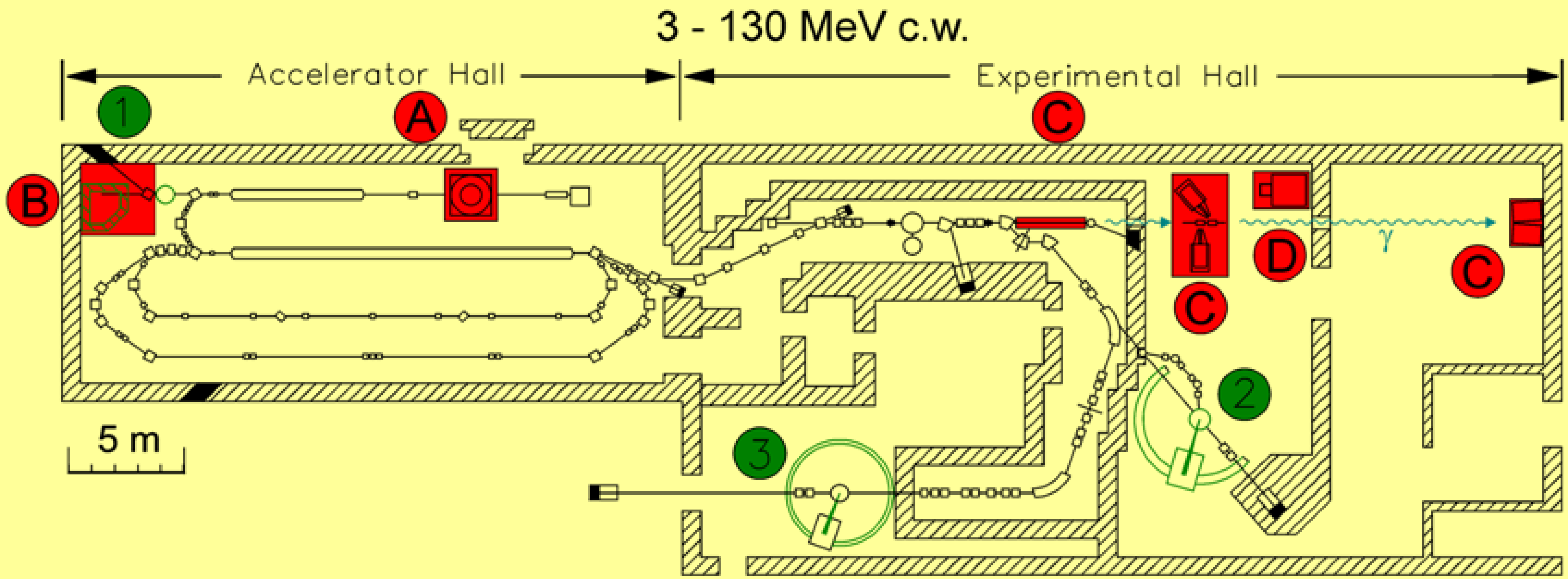
The 7th CNS International Summer School
Achim Richter 3rd Lecture

Nuclear Structure in Astrophysics Studied with Electromagnetic Probes – Some Examples

- The S-DALINAC and its experimental setups
- E1 excitations around the particle threshold: the PDR
  (TUD / U Giessen / RCNP + U Osaka / iThemba Labs / U Wits)
- Deuteron electrodisintegration under 180° and its importance for the primordial nucleosynthesis of the lightest nuclei
- Electron scattering on ^{12}C and the structure of the Hoyle state

Supported by DFG under SFB 634

Experiments at the S-DALINAC

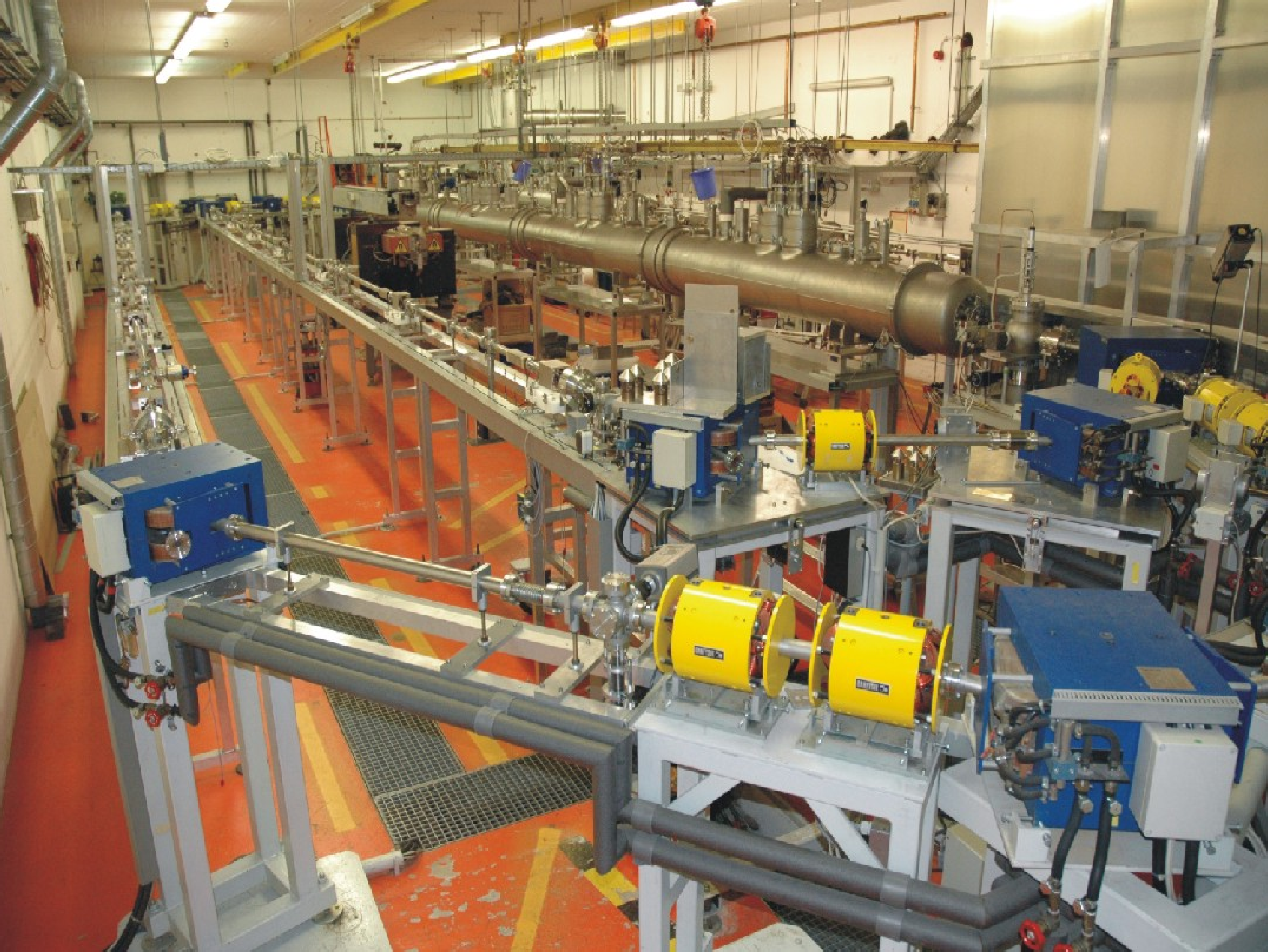


Status

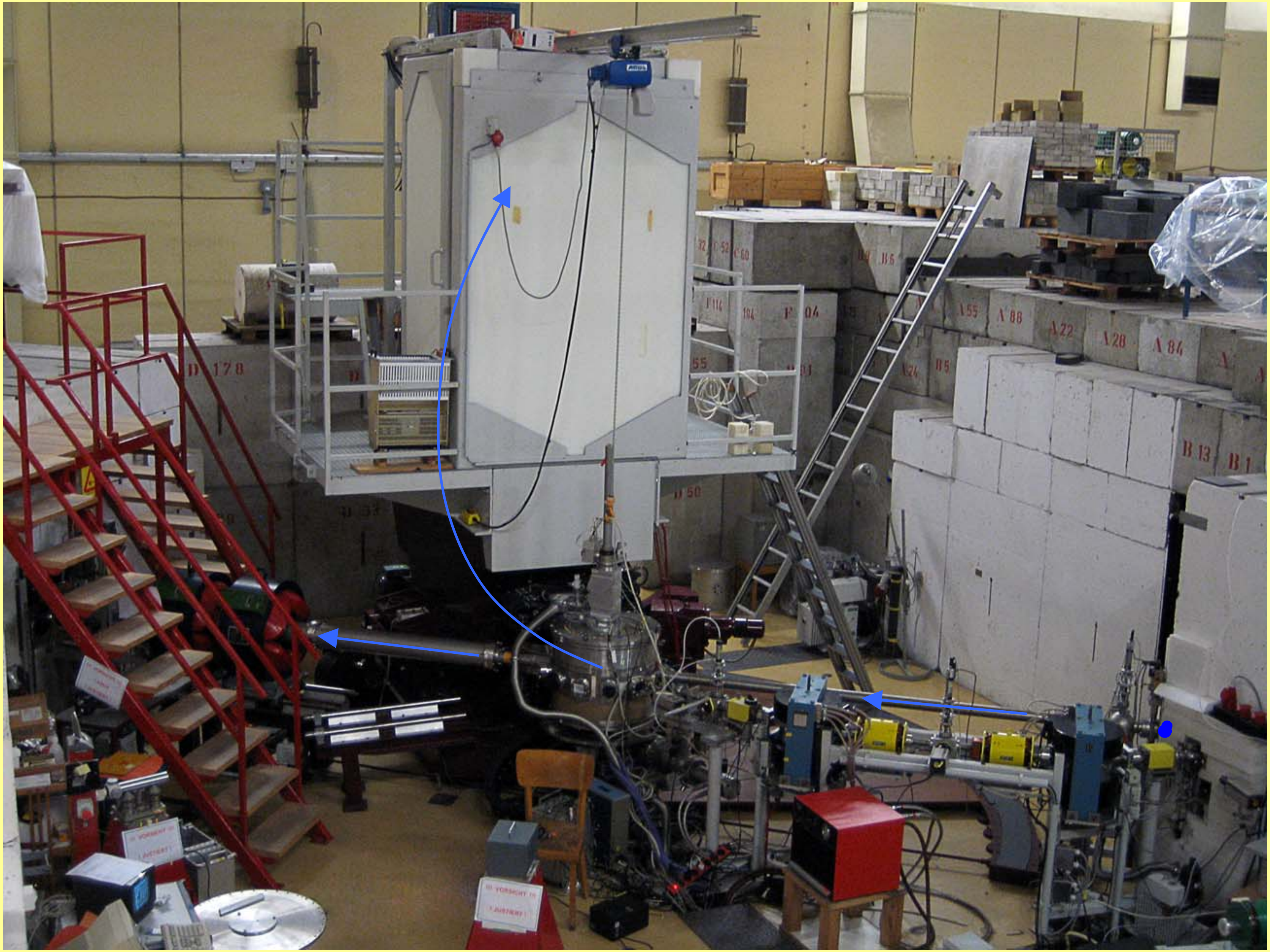
1. Nuclear resonance fluorescence
2. (e,e´) and 180° experiments
3. High-resolution (e,e´) experiments

SFB

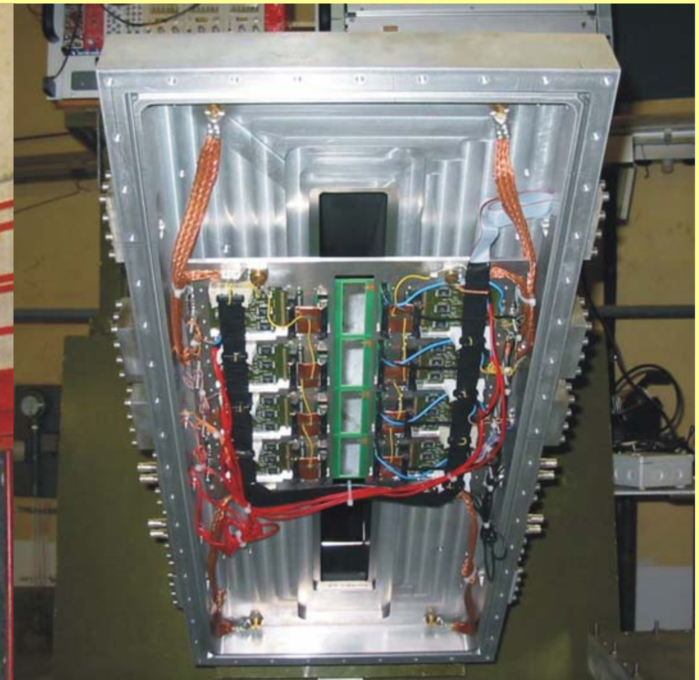
- A Polarized electron source
- B 14 MeV bremsstrahlung
- C 100 MeV bremsstrahlung for polarizability of the nucleon
- D Photon tagger



QCLAM Spectrometer

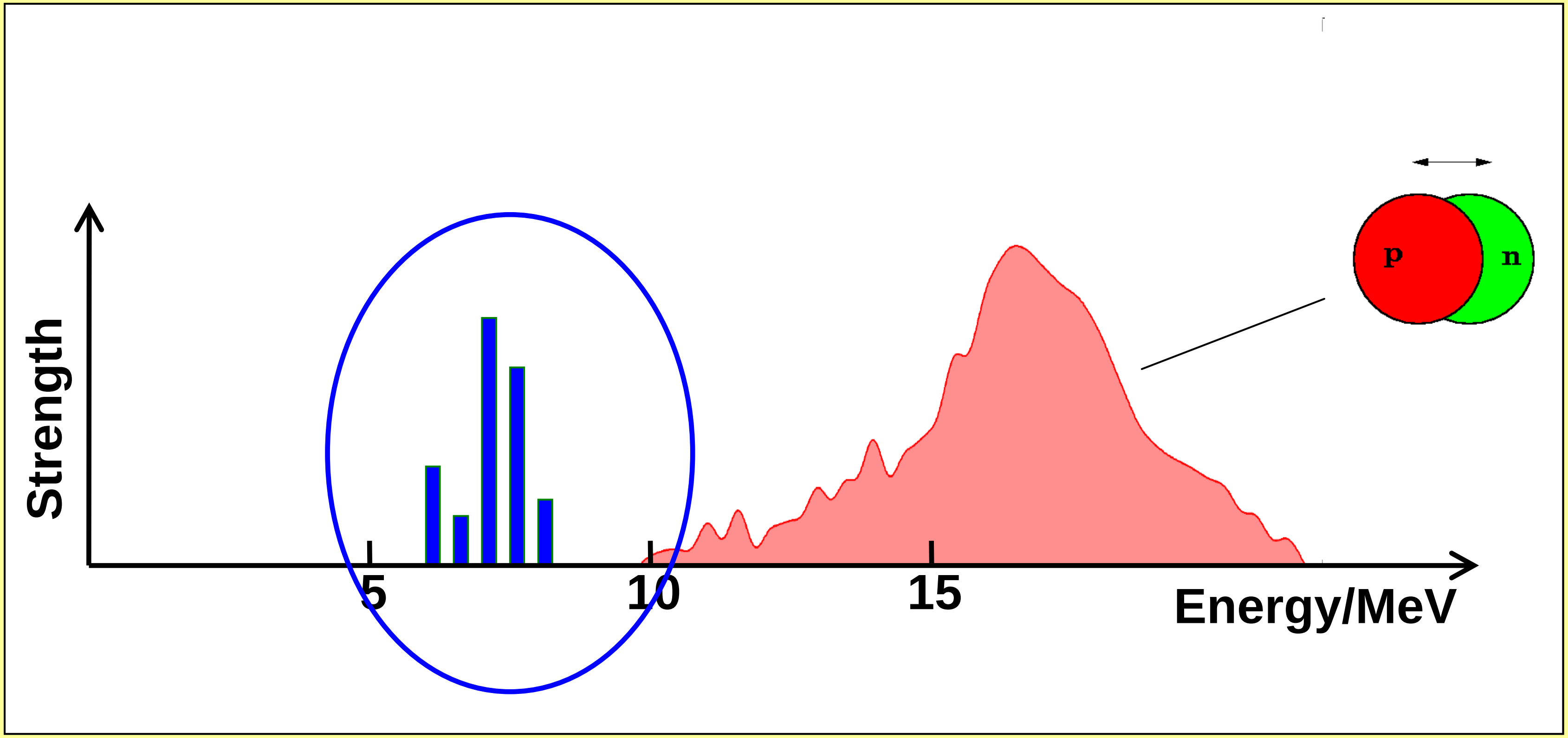


Lintott Spectrometer



- Si microstrip detector system: 4 modules, each 96 strips with pitch of 650 μm
- Count rate up to 100 kHz
- Energy resolution 1.5×10^{-4}

The Photoresponse of Atomic Nuclei



- Considerable E1 strength is predicted and also observed below the $1\hbar\omega$ region

E1 Excitations Around the Particle Threshold

- Nuclear structure phenomenon

  Fundamental E1 mode below the GDR called Pygmy Dipole Resonance (PDR)

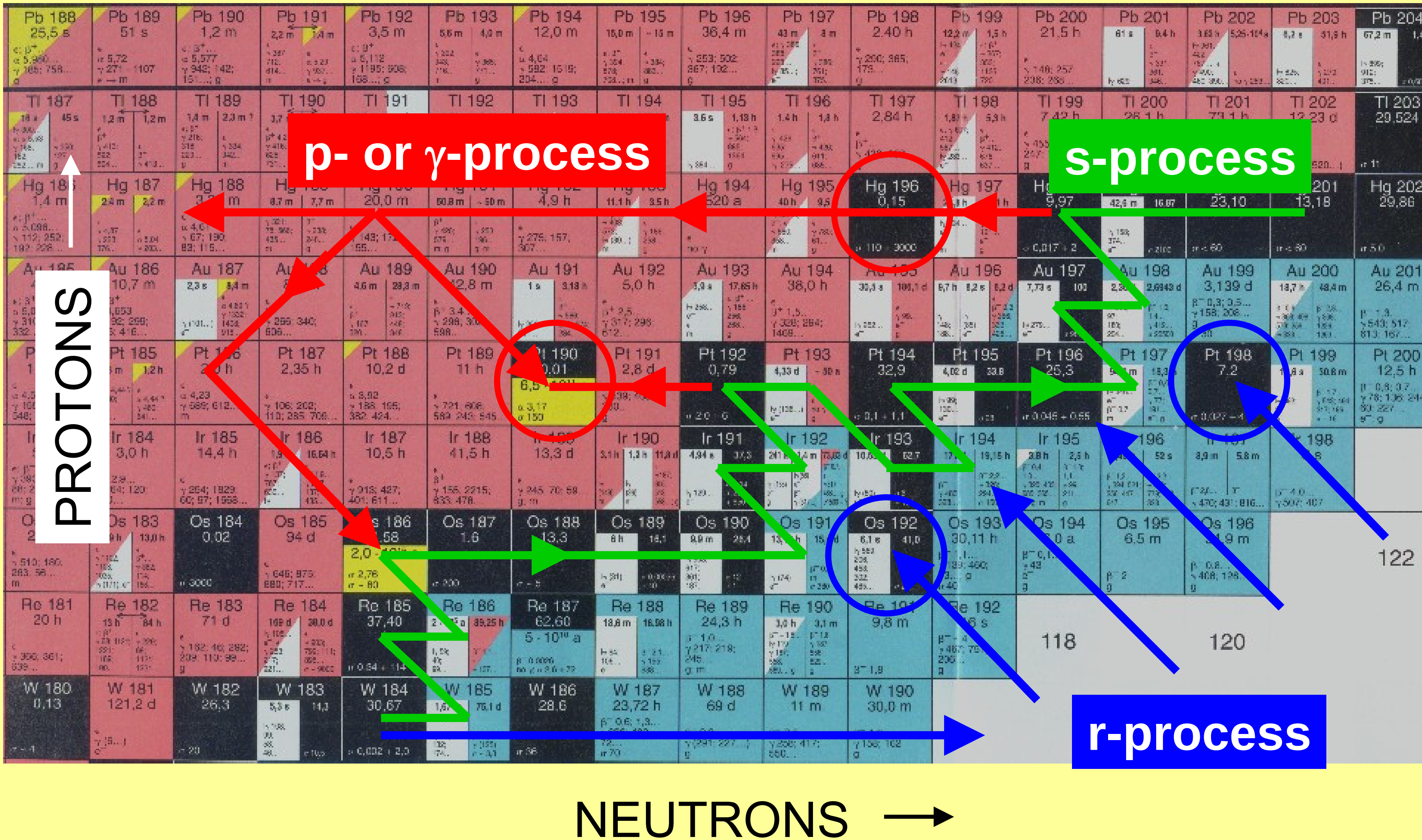
- Importance for understanding of exotic nuclei

  Will E1 strength be shifted to lower energies in neutron rich systems ?

