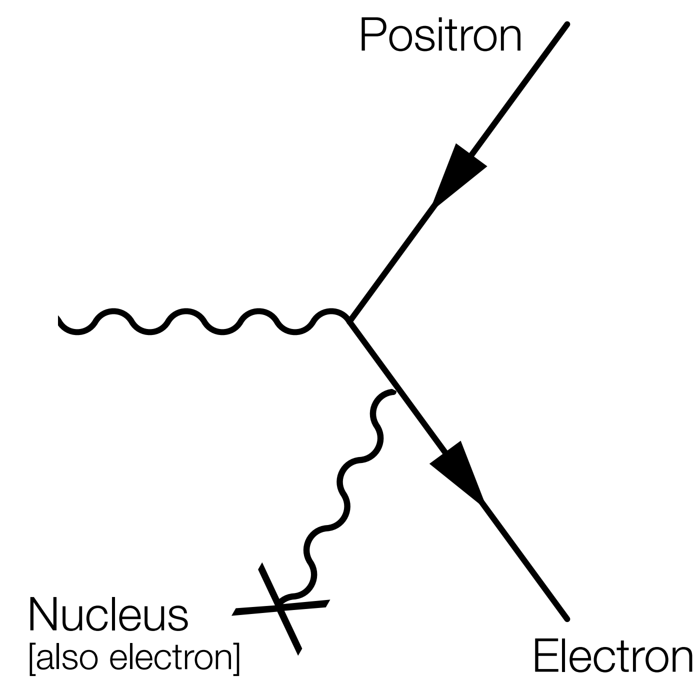
For $E_\gamma \gg m_e c^2$:

$$\sigma_{\text{pair}} = 4\, Z^2\, \alpha r_e^2 \left(\frac{7}{9} \ln \frac{183}{Z^{\frac{1}{3}}} - \frac{1}{54} \right)$$

$$\approx 4\, Z^2\, \alpha r_e^2 \left(\frac{7}{9} \ln \frac{183}{Z^{\frac{1}{3}}} \right)$$



γ + atom ➝ $e^+ + e^-$



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Interação de fótons: produção de pares

Cross Section:
[for $E_\gamma \gg m_e c^2$]

$$\sigma_{\text{pair}} \approx \frac{7}{9} \underbrace{\left(4\,\alpha r_e^2 Z^2 \ln \frac{183}{Z^{\frac{1}{3}}}\right)}_{A/N_A X_0}$$

[X_0: radiation length]
[in cm or g/cm^2]

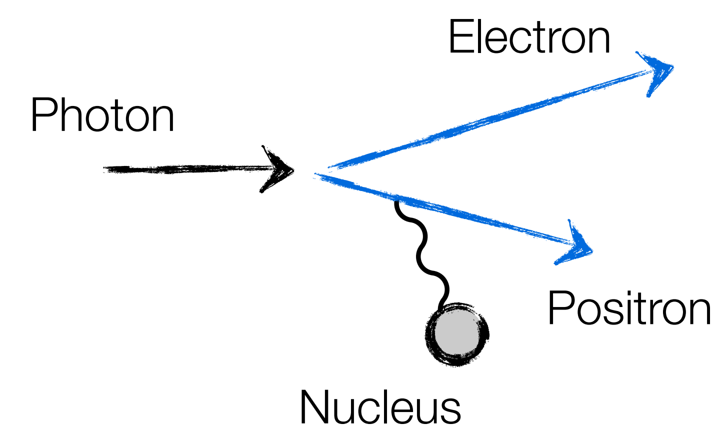
Absorption coefficient:

$\mu = n\sigma$ [with n: particle density]

$\mu = \rho \cdot N_A/A\ \sigma_{\text{pair}}$

$= 7/9\ \dfrac{1}{X_0}$

[where now X_0 is in cm]



	ρ [g/cm^3]	X_0 [cm]
H_2 [fl.]	0.071	865
C	2.27	18.8
Fe	7.87	1.76
Pb	11.35	0.56
Air	$1.2 \cdot 10^{-3}$	$30 \cdot 10^{3}$

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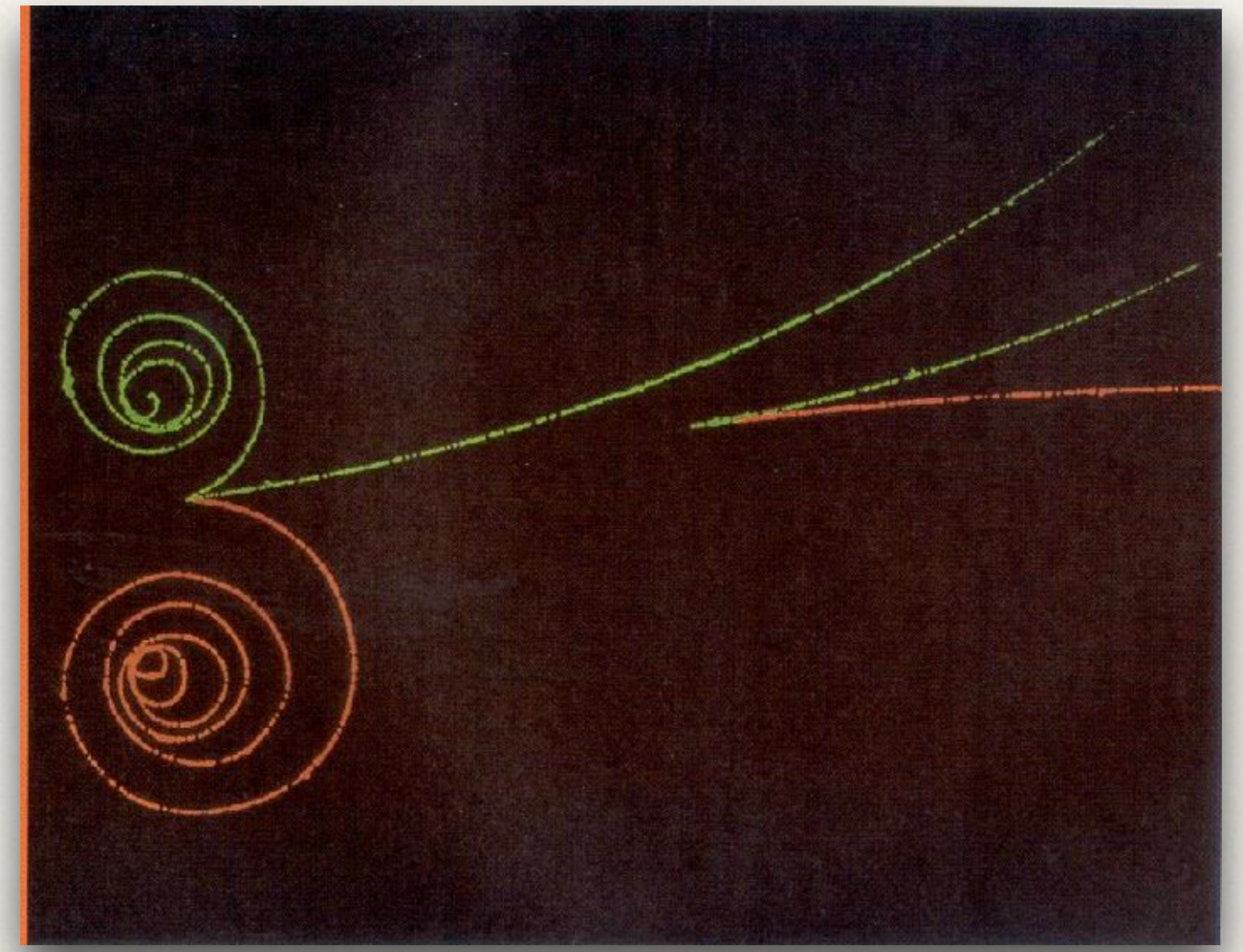
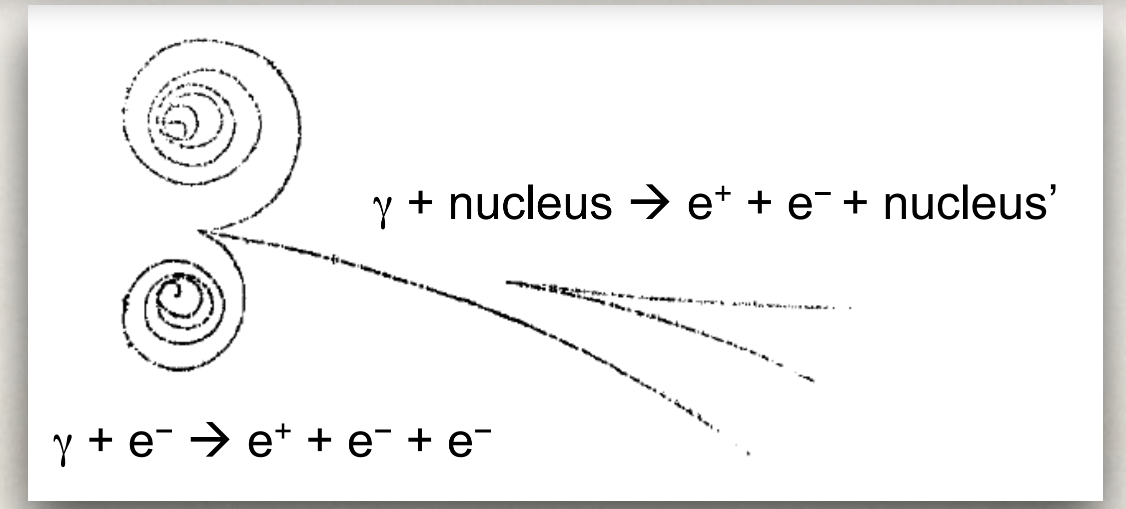
Interação de fótons: produção de pares





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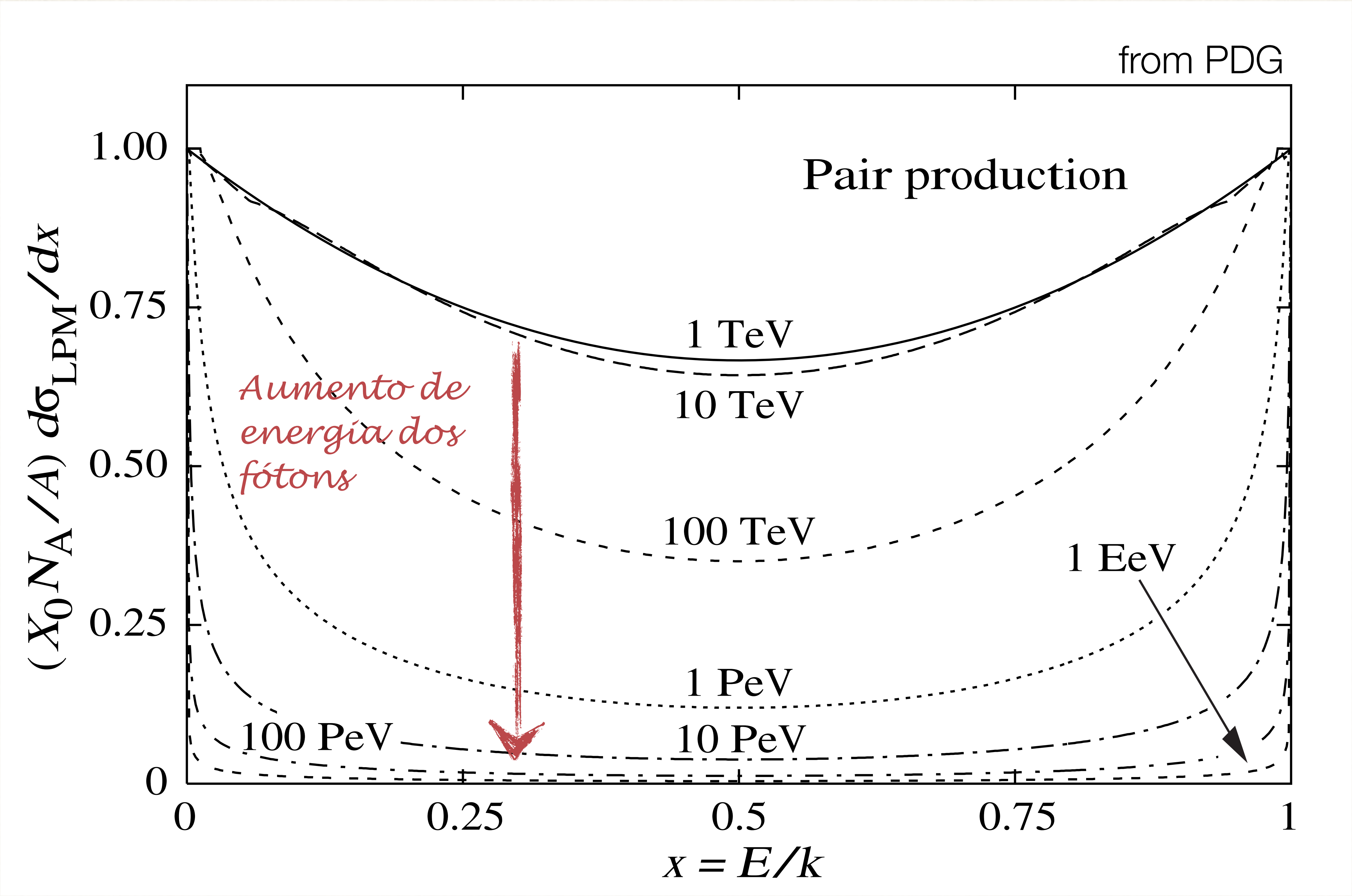
Interação de fótons: produção de pares



