# Nuclear Absorption Lines and Occulted Sources

# Outline

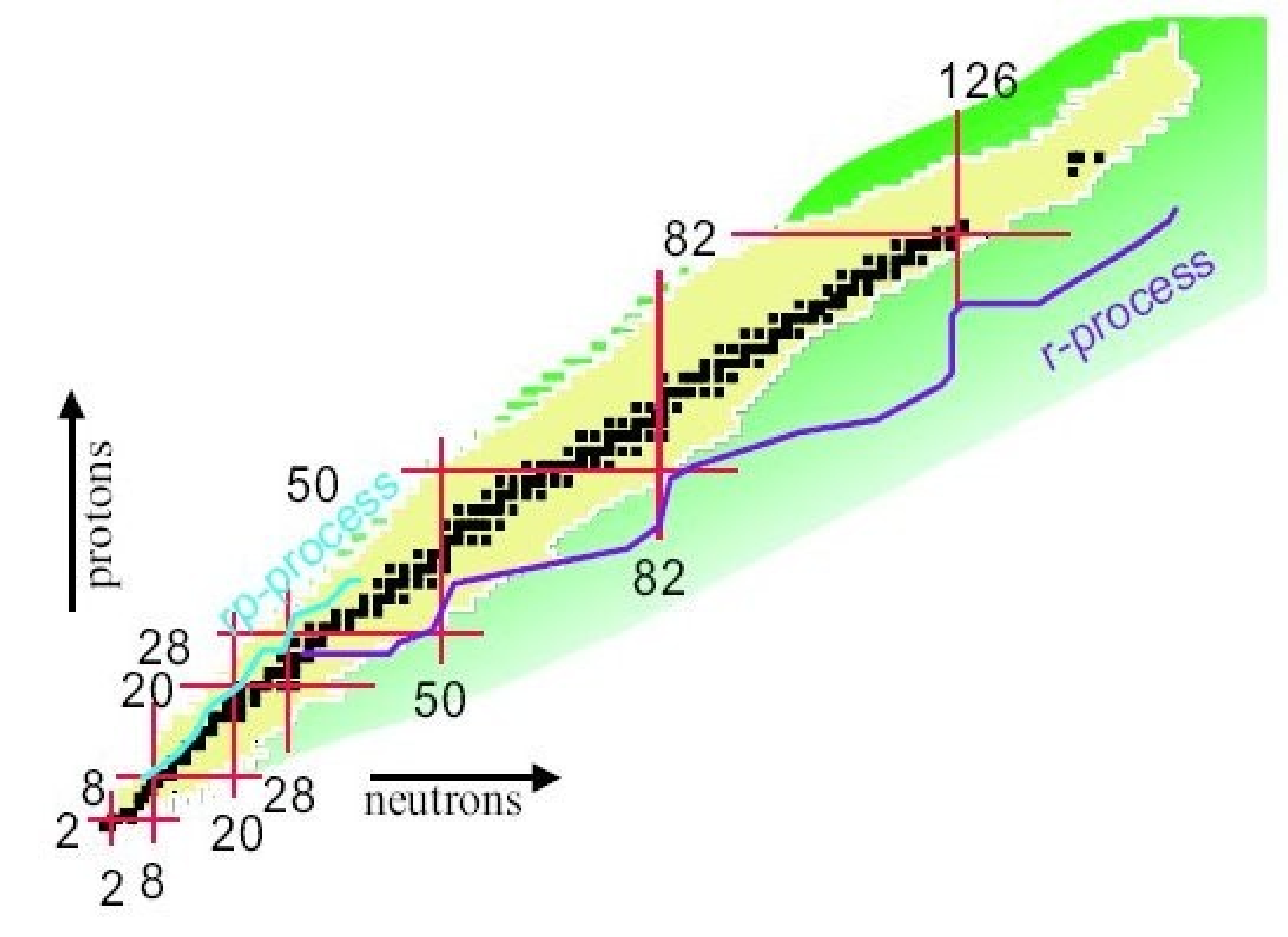
1. Nuclear Structure / Models

2. Nuclear - Photon Interaction
   2.1 Dipolinteraction - GDR
   2.2 Pygmy Dipole Resonance - PDR
   2.3 Particle Production
   2.4 Total Cross Sections

3. Photo absorption in γ-ray spectra
   3.1 Obscured Sources
   3.2 Absorption Lines
   3.3 Resonant Absorption Troughs

# Nuclear Structure

**The Nuclear Landscape:**

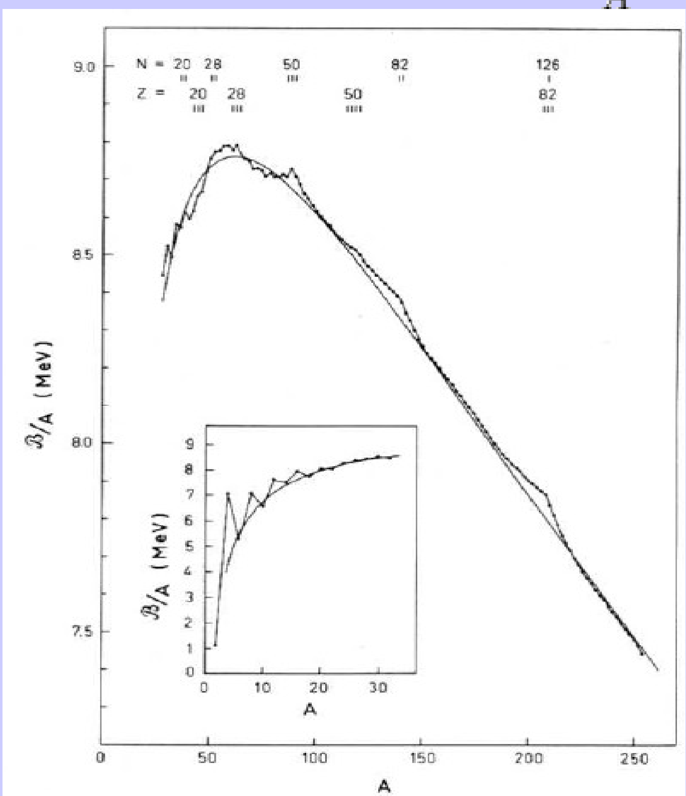


# Nuclear Structure

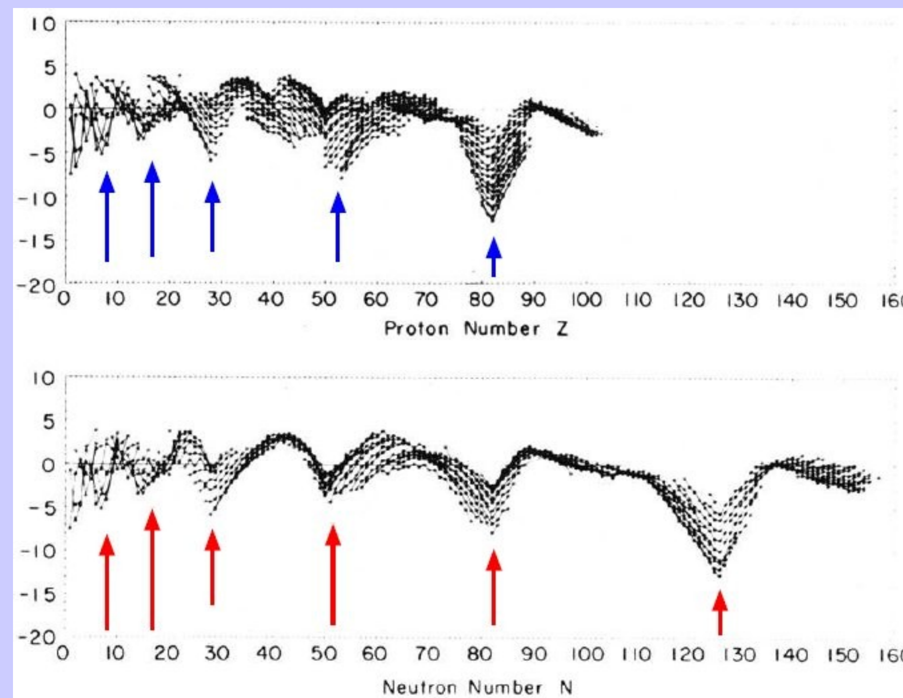
**Binding Energies described in the Nuclear Drop Model:**

**-> Weizsäcker mass formula:**

$$E_b = a_1 A - a_2 A^{2/3} - a_3 Z^2 A^{-1/3} + a_4 \frac{\left(Z - \frac{A}{Z}\right)^2}{A} \pm f_5.$$