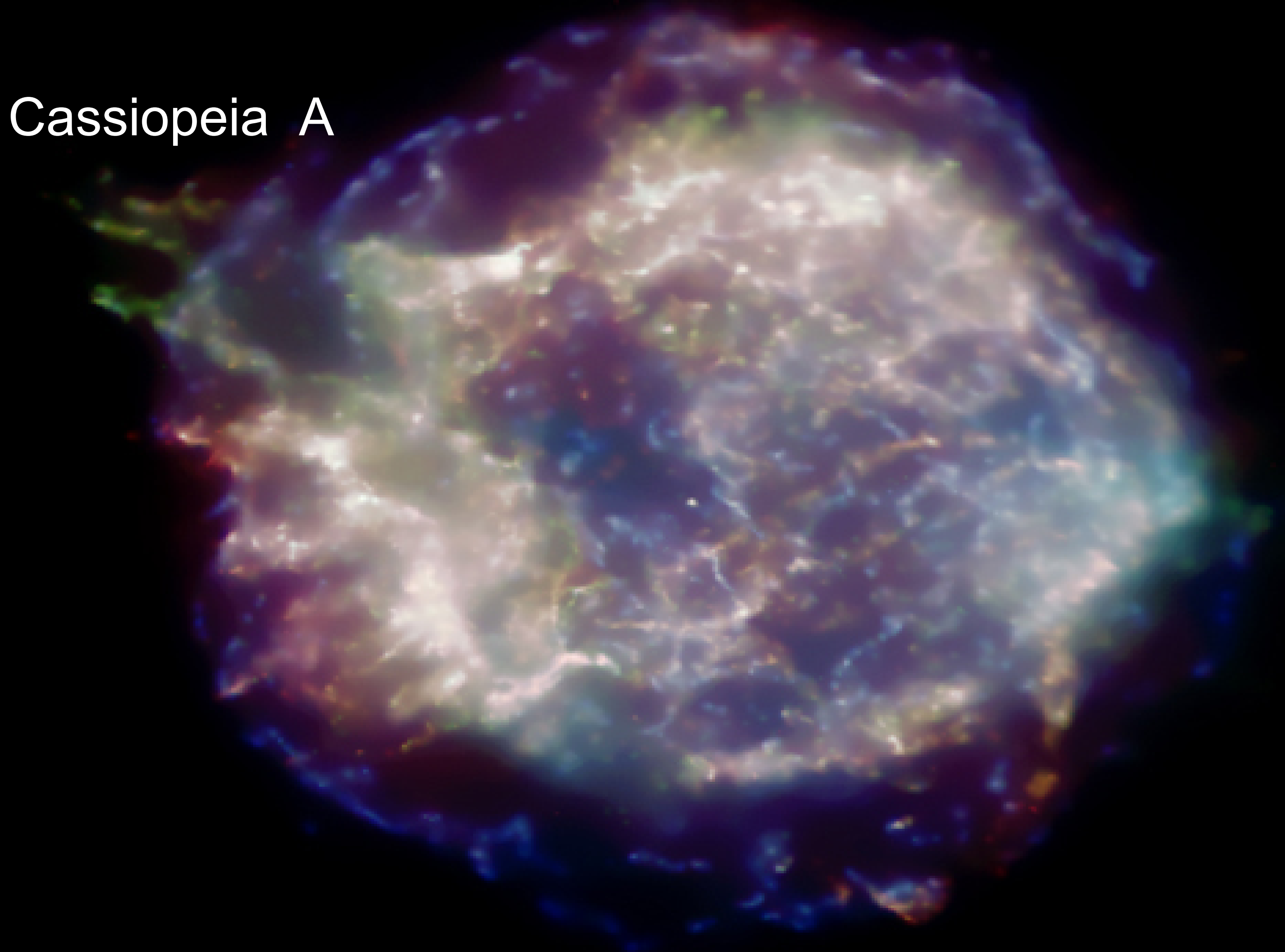
- Impact on nucleosynthesis

  Gamow window for photo-induced reactions in explosive stellar events

Impact on Nucleosynthesis

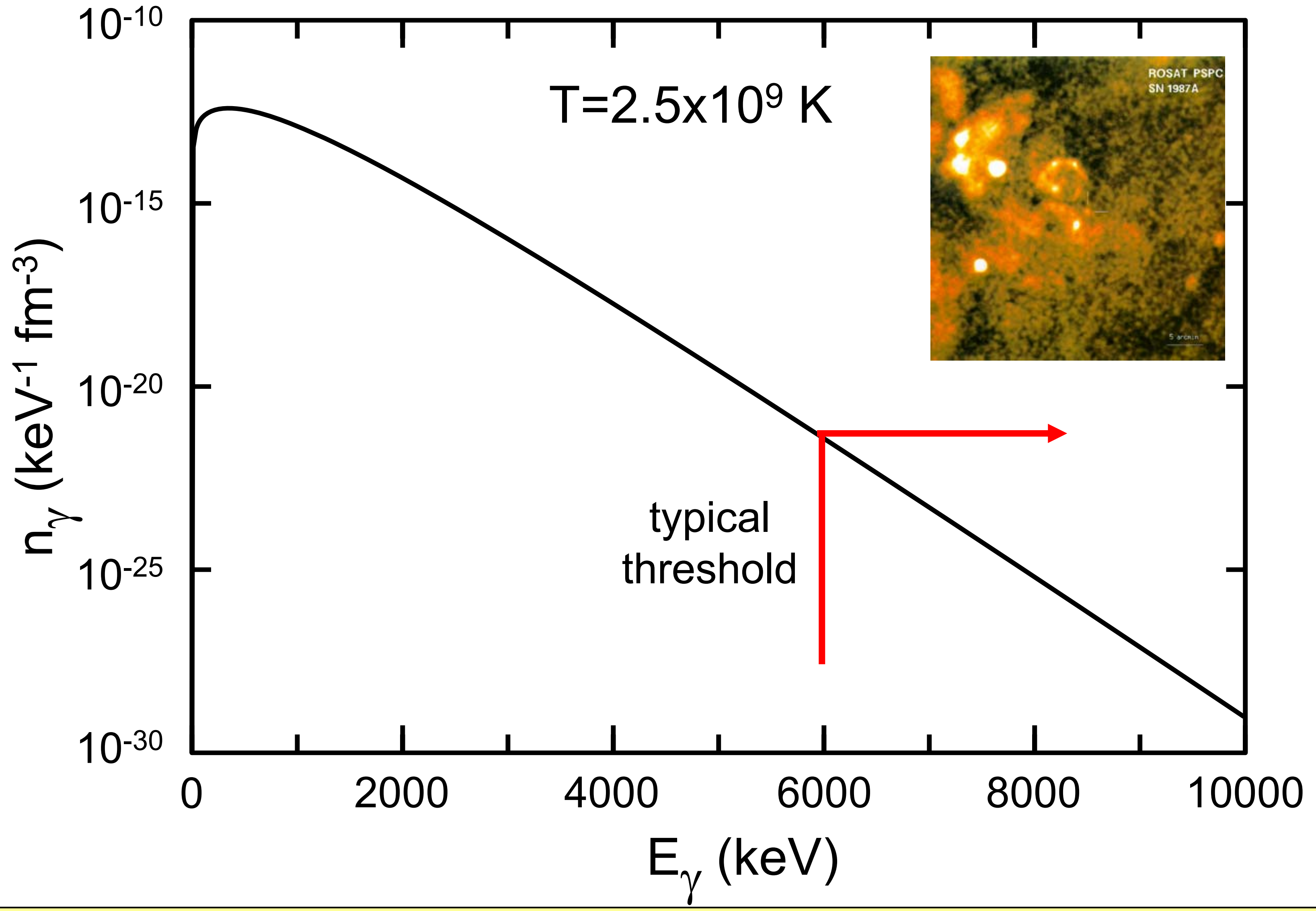


Origin of the Photons

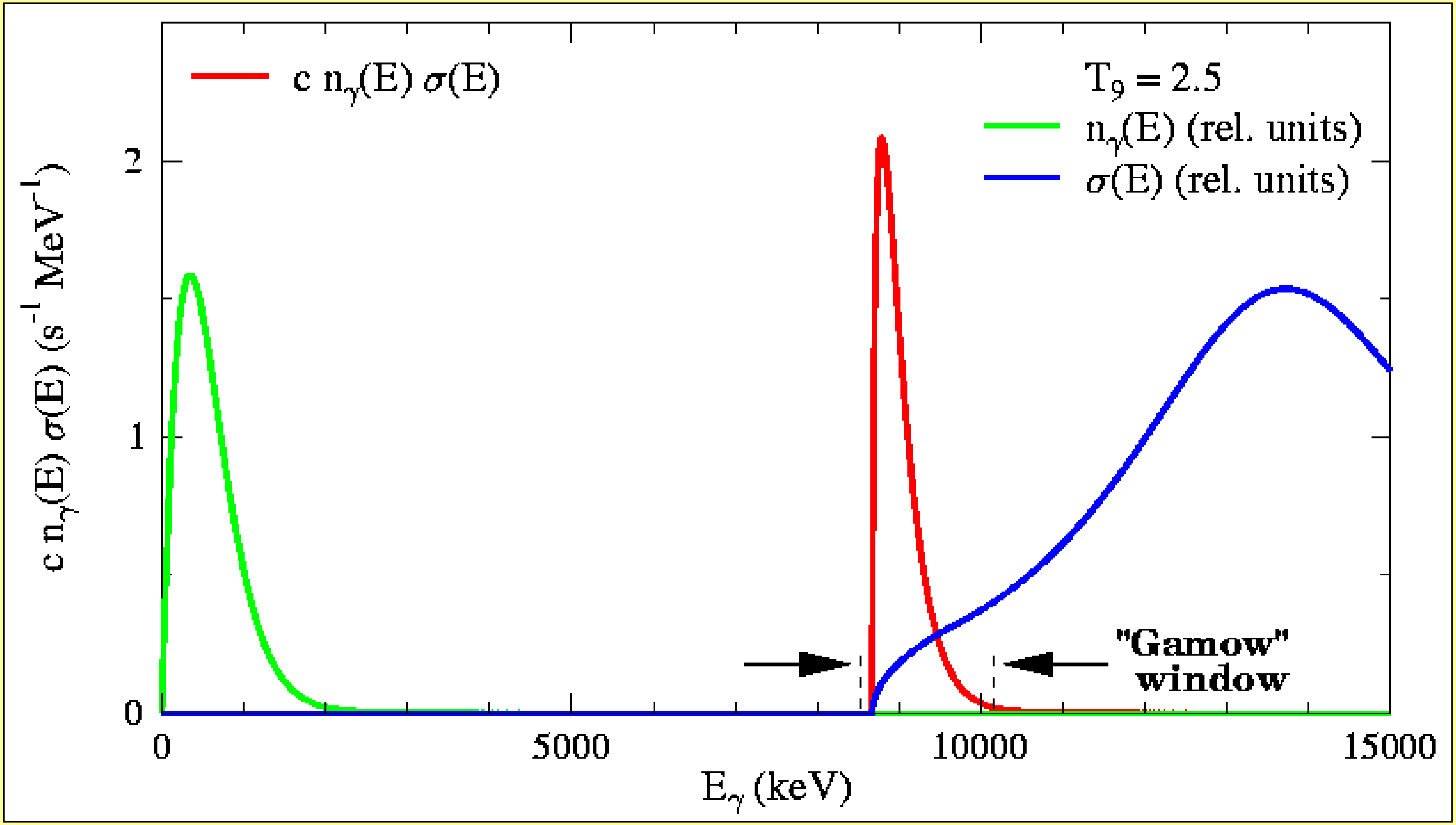


Temperatures up to 3×10^9 K ~ 200 keV

The Photon Density: Planck Spectrum

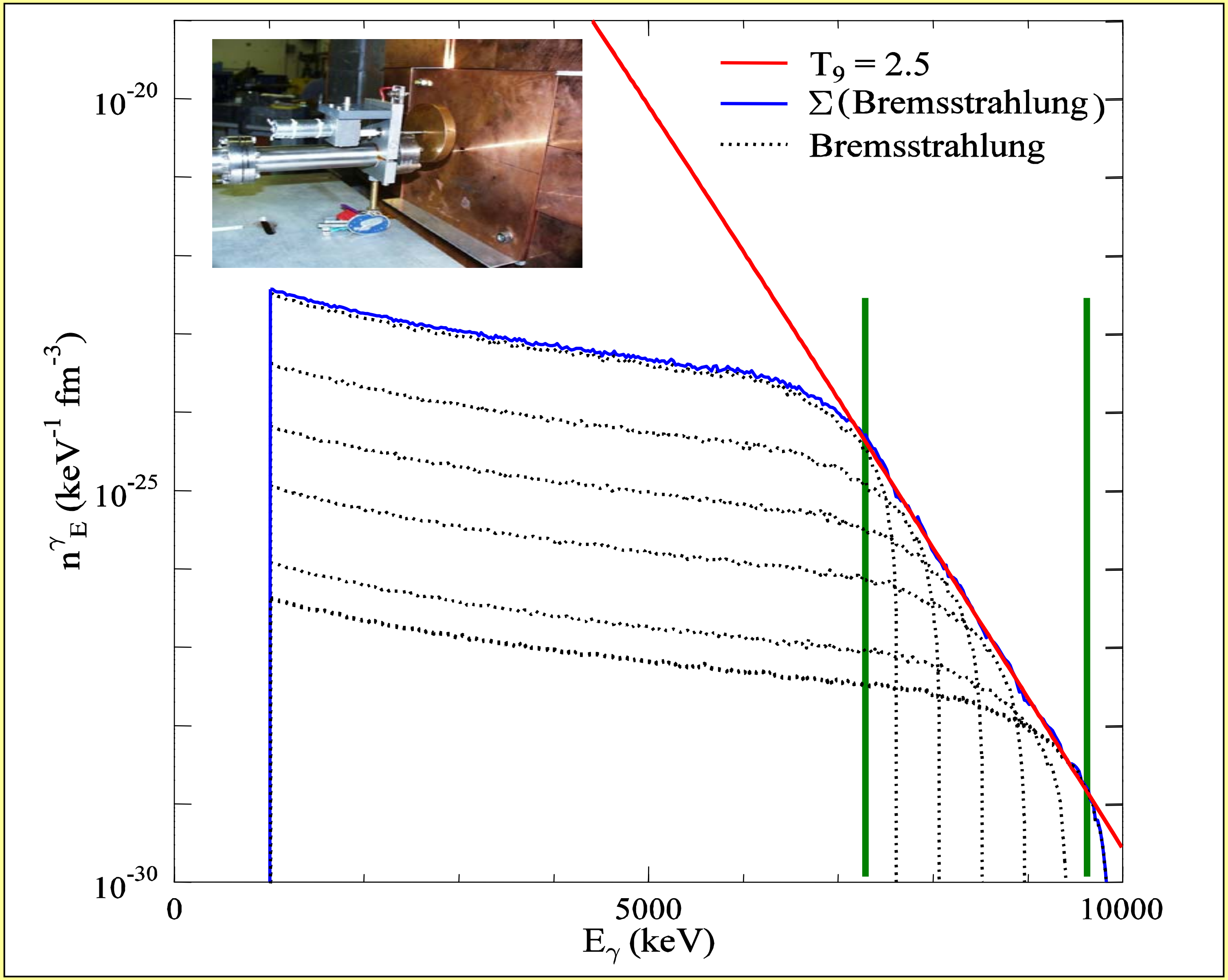


What is the Relevant Energy Range ?



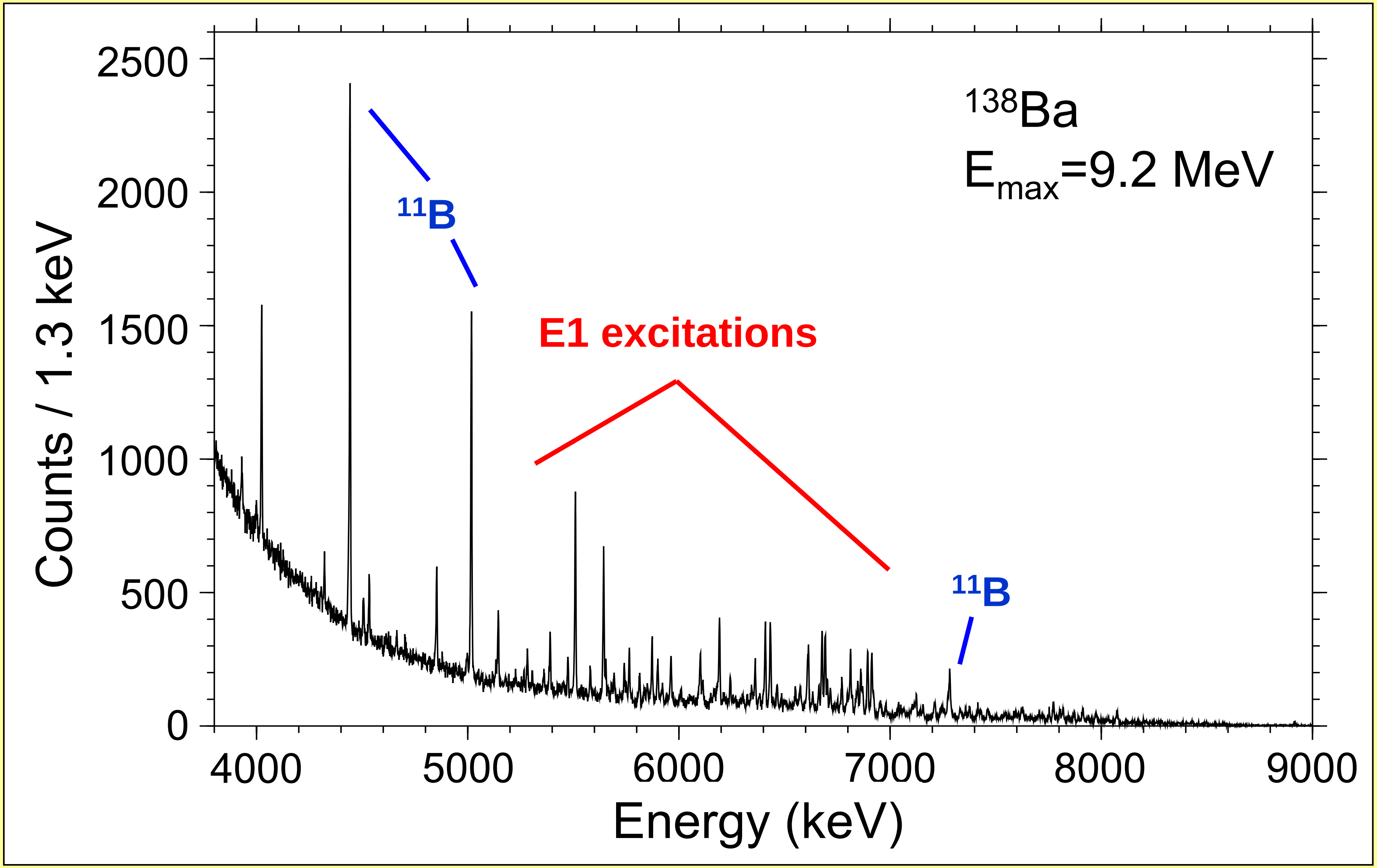
- Reaction rate: $\lambda(T) = c \int n_\gamma(E)\, \sigma(E)\, dE$

