The 6th OMEG Institute@RIBF
April 25th, 2012

Photon Probe for Neutrino-Nucleus Interactions

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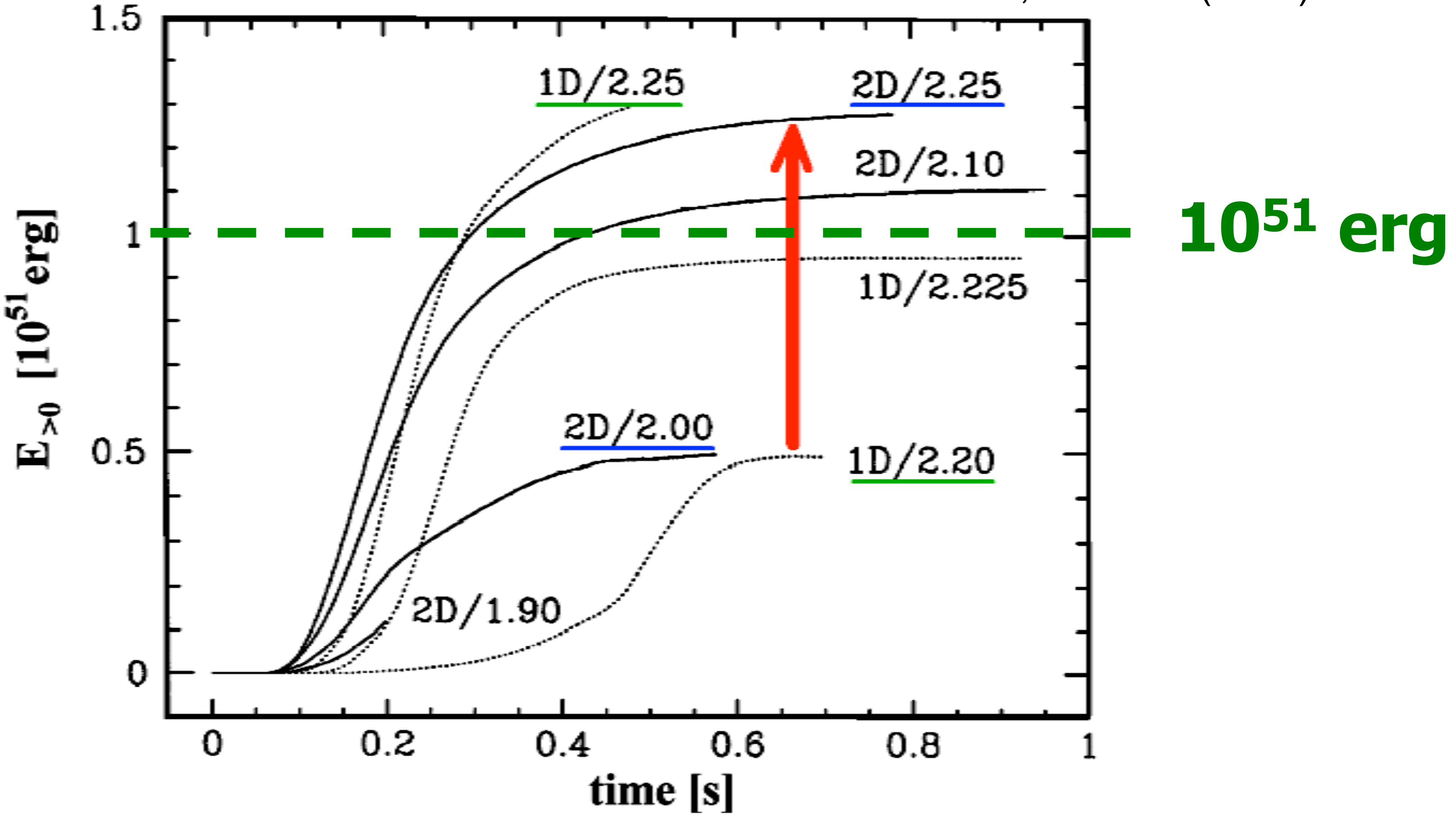
- Roles of neutrino-nucleus interactions in nucleosynthesis
- Formalism
- Photo-nuclear reaction experiment with monochromatic γ-rays

Neutrino-nucleus interactions play important roles in

- matter heating due to neutrino spallation on ^{4}He, ^{3}He, ^{3}H, D
- r-process in neutrino-driven wind;
  free neutrons supplied by neutrino spallation on light nuclei?
  post processing to original r-abundances?
- p-process; rare but unreachable by neither r- nor s-processes
  Double (p,γ)? Double (γ,n)? Double (ν,l)? Double (ν,ν'n)?
- detection of SN neutrinos ; D, ^{71}Ga, ^{100}Mo, etc.