**But: Deviations of the Binding Energy Depending on the Number of Protons/Neutrons**



# Nuclear Structure / Shell Model

**Shell Modell: Describes the Nukleon in an effective potential of the others**

**-> Magic Numbers**

**Woods Saxon Potential:**

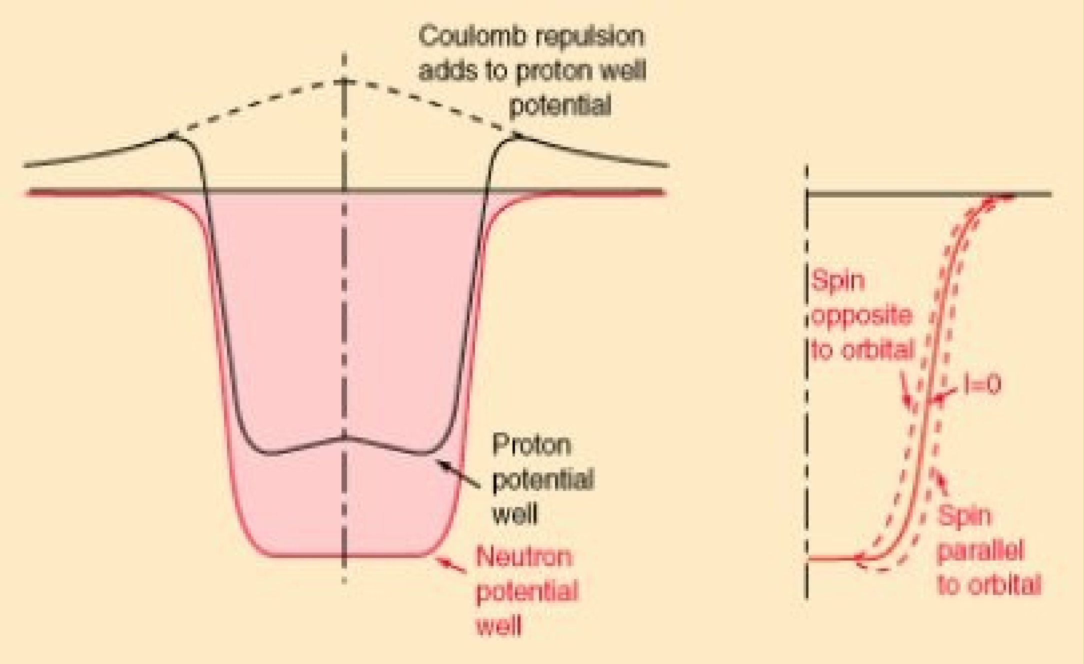
**depth of the well is proportional to the density of nucleons**

**spherical Woods-Saxon potential:**

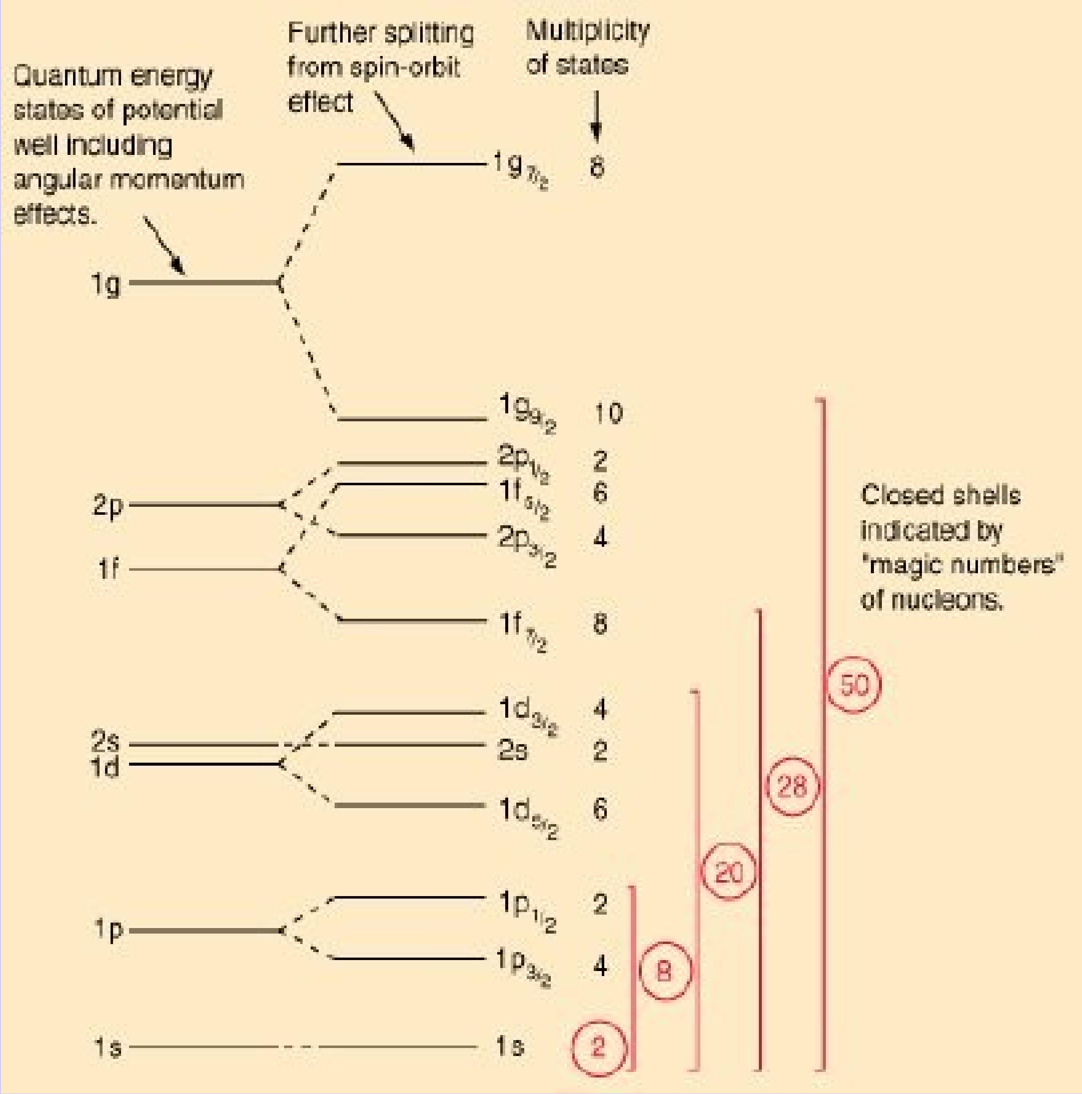
$$V = -\frac{V_0}{1 + exp[\frac{r-R}{a}]}$$

**- Spin – Orbit - Coupling**

$$V_{S.O.}(\mathbf{r};\beta_2) = -\lambda(\frac{\hbar}{2mc})^2[\nabla V(\mathbf{r};\beta_2)_{S.O.} \times \mathbf{p}] \cdot \mathbf{s}.$$



# Nuclear Structure / Shell Model




**But: Shell Model does not explain Quadrupol Moment for a number of nuclei, e.g. $^{17}O$**

-> Collective vibrations
and rotations

**-> Collective Motion of all nucleons**

# Nuclear Structure / Collective Model

**Collective model combines liquid drop and shell model:**

- **Net nuclear potential due to filled core states**
- **Nucleons in the unfilled shells move independently within the core potential**
- **Outer-shell nucleons disturb the potential**

$$V(\mathbf{r};\beta_2) = -\frac{V_0}{1+exp[r-R(\mathbf{r};\beta_2)/a]}$$

- **Potential deformation parameter β**
- **Two types of low lying (0..2 MeV), collective effects:**
    - **Excitation of surface vibrations**
    - **Rotations of the deformed shape**

# Electronic Excitations

**Fermis Golden Rule yields transition propability:**

$$dW = \frac{2\pi}{\hbar} \left| < \psi_f | H_{int} | \psi_i > \right|^2 \cdot d\rho(E)$$

**Hamiltonian for electromagnetic interactions:**

$$H_{int} = -\frac{e}{m} \vec{p}\vec{A} + e\phi \equiv j \cdot A$$

**Incoming Photon:**

$$dW_{fi} = \frac{e^2}{8\pi^2 \varepsilon_o \hbar^4 c^3} E_\gamma^3 \left| \vec{\varepsilon} \int d^3 r \psi_f^* \, \vec{r} \, e^{i\vec{k}\vec{r}} \psi_i \right|^2 d\Omega$$

**Multipolexpansion:** $e^{i\vec{k}\vec{r}} = 1 + i\vec{k}\vec{r} + \ldots$

**Dipol transmission propability (Photon spin parity :** $J^\pi = 1^-$ **)**

$$W_{fi}^{(E1)} = \frac{1}{\tau} = \frac{e^2}{3\pi \varepsilon_o \hbar^4 c^3} E_\gamma^3 \left| \int d^3 r \psi_f^* \, \vec{r} \, \psi_i \right|^2$$