Generation of Planck Spectra at S-DALINAC



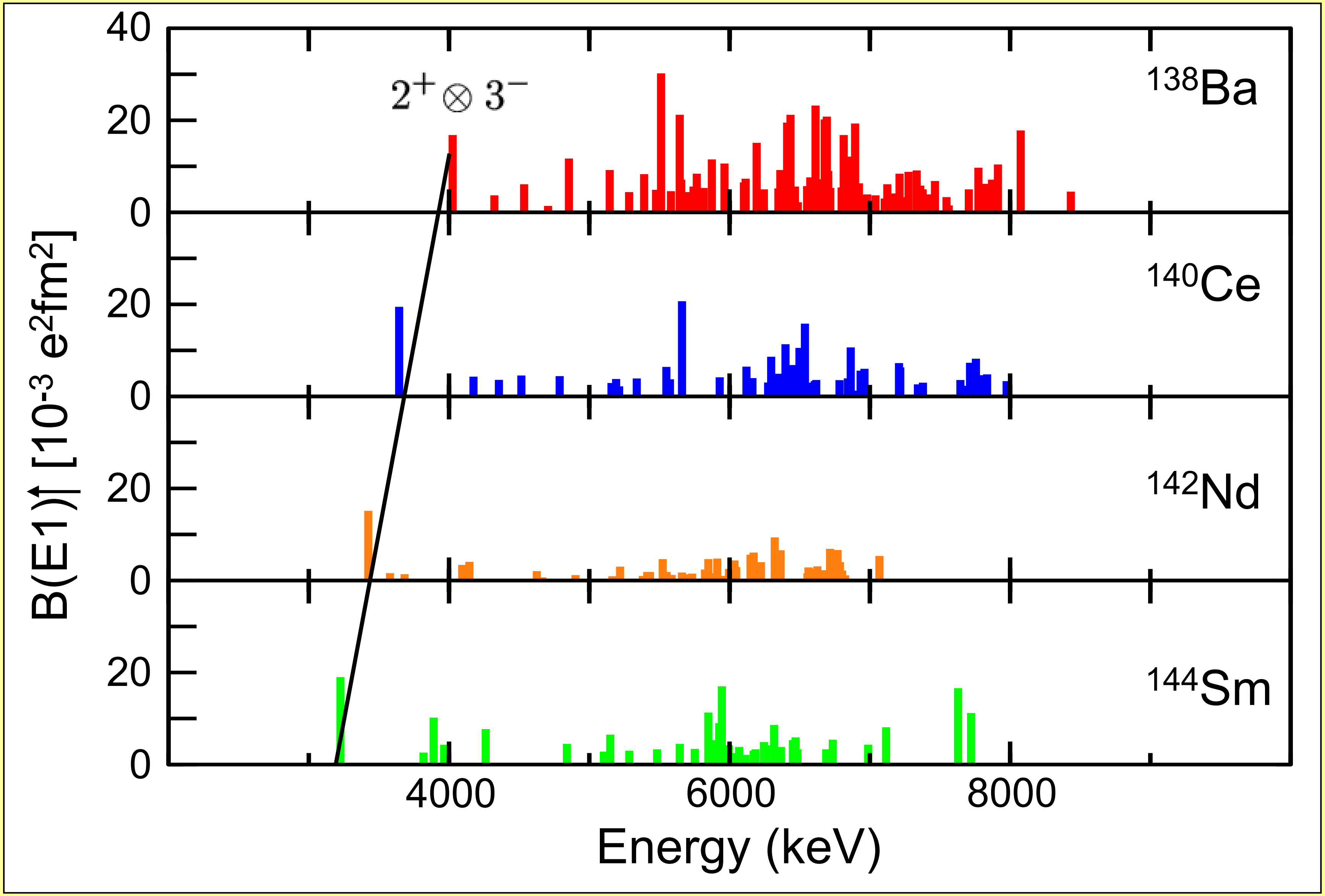
P. Mohr et al., PLB 488 (2000) 127

Photon Scattering off ^{138}Ba



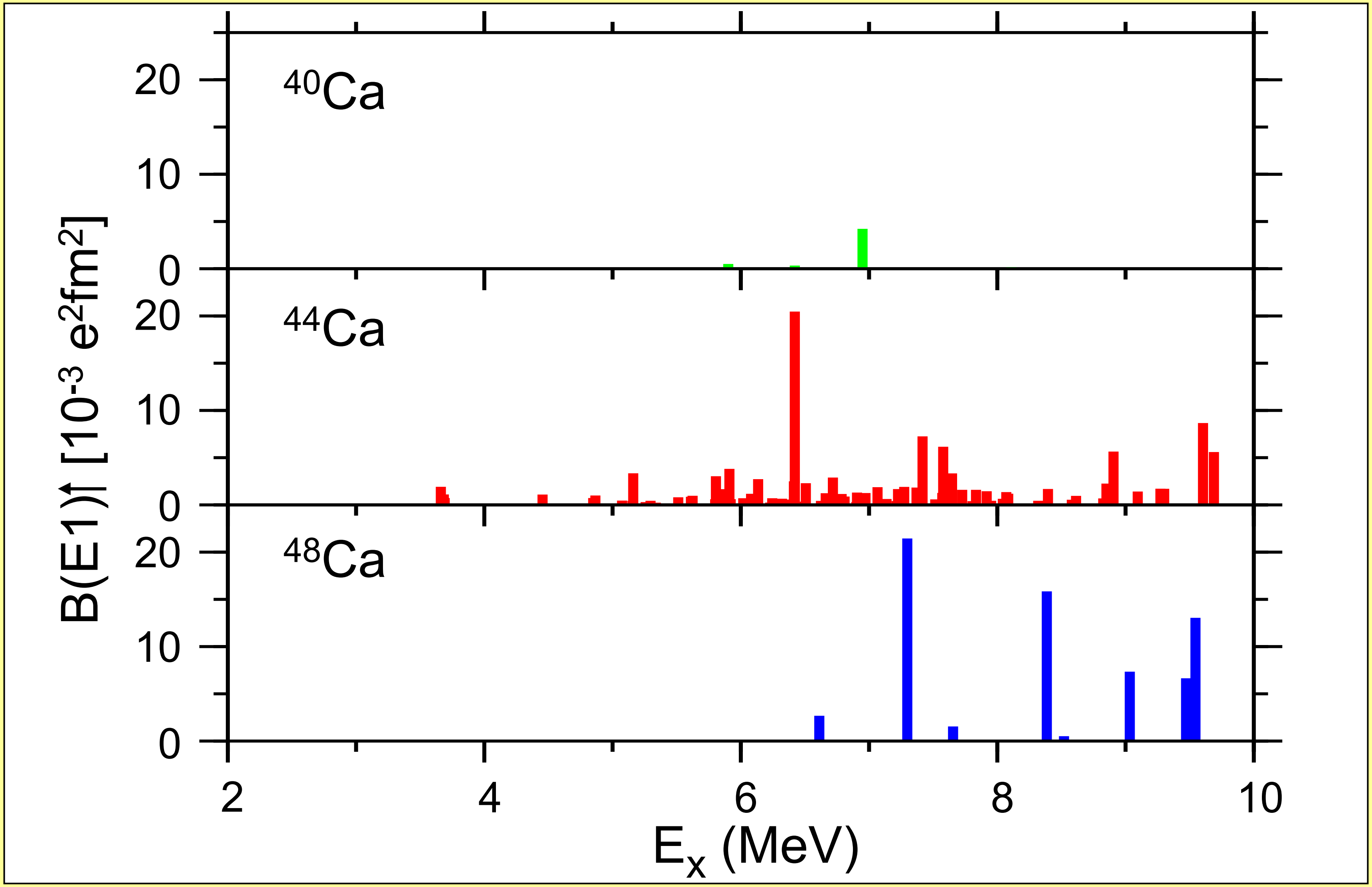
A. Zilges et al., PLB 542 (2002) 43

E1 Strength Distribution in N=82 Nuclei



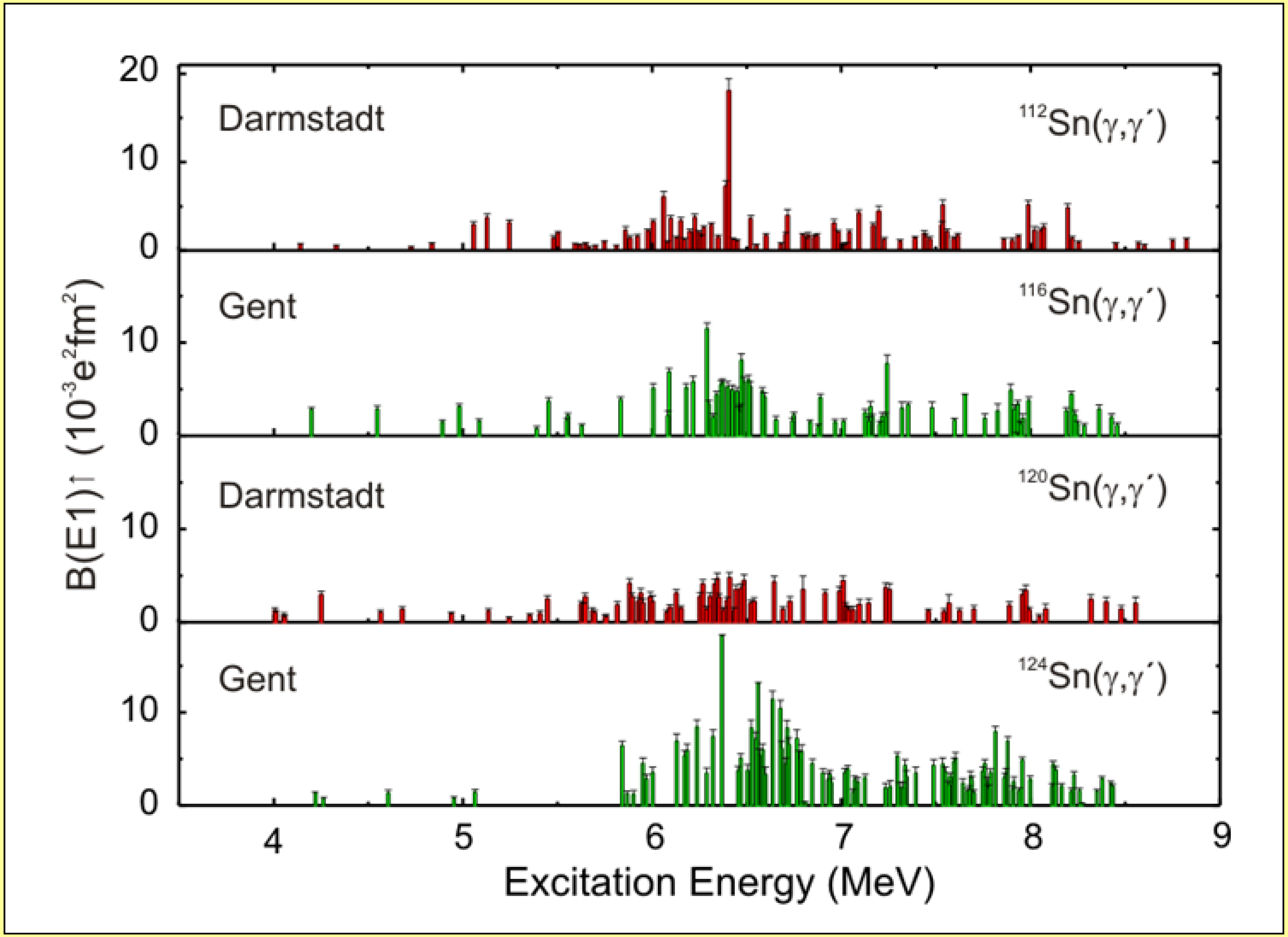
A. Zilges et al., PLB 542 (2002) 43

E1 Strength Distribution in Ca Isotopes



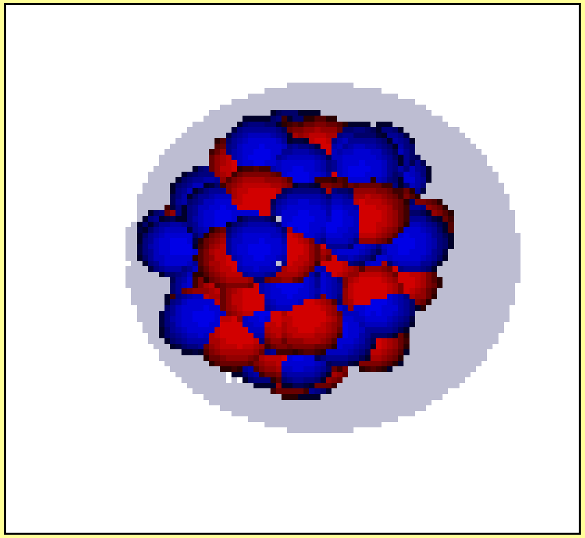
T. Hartmann et al., PRC 65 (2002) 034301

E1 Strength Distributions in Stable Sn Isotopes



+ Coulomb dissociation expt’s at GSI on unstable ^{130}Sn and ^{132}Sn

Neutron/Proton "Skin" Excitations in N > Z Nuclei

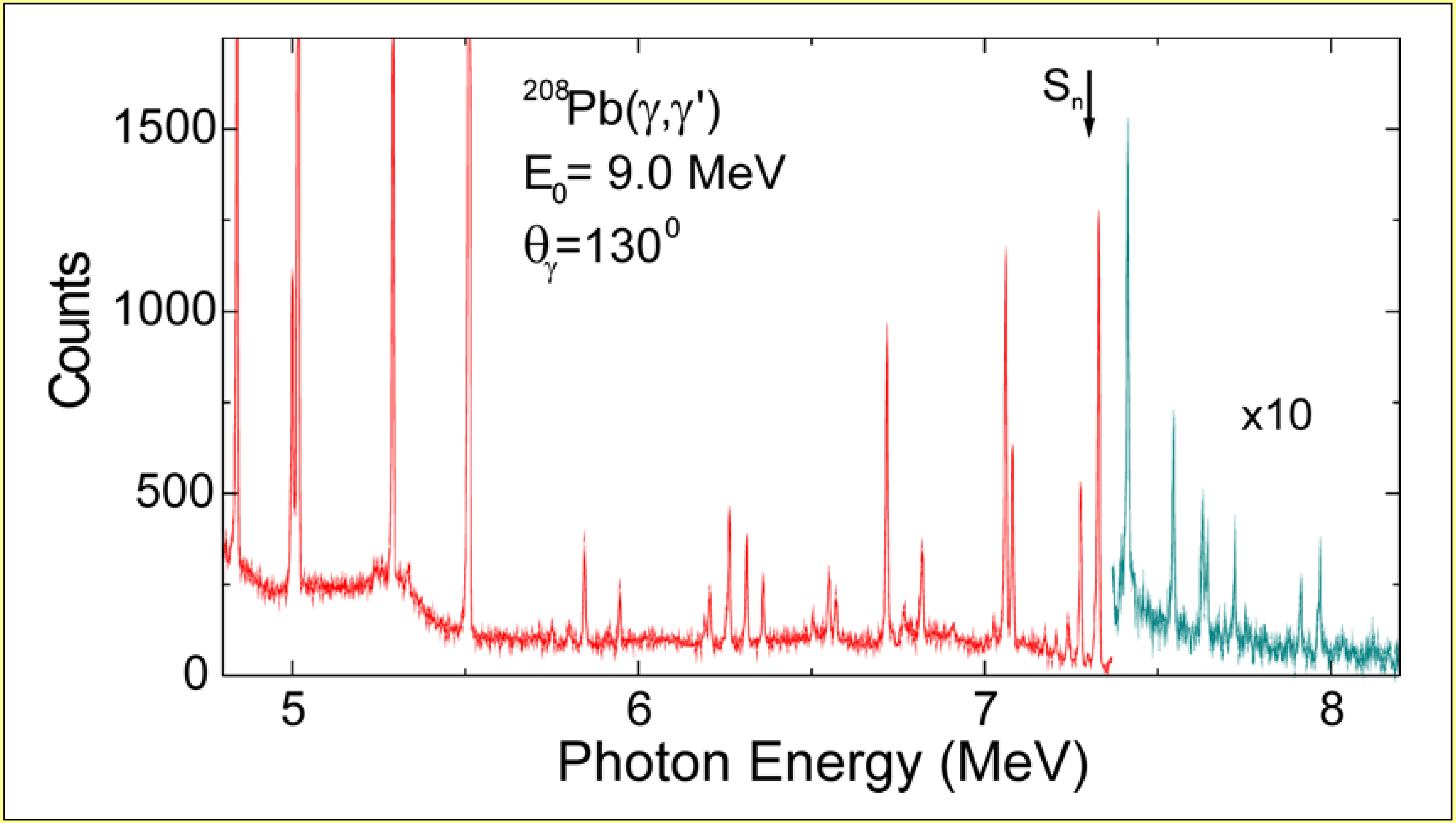


Oscillations of a neutron or proton
rich periphery vs. the core leads
to isovector E1 excitations
→ role of PDR strength for determining
the nuclear skin

- Soft Dipole Mode in exotic nuclei
- Located around 7 MeV in stable nuclei
- Up to 1% of EWSR in some stable nuclei
  → major contribution to the nuclear dipole polarizability

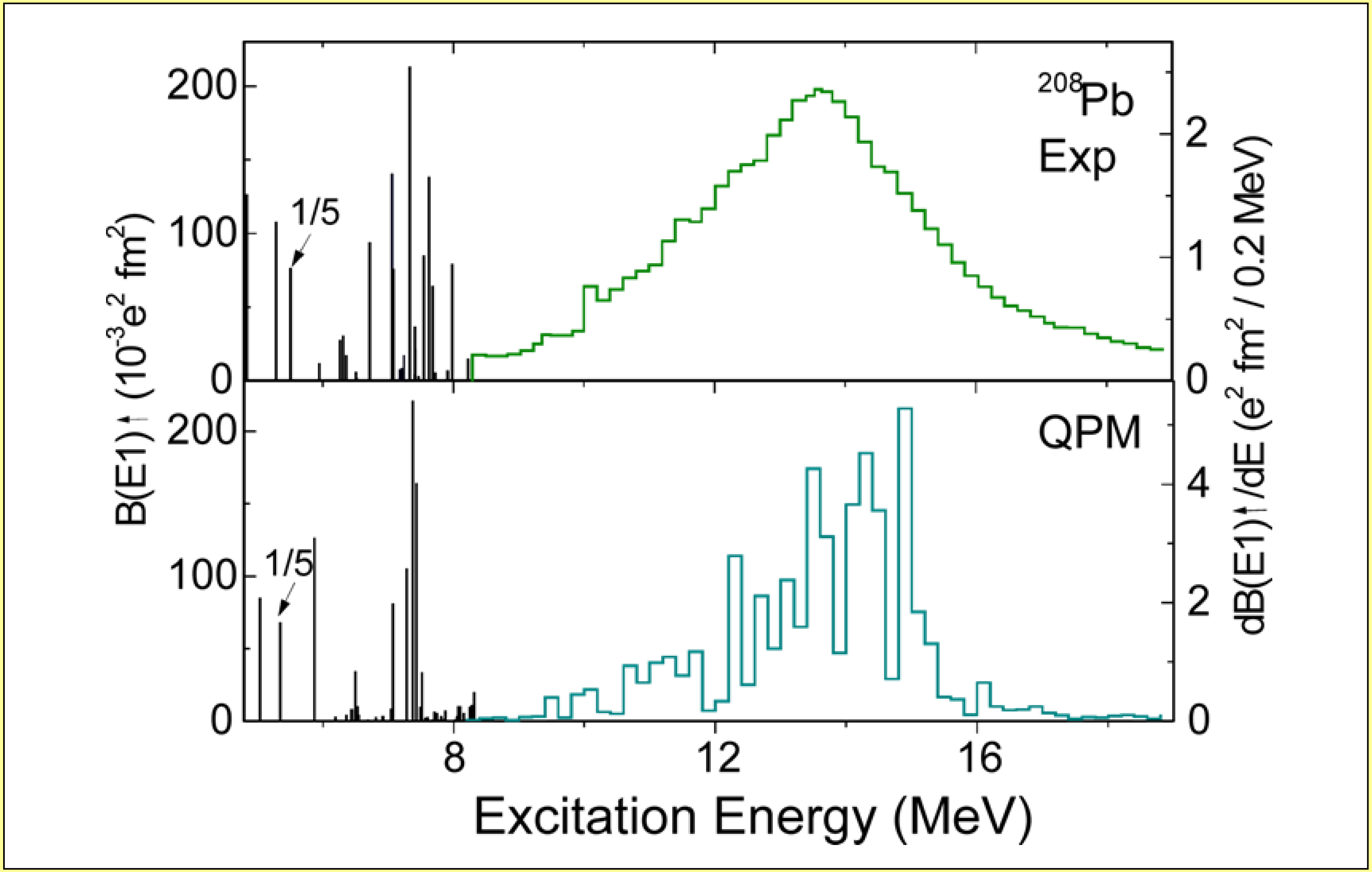
see e.g.: J. Chambers et al., PRC 50 (1994) R2671
P. van Isacker et al., PRC 45 (1992) R13

What is the Microscopic Structure of the PDR ?
Reminder: ^{208}Pb



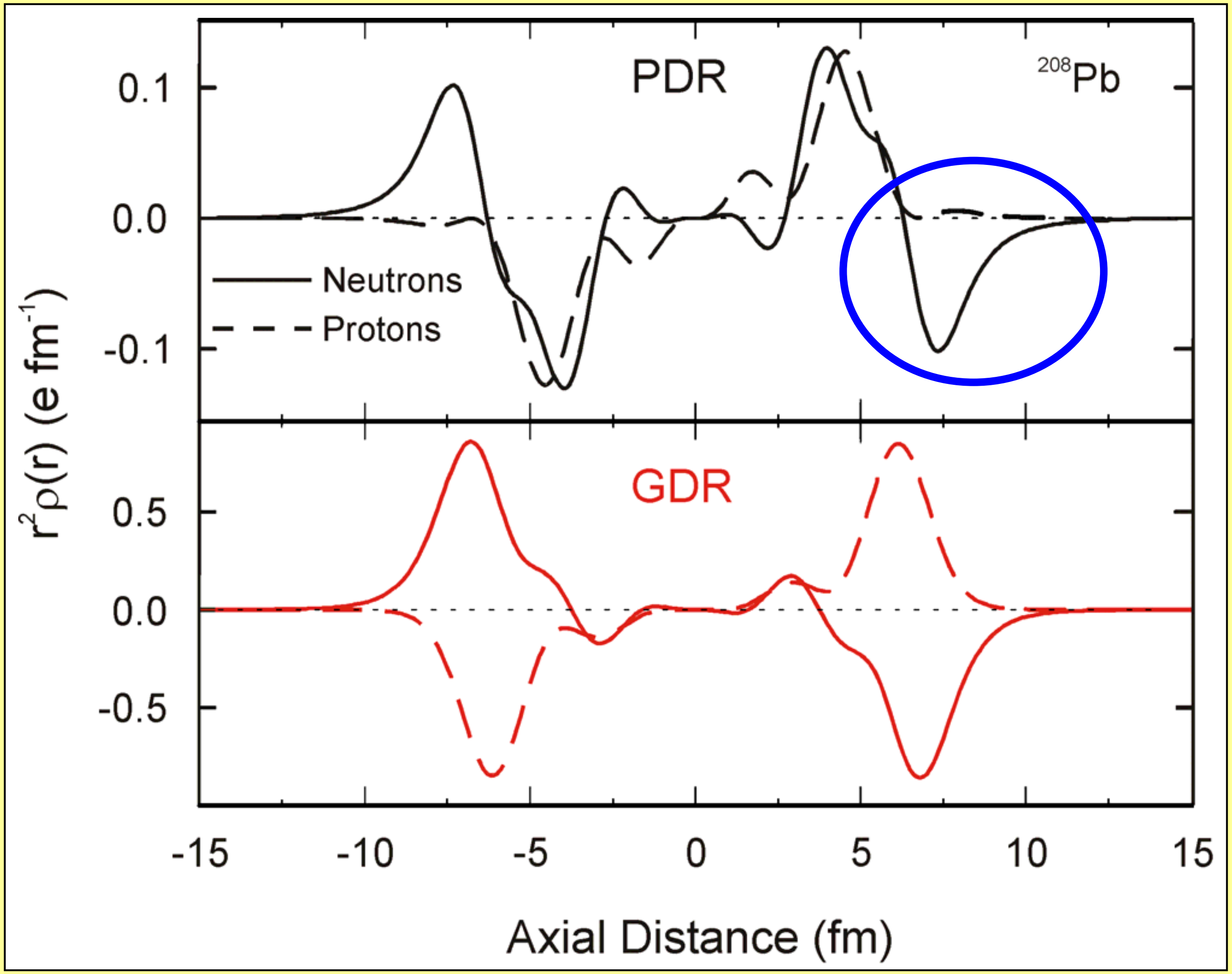
N. Ryezayeva et al., PRL 89 (2002) 272502

E1 Response in ^{208}Pb



- Excellent agreement of QPM with experiment

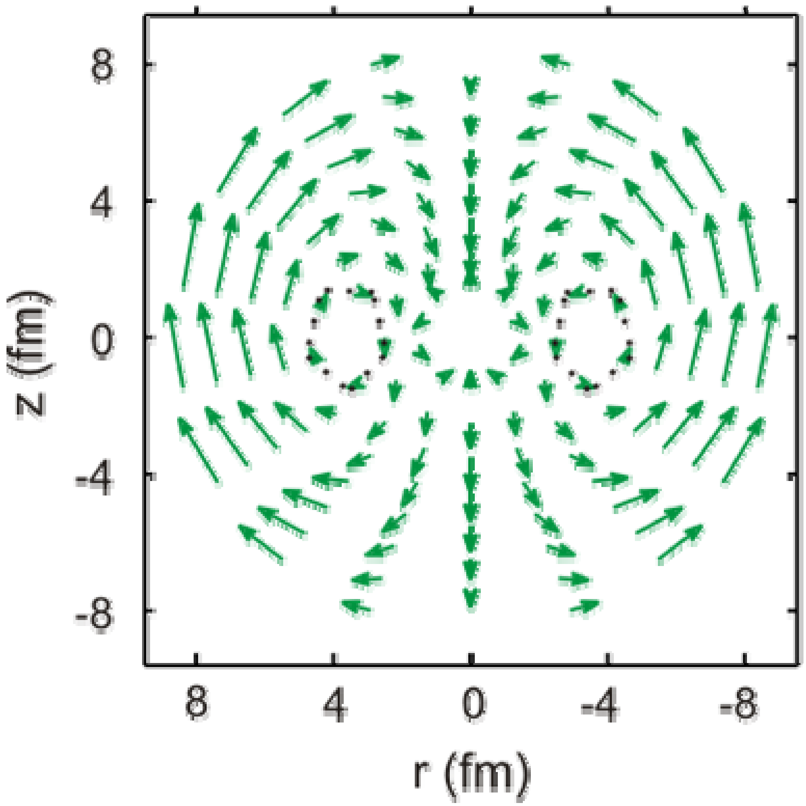
Transition Densities



- PDR largely isoscalar
- Evidence for neutron density oscillations
- Similar results from the Milano and Munich groups

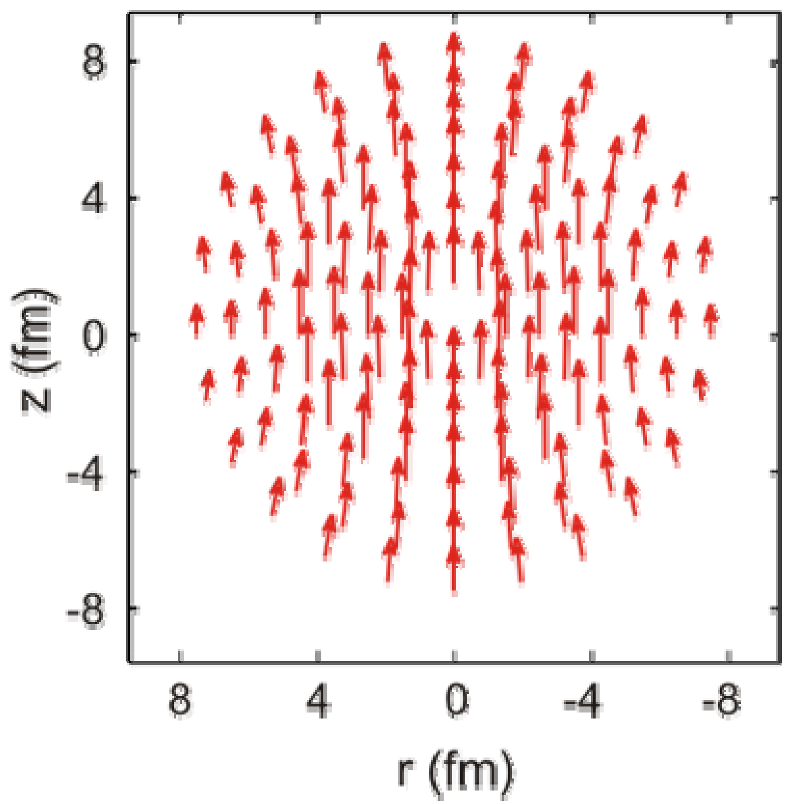
“Snapshots” of Velocity Distributions in ^{208}Pb

Toroidal mode (within the PDR)



E_x = 6.5 – 10.5 MeV

GDR

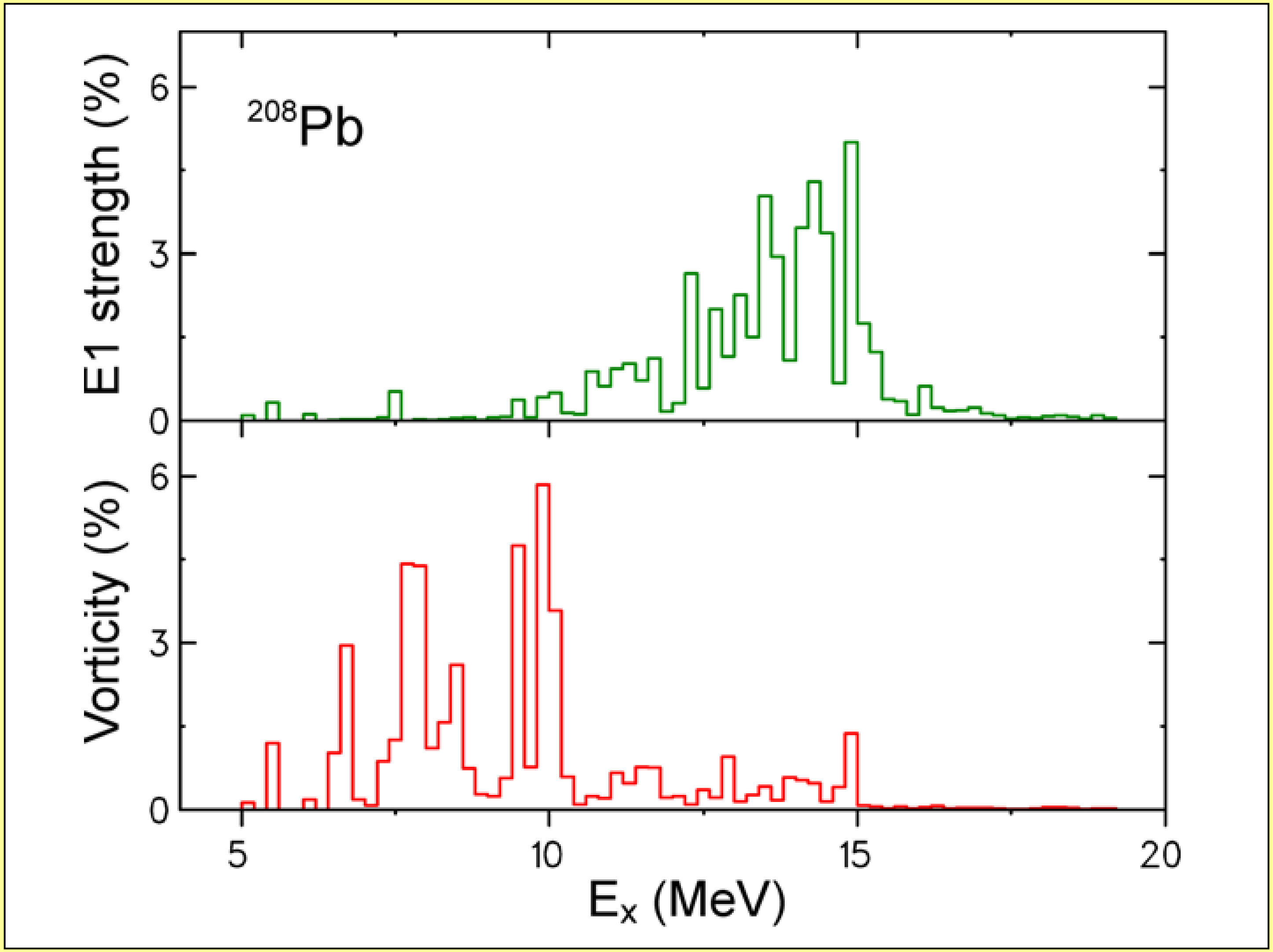


E_x > 10.5 MeV

- Toroidal (current) mode: zero sound wave
- Restoring force is not of hydrodynamic nature but elastic

- Vibrational mode

Electric Dipole Strength and Vorticity



- Vorticity density: measure for the strength of the transverse current

Structure of Low-Energy E1 Modes

- How can we elucidate the structure of the low-energy E1 modes ?