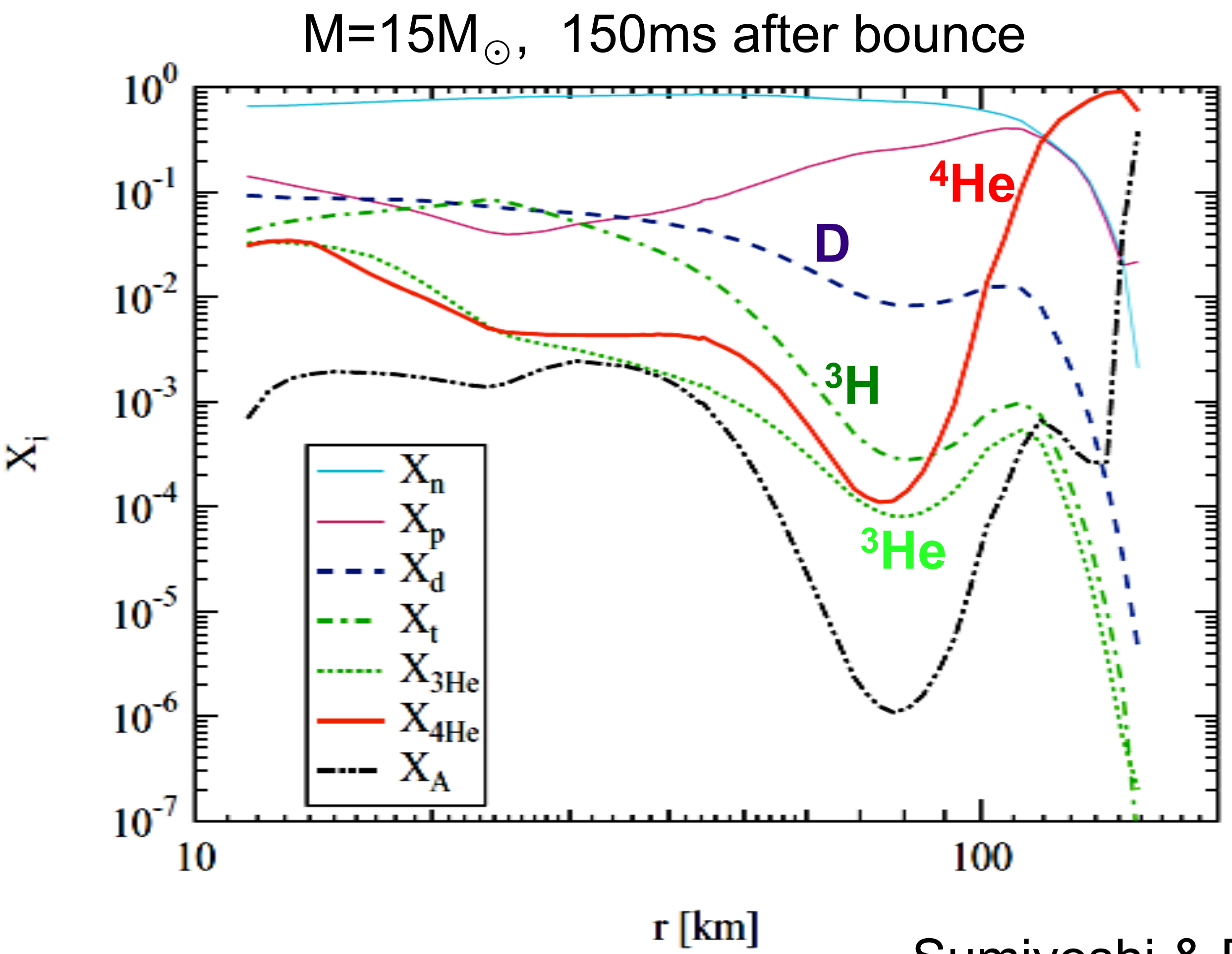
ν-heating; energy transfer via ν-A interaction