# Photo-absorption

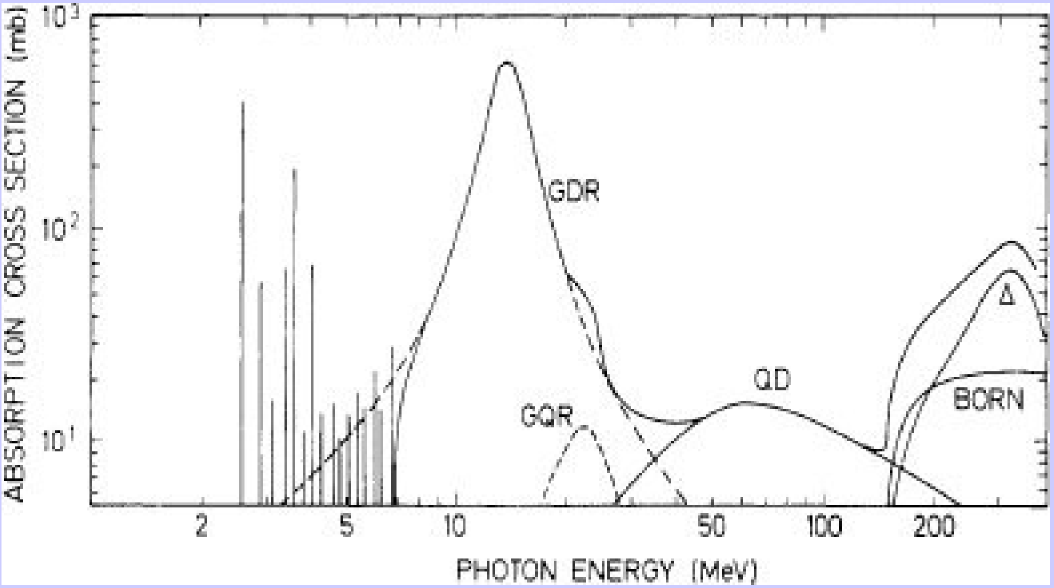
**Pygmy Dipol Resonance PDR**

**Giant Resonances:**

- **Giant Dipole Resonance GDR**
- **Giant Quadrupol Resonance  GQR**
- **Quasi-Deuteron Excitations QD**

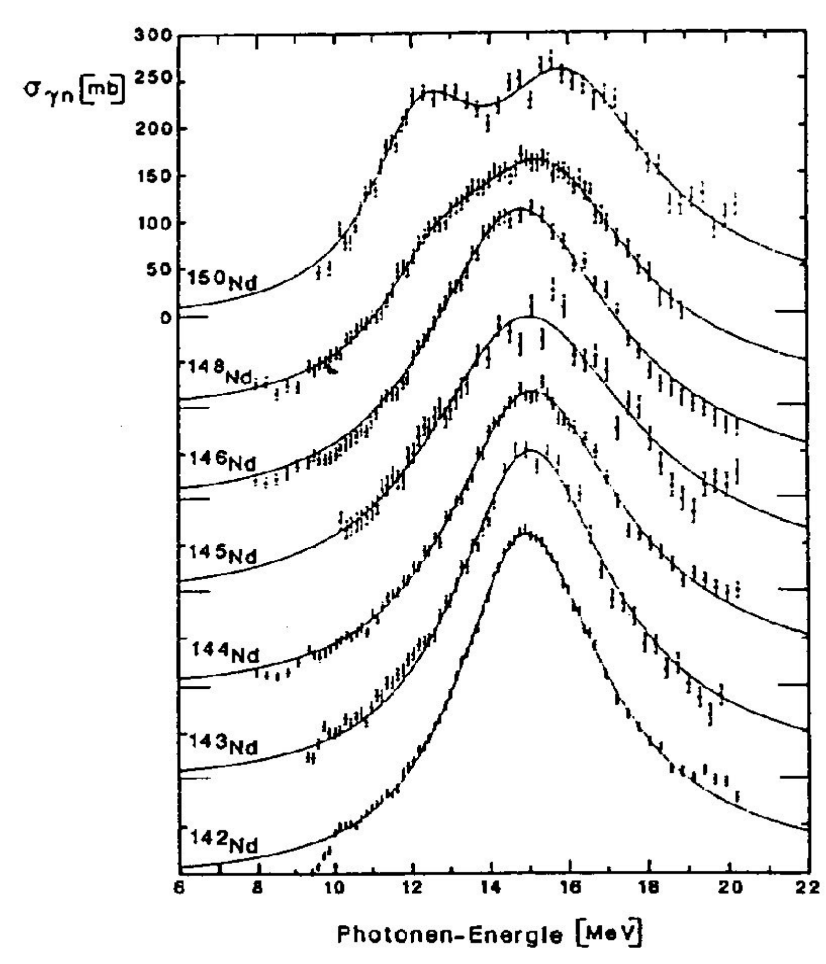
**Particle Excitations:**

- **Delta Resonance**
- **Born Meson Production**



# Giant Resonances

- Oszillation of Neutrons against Protons
- Above the particle production energy (at 8..10 MeV)
- Spherical Nuclei: Vibrations along all three perpendicular axes are equivalent and the strength is distributed equally.
- Deformed Nuclei: two peaks: Vibrations of protons against neutrons along the symmetry axis vs. Vibrations perpendicular to the symmetry axis.
- Exact describtion complicated, collective excitation of a many-body system
- GDR (Giant Dipole Resonance dominates total cross section for E1 transitions)



# Giant Resonances

• Generally described in RPA (Random Phase Approximation):

-> harmonic, mean-field description of collective excitations of a many-body system

-> collective motion is contained in the one-body density matrix $\rho$

$\rho(r,r',t)$

-> Sollution of the time dependent Hartree Fock Equation gives the equation of motion for $\rho(r)$ and the corresponding wave functions

$$i\hbar \frac{\partial \rho(\mathbf{r}, \mathbf{r}', t)}{\partial t} = \frac{\delta E[\rho]}{\delta \rho\ (\mathbf{r}, \mathbf{r}', t)}$$

-> particle-vibration coupling Hamiltonian $\delta U = k\,\alpha f$

$\alpha$ collective coordinate of the harmonic oszillator

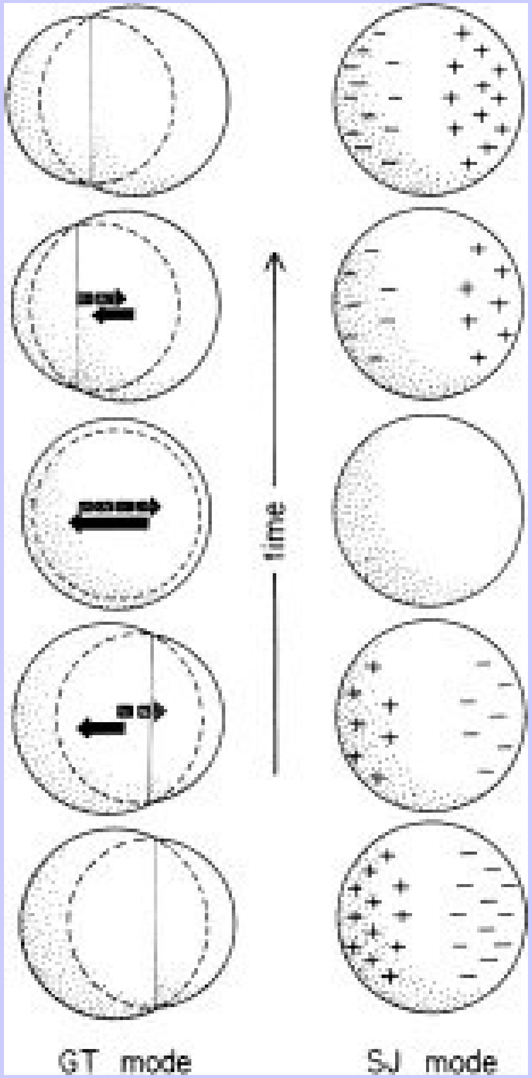
$f$ collective states exciting Operator (e.g. for GDR = D)

-> Theoretical Models described in

K. Goeke and J. Speth – Theory of Giant Resonances

Aumann – Multiphonon Giant Resonances in Nuclei

# Giant Resonances / More intuitive




- Gaint Dipole Resonance devided in

  GT Mode (Changing Surface)
  SJ Mode (Charge Fluctuations)

- Describes fairly well position and width of the GDR

$$\frac{1}{\omega_-^2} = \frac{m r_0^2}{8J} A^{2/3} + \frac{3 m r_0^2}{8Q} A^{1/3}$$

SJ Mode
J = nuclear symm. coeff.