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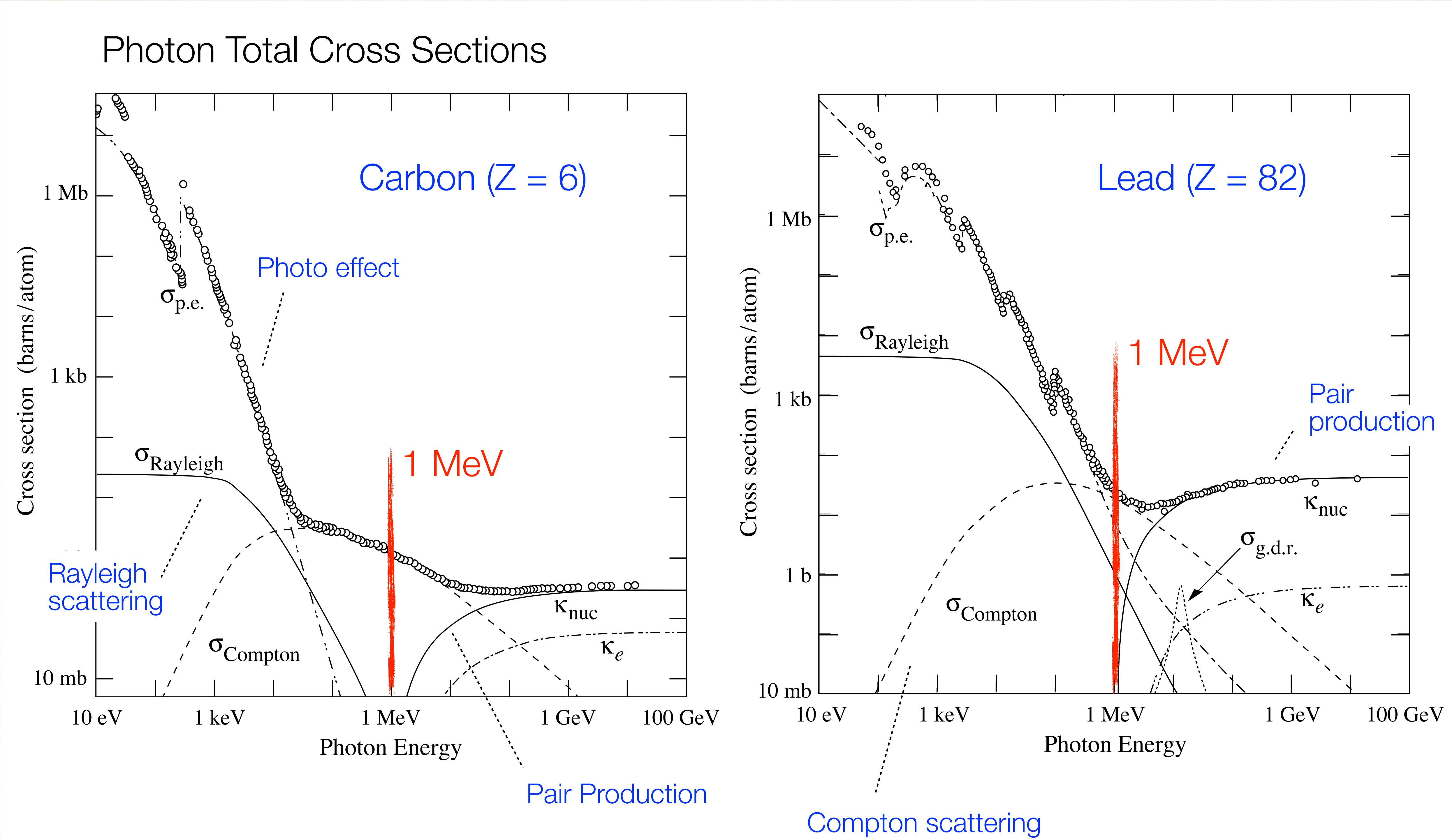
Interação de fótons: produção de pares



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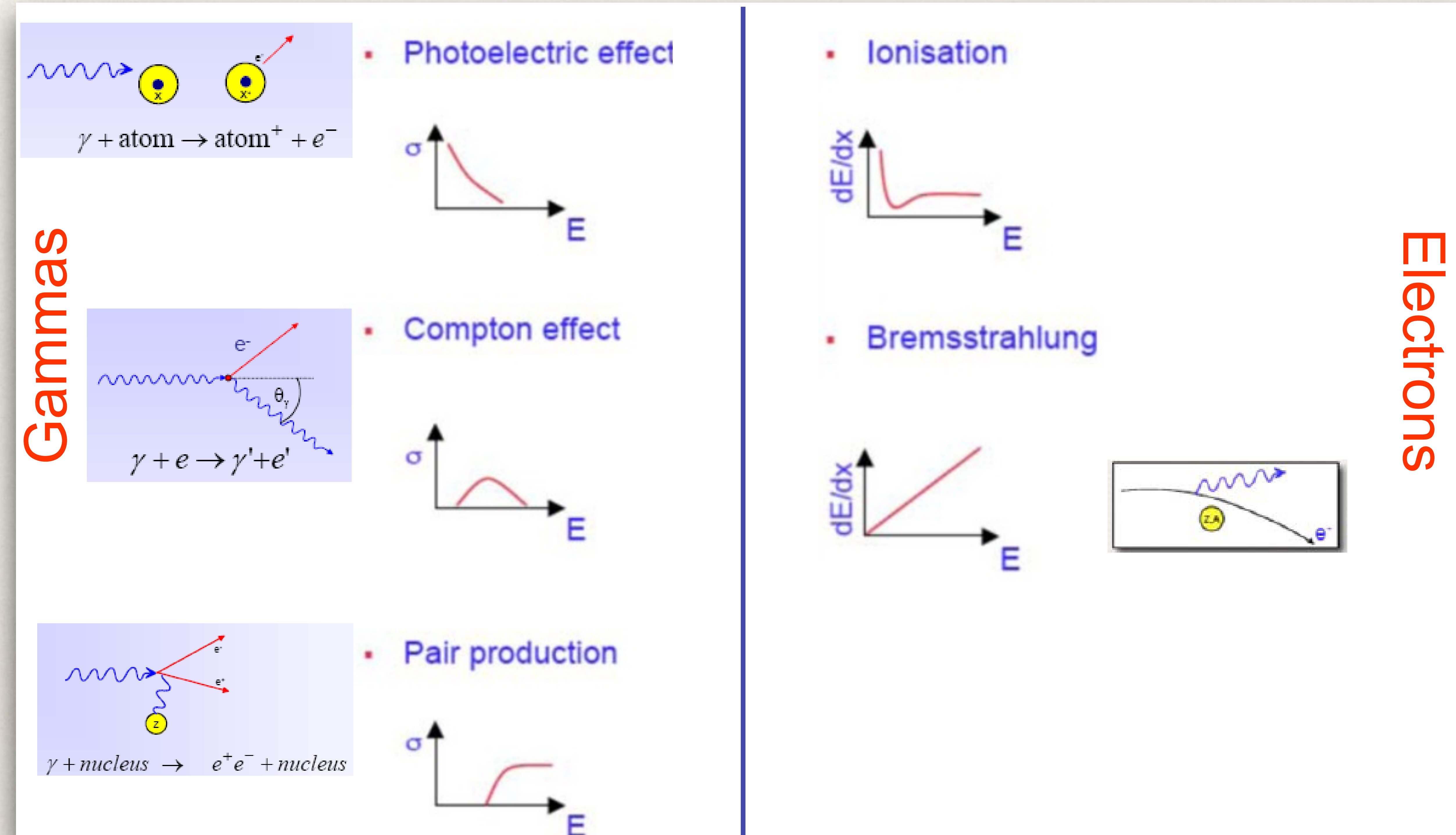
Interações eletromagnéticas



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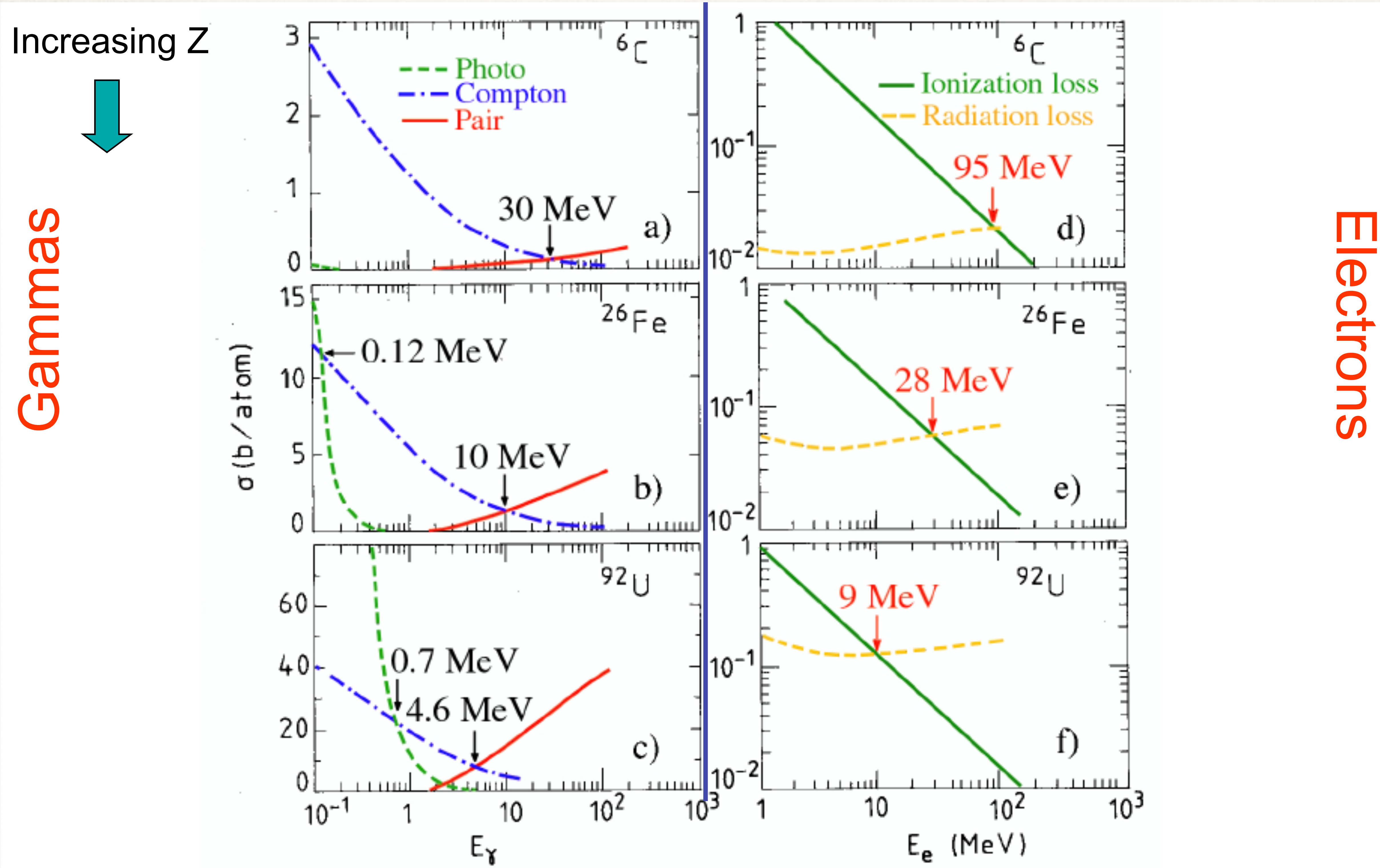
Dependência do material



Detectando Nêutrons

- Partículas eletricamente neutras *não interagem* via força eletromagnética

- Nêutrons são detectados via ***interação nuclear***.