Janka & Müller, A&A 306 (1996) 167



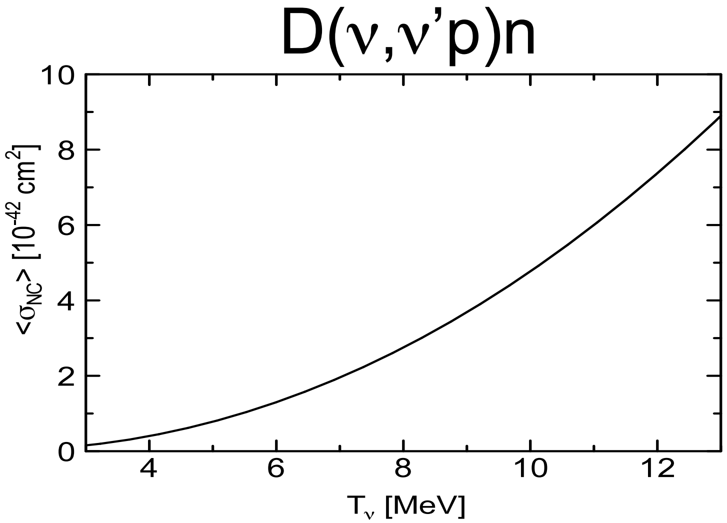
Explosion energy is satisfied with ~10% increase of neutrino luminosity, or equivalently ν-A reaction rates.

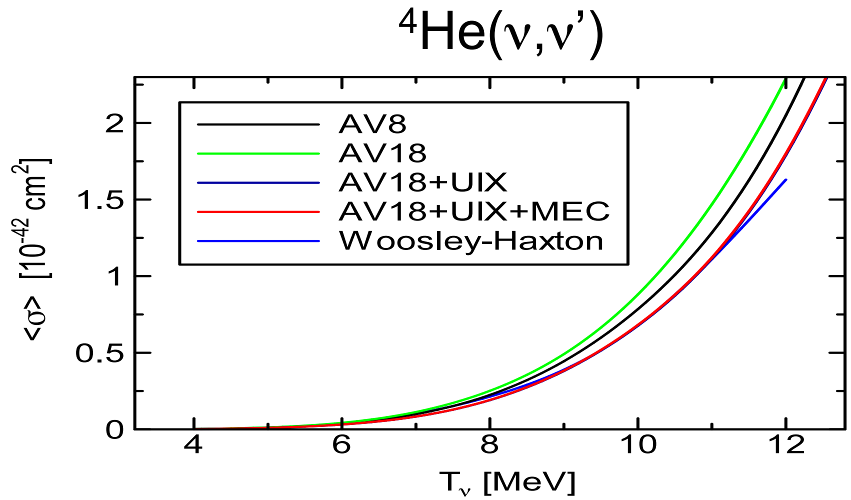
Isotopic composition of post-bounce supernova core



Sumiyoshi & Röpke (2008)

D, ^{4}He





The abundance of the deuteron is ~±2 dex of α, and its (ν,ν′) cross section is about one order of magnitude larger than that of α due to the low threshold energy.

Analogy between ν-A and γ-A interactions

Weak operators ;

$$T^{W}_{10LJ} = g^{W}_{10LJ} \cdot \tau \cdot \left[i^{L} r^{L} Y_{L} \right]_{J}$$

$$T^{W}_{11LJ} = g^{W}_{11LJ} \cdot \tau \cdot \left[i^{L} r^{L} Y_{L} \times \sigma \right]_{J}$$

$$\tau = \begin{cases} \tau_{\pm} & (\text{charged current}) \\ \tau_{3}\sqrt{2} & (\text{neutral current}) \end{cases}$$

EM operators ;

$$T^{EM}_{10LJ} = g^{EM}_{10LJ} \cdot \tau_{3}\sqrt{2} \cdot \left[i^{L} r^{L} Y_{L} \right]_{J}$$

$$T^{EM}_{11LJ} = g^{EM}_{11LJ} \cdot \tau_{3}\sqrt{2} \cdot \left[i^{L} r^{L} Y_{L} \times \sigma \right]_{J}$$

--- Photon is a useful probe for weak nuclear responses.