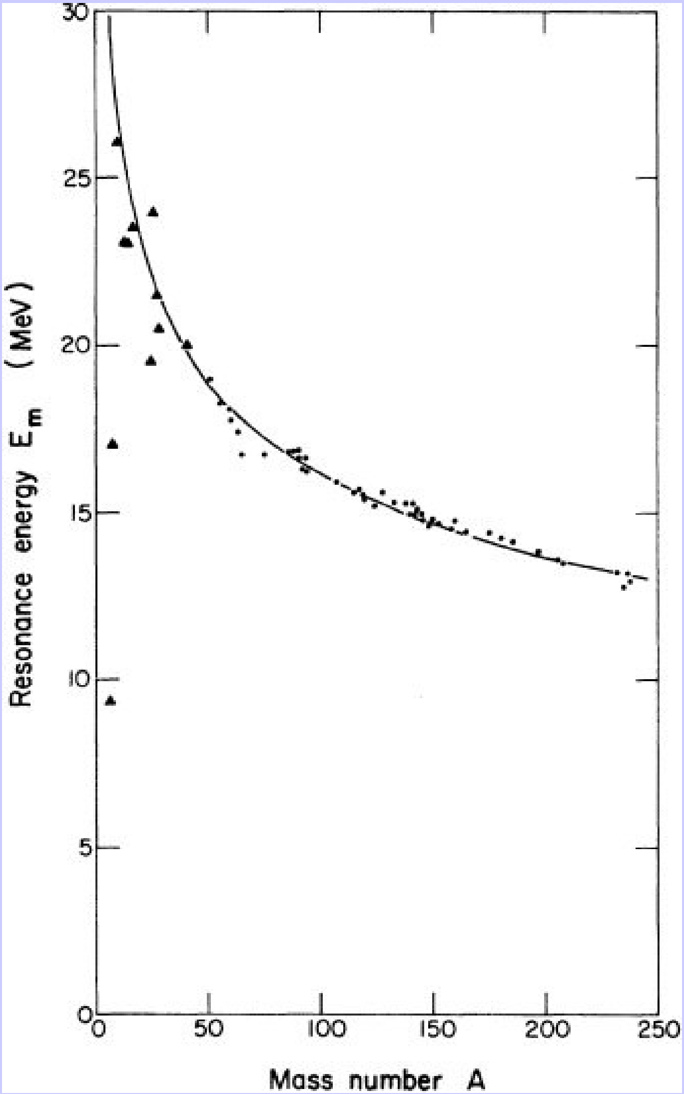
GT Mode
Q = stiffness coeff.

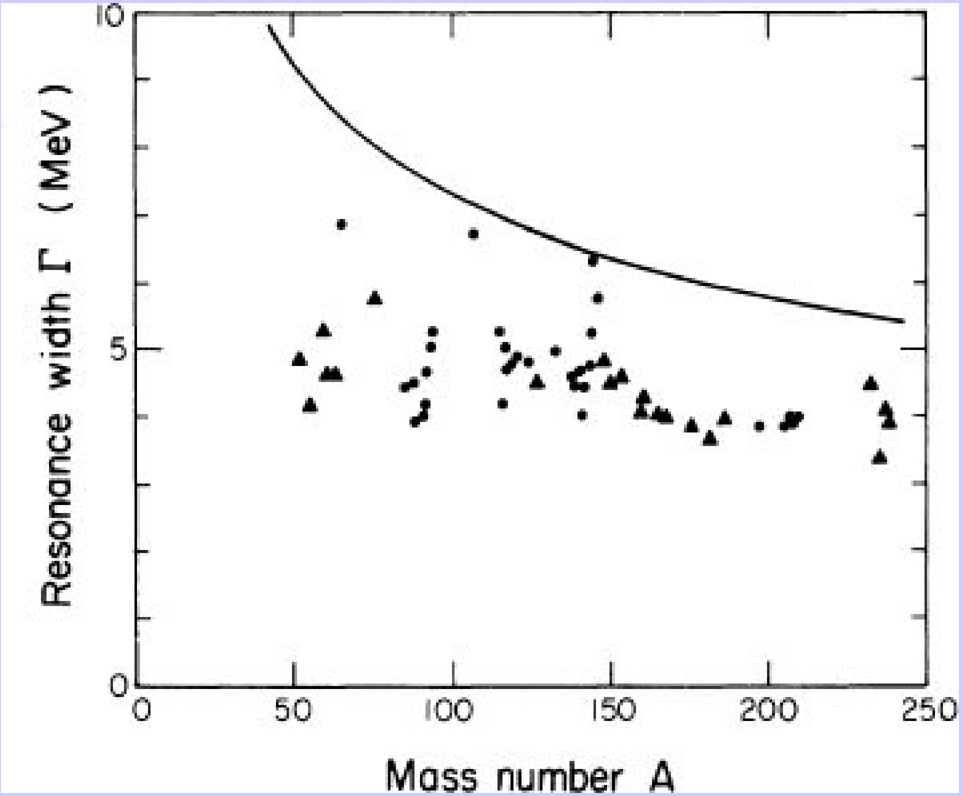
$$E_{GDR} = 31.2 A^{-1/3} + 20.6 A^{-1/6}$$

-> Mainly GT mode, with SJ mixing at high As

Width: $\Gamma = \hbar \left( \frac{\overline{v}}{R} \right)$

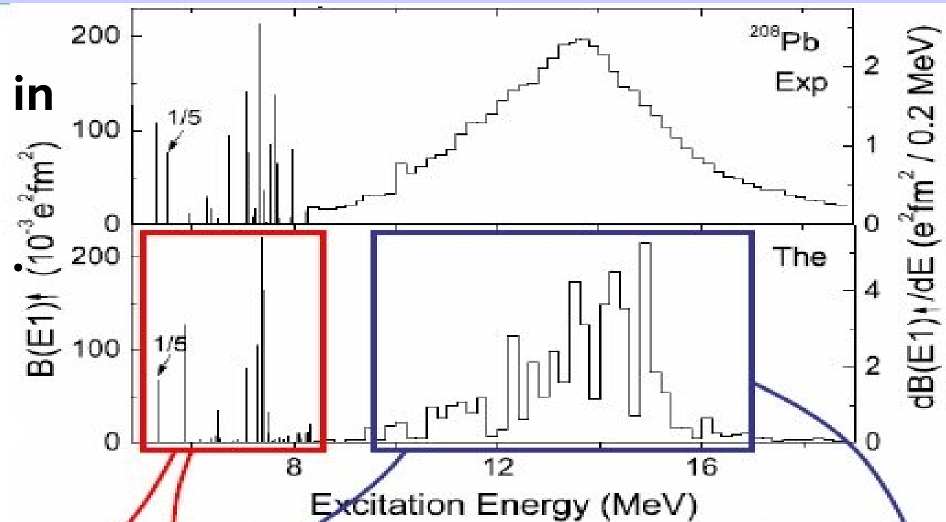
# Giant Resonances / More intuitive

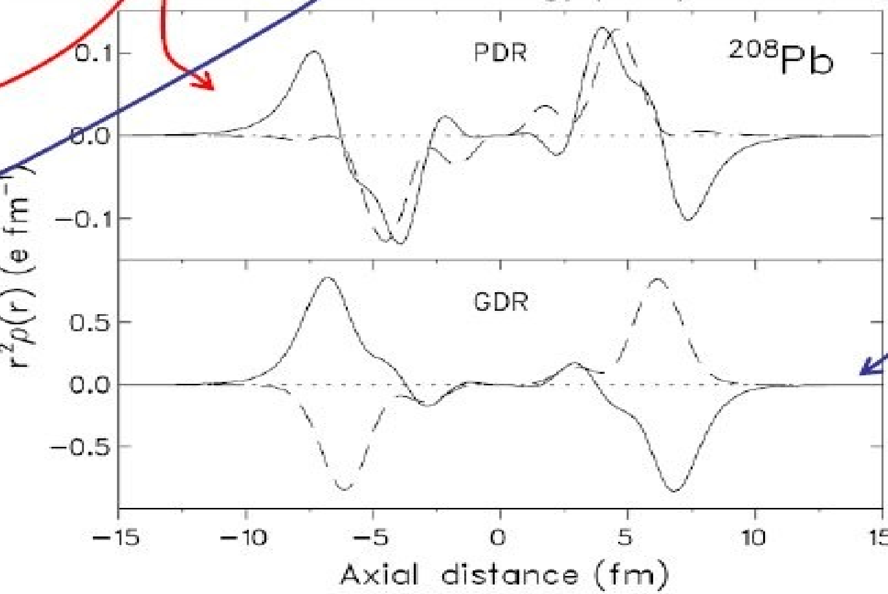


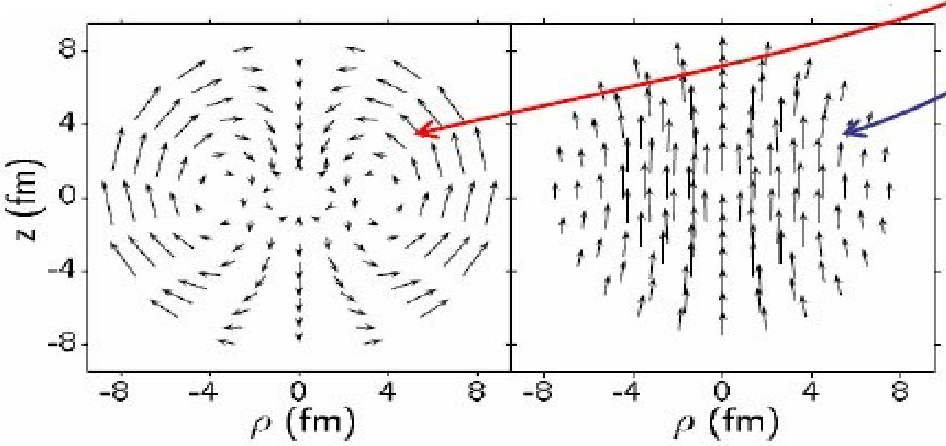



# Pygmy Dipol Resonance / PDR

- **Low-energy electric dipole resonance in stable nucleir**
- **Between 5 and 8 MeV (at or below the particle threshold)**
- **Small total cross sections compared to GDR**