- Proton scattering at 0°

  intermediate energy (300 MeV optimal)

  high resolution

  angular distribution (E1/M1 separation)

  polarisation observables (spinflip / non-spinflip separation)

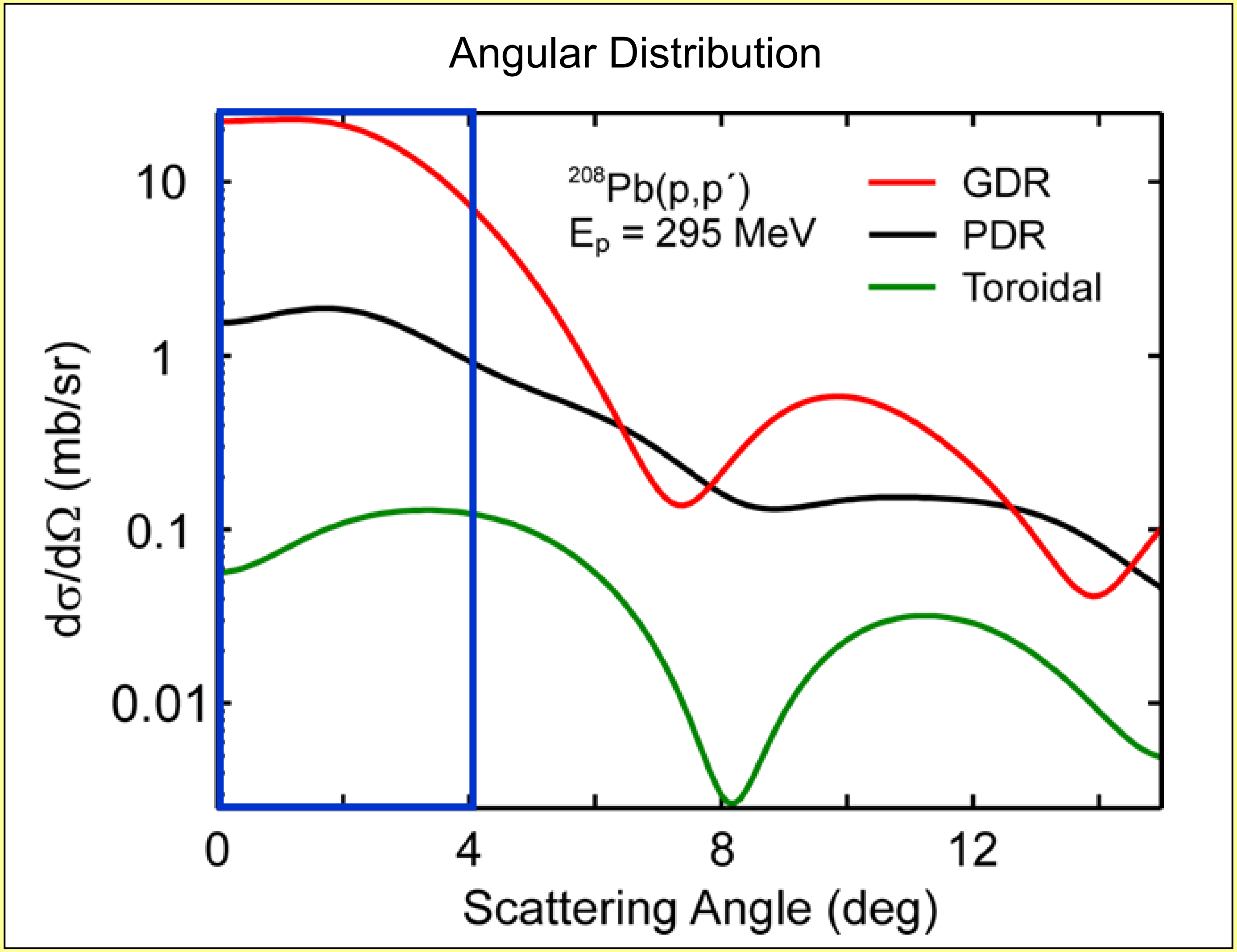
- Electron scattering (preferentially at 180°)

  high resolution

  transverse form factors needed

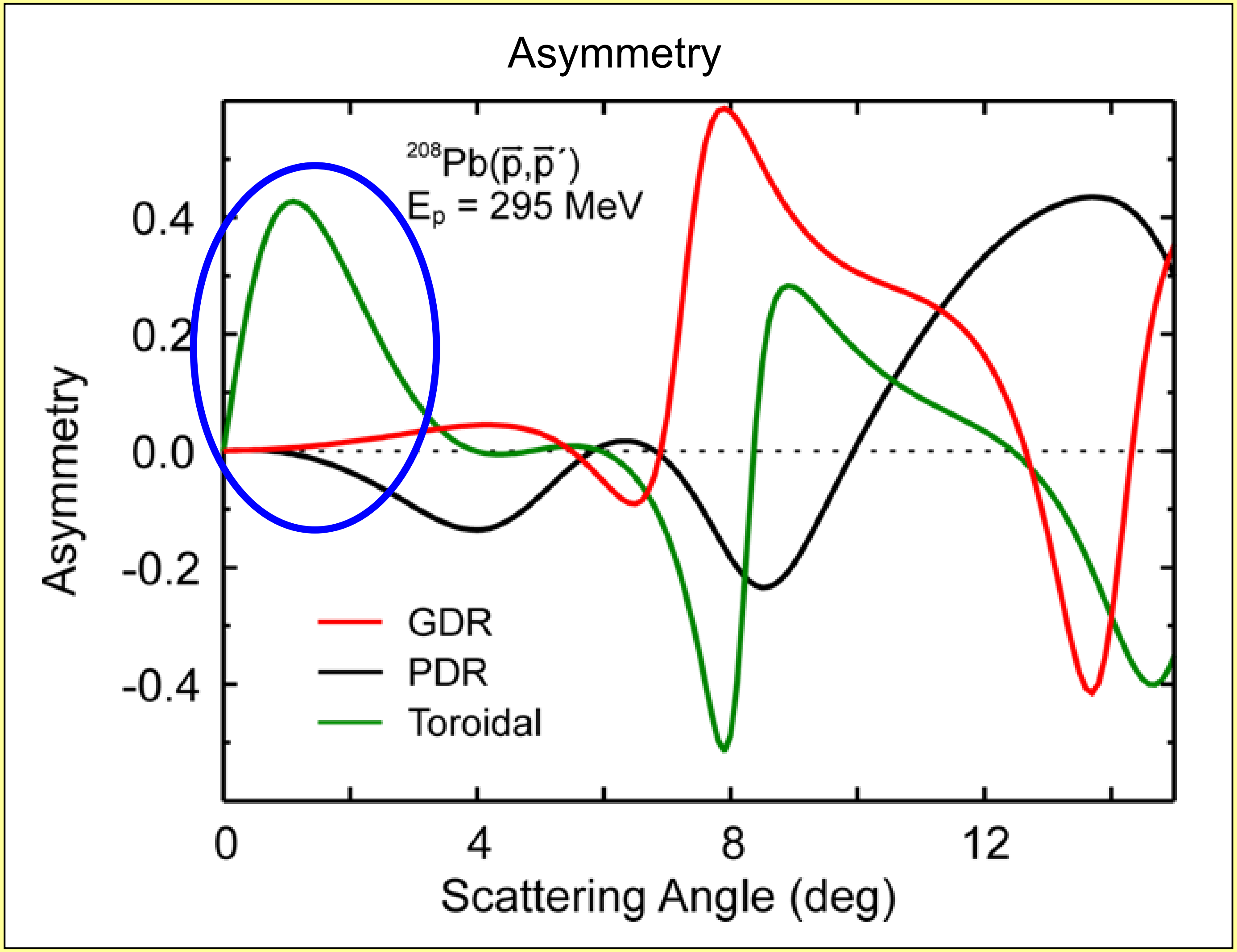
  very sensitive to structure of the different modes

Signatures of Different E1 Modes in (p,p´)



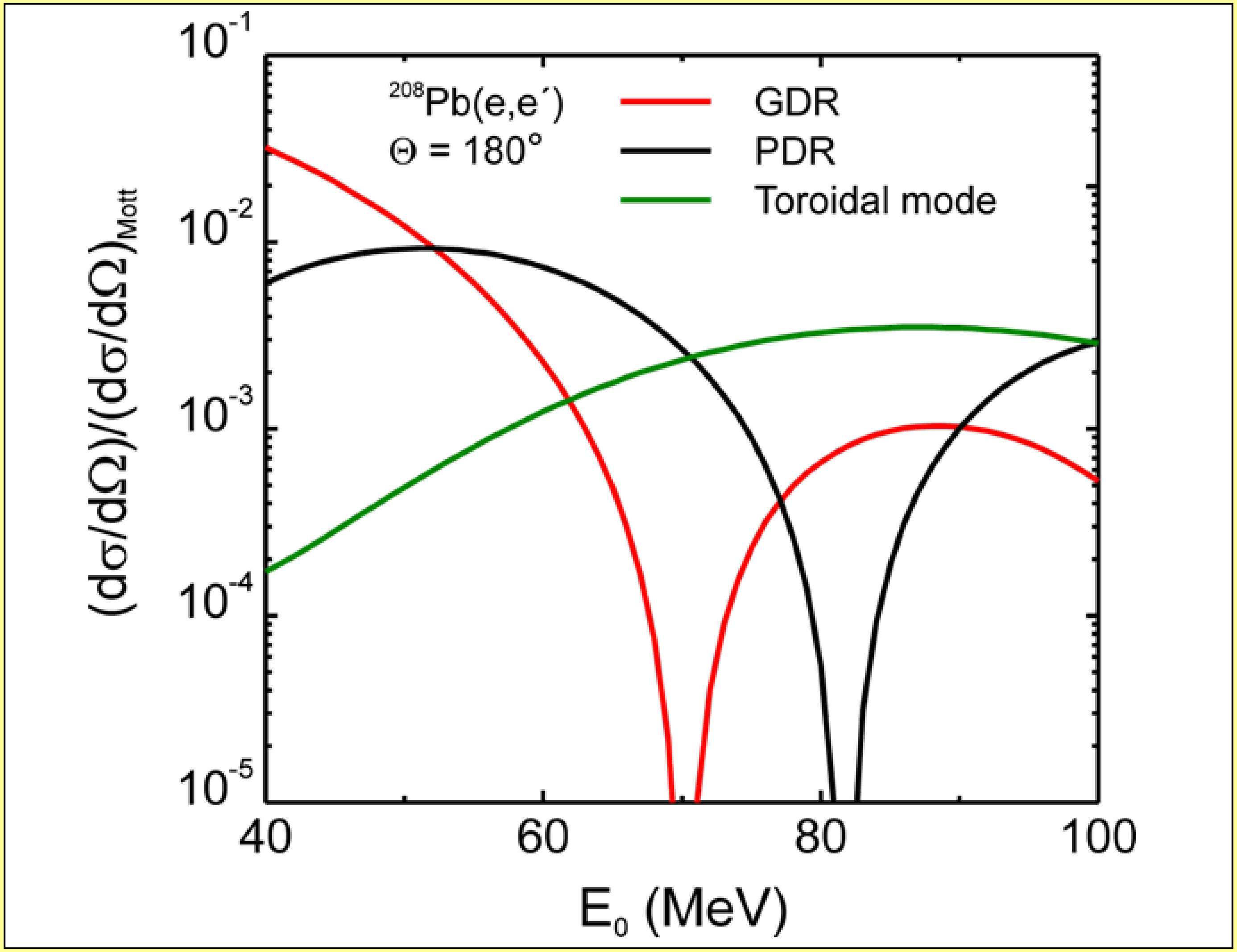
- Pronounced differenes at small angles due to Coulomb-nuclear interference

Signatures of Different E1 Modes in $(\vec{p},\vec{p}')$



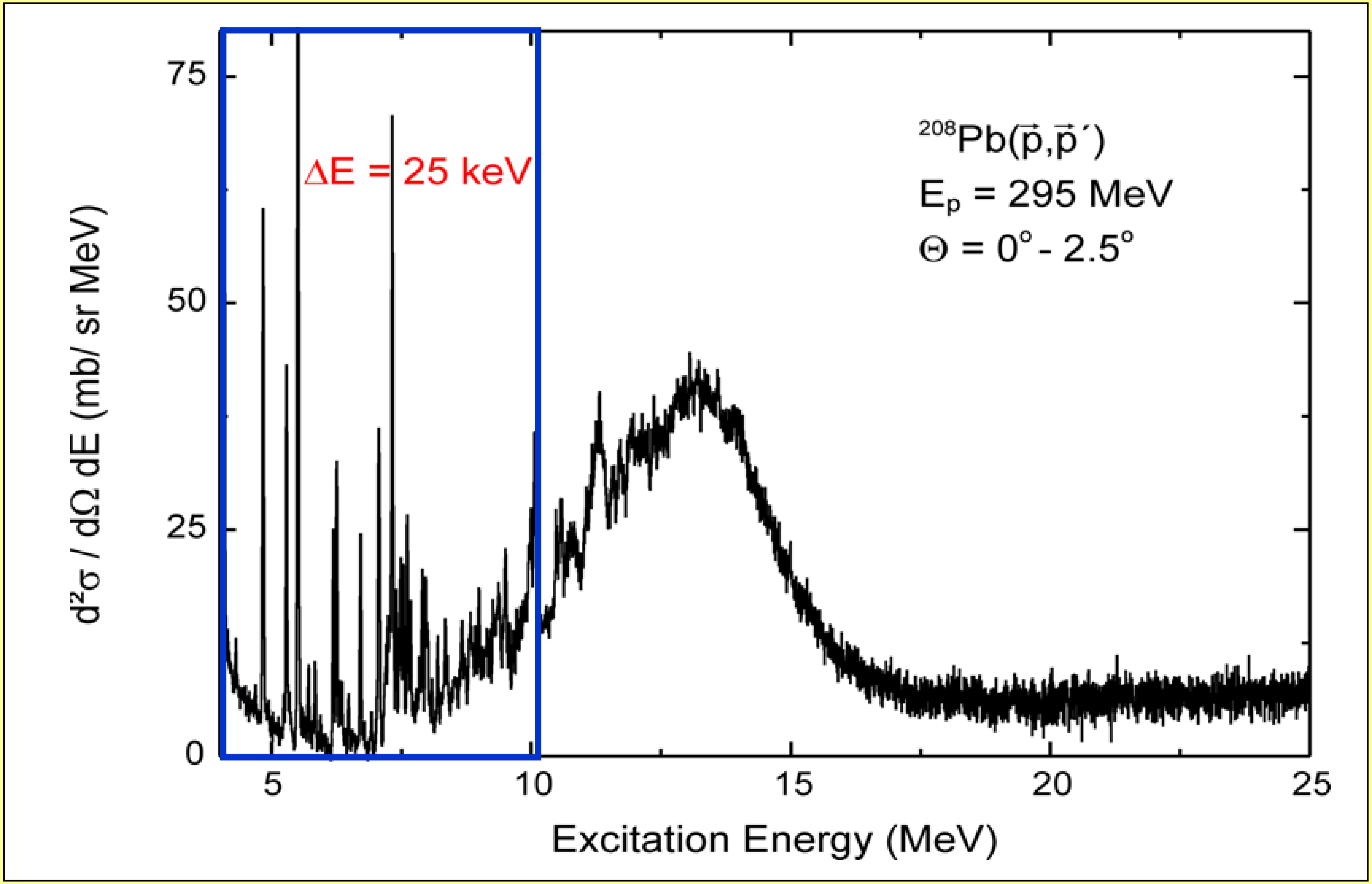
- Signature of toroidal mode in the asymmetry at small angles ?

Signatures of Low-Energy E1 Modes in (e,e´)

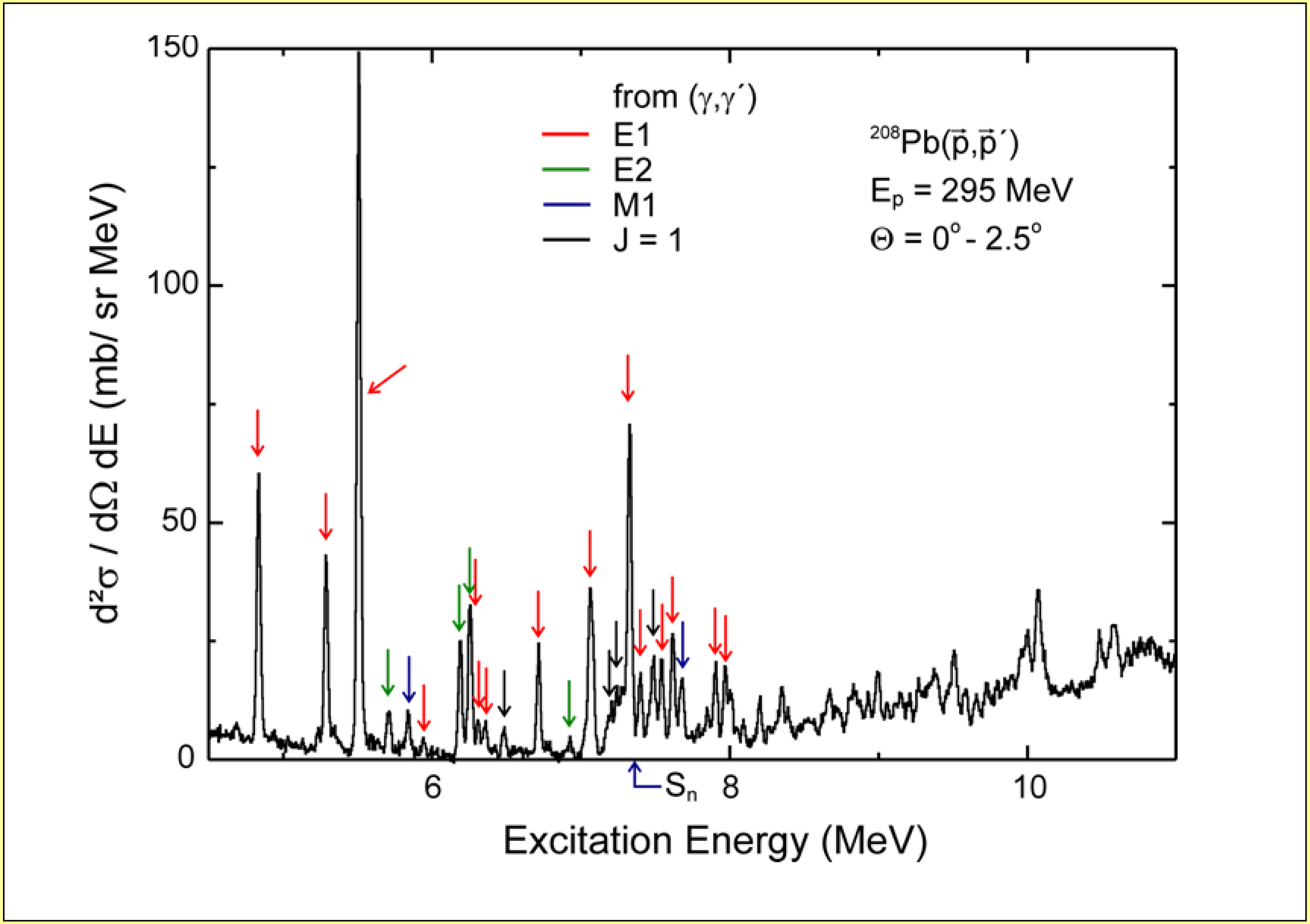


- Large difference in the momentum transfer dependence

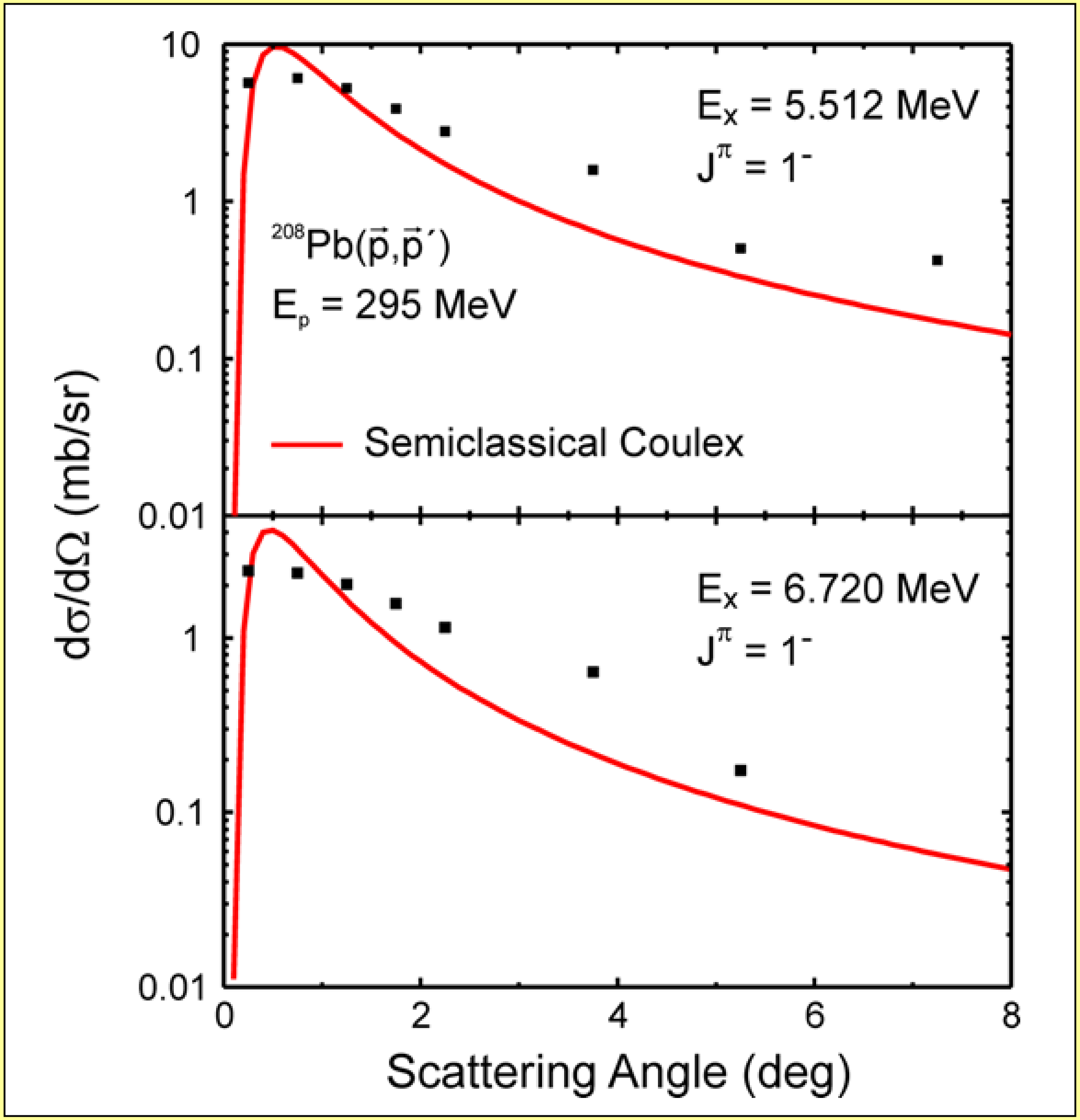
First Results: Background-Subtracted Spectrum