Hamiltonian

$$H_W = \begin{cases} \dfrac{G_F \cos\theta_C}{\sqrt{2}} \int dx \left[J_\lambda^{CC}(x) L^\lambda(x) + H.c. \right] & \text{(Charged Current)} \\ \\ \dfrac{G_F}{\sqrt{2}} \int dx \left[J_\lambda^{NC}(x) L^\lambda(x) + H.c. \right] & \text{(Neutral Current)} \end{cases}$$

$$J_\lambda^{CC}(x) = V_\lambda^{\pm}(x) + A_\lambda^{\pm}(x)$$

$$J_\lambda^{NC}(x) = \left(1 - 2\sin^2\theta_W\right) V_\lambda^3(x) + A_\lambda^3(x) - 2\sin^2\theta_W V_\lambda^S$$

Hadronic currents (Impulse Approximation)

- for C.C.

$$\langle N(p')|V_\lambda^\pm(0)|N(p)\rangle = \bar{u}(p')\left[f_V\gamma_\lambda + i\frac{f_M}{2M_N}\sigma_{\lambda\rho}q^\rho\right]\tau^\pm u(p)$$

$$\langle N(p')|A_\lambda^\pm(0)|N(p)\rangle = \bar{u}(p')\left[f_A\gamma_\lambda\gamma^5 + f_P\gamma_5 q_\lambda\right]\tau^\pm u(p)$$

- for N.C. replace $\tau^\pm$ with $\tau^3/2$

- for isoscaler current

$$\langle N(p')|V_\lambda^S(0)|N(p)\rangle = \bar{u}(p')\left[f_V\gamma_\lambda + i\frac{f_M^S}{2M_N}\sigma_{\lambda\rho}q^\rho\right]\frac{1}{2}u(p)$$

Induced interactions on meson cloud

Hadronic currents (Exchange currents)

(1) Axial vector currents

- for C.C.

$$\overline{A_\Delta^{\pm}}(x) = 4\pi\ f_A \delta(x - r_i) \int \frac{dq' e^{-iq'\cdot r}}{(2\pi)^3} \left[\frac{K_\pi^2(q'^2)}{\omega_\pi^2} \left\{ c_0 q' \tau_2^{\pm} + d_1 (\sigma_1 \times q') [\tau_1 \times \tau_2]^{\pm} \right\} (\sigma_2 \cdot q') \right.$$

$$\left. + \frac{K_\rho^2(q'^2)}{\omega_\rho^2} \left\{ c_\rho q' \times (\sigma_2 \times q') \tau_2^{\pm} + d_\rho \sigma_1 \times [q' \times (\sigma_2 \times q')] [\tau_1 \times \tau_2]^{\pm} \right\} \right] + (1 \leftrightarrow 2)$$

- for N.C. replace $\tau_i^{\pm}$ and $[\tau_1 \times \tau_2]^{\pm}$ with $\tau_i^3/2$ and $[\tau_1 \times \tau_2]^3/2$