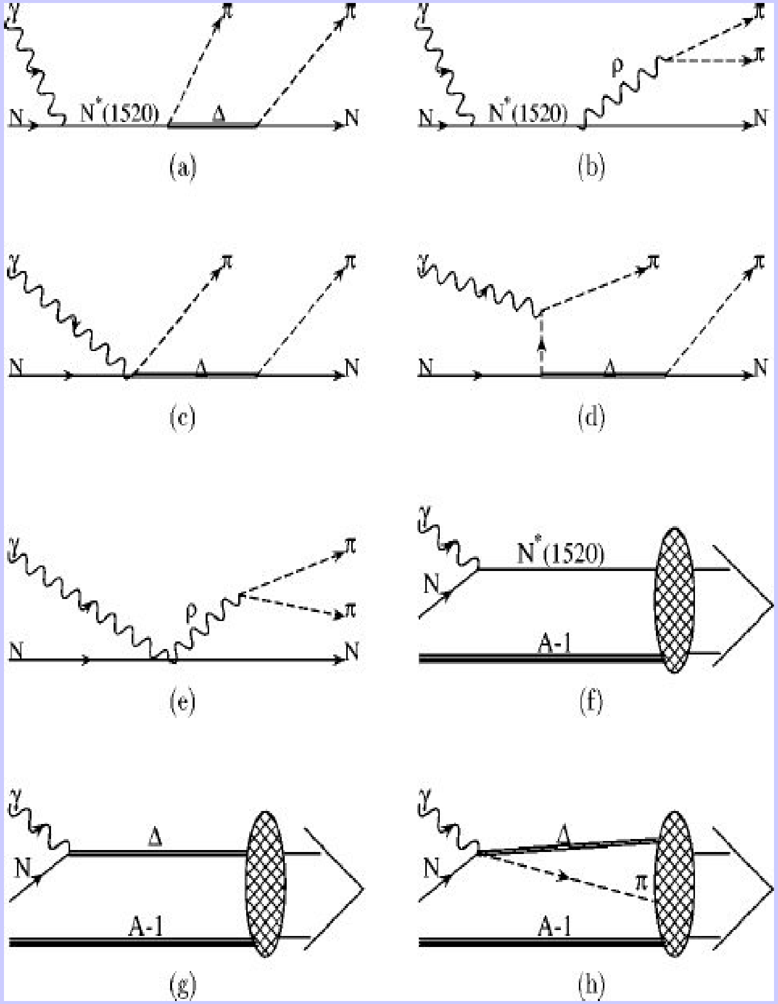


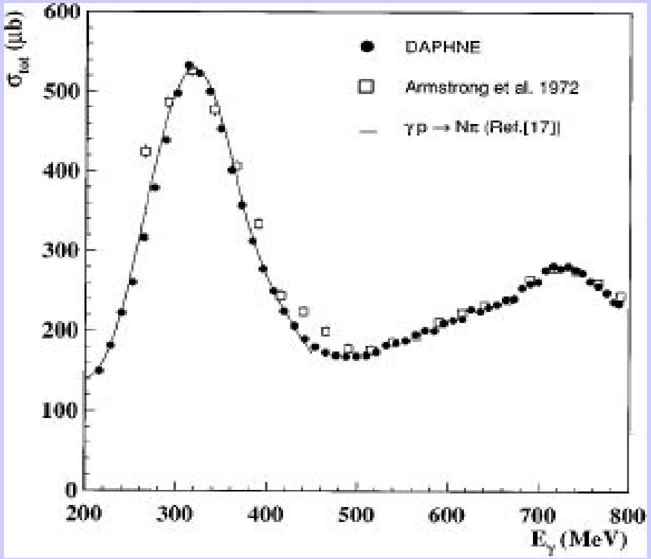
# Particle Production / Delta Resonance

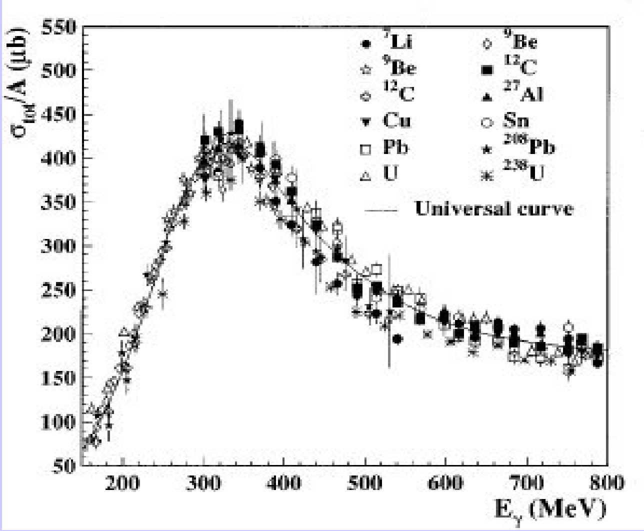
- **Photon induced particle production**
- **Two prominent in between states**
  **Delta and N* between 300 and 800 MeV**
- **Produced in different reaction channels**
- **No Position change (327 MeV peak for Δ)**
- **Δ = Spinflip of one quark**
- **N* = Excited state of one nuclei**



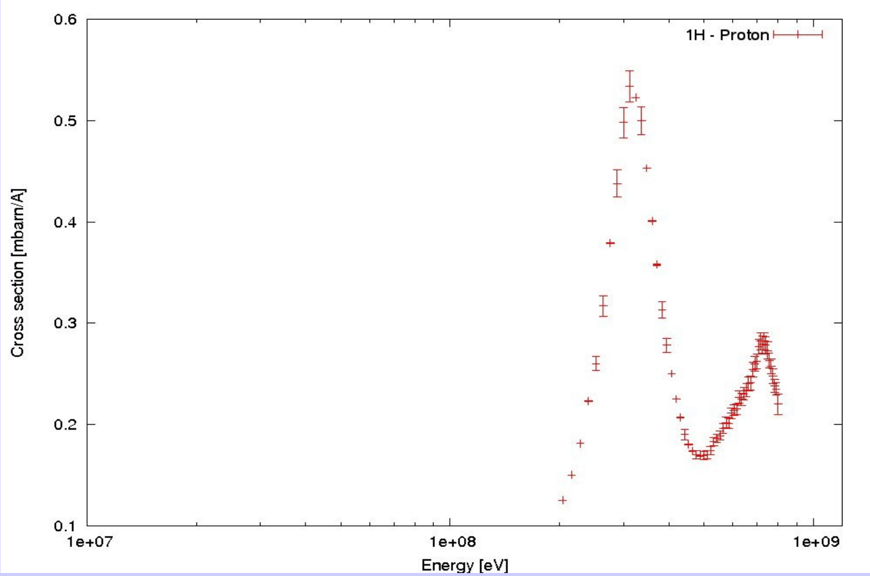
# Particle Production / Delta Resonance

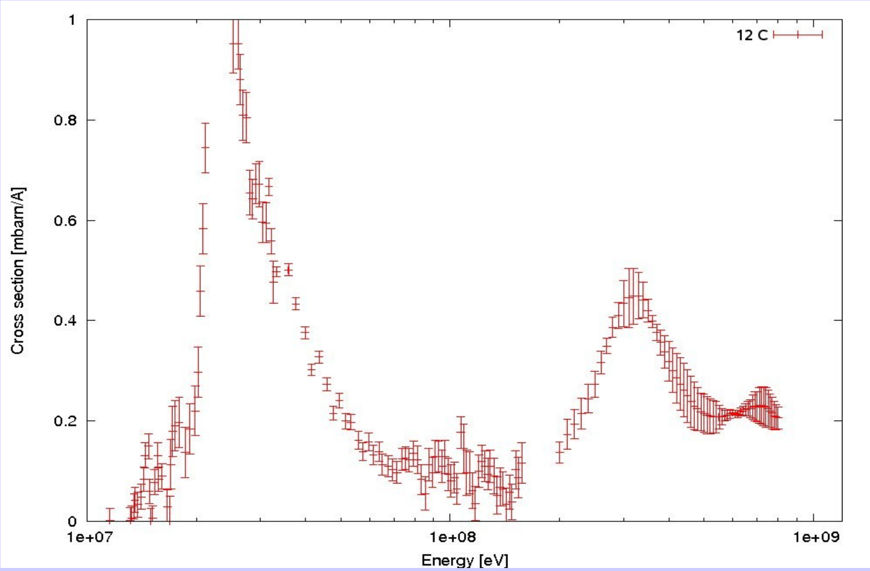
- For light elements: A=1..4 -> N*
- For heavy elements: A>7 No N* contribution
- Broadening of the Δ Resonance from
  ~160 MeV for a proton/neutreon to
  ~300 MeV for a nuclei
  -> More open decay channels