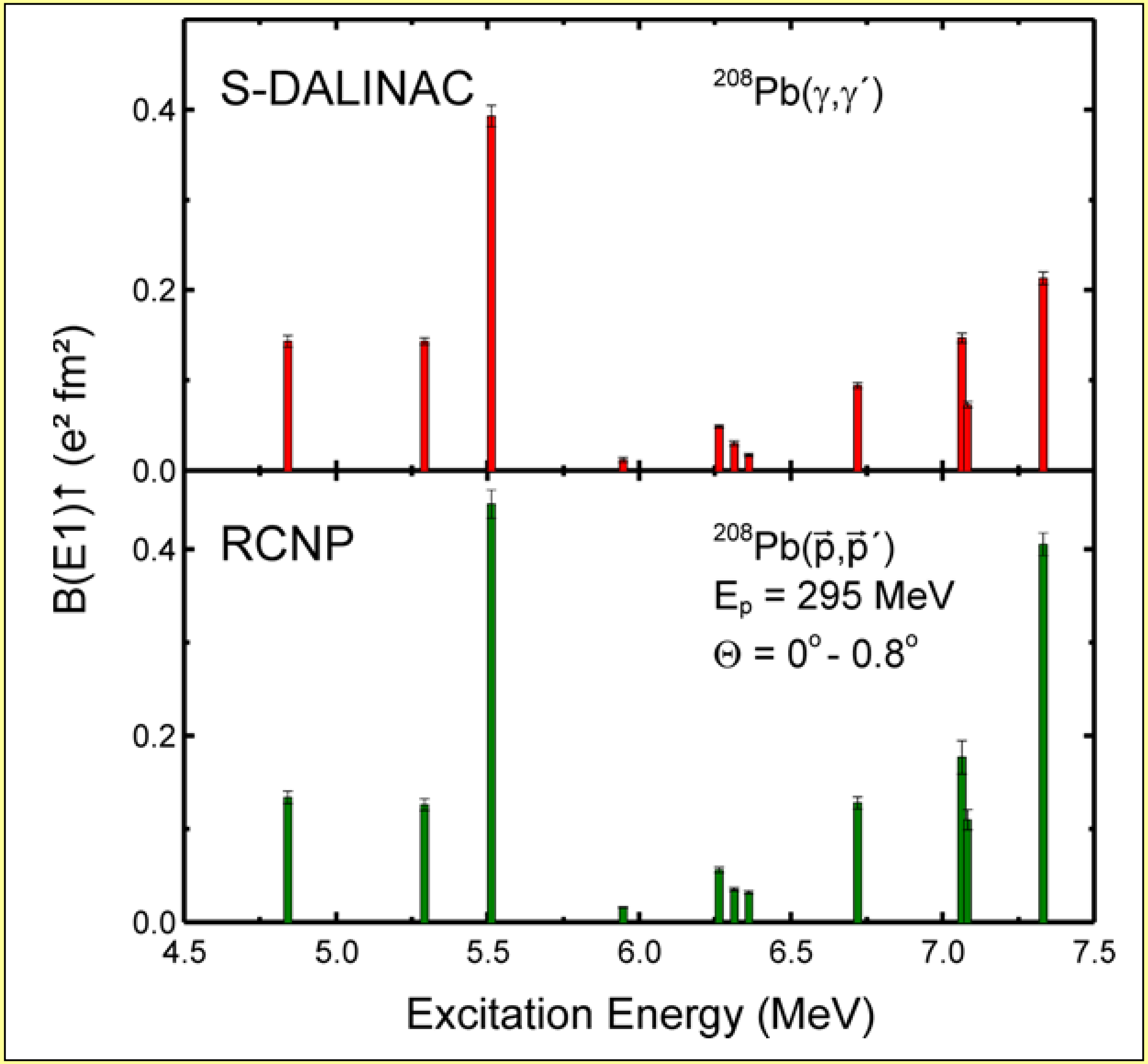
First Results: Spectrum (Expanded)



First Results: Typical Angular Distributions



First Results: B(E1) Strength



- Excellent agreement

Status and Outlook

- PDR in ^{208}Pb identified in (γ,γ') and verified in $(\vec{p},\vec{p}')$
- PDR fraction is ~ 1% EWSR and 5% IEWSR (large contribution to the nuclear dipole polarizability)
- Polarized intermediate energy proton scattering at 0° is established to study B(E1) strength
- High-resolution study of ^{208}Pb as reference case
- E1/M1 decomposition
- Detect PDR and toroidal signatures in (e,e´) form factors and $(\vec{p},\vec{p}')$ angular distributions and spin-flip observables
- Importance of PDR in astrophysical processes

Deuteron Electrodisintegration under 180°

- Astrophysical motivation: Big-Bang nucleosynthesis

- Experiment: 180° electron scattering

  High selectivity

  High energy resolution

- Precision test of theoretical models

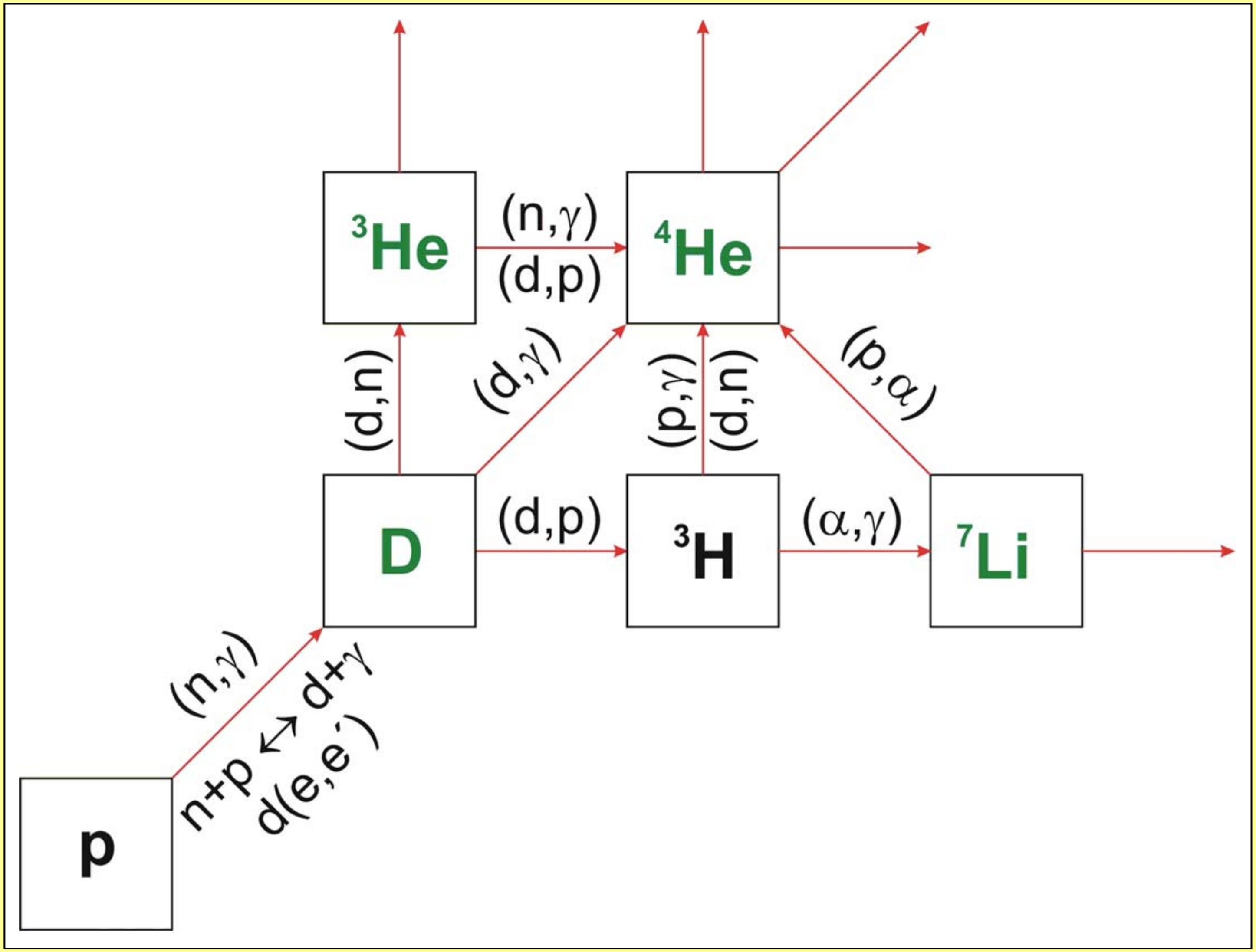
  NN potentials

  EFT

- Summary and outlook

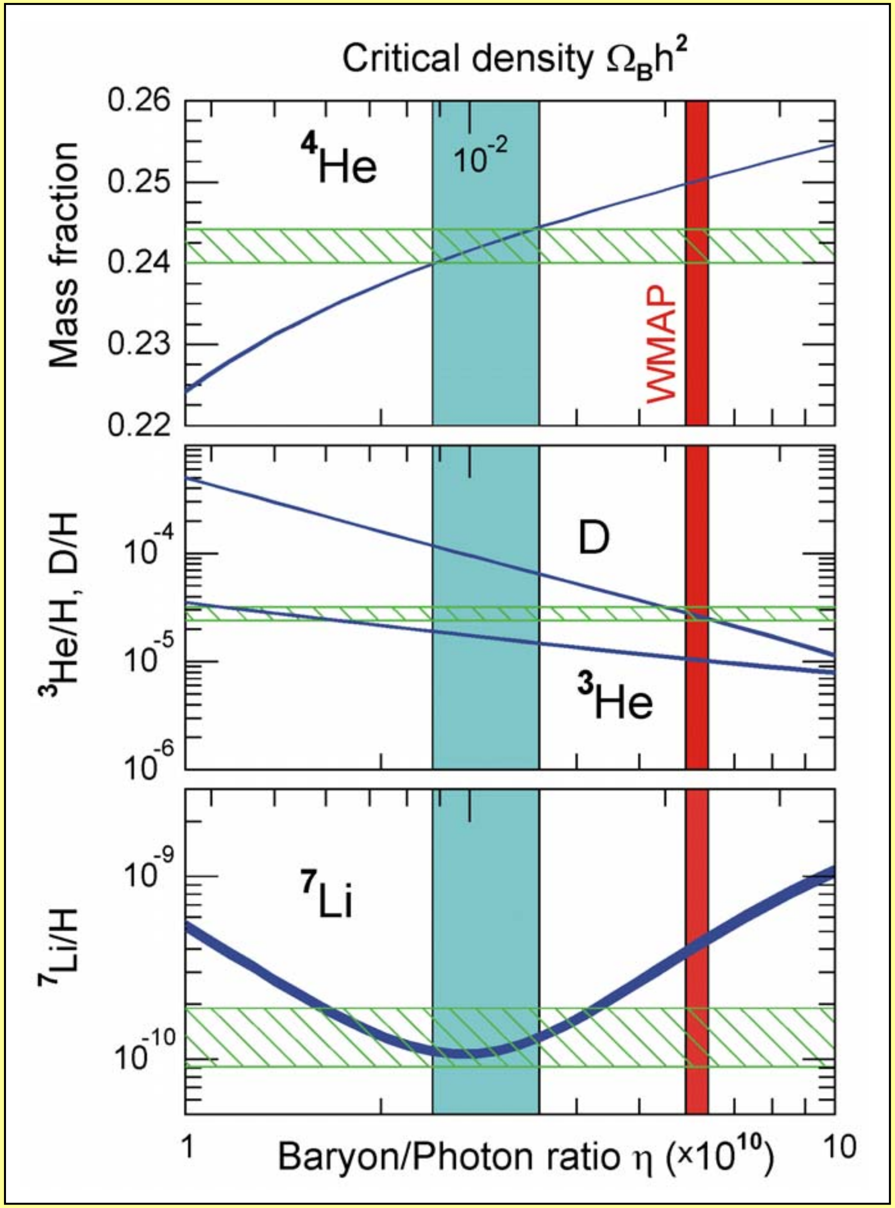
N. Ryezayeva et al., PRL 100 (2008) 172501

Primordial Nucleosynthesis



- D, ^{3}He, ^{4}He, ^{7}Li are synthesized

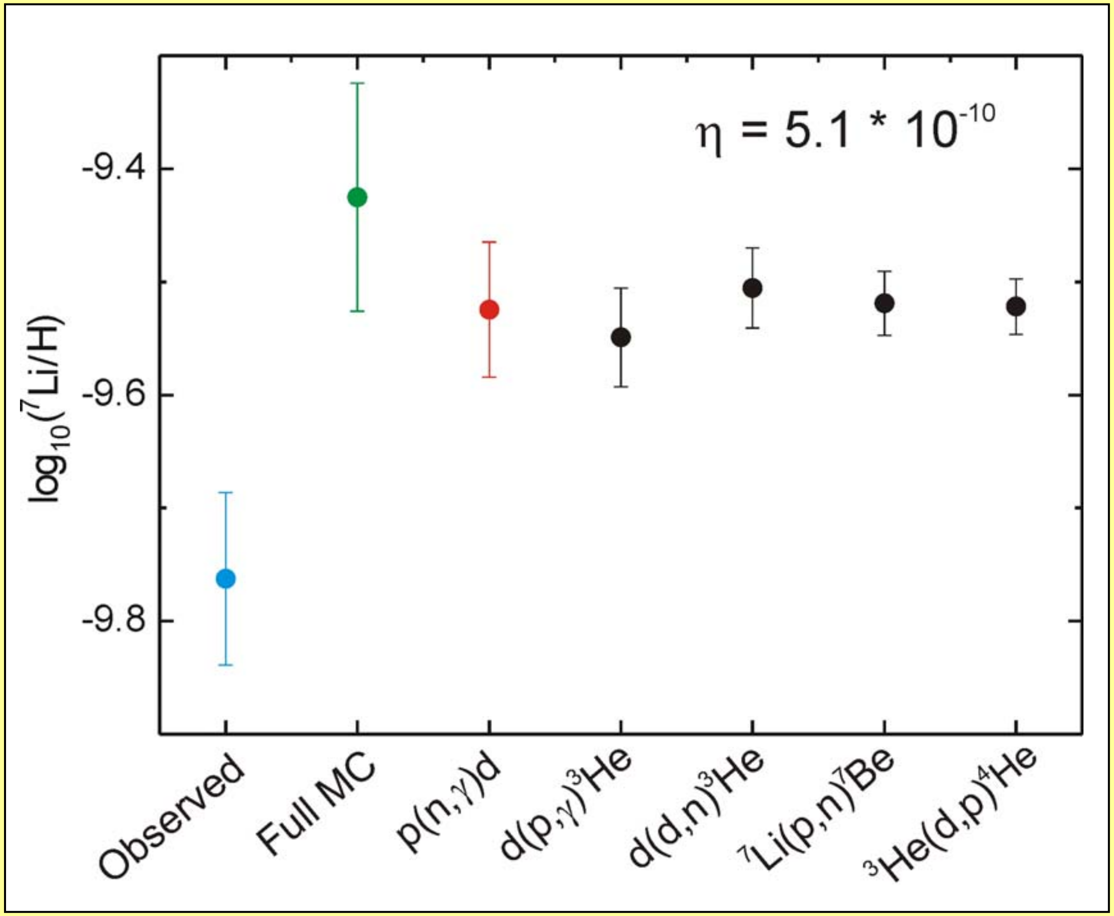
Test of Cosmological Standard Model



- Abundances depend on baryon/photon ratio (baryon density)
- Observational constraints: WMAP disagrees with spectroscopic information and/or BBN
- Critical density derived from ^{4}He and ^{7}Li is different from D

Adopted from A. Coc *et al.*, ApJ 600 (2004) 544

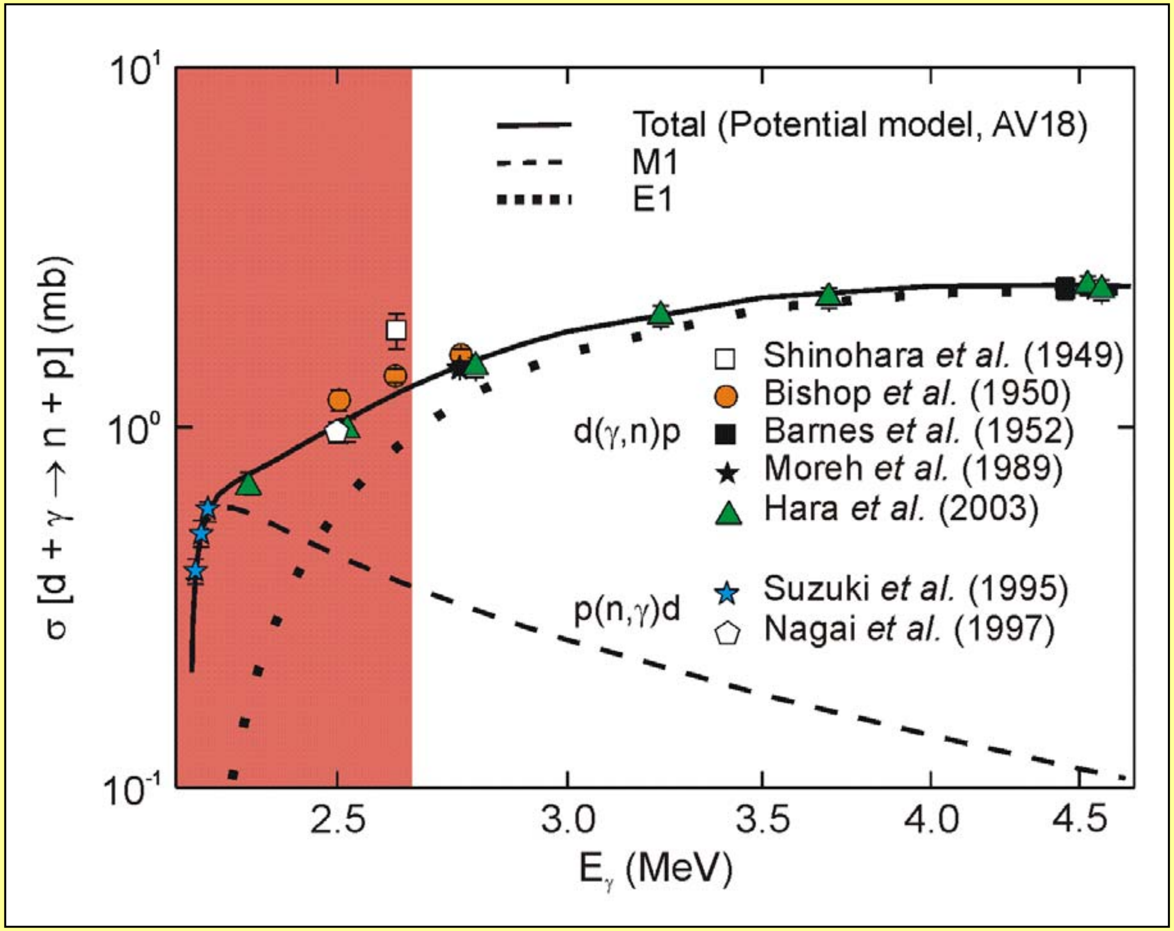
Uncertainty of ^{7}Li Abundance



- Largest uncertainty from *p(n,γ)d* reaction
- Relevant energy window 15 - 200 keV above threshold

S. Burles et al., PRL 82 (1999) 4176

d(γ,*n*)*p*: Data and Predictions

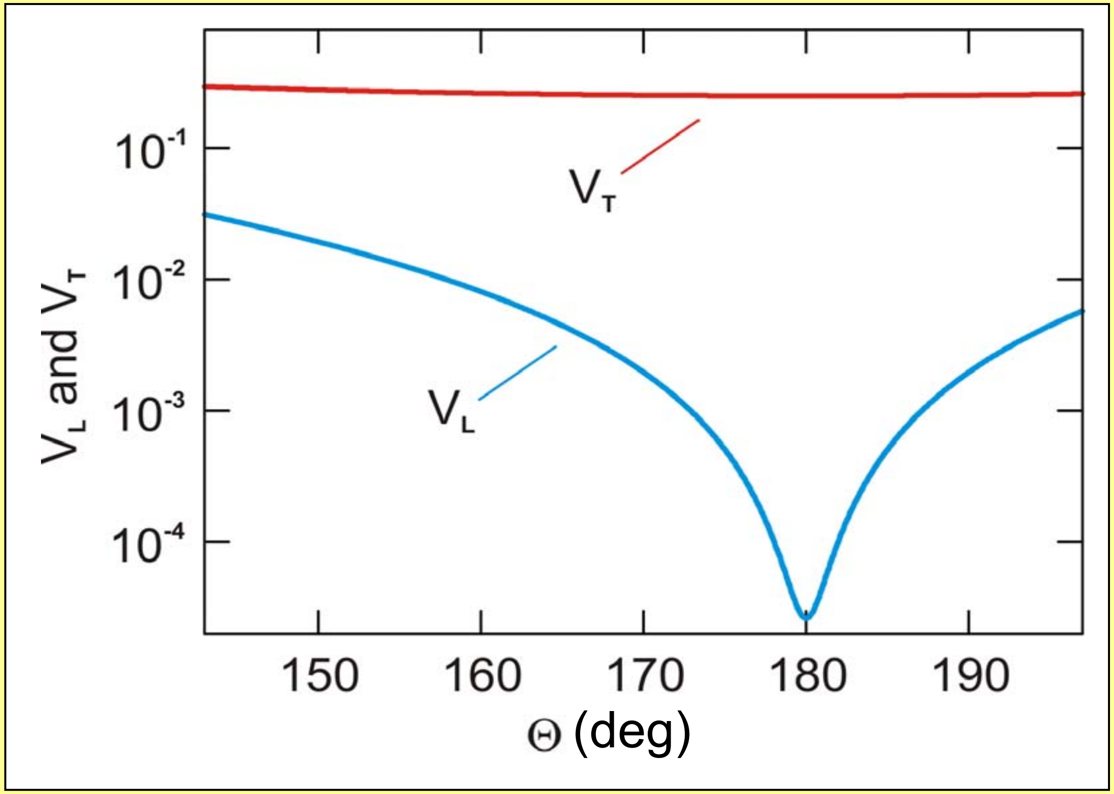


- Potential model (AV18) calculations by H. Arenhövel
- EFT calculations (J.-W. Chen and M.J. Savage, S. Ando *et al.*) are very similar
- Scarce data at the threshold
- M1 dominates: *d*(e,e´) at 180°

Why Electron Scattering under 180°?