- Interação a ser escolhida para a detecção de nêutrons depende do *intervalo de energia* que se deseja investigar.

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Detectando Nêutrons

- Nêutron de alta energia: Calorímetro hadrônico

  (mede-se a energia depositada em forma de chuveiro hadrônico; neutralidade da partícula tem pouco efeito)

- Nêutron de energia moderada: Espalhamento n-p

  (detecta-se os nêutrons através do espalhamento em material contendo hidrogênio em grandes quantidades; detecta-se o recuo dos prótons.)

- Nêutron de baixa energia: Processos Nucleares Exoérgicos

  (utiliza-se material com alta taxa de captura de nêutrons para nêutrons de baixa energia; processo de captura de nêutrons resulta em núcleos instáveis. Decaimentos desses núcleos produzem sinais que podem ser detectados.)

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Detectando Nêutrons

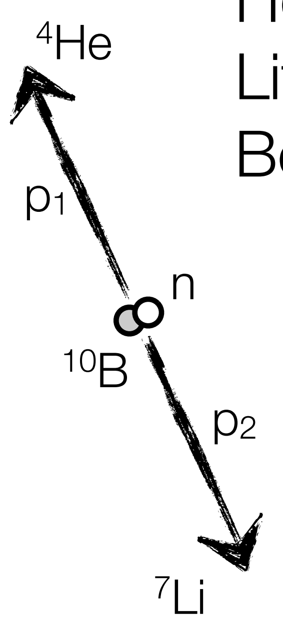
Nuclear reactions used for neutron detectors ...

charged nuclei

Q-values

extra γ

Helium:	$n + {}^{3}He$	➛ $^{3}H + {}^{1}H$	$+\ 0.76$ MeV		
Lithium:	$n + {}^{6}Li$	➛ $^{4}He + {}^{3}H$	$+\ 4.79$ MeV		
Boron:	$n + {}^{10}B$	➛ $^{7}Li^{*} + {}^{4}He$	$+\ 2.31$ MeV	$+\ 0.48$ MeV	(93%)
		➛ $^{7}Li + {}^{4}He$	$+\ 2.78$ MeV		(7%)



Kinetic energy
of decay products:

$$\vec{p}_1 = -\vec{p}_2$$

$$\frac{\vec{p}_1^{\,2}}{2m_1} + \frac{\vec{p}_2^{\,2}}{2m_2} = \frac{\vec{p}_1^{\,2}}{2m_1}\left(1 + \frac{m_1}{m_2}\right) = Q$$

$$E({}^{4}\mathrm{He}) = \frac{m_{\mathrm{Li}}}{m_{\mathrm{Li}} + m_{\mathrm{He}}} \approx \frac{7}{11}Q = 1.77\ \mathrm{MeV}$$

$$E({}^{7}\mathrm{Li}) = \frac{m_{\mathrm{He}}}{m_{\mathrm{Li}} + m_{\mathrm{He}}} \approx \frac{4}{11}Q = 1.01\ \mathrm{MeV}$$

Gadolinium:

$n + {}^{155}Gd$ ➛ Gd^{*} ➛ γ-ray spectrum ➛ conversion electron spectrum

$n + {}^{157}Gd$ ➛ Gd^{*} ➛ γ-ray spectrum ➛ conversion electron spectrum

Uranium: $n + {}^{235}U$ fission fragments + ~160 MeV

Plutonium: $n + {}^{239}Pu$ fission fragments + ~160 MeV

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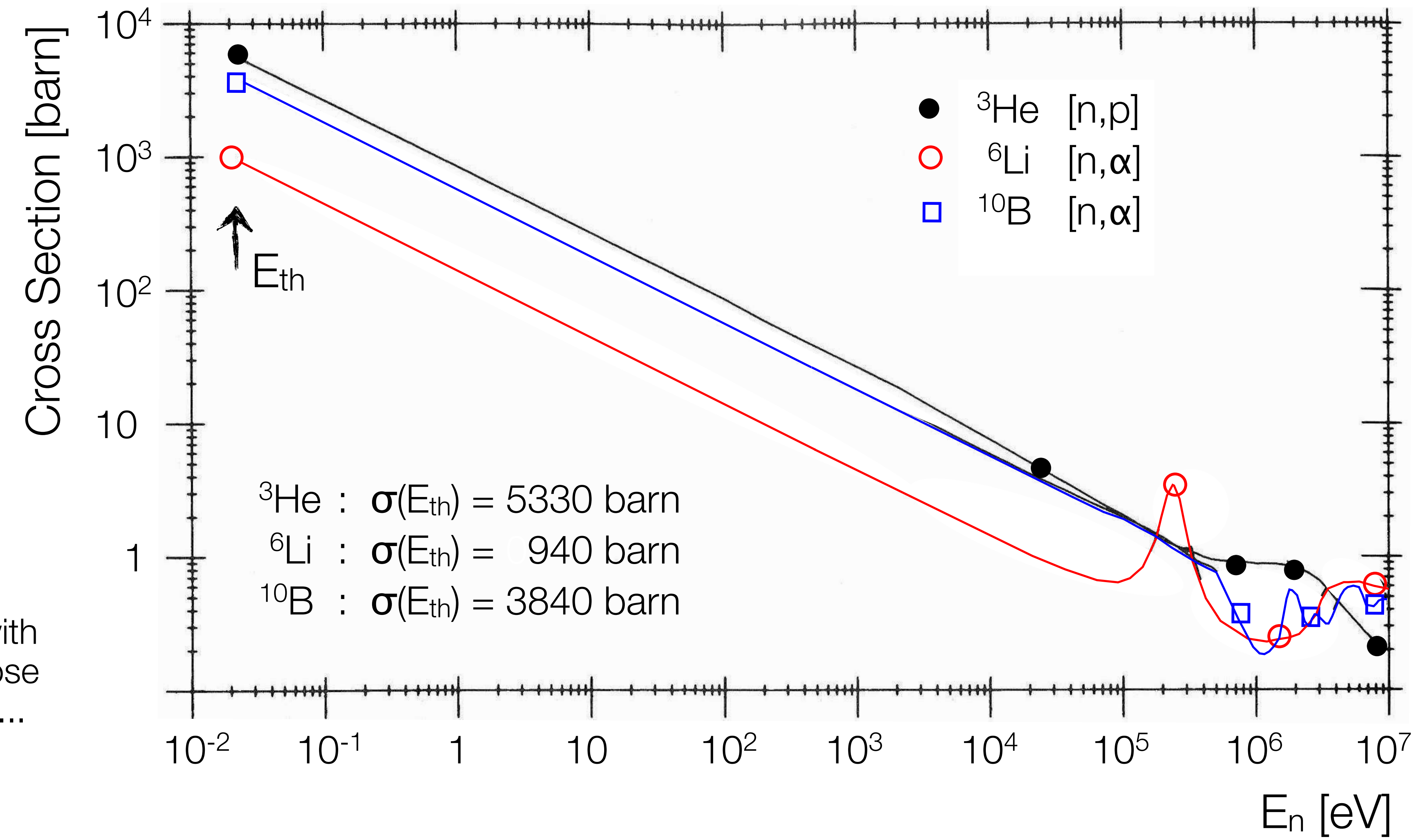
Detectando Nêutrons

Cross Section

for neutron capture process ...

$$\sigma(E) = \sigma(E_{\text{th}}) \cdot \frac{v_{\text{th}}}{v}$$



^3He : $\sigma(E_{th})$ = 5330 barn
^6Li : $\sigma(E_{th})$ = 940 barn
^{10}B : $\sigma(E_{th})$ = 3840 barn

Interpretation:

x-Section increases with time the neutron is close to absorbing nucleus ...

➛ v-dependence ...

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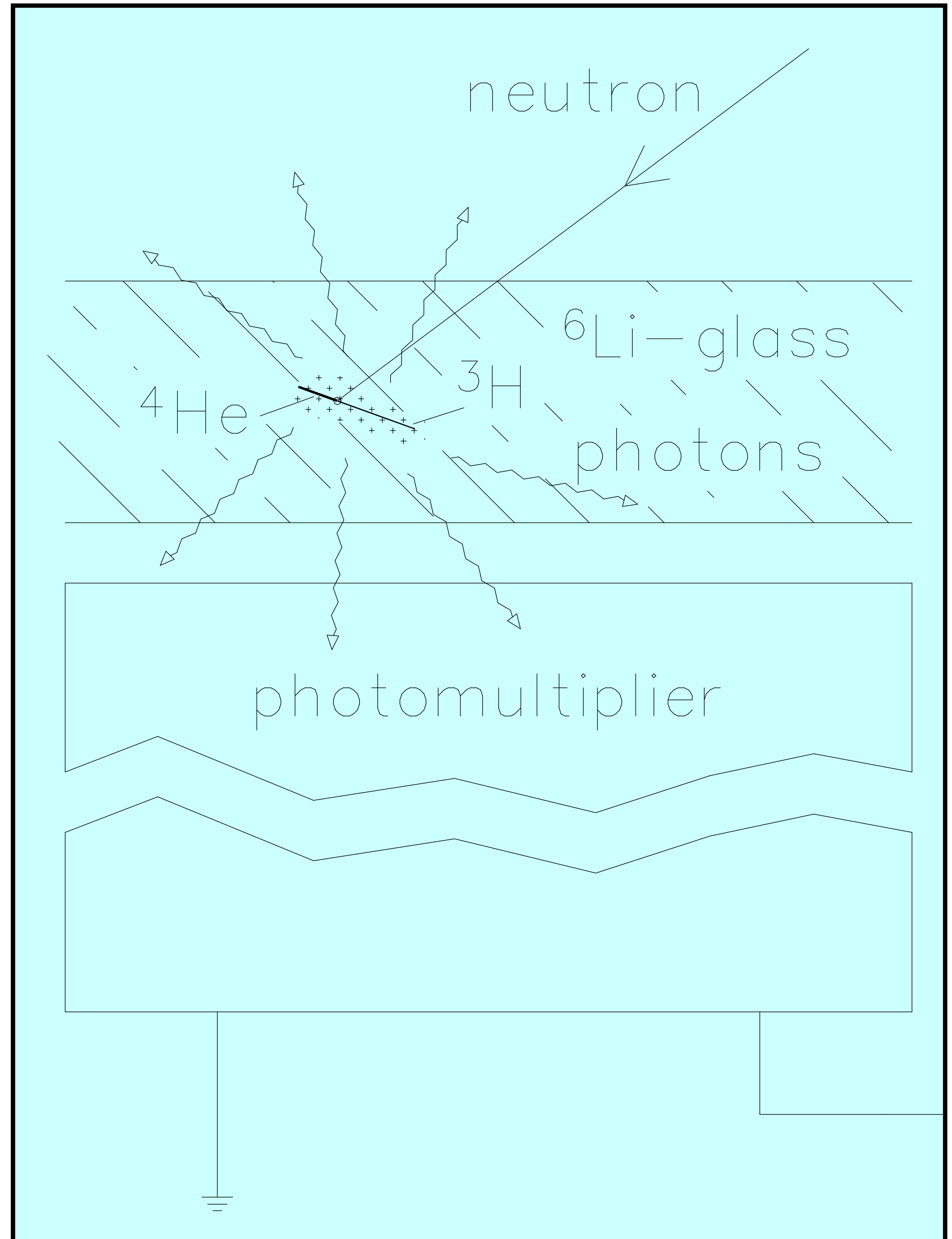
Detectando Nêutrons

Scintillation Detectors ...