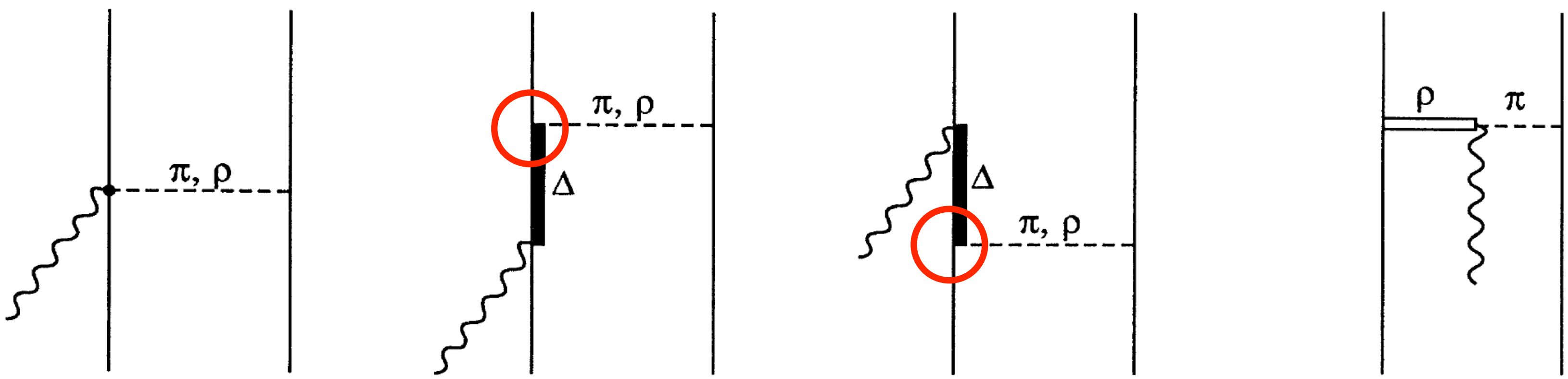
(2) Vector currents

$$V_\Delta^{\pm,3}(x) = -\frac{f_V + f_M}{2 M_N\ f_A} \cdot \nabla \times \overline{A_\Delta^{\pm,3}}$$

!

Axial exchange-current mechanisms

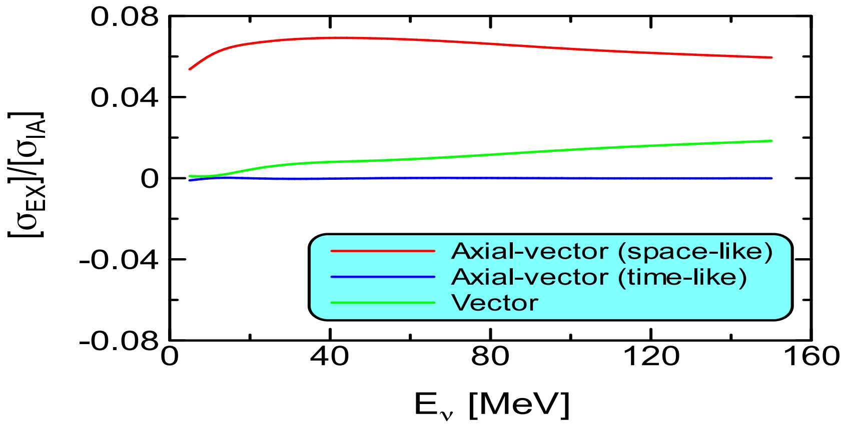
In addition to one-body currents, meson-exchange currents (MEX) give contributions of up to ~10% to the total cross section.



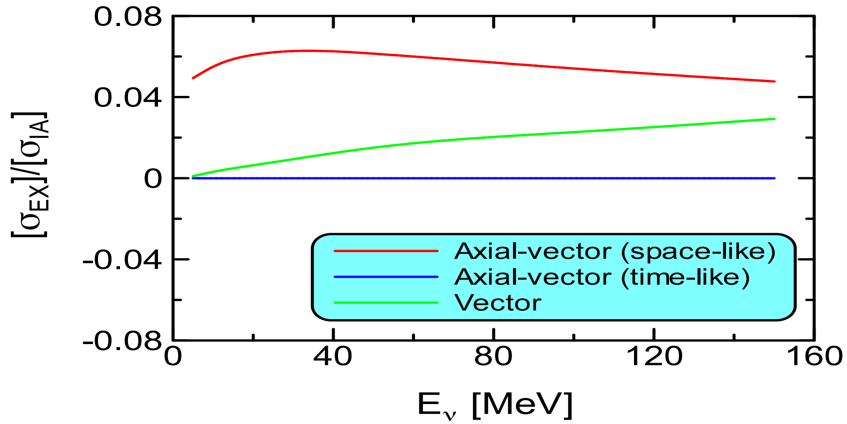
Among all processes of MEX, largest correction to one-body is from the diagrams including **πNΔ** coupling, which can be calibrated by referring to **D(γ,n)p** data.