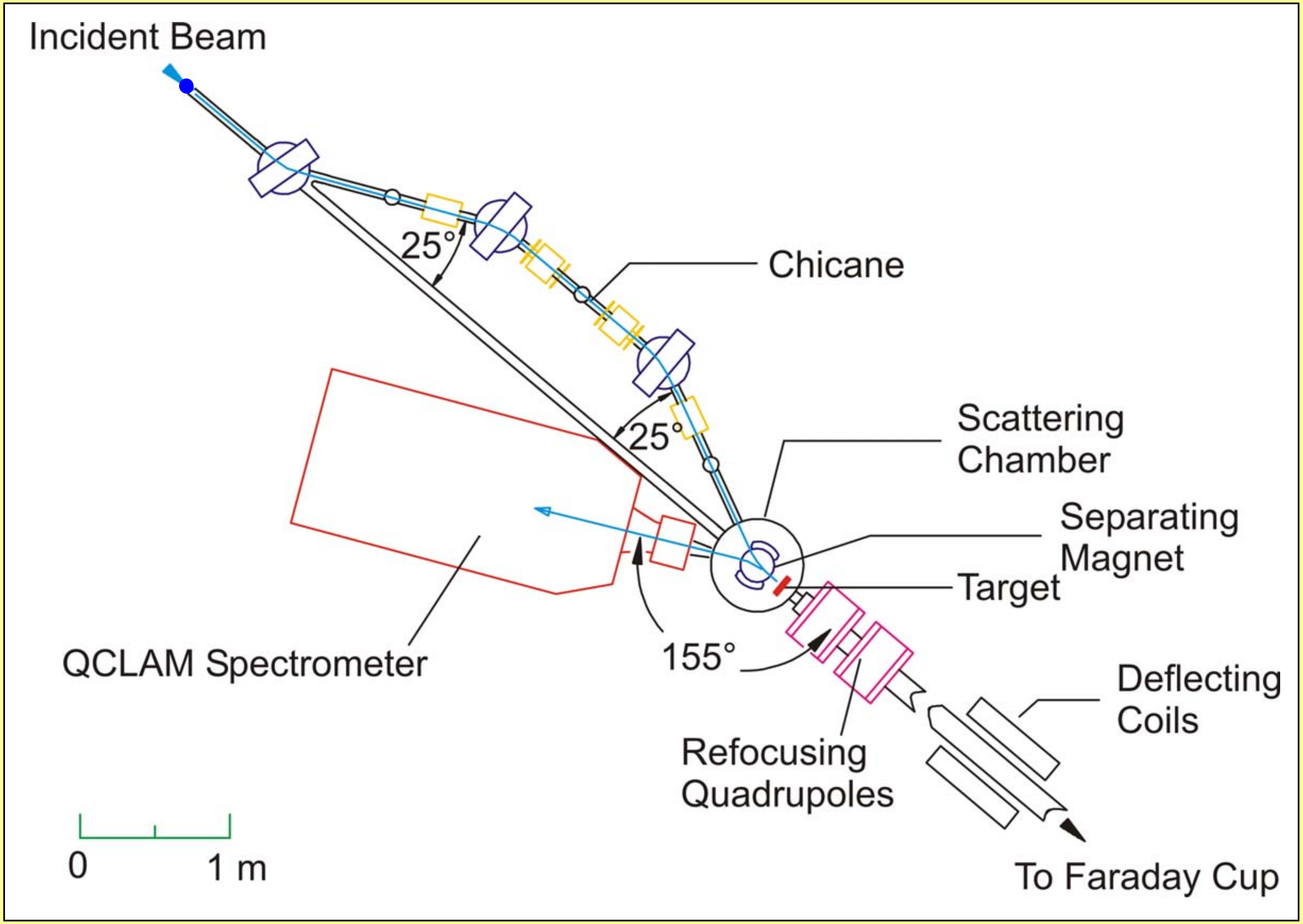
$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_L + \left(\frac{d\sigma}{d\Omega}\right)_T$$

$$V_L \times |F_L(q)|^2 \qquad\qquad V_T \times |F_T(q)|^2$$

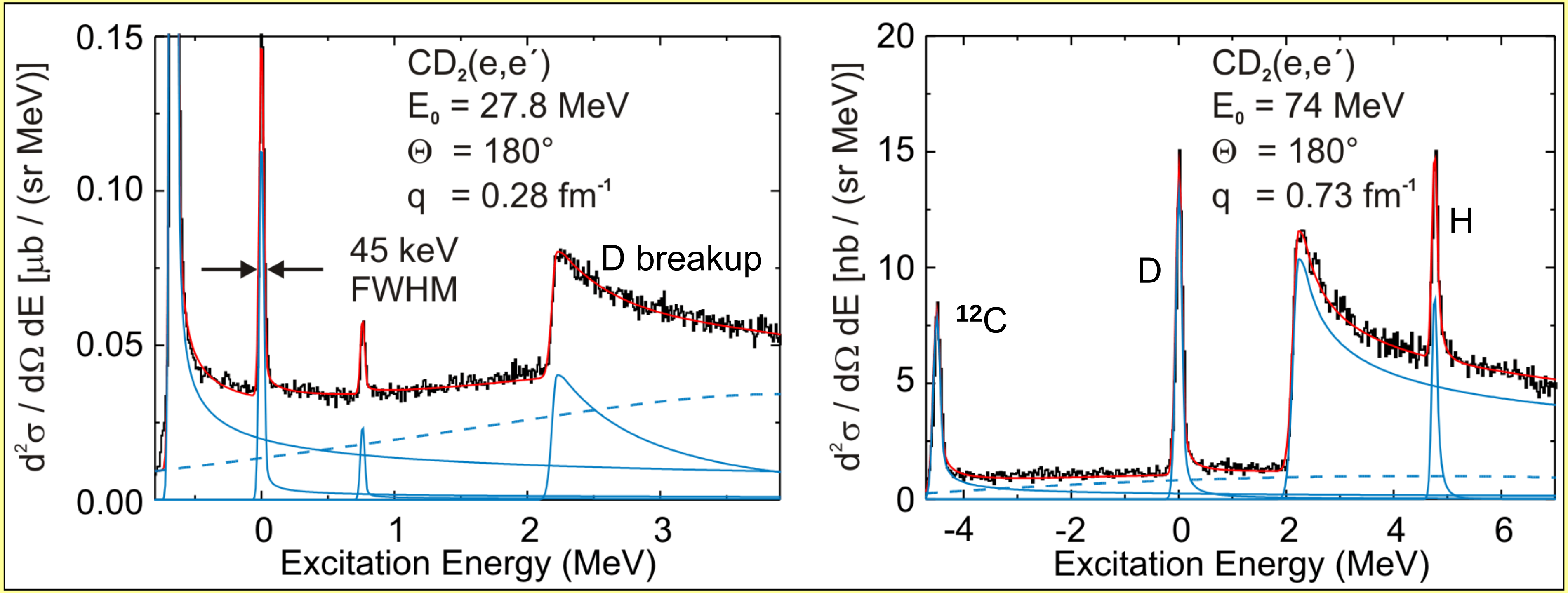


- Scattering at 180° is ideal for measuring transverse excitations: M1 enhanced

180° System at the S-DALINAC

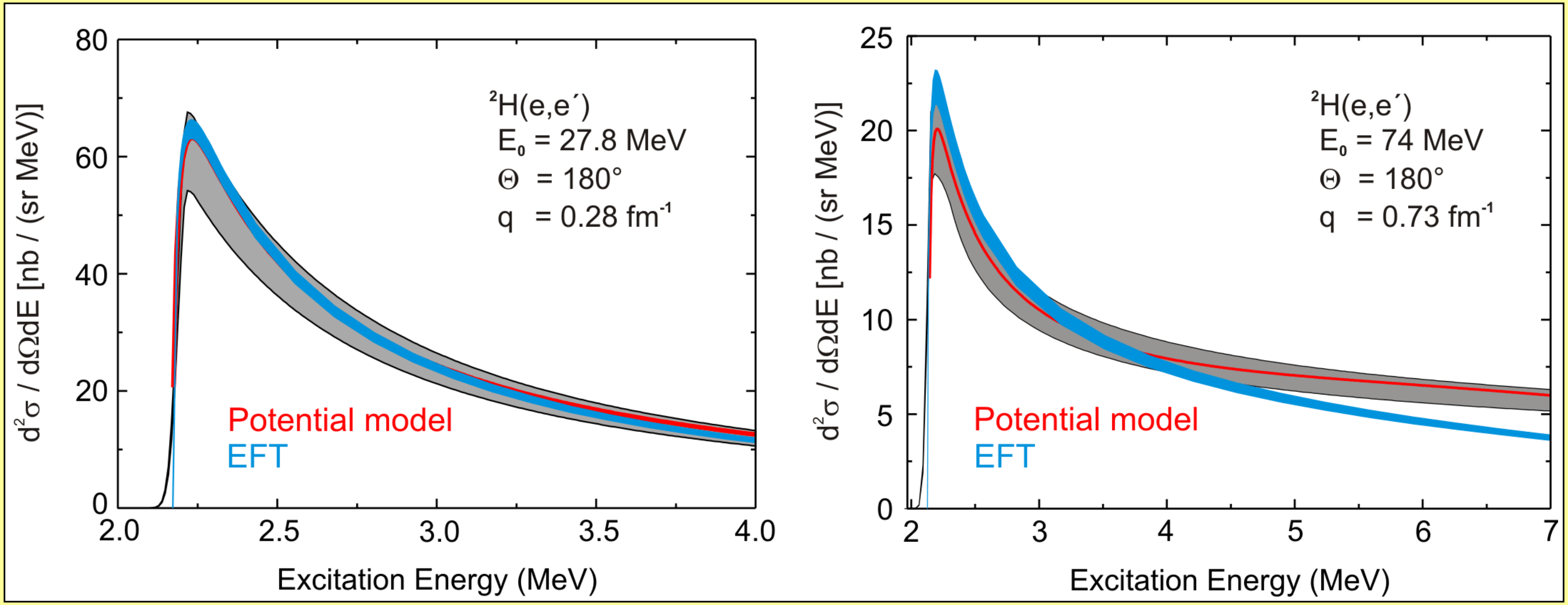


Decomposition of the Spectra



- Absolute and relative normalization agree within 5 - 6%

Comparison to Potential Model and EFT Calculations



- Excellent agreement with potential model (H. Arenhövel)
- Deviations for EFT (H. Griesshammer) at higher *q*

Extraction of the Astrophysical $np \to d\gamma$ Cross Section

- $$\frac{d\sigma}{d\Omega}(\theta = 180^\circ, q) \sim F_T^2(q)$$

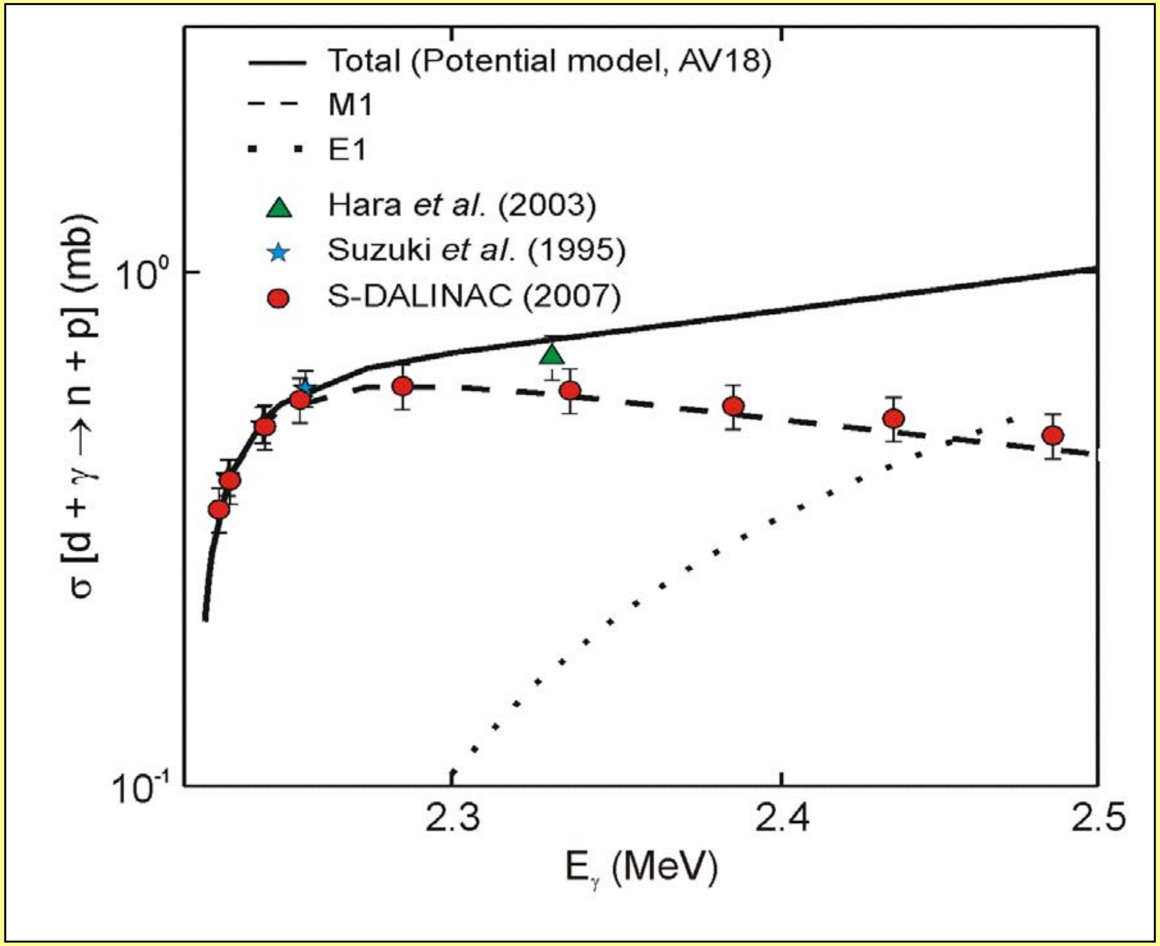
- $$B(M1, q) \sim \frac{1}{q^2} F_T^2(q)$$

- For $q \to k$ (photon point) take q-dependence of B(M1,q) from elastic scattering $\to \Gamma_\gamma$

- $$\sigma(d\gamma \to np) \sim \frac{1}{E_\gamma^2} \frac{\Gamma_n \Gamma_\gamma}{(E_\gamma - E_R)^2 + \Gamma^2/4}$$

- Detailed balance $\to \sigma(np \to d\gamma)$

Importance for Big-Bang Nucleosynthesis



- BBN relevant energy window
- Precision test of modern theoretical models (potential model, EFT)

Summary and Outlook

- Summary

  180° measurements of the M1 deuteron breakup

  Precision test of modern theoretical models (potential model, EFT)

  Excellent description of the data

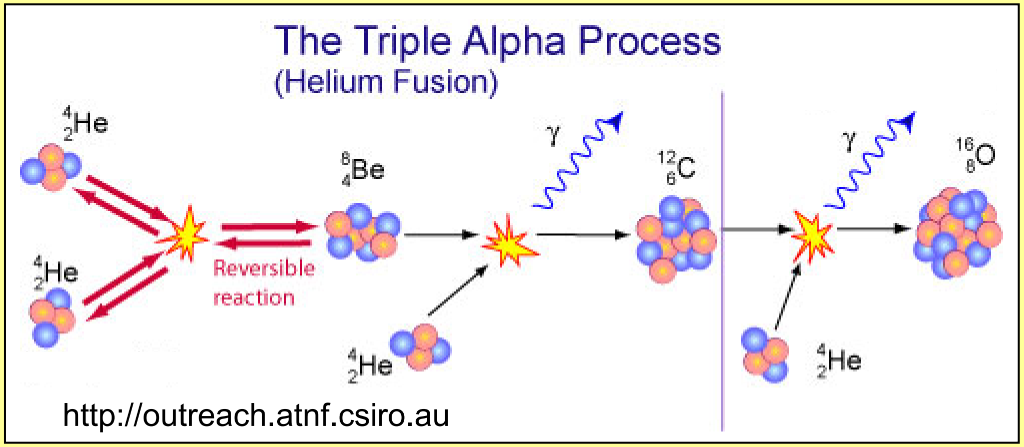
  Precise prediction for *p(n,γ)d* cross section possible in the astrophysically relevant region

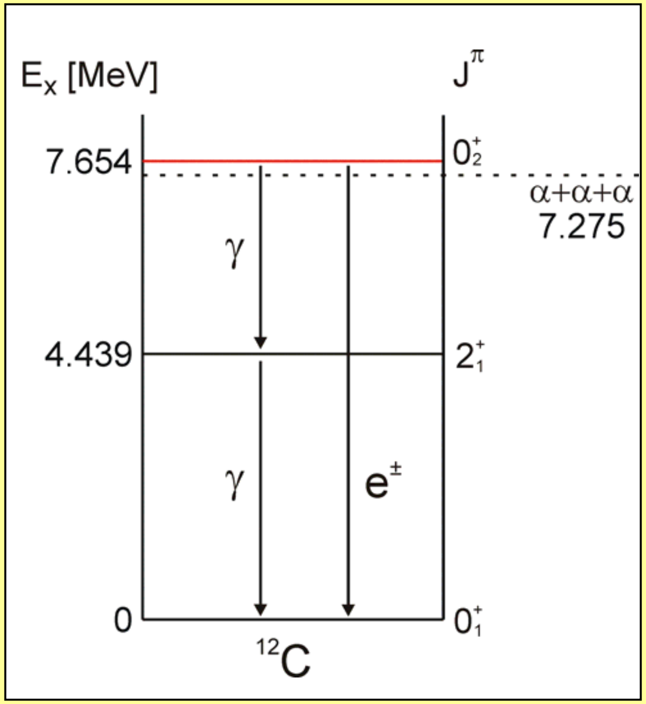
  Latest BBN calculations use already EFT calculations

- Outlook

  ^{9}Be(e,e´) under 180°

Astrophysical Importance of the Hoyle State





- Triple alpha reaction rate

$$r_{3\alpha} \propto \Gamma_{rad} \exp\left(-\frac{Q_{3\alpha}}{kT}\right)$$

$$\Gamma_{rad} = \Gamma_\gamma + \Gamma_\pi = \frac{\Gamma_\gamma + \Gamma_\pi}{\Gamma} \cdot \frac{\Gamma}{\Gamma_\pi} \cdot \Gamma_\pi$$

(α,α´γ γ)
(p,p´γ γ)

(p,p´e⁺e⁻)

(e,e´) → ME → Γ_π

- Reaction rate with accuracy $\pm 6\%$ needed

S.M. Austin, NPA 758 (2005) 375c

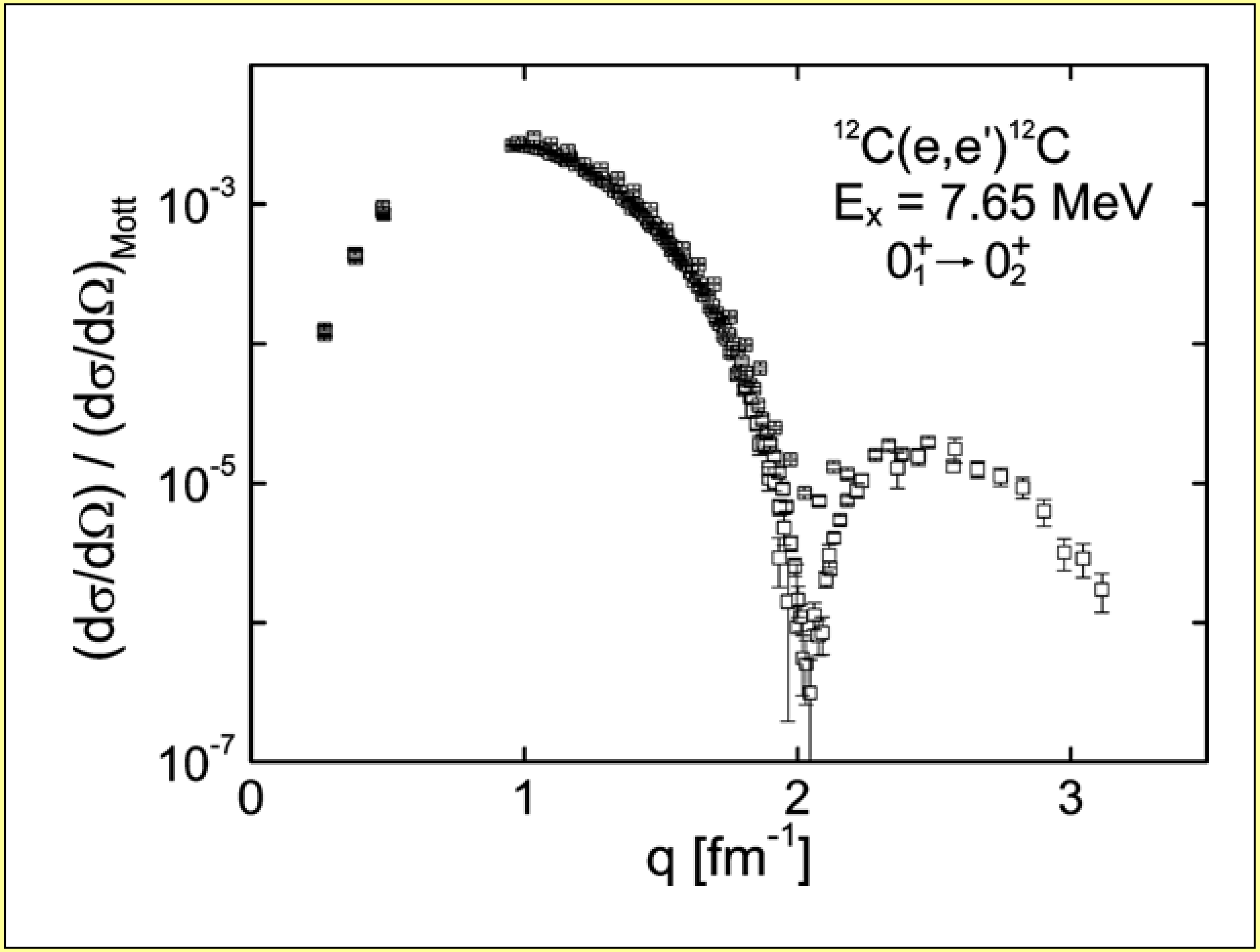
Uncertainties of the Astrophysical Relevant Quantities

$$r_{3\alpha} \propto \Gamma_{rad} \exp\left(-\frac{Q_{3\alpha}}{kT}\right) \qquad \Gamma_{rad} = \Gamma_\gamma + \Gamma_\pi = \frac{\Gamma_\gamma + \Gamma_\pi}{\Gamma} \cdot \frac{\Gamma}{\Gamma_\pi} \cdot \Gamma_\pi$$