Detect scintillation light produced in capture process ...

e.g. Lithium glass:

$$n + {}^{6}Li \rightarrow {}^{4}He + {}^{3}H + 4.79\ MeV$$



Common scintillators used for neutron detection ...

	Density of ^{6}Li atoms [10^{22} cm^{-3}]	Scintillation efficiency [in %]	Photon wavelength [nm]	Photons per neutron
Li-glass (Ce)	1.75	0.45	395	~ 7000
LiI (Eu)	1.83	2.8	470	~ 51000
ZnS (Ag) - LiF	1.18	9.2	450	~ 160 000

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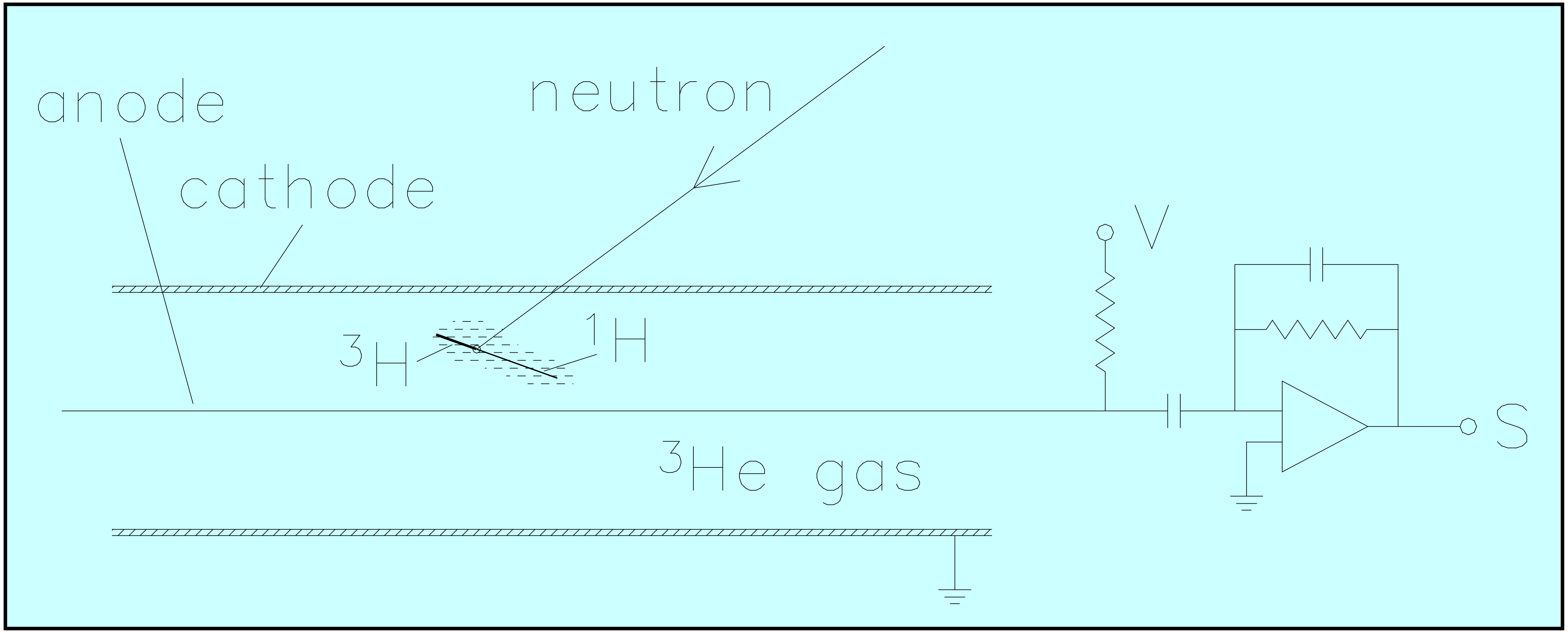
Detectando Nêutrons

Gas Detectors ...

Standard Geiger counter with He or BF_3 as counting gas ...

e.g. Helium: $n + {}^3He \rightarrow {}^3H + {}^1H + 0.76$ MeV

[About 25000 ionizations produced per neutron; charge ≈ 4 fC]



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Detectando Nêutrons

- Nêutrons rápidos

detecção baseia-se na observação de reação nuclear induzida pela absorção de nêutrons;

seção de choque de absorção de nêutrons rápidos é pequena se comparada com nêutrons de baixa energia: $\sigma_{cap} \sim 1/v$

Duas possibilidades:
1- Termalizar/moderar antes de promover a captura dos nêutrons (permite apenas a contagem do fluxo de nêutrons);
2- Espalhamento elástico em prótons de altas-energias (prótons são “fáceis” de se detectar). Permite que a energia seja medida.

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Detectando Nêutrons

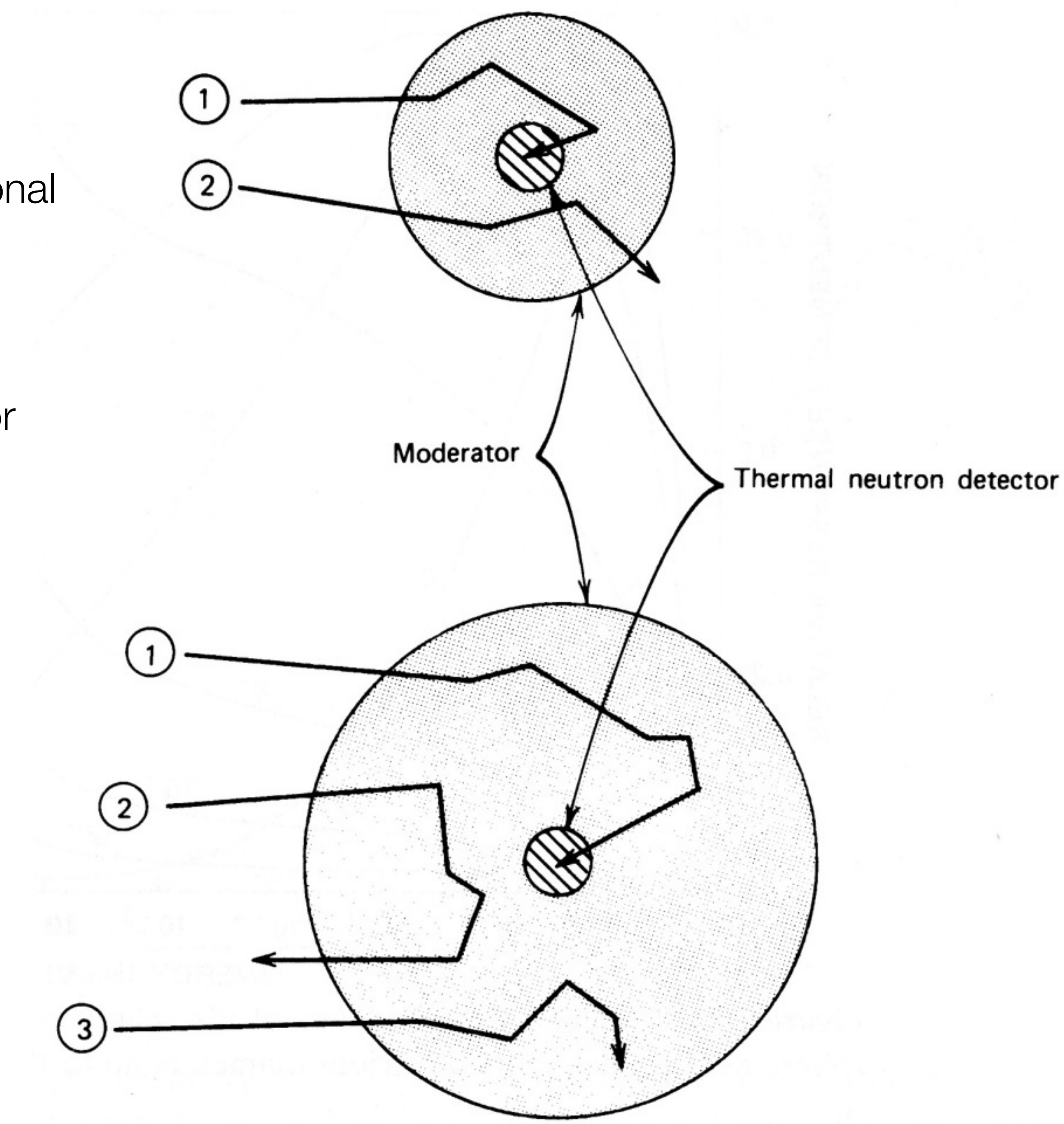
Neutron moderation ...

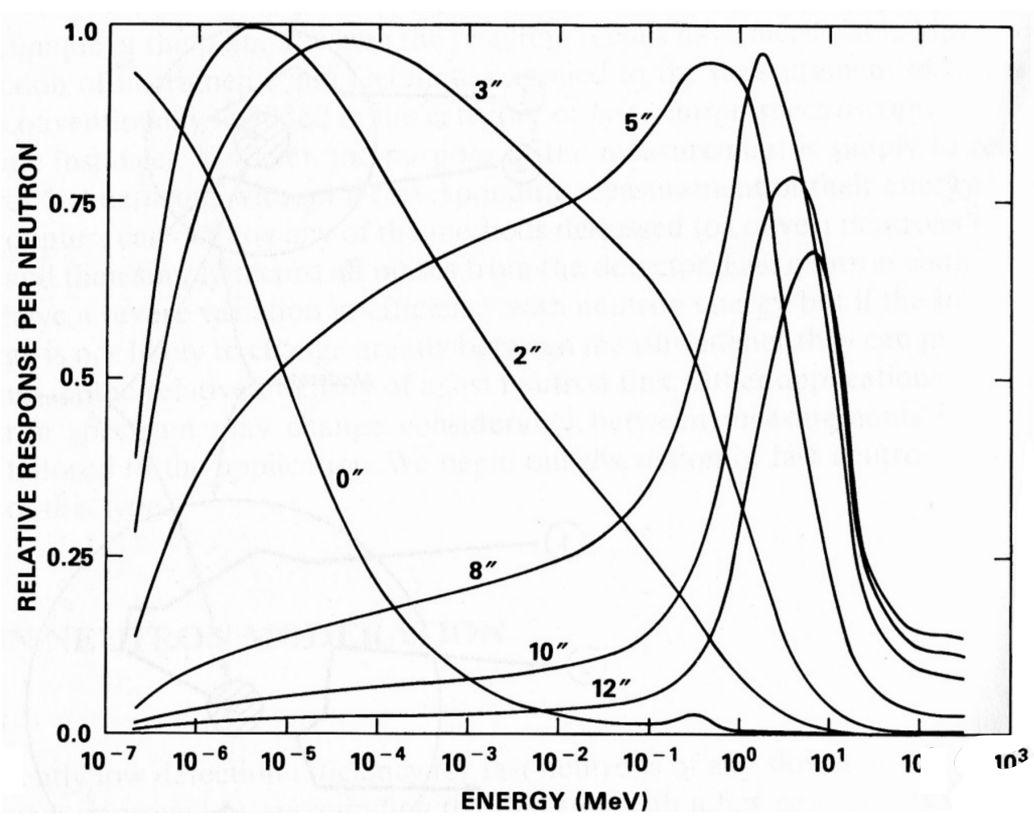
Moderate neutrons to increase efficiency in conventional slow-neutron detectors ...