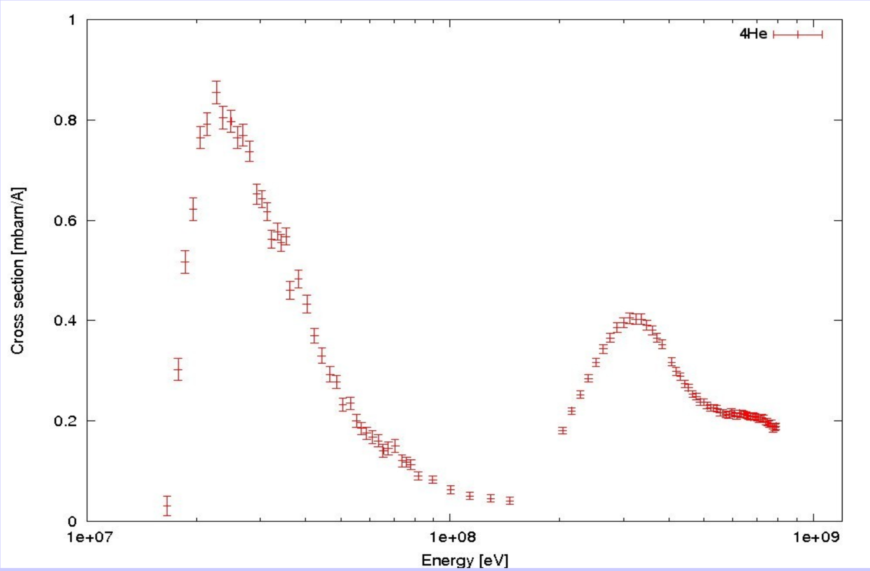


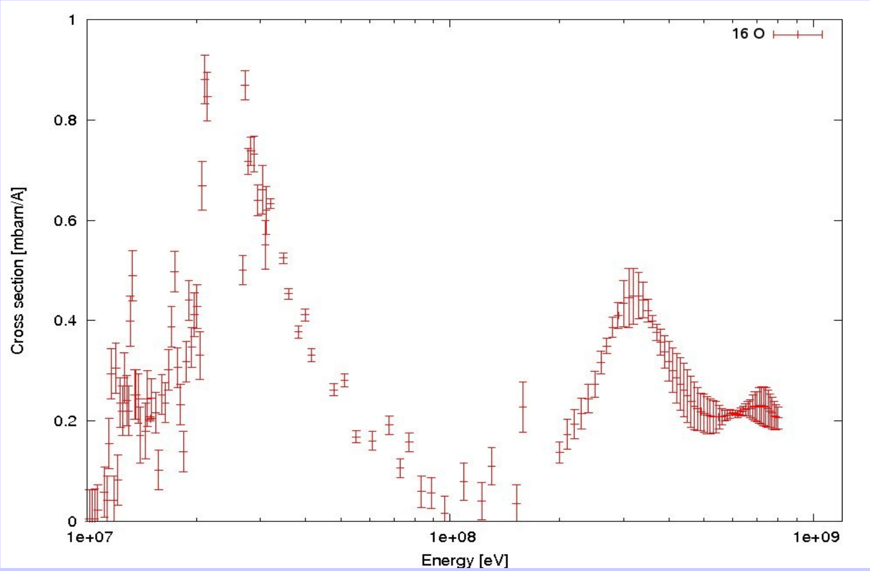



# Total Cross sections



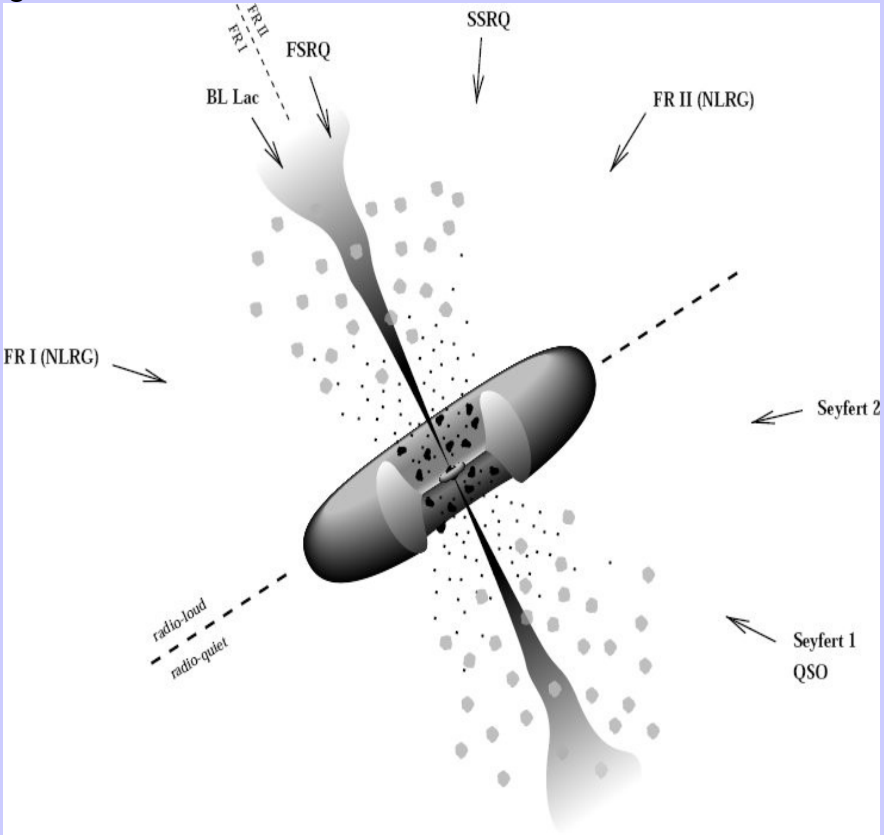
# γ-ray Sources / AGNs

Active Galactic Nuclei

-> ~3% of all Galaxies are considered as active
-> Large luminousity released in small core regions

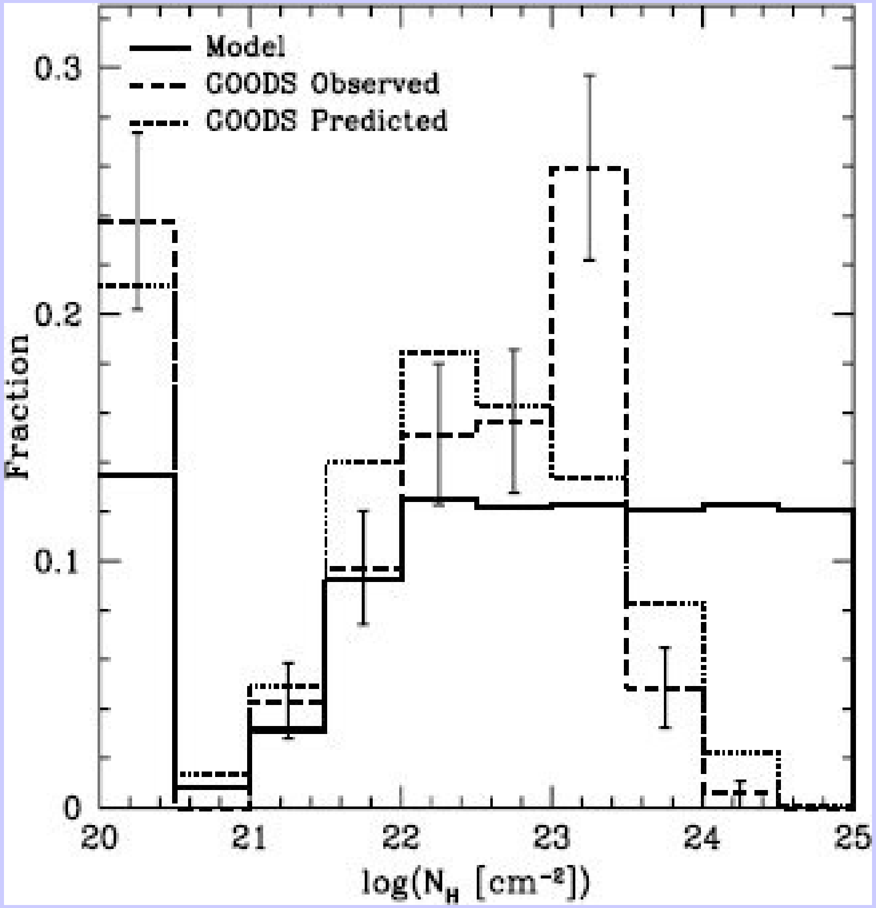
-> Supermassive Black hole in the center >$10^6$ $M_\odot$
-> Accretion of matter from an accretion disc feeds the black hole
-> Highly relativistic jet along the rotation axis