Quantity	Value	Error (%)	
$Q_{3\alpha}$	379.38 ± 0.20 keV	1.2	($T_9=0.2$)
Γ_{rad}/Γ	$(4.12 \pm 0.11)\times 10^{-4}$	2.7	
Γ_π/Γ	$(6.74 \pm 0.62)\times 10^{-6}$	9.2	
Γ_π	$(62.0 \pm 6.0)\times 10^{-6}$ eV	9.7	Crannell *et al.* (1967)
Γ_π	$(59.4 \pm 5.1)\times 10^{-6}$ eV	8.6	Strehl (1970)
Γ_π	$(52.0 \pm 1.4)\times 10^{-6}$ eV	2.7	Crannell *et al.* (2005)

- Total uncertainty $\Delta r_{3\alpha}/r_{3\alpha} = \pm 11.6\%$ presently

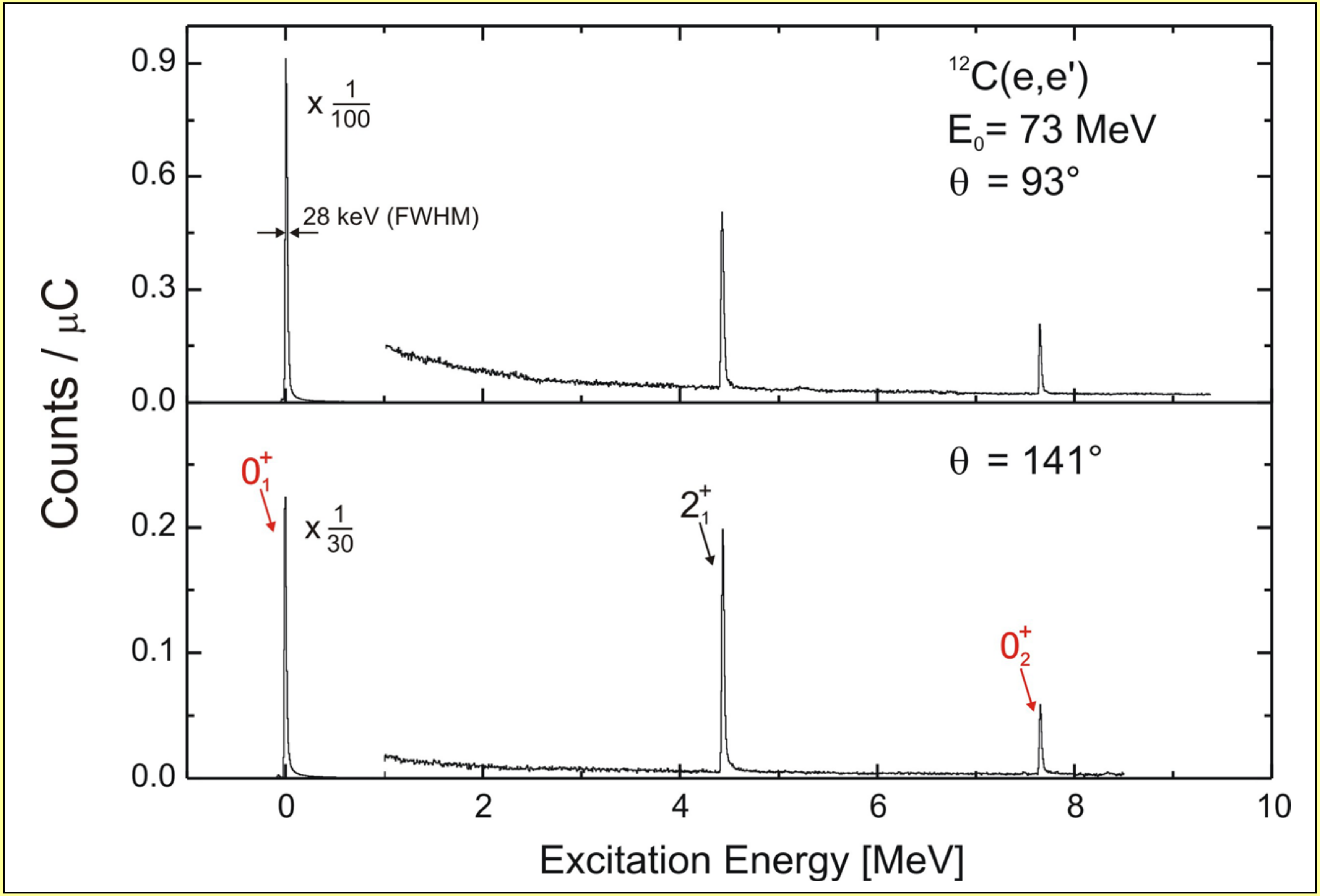
Transition Form Factor to the Hoyle State



- Extrapolation to zero momentum transfer
- Fourier-Bessel analysis

H. Crannell, data compilation (2005)

Measured Spectra



Model-independent PWBA Analysis

$$\left(\frac{d\sigma}{d\Omega}\right)_{PWBA} = 4\pi\left(\frac{e^2}{E_0}\right)^2 f_{rec}\;\; V_L(\theta)\;\; B(C0,q)$$

$$4\pi B(C0,q) = \left[\langle 0_2^+|\int \hat{\rho}_N\, j_0(qr)\, d^3r|0_1^+\rangle\;\right]^2$$

$$\langle r^\lambda\rangle_{tr} = \langle 0_2^+|\int \hat{\rho}_N\, r^\lambda\, d^3r|0_1^+\rangle$$

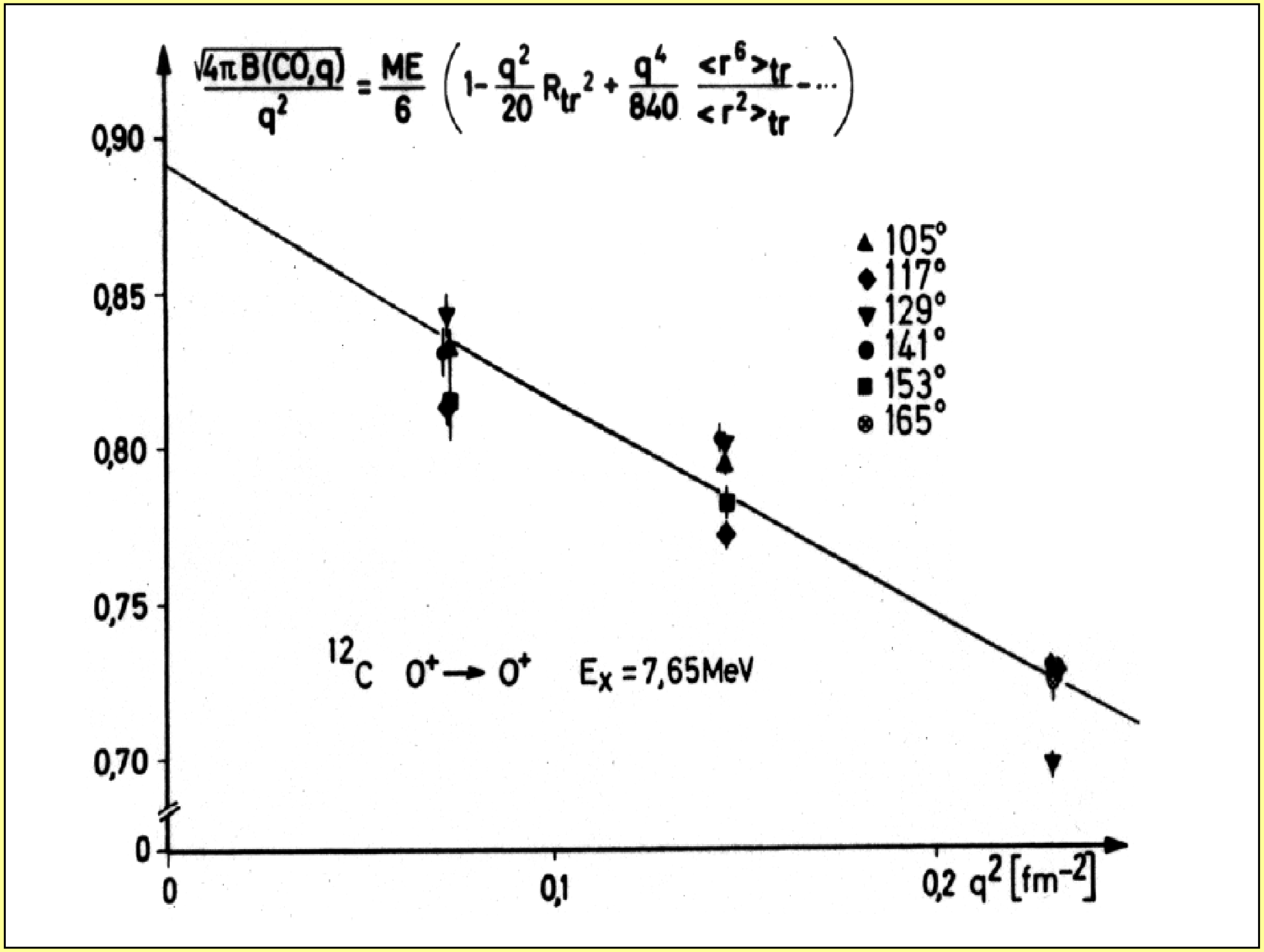
$$ME = \langle r^2\rangle_{tr}\,, \qquad R_{tr}^2 = \frac{\langle r^4\rangle_{tr}}{\langle r^2\rangle_{tr}}$$

$$\sqrt{4\pi\, B(C0,q)} = \frac{q^2}{6}(ME)\left[1 - \frac{q^2}{20}R_{tr}^2 + \;\cdots\right]$$

$$\Gamma_\pi \propto (ME)^2$$

- Model-independent extraction of the partial pair width Γ_π

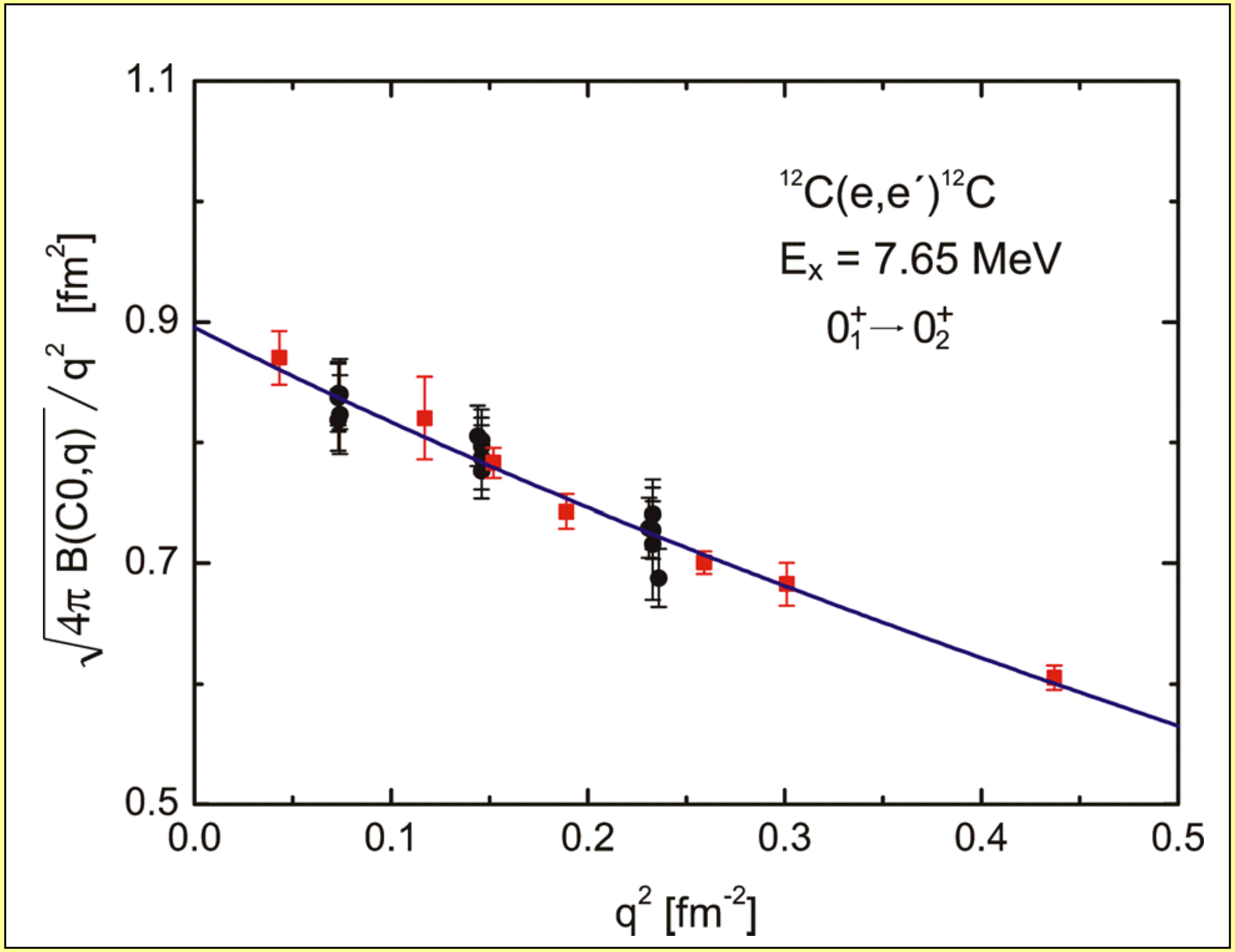
Model-independent PWBA Analysis



- ME = 5.37(22) fm^2, R_{tr} = 4.24(30) fm
- Large uncertainty because of narrow momentum transfer region

P. Strehl, Z. Phys. 234 (1970) 416

Model-independent PWBA Analysis



$$\sqrt{4\pi\, B(C0,q)} = \frac{q^2}{6}(ME)\left[1 - \frac{q^2}{20}R_{tr}^2 + \cdots\right]$$

- ME = 5.37(7) fm^2, R_{tr} = 4.30(12) fm

Fourier-Bessel Analysis

- Transition form factor is the Fourier-Bessel transform of the transition charge density

$$F(q) = 4\pi \int_0^\infty \rho_{tr}(r)\, j_0(qr)\, r^2\, dr$$

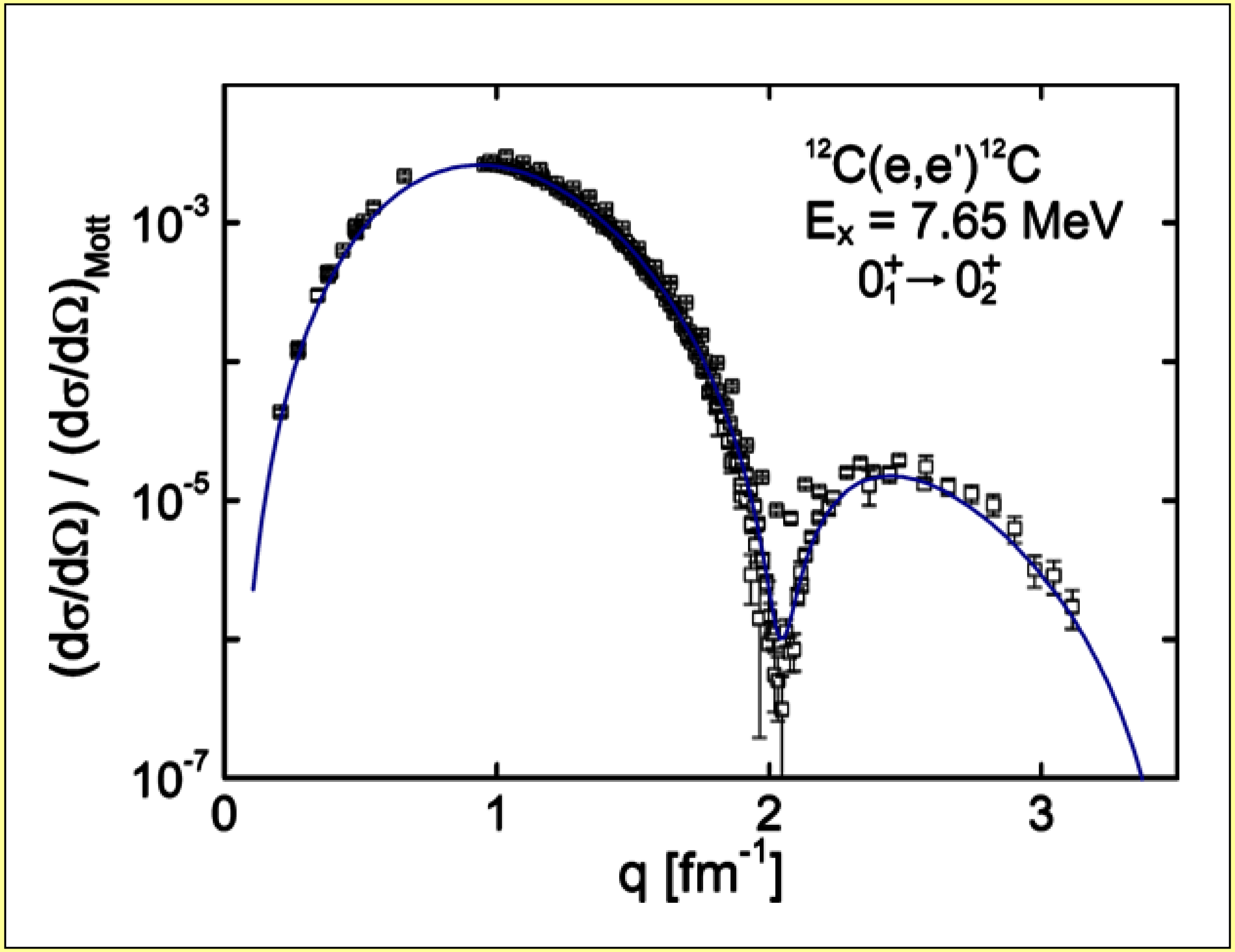
$$\rho_{tr}(r) = \begin{cases} \sum_{\mu=1}^{\infty} a_\mu\, j_0(q_\mu r) & \text{for } r < R_c \\ 0 & \text{for } r \geq R_c \end{cases}$$

with

$$q_\mu = \frac{\mu\pi}{R_c}$$

- Data should be measured over a broad momentum transfer range

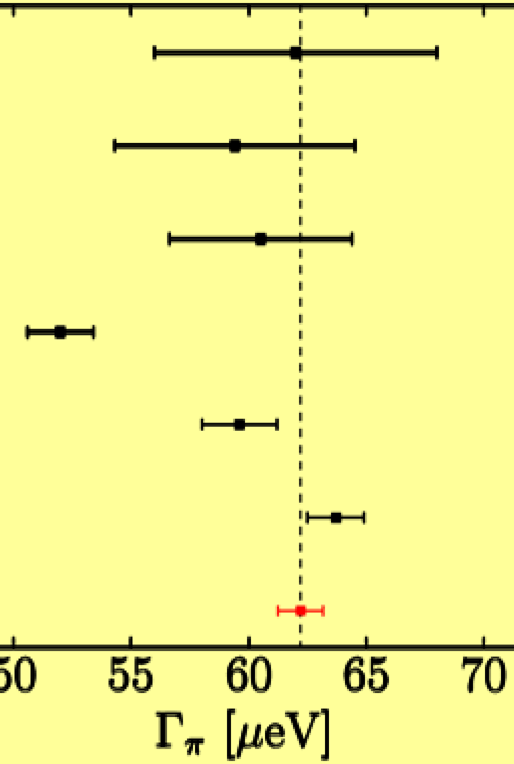
Fourier-Bessel Analysis



- q = 0.2 – 3.1 fm^{-1}
- *ME* = 5.55(5) fm^2

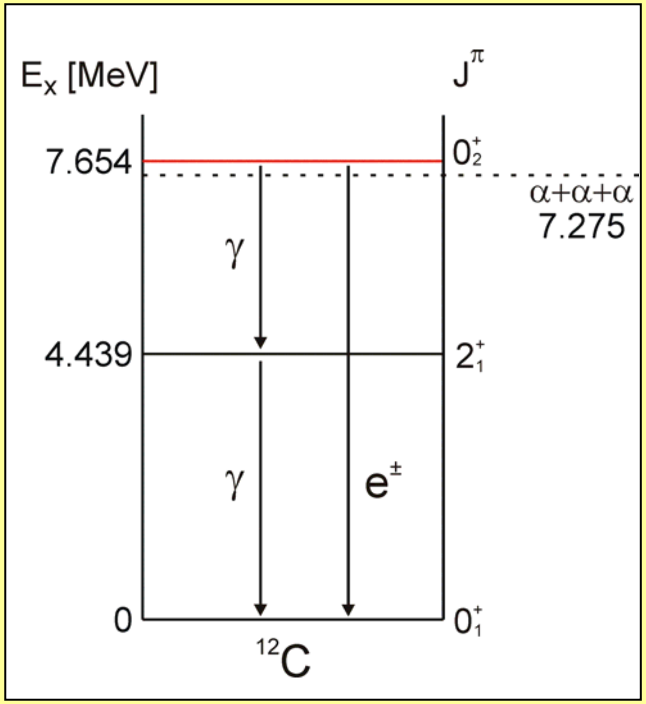
Results

Year	Analysis	Pair width	Ref.
1967	PWBA		Crannell *et al.*
1970	PWBA		Strehl
1970	Old average		Ajzenberg-Selove
2005	Fourier-Bessel		Crannell *et al.*
2008	PWBA		Present work
2008	Fourier-Bessel		Present work
2008	New average		Present work



- $\Gamma_\pi = 62.2(10) \times 10^{-6}\,\mathrm{eV}$
- Total uncertainty $\Delta r_{3\alpha}/r_{3\alpha} = \pm 10\%$
- Only Γ_π/Γ needs still to be improved now

Structure of the Hoyle State in ^{12}C



- The Hoyle state is a prototype of α-cluster states in light nuclei
- Cannot be described within the shell-model but within α-cluster models
- Some α-cluster models predict the Hoyle state to consist of a dilute gas of weakly interacting α particles with properties of a Bose-Einstein Condensate (BEC)
- Comparison of high-precision electron scattering data with predictions of FMD and α-cluster models

➡ Hoyle state cannot be understood as a true BEC

M. Chernykh et al., PRL 98 (2007) 032501

Some Theoretical Approaches Towards the Hoyle State: FMD model

- Antisymmetrized A-body state

$$|Q\rangle = \mathcal{A}(|q_1\rangle \otimes |q_2\rangle \otimes \ldots \otimes |q_A\rangle)$$

Single-particle states

$$\langle \mathbf{x}|q\rangle = \sum_i c_i \exp\left[-\frac{(\mathbf{x}-\mathbf{b}_i)^2}{2a_i}\right] \otimes |\chi_i^\uparrow, \chi_i^\downarrow\rangle \otimes |\xi\rangle$$

Gaussian wave packets in phase space (a_i is width, complex parameter $\mathbf{b}_i$ encodes mean position and mean momentum), spin is free, isospin is fixed