Moderation with hydrogenous materials such as polyethylene or paraffin ...

Optimum thickness between few cm to tens of cm for energies of keV to MeV ...

Trade-off between sufficient slow down and detection cross section ...





Relative response
vs. energy for different absorber thicknesses

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Detectando Nêutrons

Detector Type	Size	Neutron Active Material	Incident Neutron Energy	Neutron Detection Efficiency[a] (%)	Gamma-Ray Sensitivity (R/h)[b]
Plastic scintillator	5 cm thick	^{1}H	1 MeV	78	0.01
Liquid scintillator	5 cm thick	^{1}H	1 MeV	78	0.1
Loaded scintillator	1 mm thick	^{6}Li	thermal	50	1
Hornyak button	1 mm thick	^{1}H	1 MeV	1	1
Methane (7 atm)	5 cm diam	^{1}H	1 MeV	1	1
^{4}He (18 atm)	5 cm diam	^{4}He	1 MeV	1	1
^{3}He (4 atm), Ar (2 atm)	2.5 cm diam	^{3}He	thermal	77	1
^{3}He (4 atm), CO_2 (5%)	2.5 cm diam	^{3}He	thermal	77	10
BF_3 (0.66 atm)	5 cm diam	^{10}B	thermal	29	10
BF_3 (1.18 atm)	5 cm diam	^{10}B	thermal	46	10
^{10}B-lined chamber	0.2 mg/cm^2	^{10}B	thermal	10	10^3
Fission chamber	2.0 mg/cm^2	^{235}U	thermal	0.5	$10^6 - 10^7$

[a]Interaction probability for neutrons of the specified energy striking the detector face at right angles.
[b]Approximate upper limit of gamma-ray dose that can be present with detector still providing usable neutron output signals.

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Detectando Nêutrons

Cascade Detector ...

GEM: Gas electron multiplier

Setup: Multi Boron Layers on GEM foils ...

GEMs:

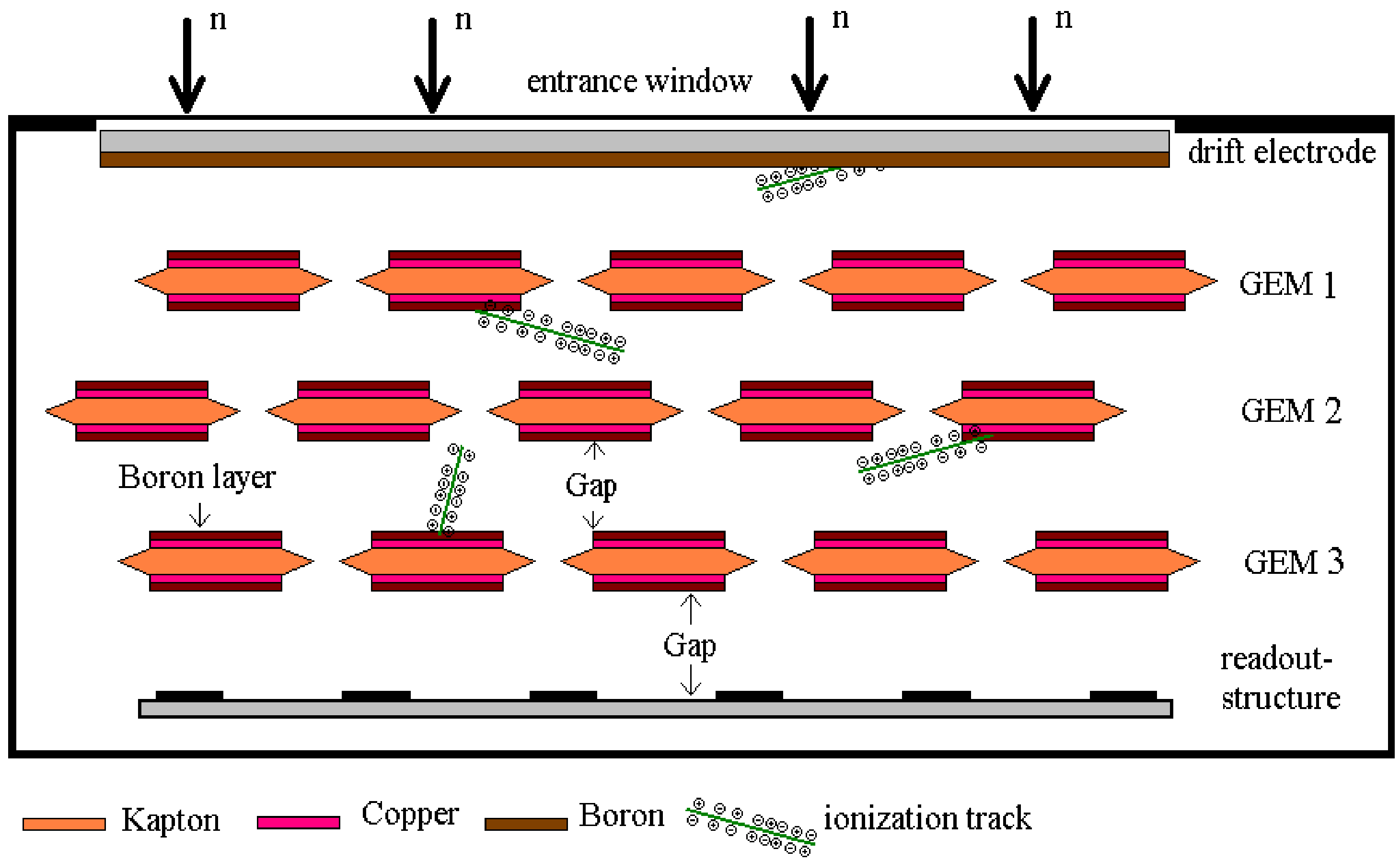
- can be operated to be transparent for produced charges ...
- can be cascaded ...
- each can carry two Boron layers ...
- last one is operated as an amplification layer ...

The GEMs inherently introduce high rate capability ...

[10^7 Hz/cm^2]

Capture Process:

$$n + {}^{10}B \rightarrow {}^{7}Li^{*} + {}^{4}He + 2.31\text{ MeV} \quad (93\%)$$
$$\rightarrow {}^{7}Li + {}^{4}He + 2.78\text{ MeV} \quad (7\%)$$



Cascade
Neutron Detector

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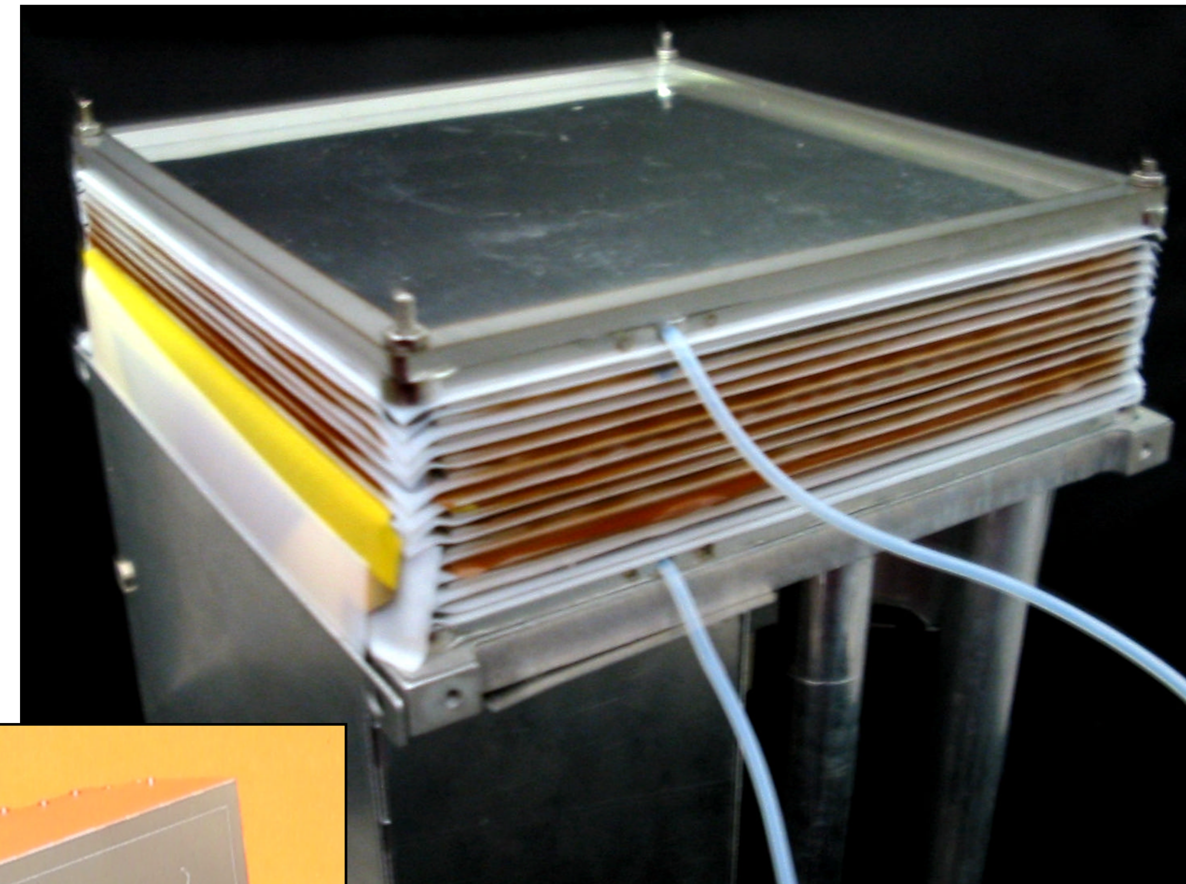
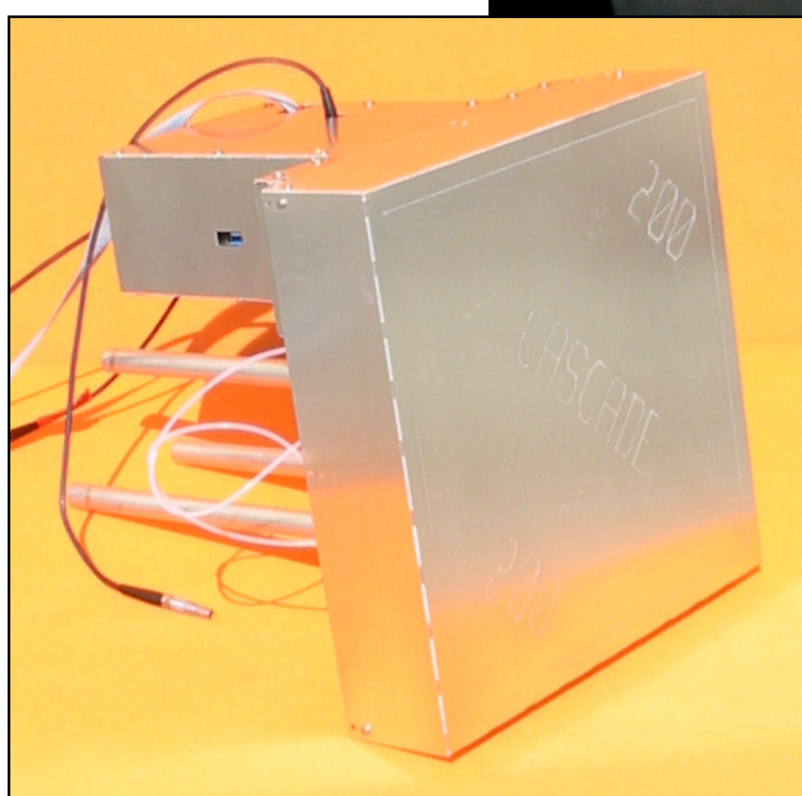
Detectando Nêutrons

Cascade Detector ...