-> Seen along the jet axis (<10°) : Blazar
-> Quasar or Seyfert 1: AGN seen at ~30°
-> Seyfert 2: Seen at the higher angles >60°
-> Radio galaxy: Seen perpendicular to the jet



# γ-ray Sources / AGNs

- The viscous disc is heated up and shines brightly in the UV and soft X-ray region (Hard X- and γ-rays are produced very near the black hole)
- The central regions of many AGNs contain obscuring material (probably dust)
- AGNs account for most of the XRB.
- Geometry of the dust torus determines the amount of obscuring material along the observers line of sight the central emitting region
- Bimodial distribution between unabsorbed/absorbed sources ($N_H=10^{22}$ $cm^{-2}$)
- Chandra (to 10 keV) and XMM Newton (12 keV) find ¾ of all AGNs are absorbed
- Deep X-ray surveys miss a fraction of sources due to large obscuration



# γ-ray Sources / AGNs

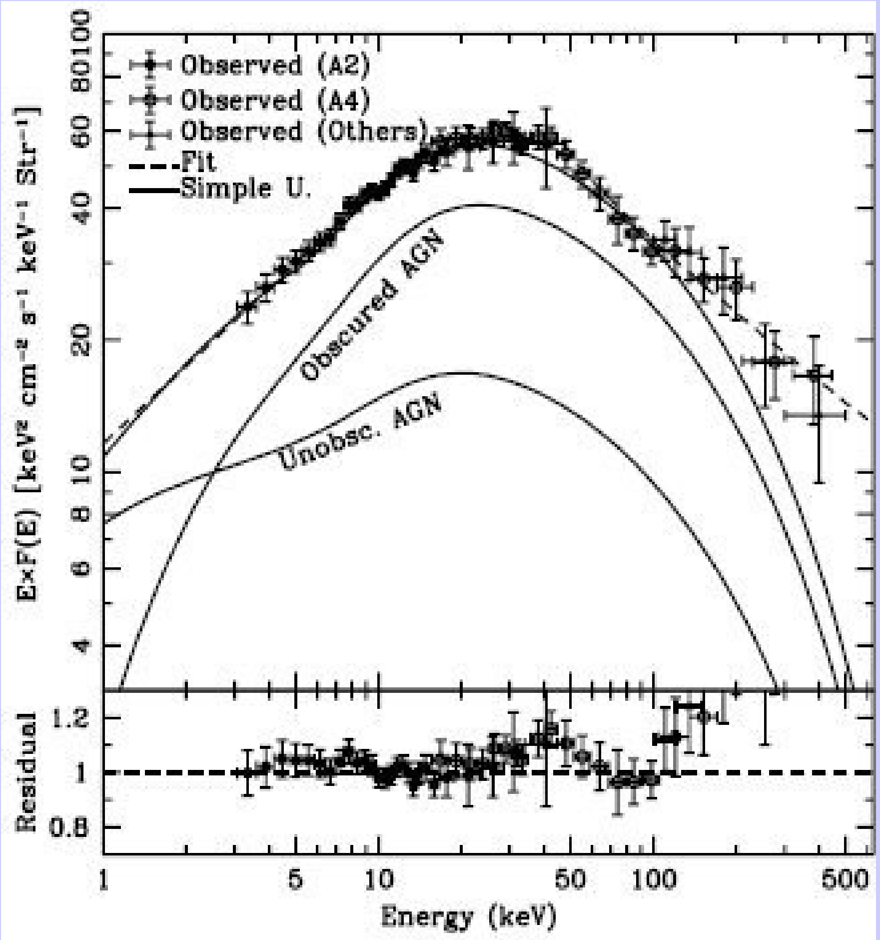
- Need for hard X-ray, γ ray studies sensitive > $N_H=10^{25}$ $cm^{-2}$
- Soft X-rays surveys are sensitive to max $N_H=10^{24}$ $cm^{-2}$
- Above 15 keV, Compton-thick sources can be probed

Compton-thick: $N_H > 1.5\ 10^{24}$ $cm^{-2}$

Mildly Compton-thick : $N_H < 10^{25}$ $cm^{-2}$

Heavily Compton-thick : $N_H > 10^{25}$ $cm^{-2}$

-> Source is visible only above 10 keV



# γ-ray Troughs in QSOs environments

- γ-ray studies with COMPTEL (1 MeV to 30 MeV) and EGRET (20~MeV to 30~GeV) from CGRO
- Analysis of the absorption troughs from bright γ-ray sources PKS 0528, 3C279 and some others
- Photon flux on detectable on Earth

$$\frac{\mathrm{d}N}{\mathrm{d}E} = \left(\frac{\mathrm{d}N}{\mathrm{d}E}\right)_{\text{unabsorbed}} \cdot e^{-\tau(E,z)}.$$

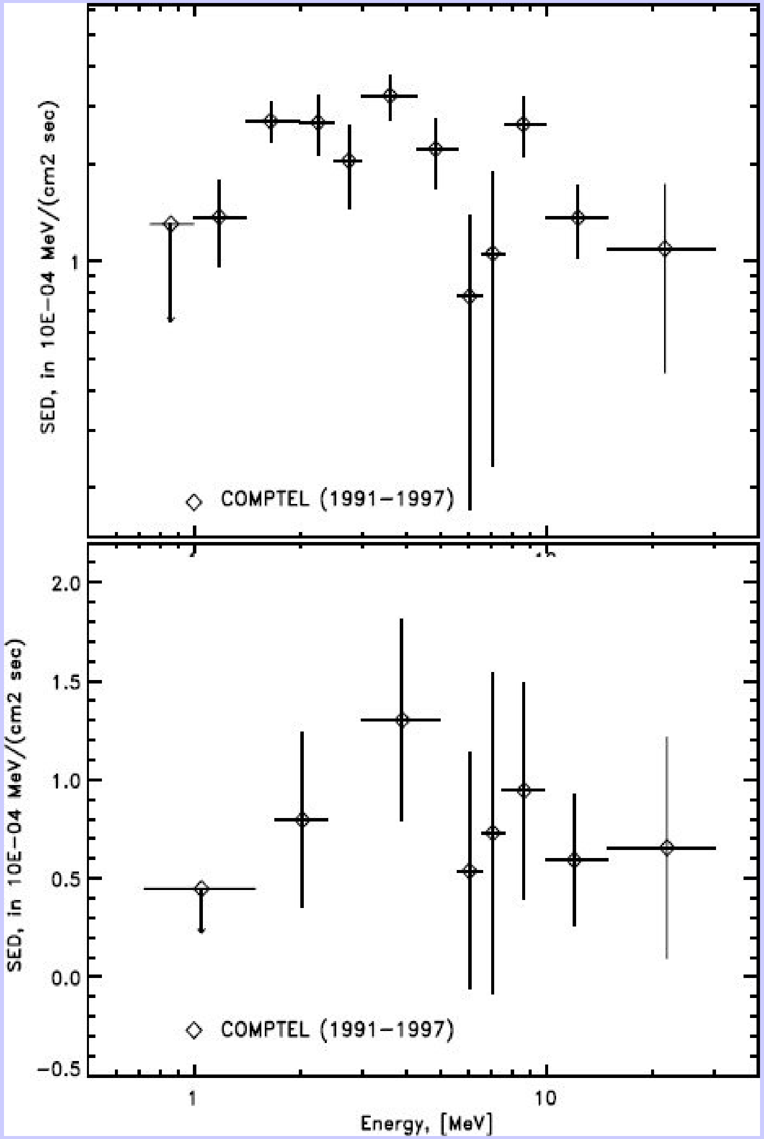
- Spectrum is fitted by two smoothly connected Power laws („Band function“)

$$N_E(E) = A\left(\frac{E}{100\,\text{keV}}\right)^{\alpha} \exp\left(-\frac{E}{E_0}\right),$$

$$\text{for} \quad (\alpha-\beta)E_0 \geq E,$$

$$N_E(E) = A\left[\frac{(\alpha-\beta)E_0}{100\,\text{keV}}\right]^{\alpha-\beta} \exp(\beta-\alpha)\left(\frac{E}{100\,\text{keV}}\right)^{\beta},$$