Describes α-cluster states as well as shell-model–like configurations

- UCOM interaction

Derived form the realistic Argonne V18 interaction

Adjusted to reproduce binding energies and charge radii of some "closed-shell" nuclei

Theoretical Approaches: α-Cluster and "BEC" Models

- α-cluster model

  FMD wave function restricted to α-cluster triangle configurations only

- "BEC" model

  System of 3 ^{4}He nuclei in 0s state (like α condensate)

  Hoyle state is a "dilute gas" of α particles

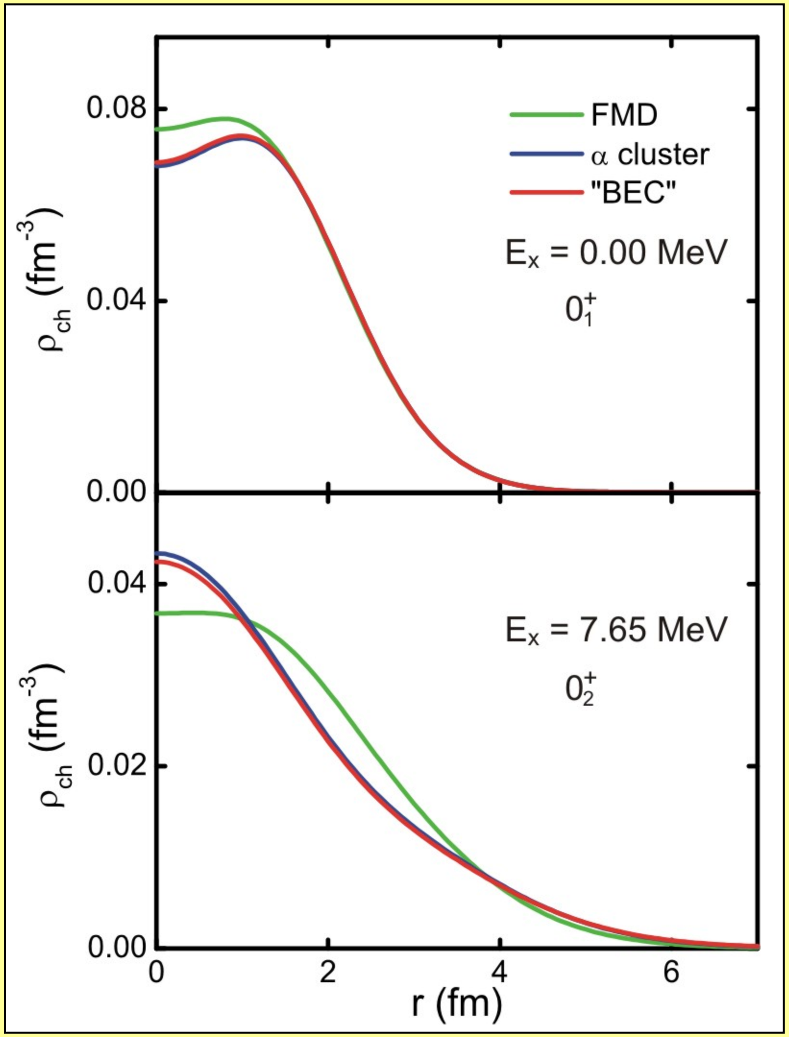
- Volkov interaction

  Simple central interaction

  Parameters adjusted to reproduce α binding energy, radius,
  α–α scattering data and ground state energy of ^{12}C

  Only reasonable for ^{4}He, ^{8}Be and ^{12}C nuclei

^{12}C Densities



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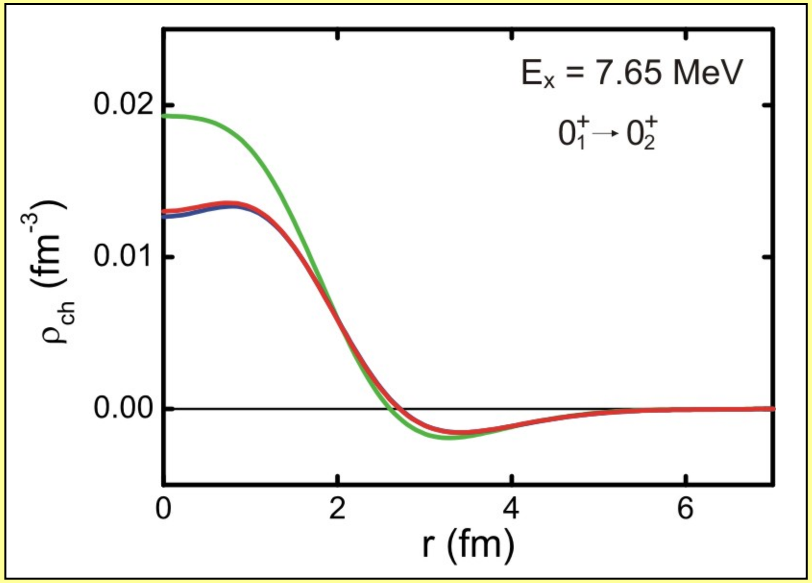
- Ground state density can be tested via elastic form factor



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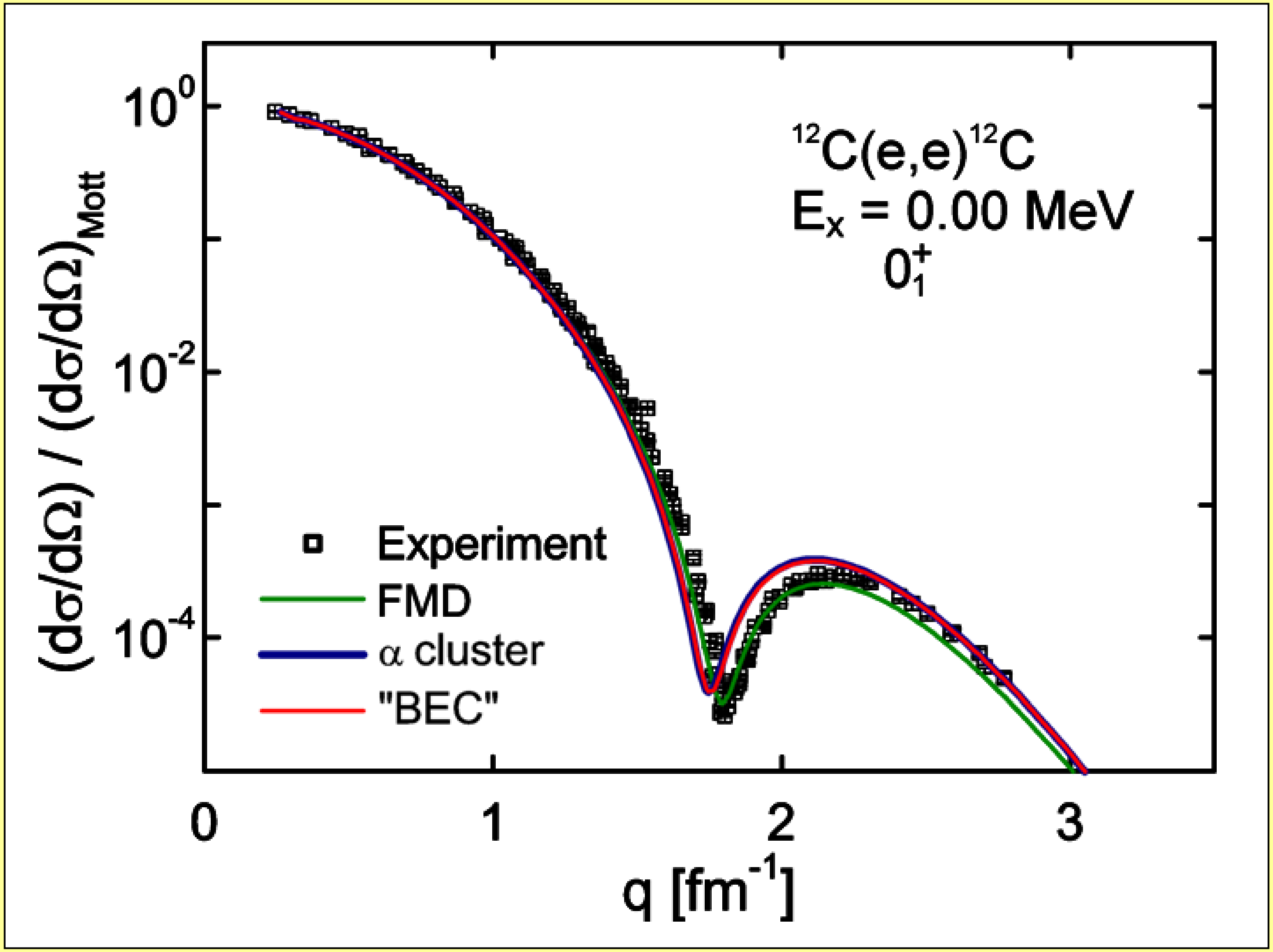
- Transition density can be tested via transition form factor

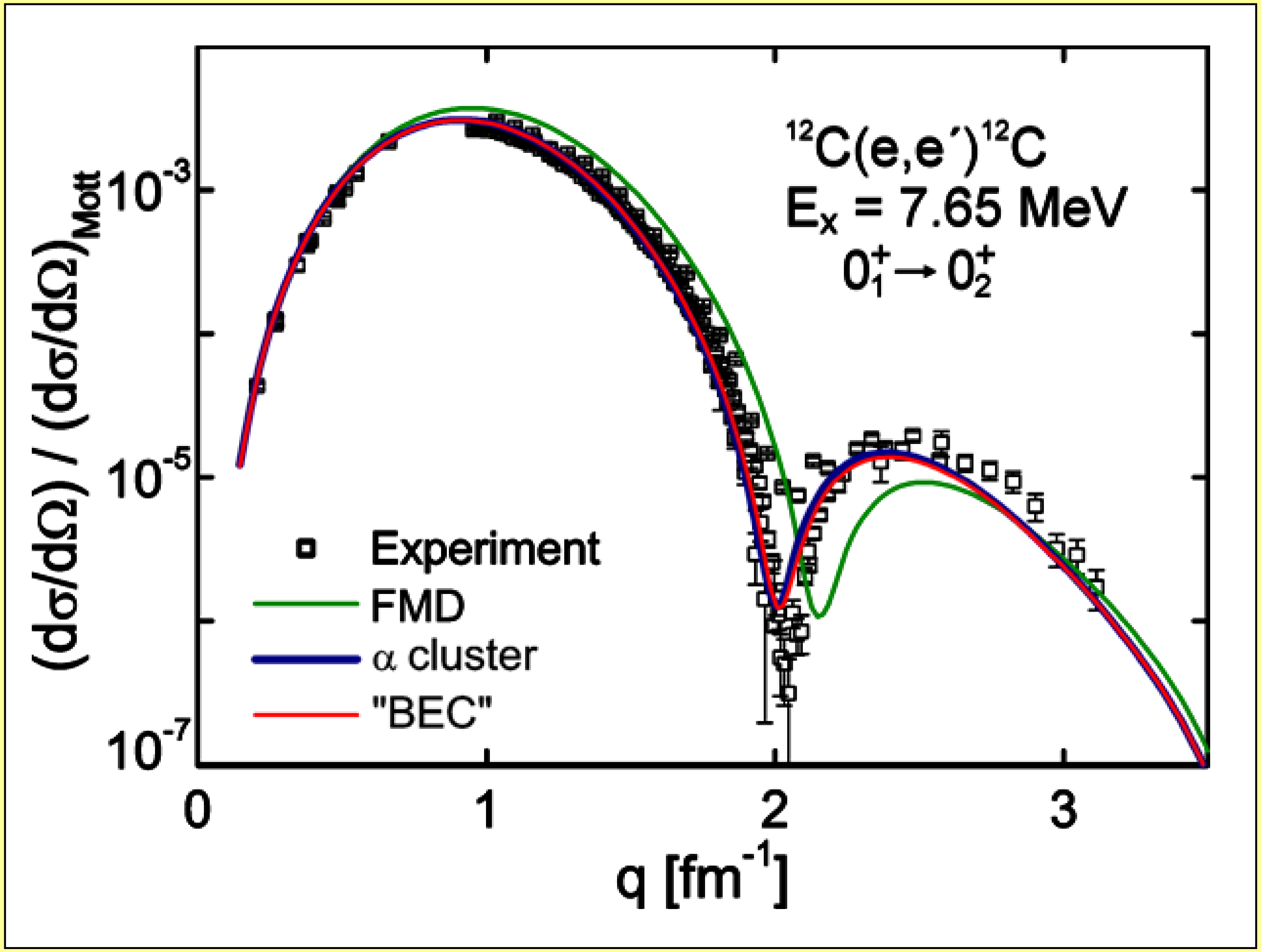
- Note the depression of the central density
- Electron scattering as test of theoretical predictions

Elastic Form Factor



- Described well by FMD

Transition Form Factor to the Hoyle State

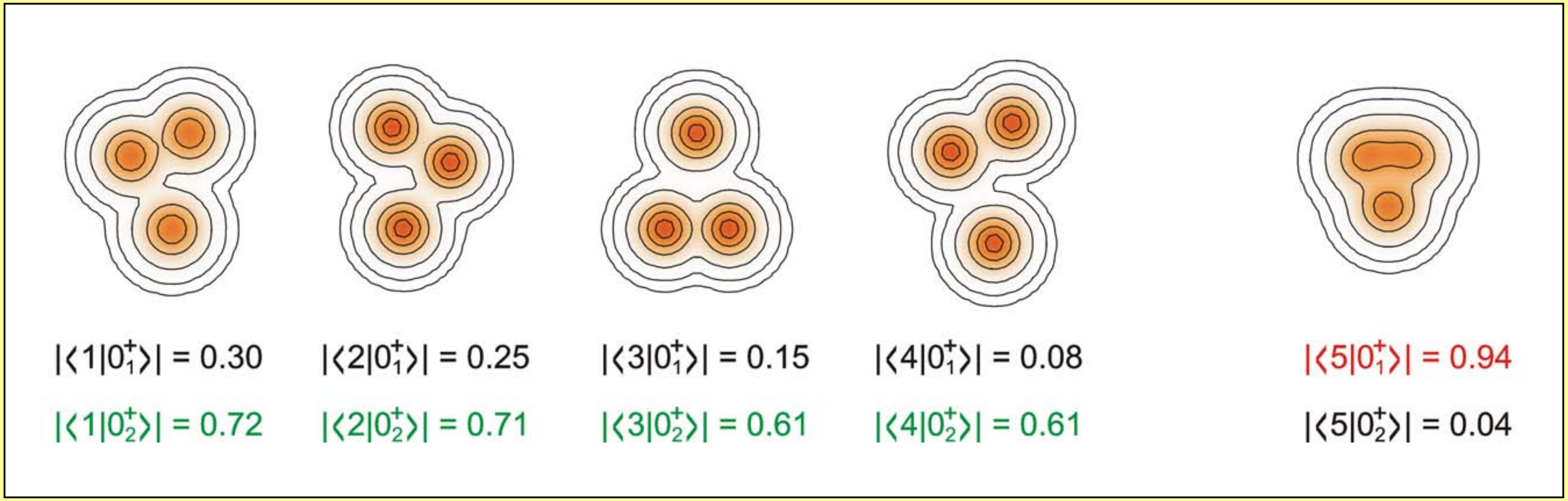


- Described better by α-cluster models
- FMD might be improved by taking α-α scattering data into account

H. Crannell, data compilation (2005)

What is the Actual Structure of the Hoyle State ?

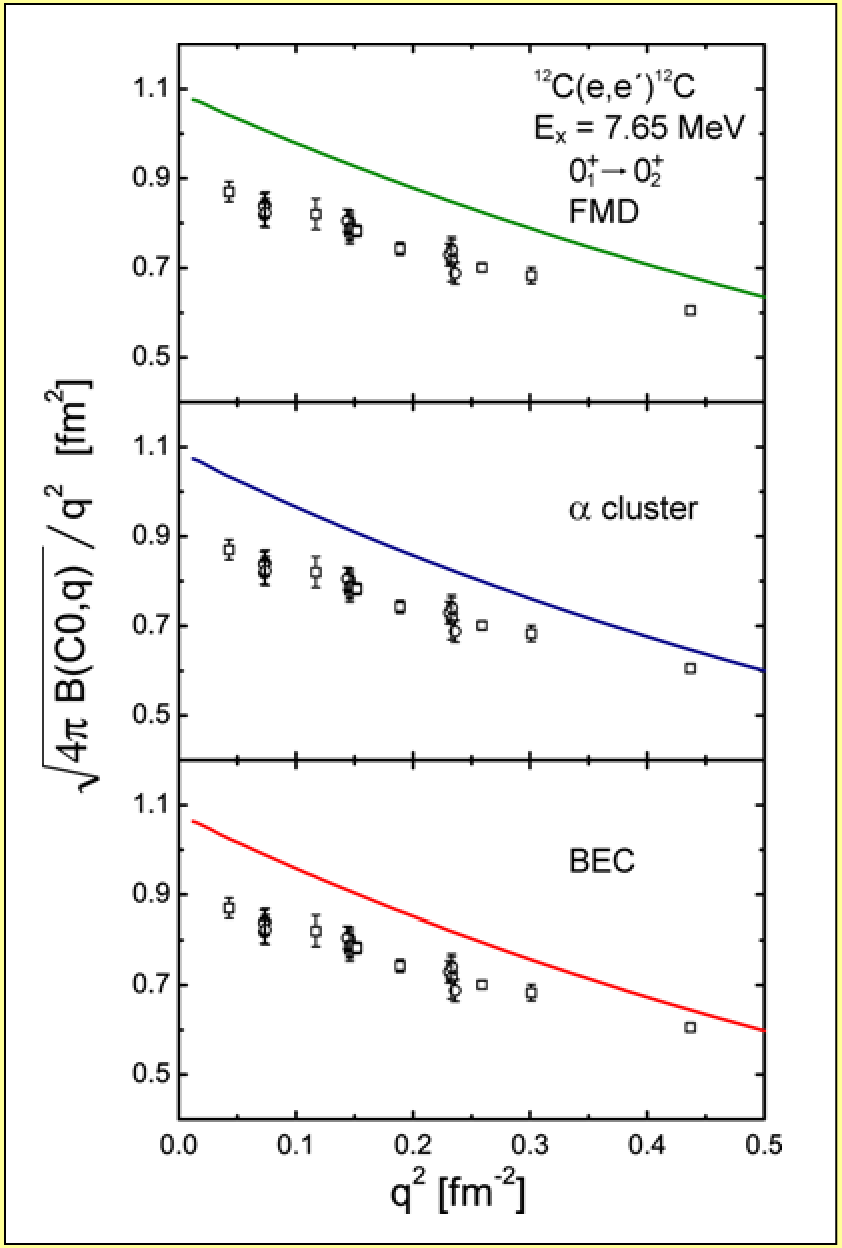
- Overlap with FMD basis states



- In the FMD and α-cluster model the leading components of the Hoyle state are cluster-like and resemble ^{8}Be + ^{4}He configurations

- But in the "BEC" model the relative positions of α clusters should be uncorrelated

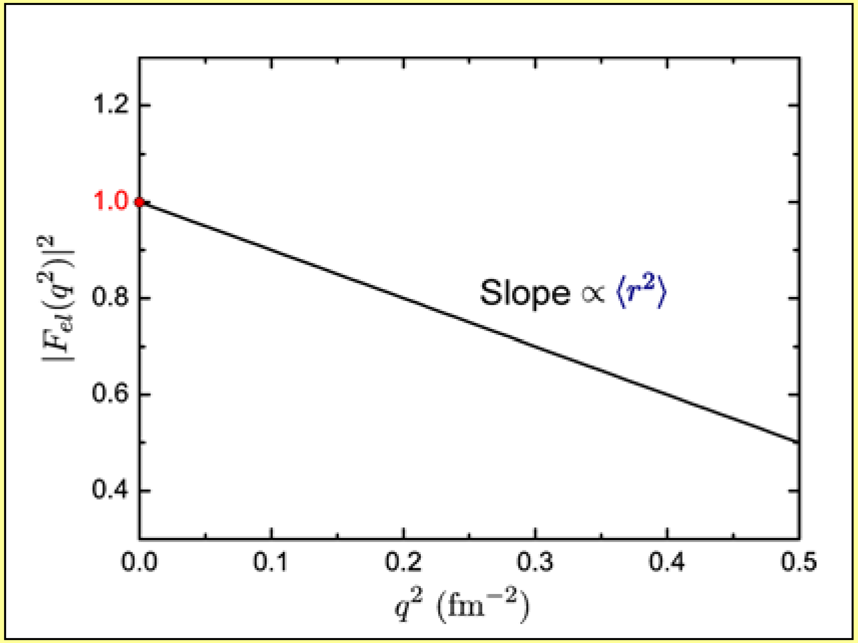
Model Predictions at Low Momentum Transfer

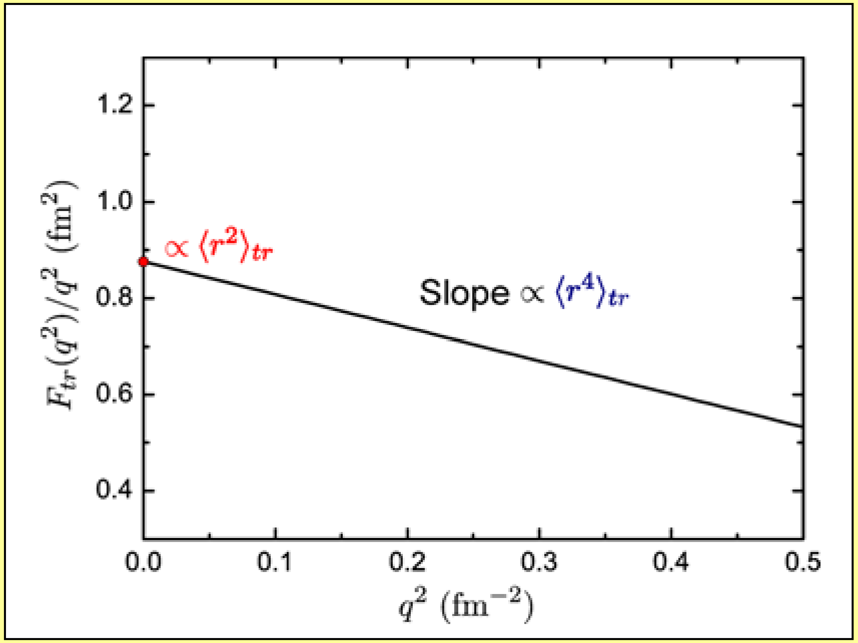


- Theory systematically overpredicts experiment

Elastic and Transition Form Factors at Low Momentum Transfer

- $|F_{el}(q^2)|^2 \approx 1 - \frac{q^2 \langle r^2 \rangle}{6} + \ldots$
- $F_{tr}(q^2) \propto \frac{q^2 \langle r^2 \rangle_{tr}}{6} - \frac{q^4 \langle r^4 \rangle_{tr}}{120} + \ldots$





- Slope is defined by $\langle r^2 \rangle$ term
- Slope is defined by $\langle r^4 \rangle_{tr}$ term
- $\Gamma_\pi \propto (ME)^2 \propto |F_{tr}(q=0)|^2$ also

Summary and Outlook

- Summary

  Hoyle state is very important in astrophysics

  Pair width Γ_π for the decay of the Hoyle state
  has been determined from (e,e´)

  Hoyle state is not a true “Bose-Einstein condensate”

  ^{8}Be + α structure

- Outlook

  ^{12}C: 0_3^+ and 2_2^+ states

  ^{16}O: 6th excited 0^+ state at 15.1 MeV is the “Hoyle” state ? → ^{16}O(e,e´α)

  Kyoto/Orsay (2008)