CASCADE-GEM Module
GEM-foil glued onto a frame



CASCADE Module

Several GEM-modules stacked together with readout structure and drift electrodes to form a detector module

First 200 x 200 mm^2
Cascade neutron detector

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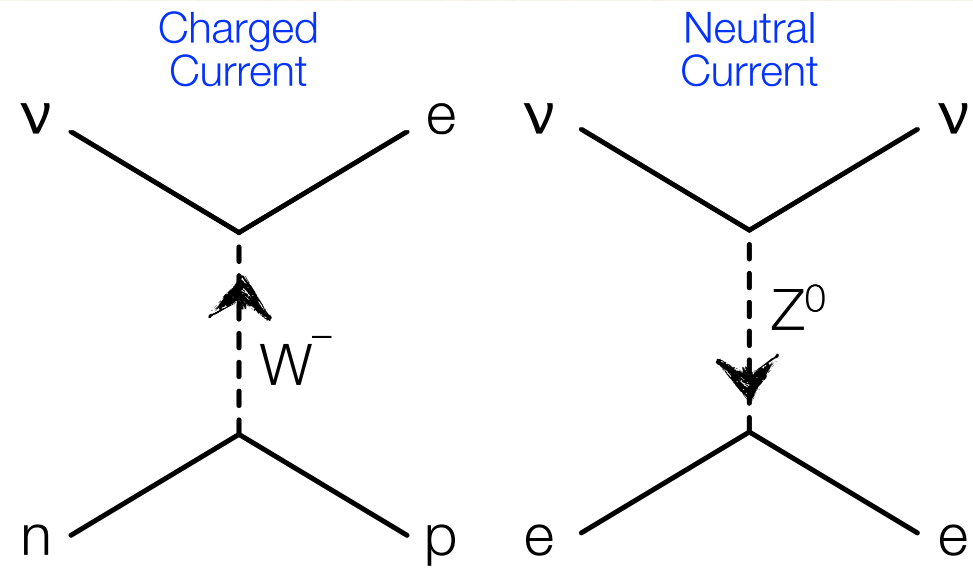
Detectando Neutrinos

- Neutrinos são detectados via *interação fraca*.



Charged Current Reactions:

$$\begin{aligned}
\nu_e + n &\rightarrow e^- + p\\
\bar{\nu}_e + p &\rightarrow e^+ + n\\
\nu_\mu + n &\rightarrow \mu^- + p\\
\bar{\nu}_\mu + p &\rightarrow \mu^+ + n\\
\nu_\tau + n &\rightarrow \tau^- + p\\
\bar{\nu}_\tau + p &\rightarrow \tau^+ + n\\
&\ldots\\
\bar{\nu}_e + e^- &\rightarrow \mu^- + \bar{\nu}_\mu\\
\bar{\nu}_e + e^- &\rightarrow \tau^- + \bar{\nu}_\tau
\end{aligned}$$

Neutral Current Reactions:

$$\begin{aligned}
\nu_e + e^- &\rightarrow \nu_e + e^-\\
\nu_\mu + e^- &\rightarrow \nu_\mu + e^-\\
\nu_\tau + e^- &\rightarrow \nu_\tau + e^-
\end{aligned}$$

Remark:
Neutral Current νN-interactions not usable due to small energy transfer

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Detectando Neutrinos

Neutrino nucleon x-Section:
[examples]

10 GeV neutrinos: $\sigma = 7 \cdot 10^{-38}$ cm^2/nucleon

Interaction probability for 10 m Fe-target: $R = \sigma \cdot N_A\,[\text{mol}^{-1}/\text{g}] \cdot d \cdot \rho = 3.2 \cdot 10^{-10}$
with $N_A = 6.023 \cdot 10^{23}$ g^{-1}; $d = 10$ m; $\rho = 7.6$ g/cm^3

Solar neutrinos [100 keV]: $\sigma = 7 \cdot 10^{-45}$ cm^2/nucleon

Interaction probability for earth: $R = \sigma \cdot N_A\,[\text{mol}^{-1}/\text{g}] \cdot d \cdot \rho \approx 4 \cdot 10^{-14}$
with $N_A = 6.023 \cdot 10^{23}$ g^{-1}; $d = 12000$ km; $\rho = 5.5$ g/cm^3

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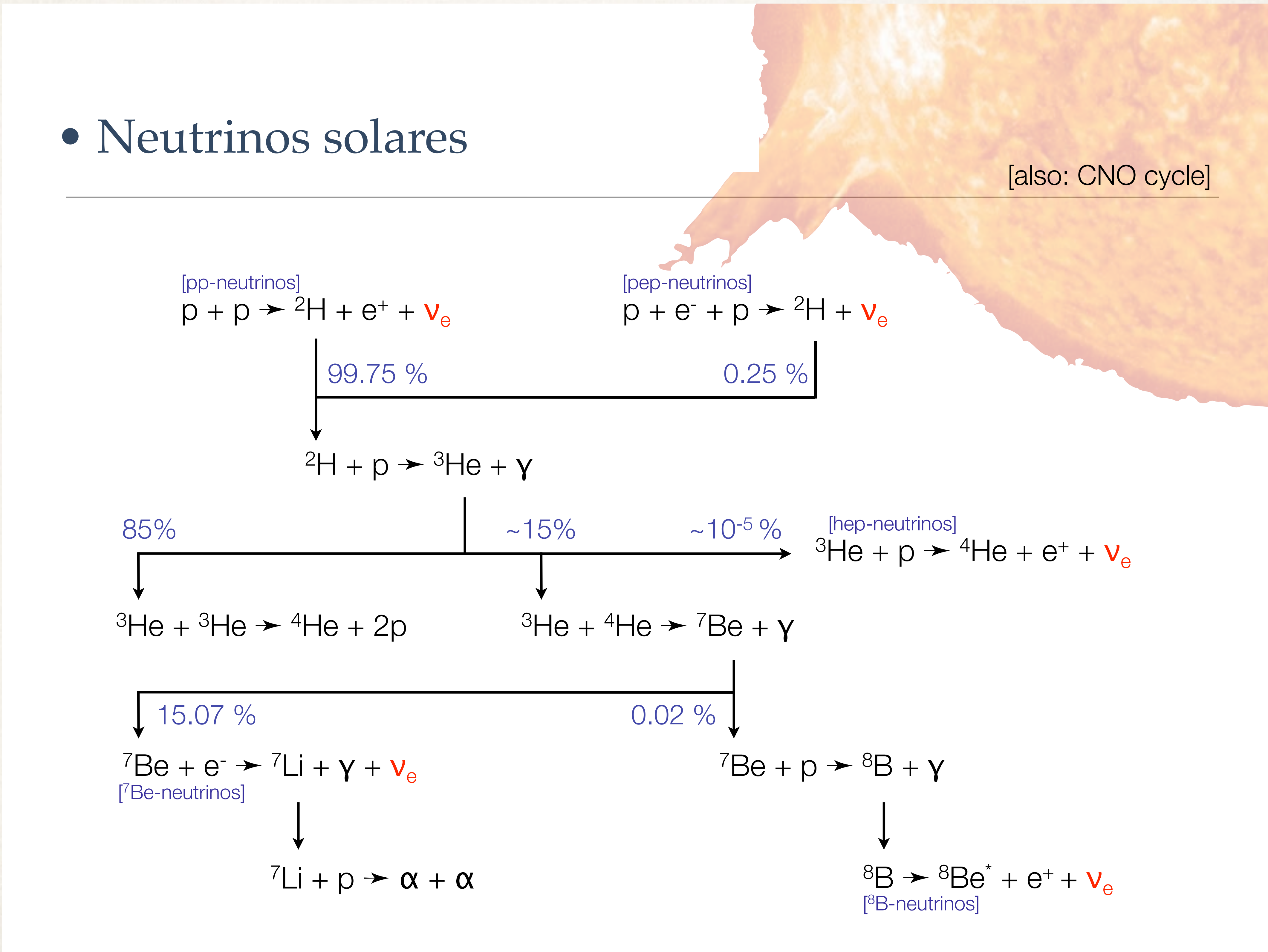
Detectando Neutrinos



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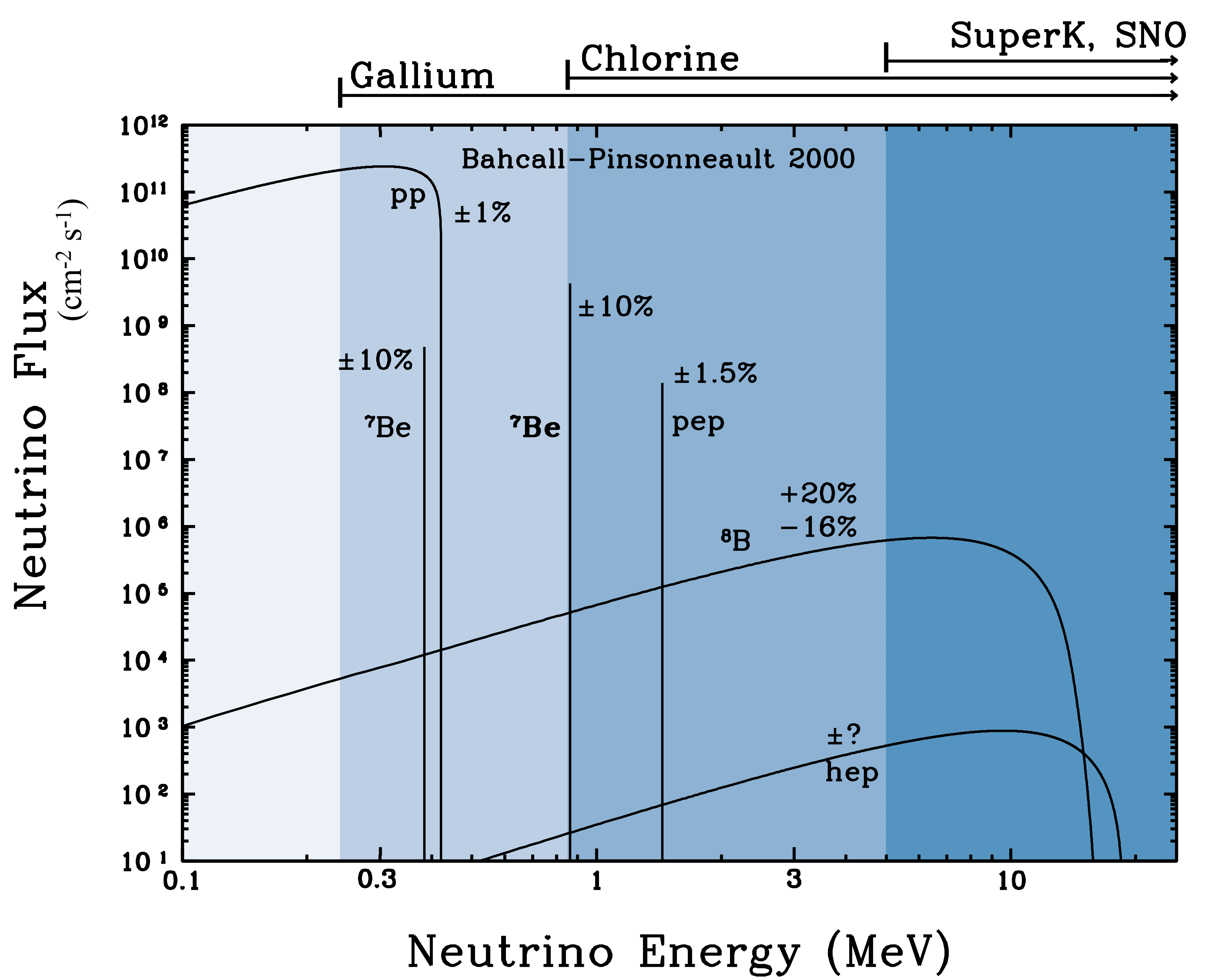
Neutrinos solares