Contribution of meson-exchange currents

$d(\nu,\nu')pn$



$d(\nu,e^-)pp$

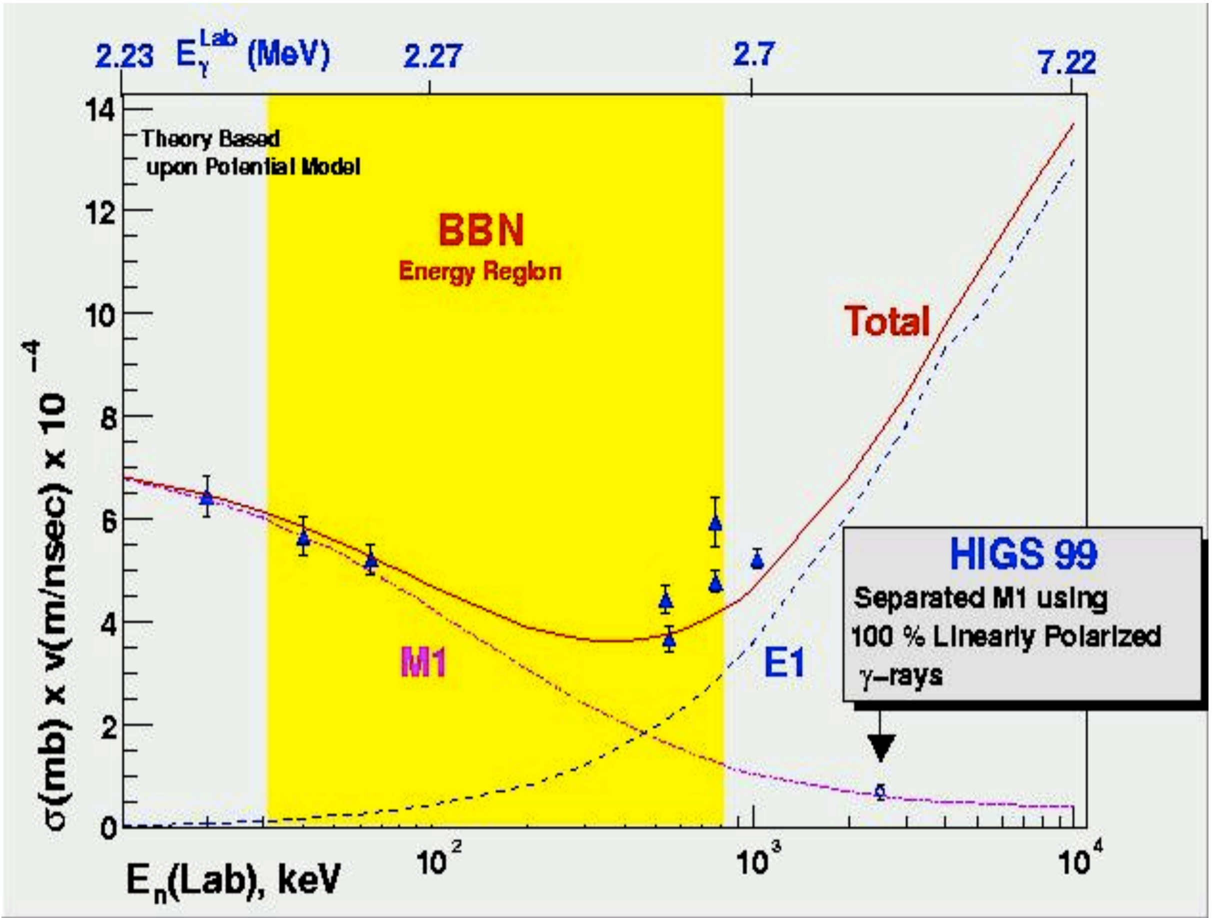


S.Nakamura, T.Sato, V.Gudkov, K.Kubodera, PRC63, 034617 (2001)

Theoretical models can be tested via comparison with experimental data of analogous **$D(\gamma,n)p$**.

M1/E1 ratio in D(γ,p)n

Calculation	%M1 Contribution	Asy(150⁰)
Chen	7.85%	0.81
Arenhövel	7.31%	0.81
Experiment	9.26 ± 2.6%	0.786 ±0.052



Calculation needs information on

- weak form factors (f_V, f_A, f_M, f_P)