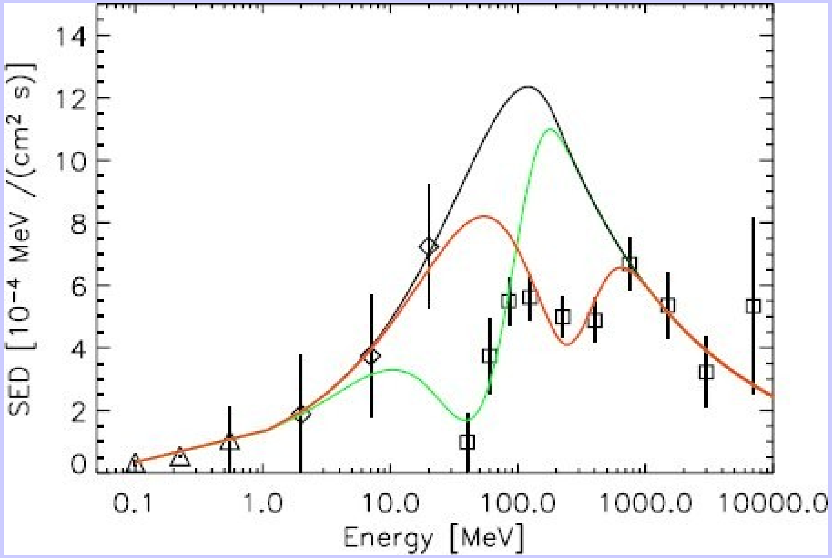
$$\text{for} \quad (\alpha-\beta)E_0 \leq E.$$

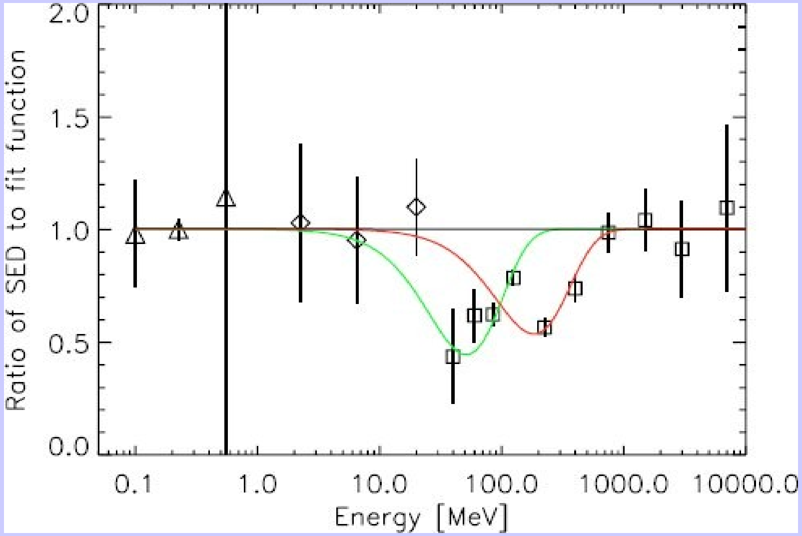


# γ-ray Troughs in QSOs environments

- 3C279: Optical variable Quasar:
  Luminosity variation in the optical,
  radio and X-ray band
  Redshift z=0.54
  - Different Observations between 91 and 96
  - Identification of γ-ray absorption from GDR and Δ-Resonance
  - Flux depression of 40% for Δ- and 93% for GDR
  - Δ Resonance at 204±4 MeV

    -> $E(\Delta)^{3C279}$=313±10 MeV
    -> $E(\Delta)^{real}$=327 MeV
  - GDR at ~ 23 MeV
    -> Depending on the metallicity of the environment

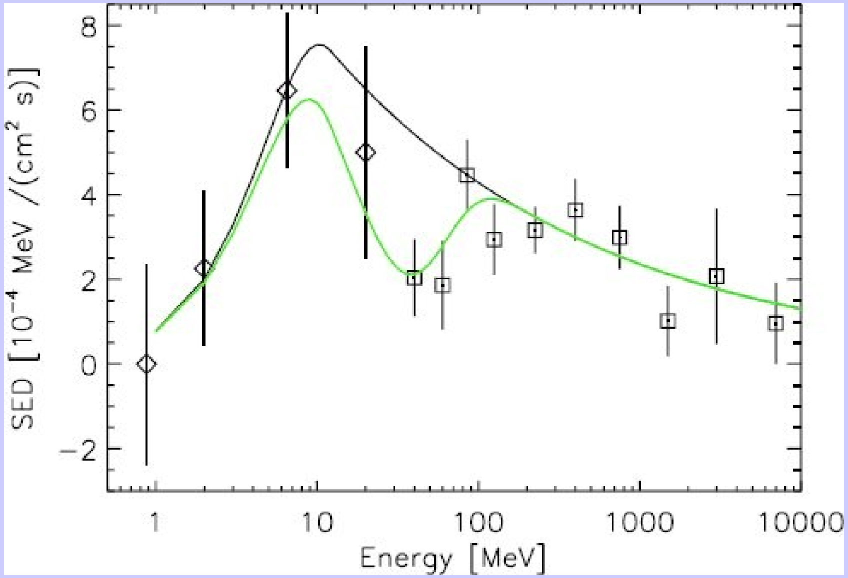


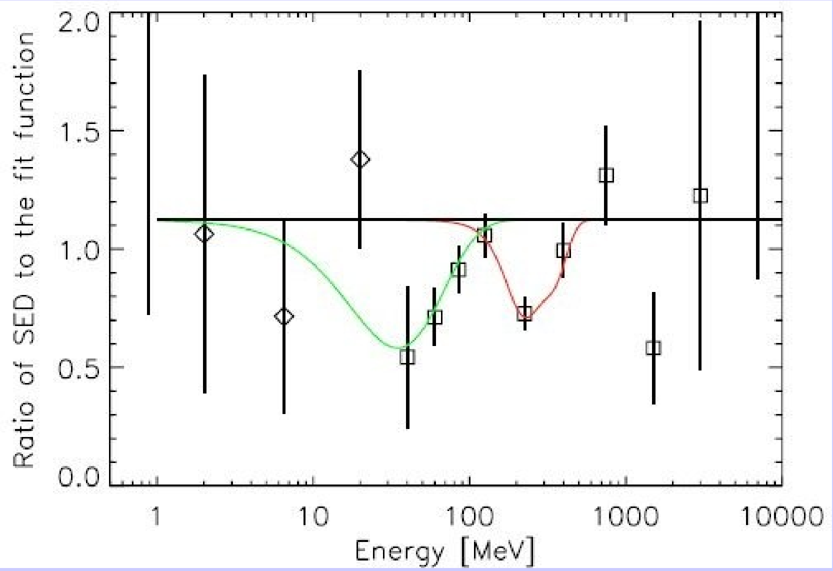



# γ-ray Troughs in QSOs environments

- PKS 0528+134
  Redshift z=2.08
  - Observations from March 1993
  - Again, identification of γ-ray absorption from GDR and Δ-Resonance (1bin)
  - Flux depression of 34% for Δ- and 60% for GDR
  - Δ Resonance at 106±49 MeV

    -> $E(\Delta)^{3C279}$=326±152 MeV
    -> $E(\Delta)^{real}$=327 MeV
  - GDR at ~ 34±20 MeV
    -> Depending on the metallicity of the environment



# γ-ray Troughs in QSOs environments

- Absorption column densities
  Assume cross sections of 0.5 mbarn for Δ and 3.6 mbarn for GDR
  -> $N_H = 10^{27}$ cm$^{-2}$

- Depending on the sensitivity , source brightness and exposure time

- Smearing effect – Compton down scattering in Resonance regions

- Assume metallicity, geometry ->

$$F_{\mathrm{Obs}}(E) = F_0(E)\left[\exp\left(-\sigma_{\mathrm{eff}} N_{\mathrm{H}}^{\Delta r}\right)\right]$$

$$\frac{\Delta F_j}{F_j} = \left[1 - \exp\left(-\sigma_{\mathrm{eff}} N_{\mathrm{H}}^{\Delta r}\right)\right]$$

- With flux depression as quoted, follows:

-> for 3C279: $N_H = 8 \cdot 10^{26}$ cm$^{-2}$
-> for PKS0528+134: $N_H = 7 \cdot 10^{26}$ cm$^{-2}$

# What to remember ?

- Nuclear Models
- Nuclear Photoabsorption in the MeV region
- GDR, PDR and Δ Resonance
- AGNs
- γ ray absorption promising tool for probing high column desities, the content and metallicity of QSOs host galaxies and verify/measuring the redshift of known/unknown objects
- Upcoming mission GLAST (2007) with its instruments LAT (~20 MeV - ~300 GeV) and BAT (~20 keV - ~30 MeV) should provide evidence of γ-ray absorption troughs

# Thank you for your attention