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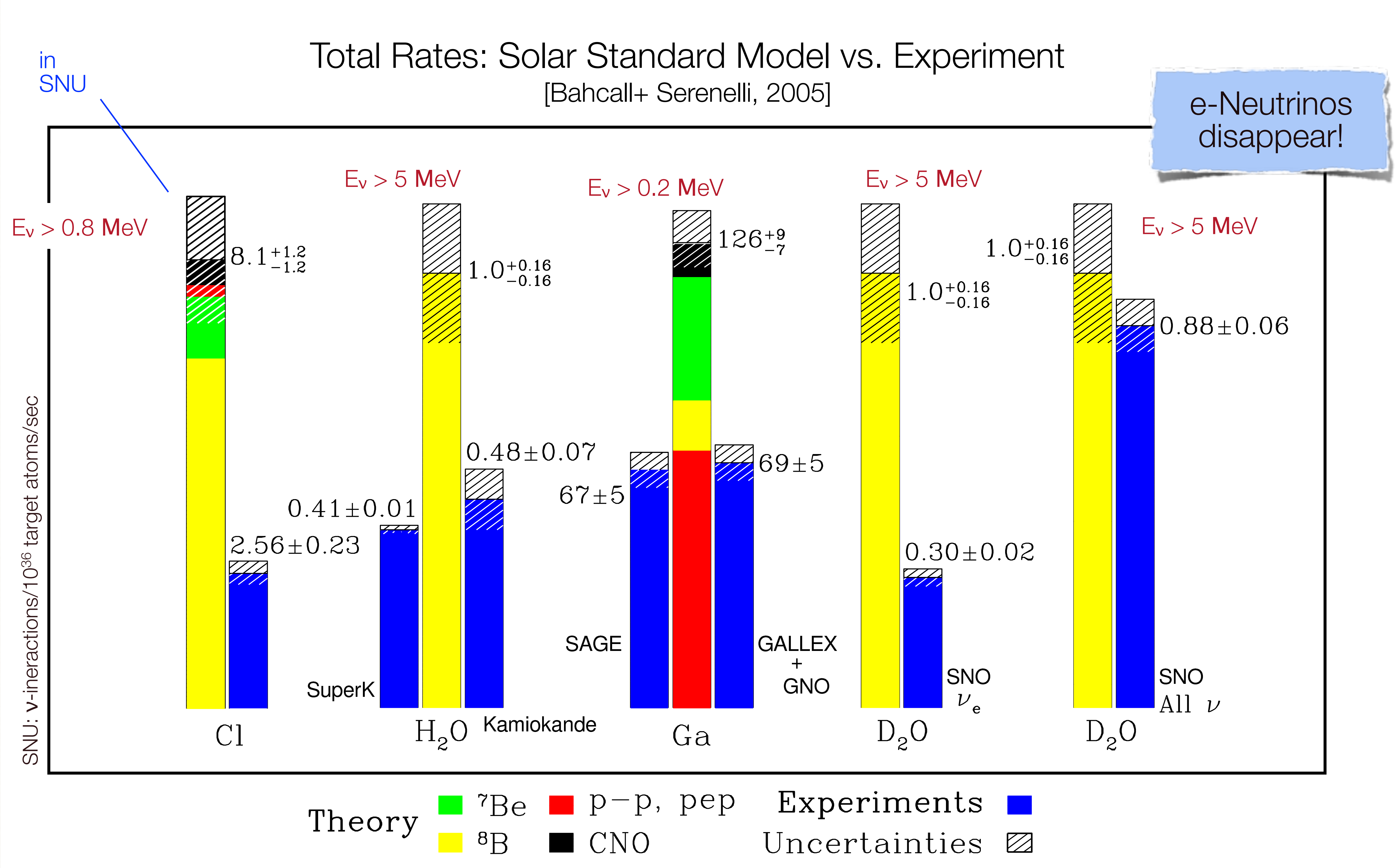
Detectando Neutrinos



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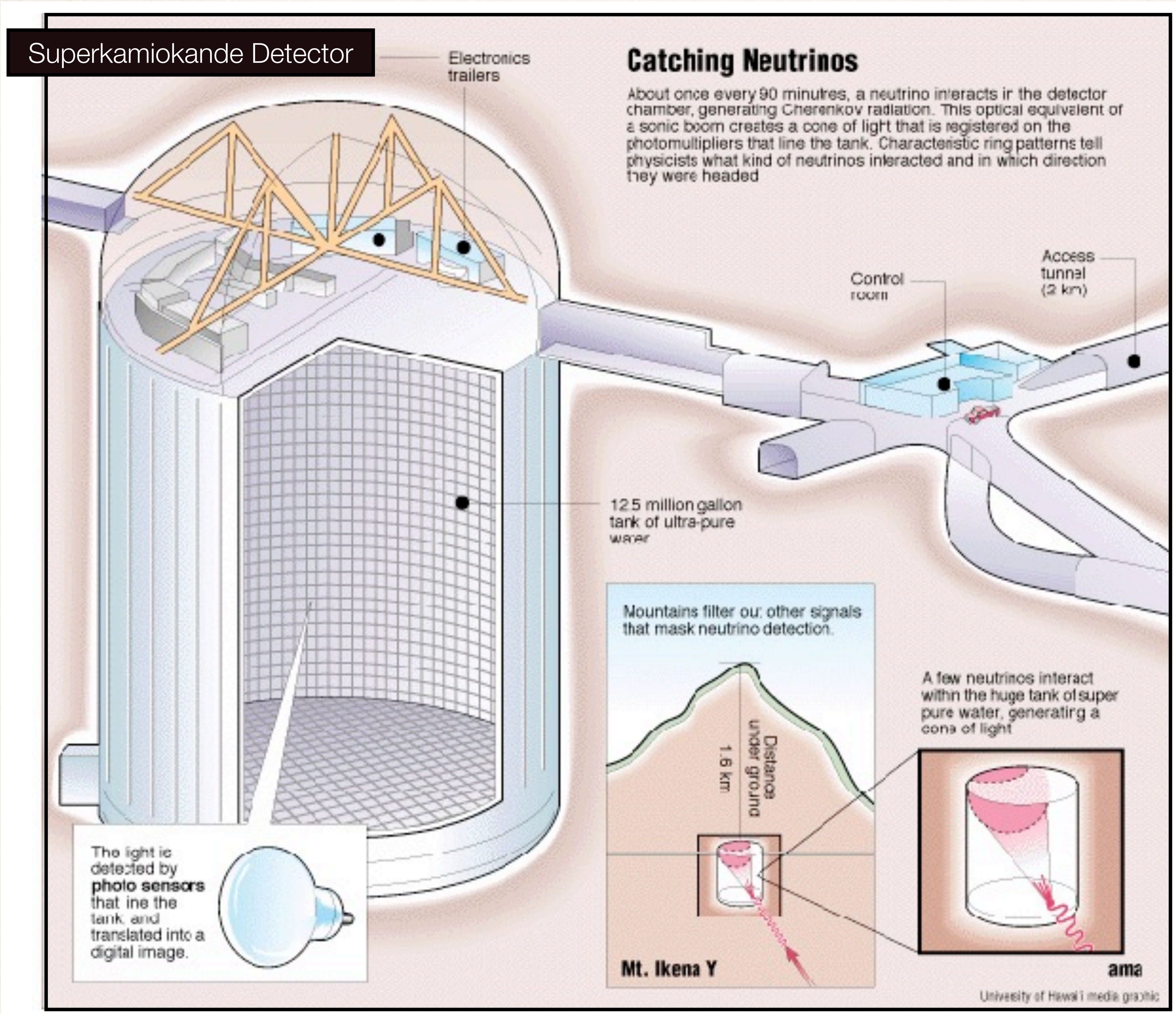
Detectando Neutrinos



Water tank
1.6 km below ground

50 Million liter
ultra-pure water

1 Neutrino-interaction
every 1.5 hours

Neutrino detection
via Cherenkov light

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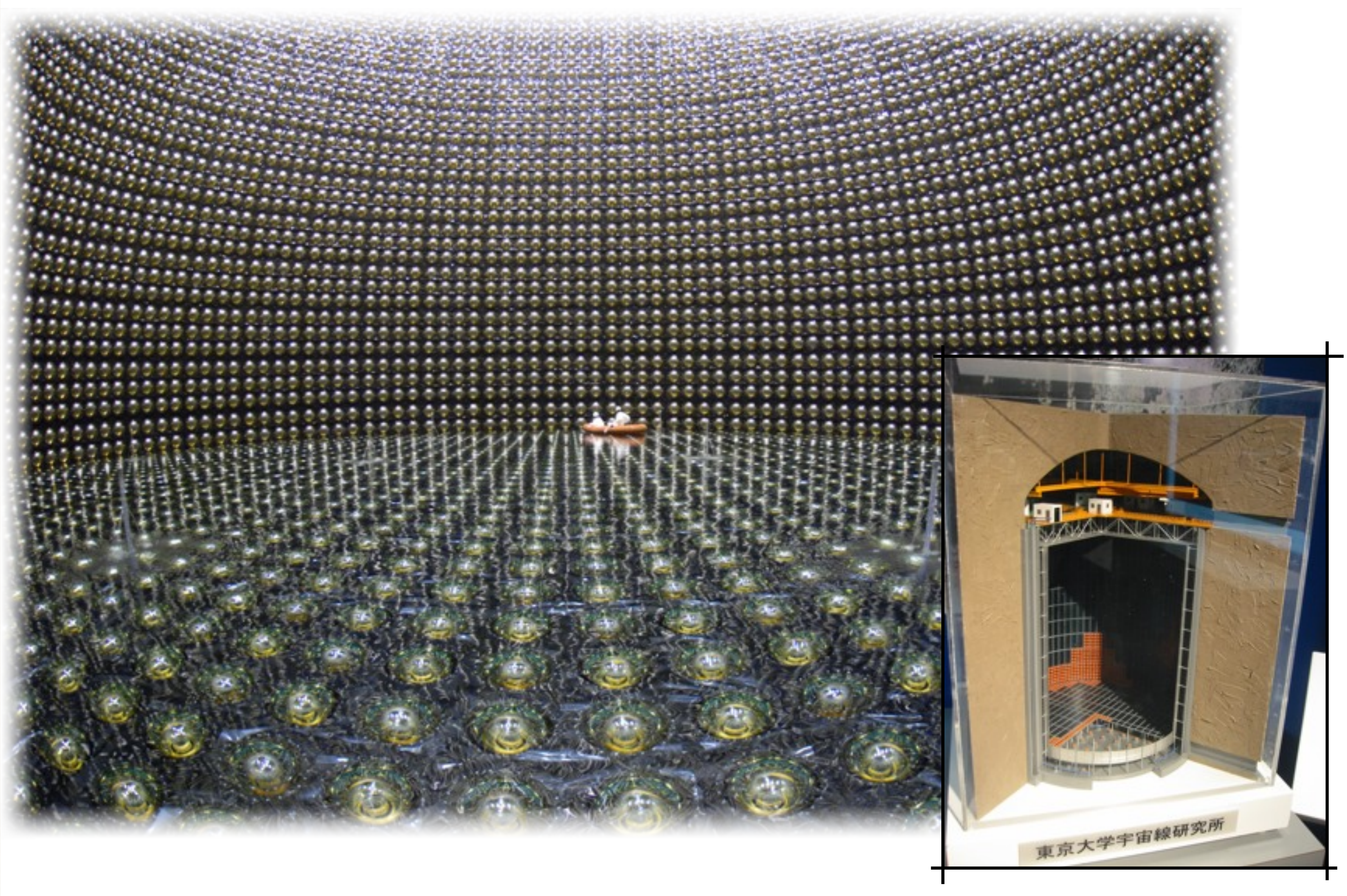
Detectando Neutrinos



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Detectando Neutrinos

Mounting of Photomultiplier Tubes

Total: 11,146 20″ pmts
1,885 8″ pmts

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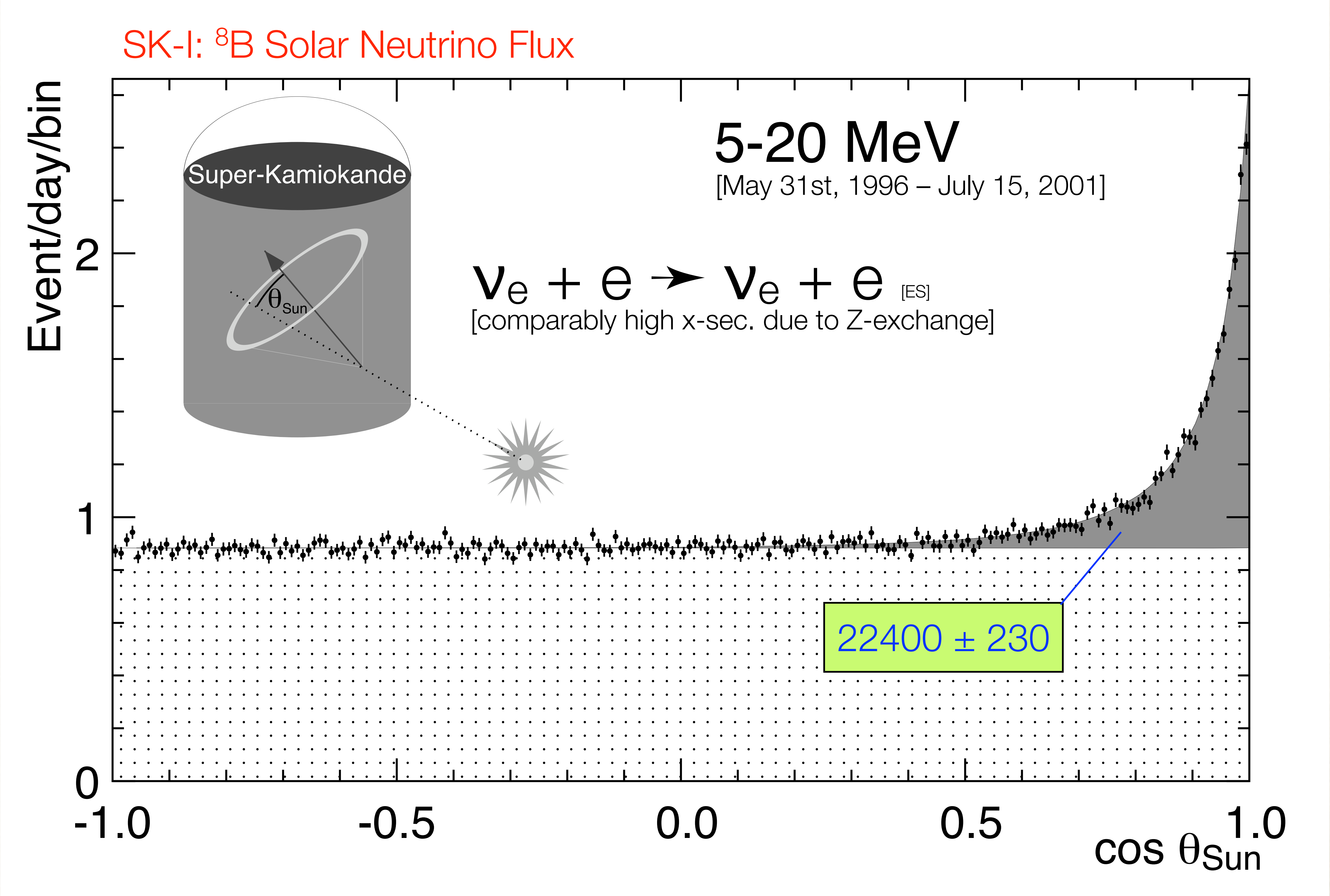
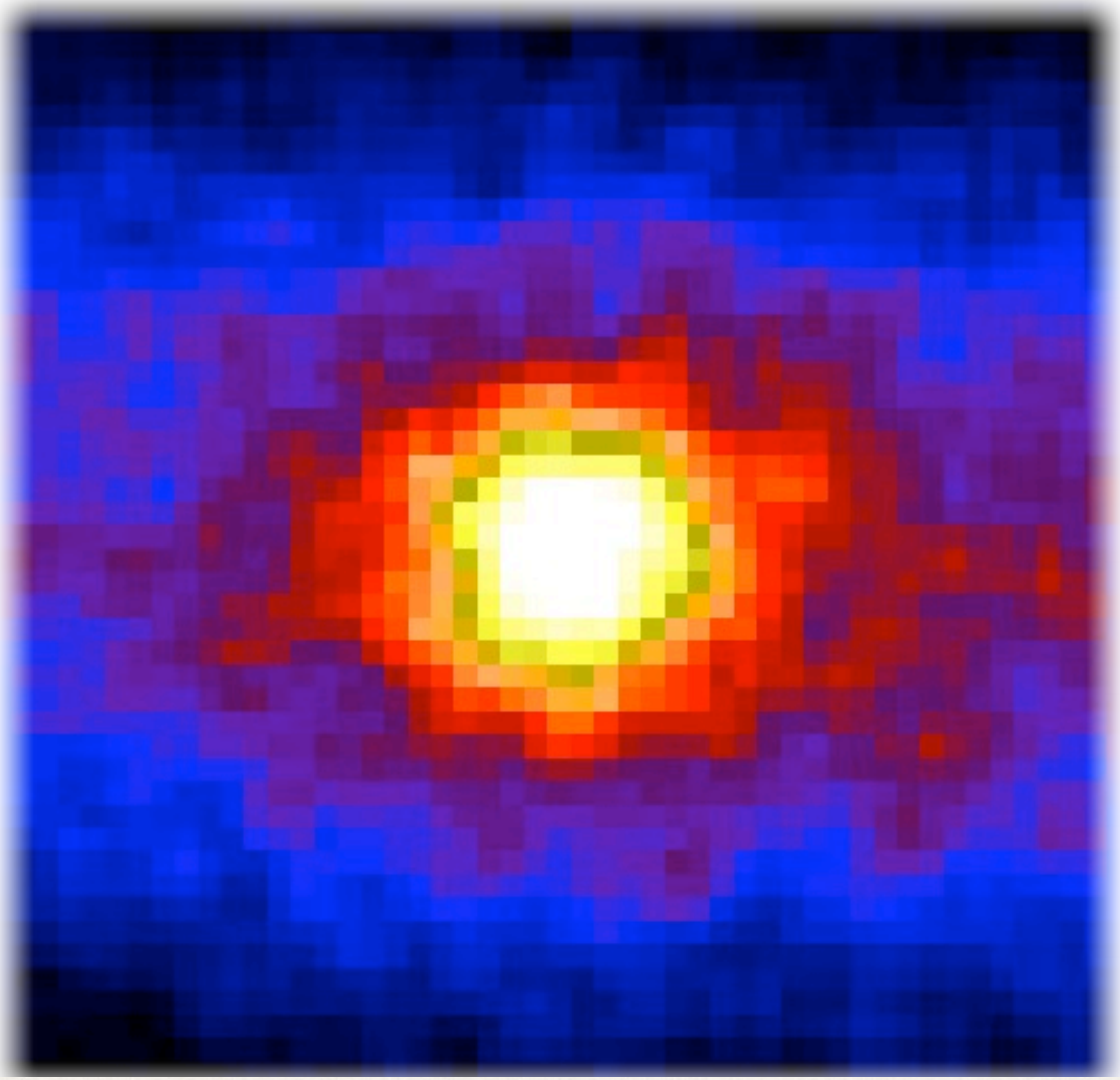
Detectando Neutrinos



Detectando Neutrinos



The sun seen through the earth in neutrino light

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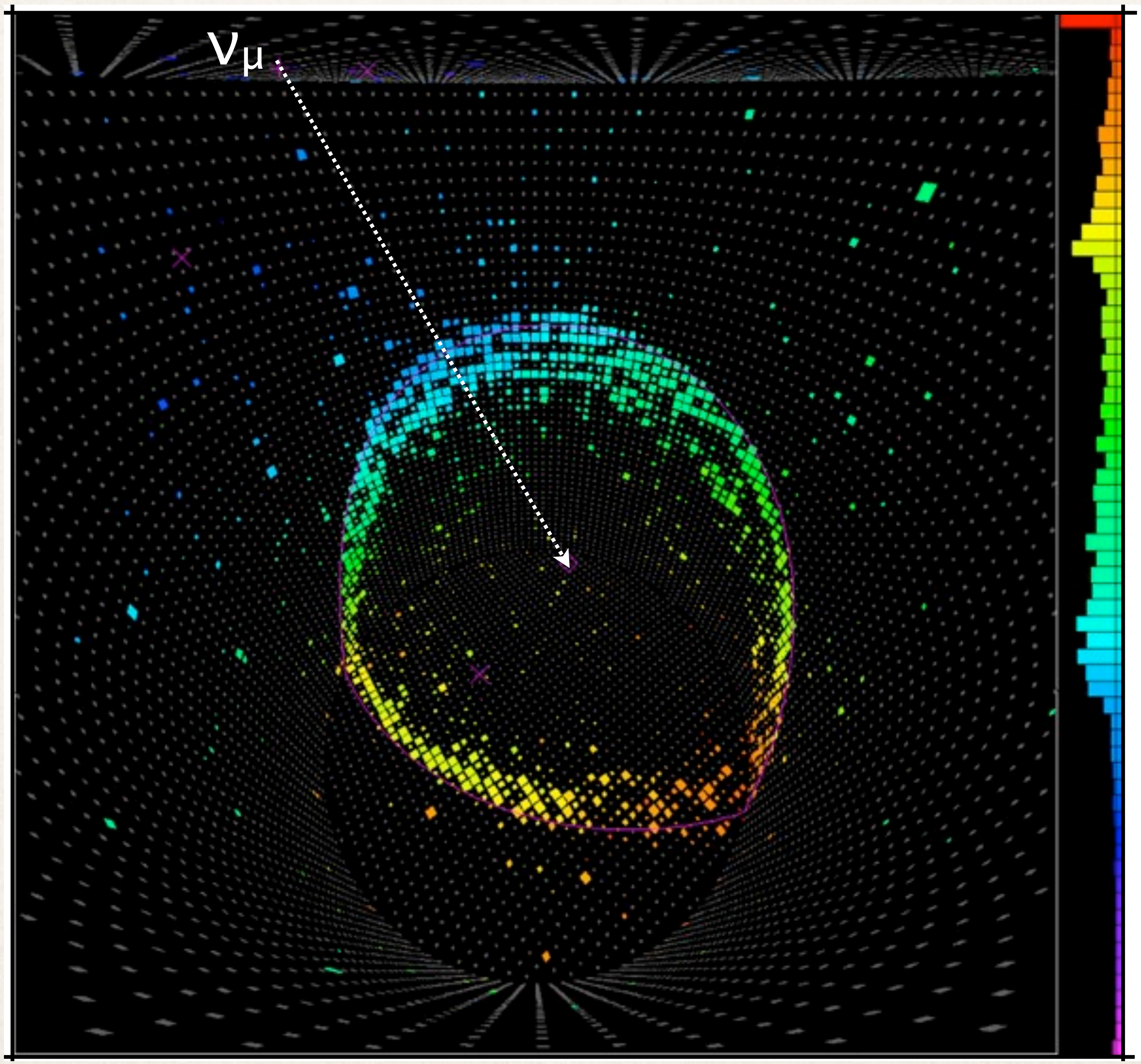
Detectando Neutrinos



Muon event
[603 MeV]

Observation of
clean Cherenkov ring
with sharp edges

Flight direction from
timing measurements
[blue: early; red: late]

Energy from amount
of light observed in PMTs

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