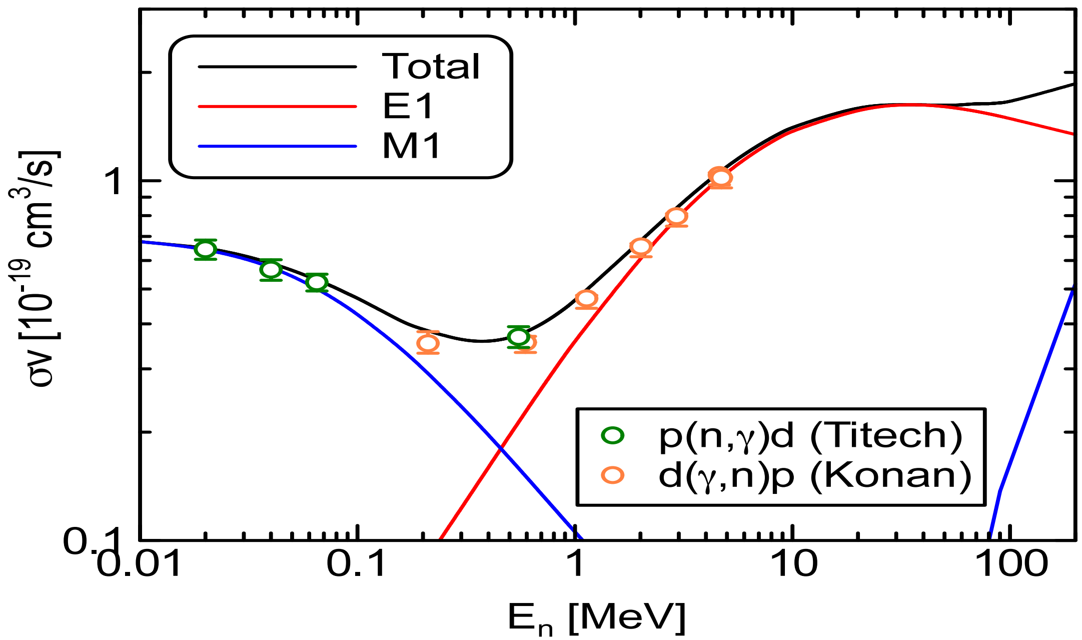
  ⇐ nuclear β-decay, μ-capture

- wave functions

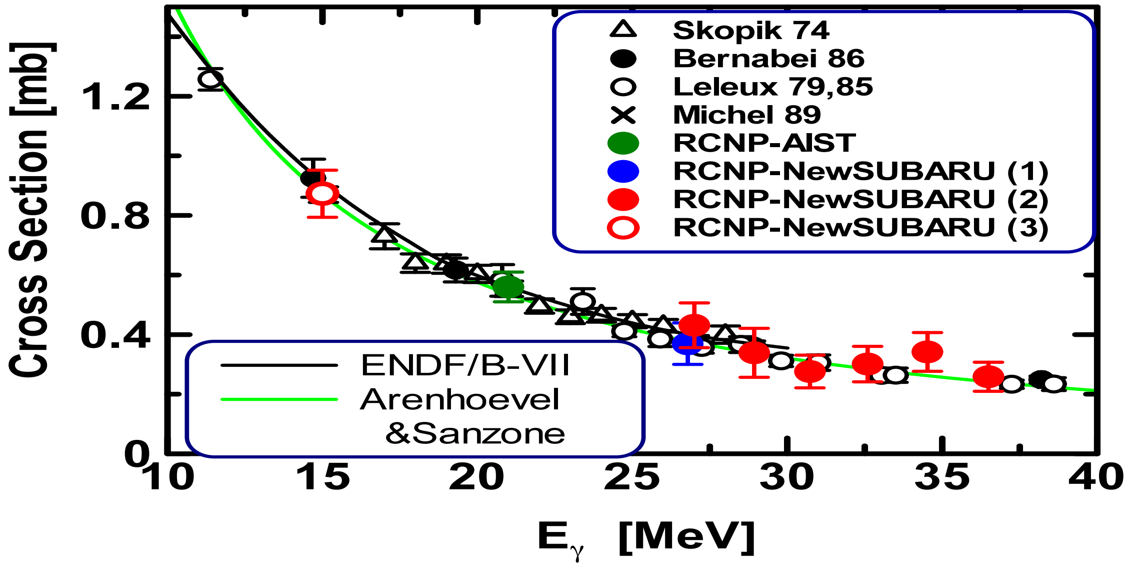
  nuclear potential
  model (shell model, cluster, RPA, TDHF,...)
  approximations (one-meson exchange,
  long-wave approx., Siegert theorem, ...)

  ⇐ EM probes **---** **Photonuclear reactions**

p(n,γ)d; Theory v.s. Experiment

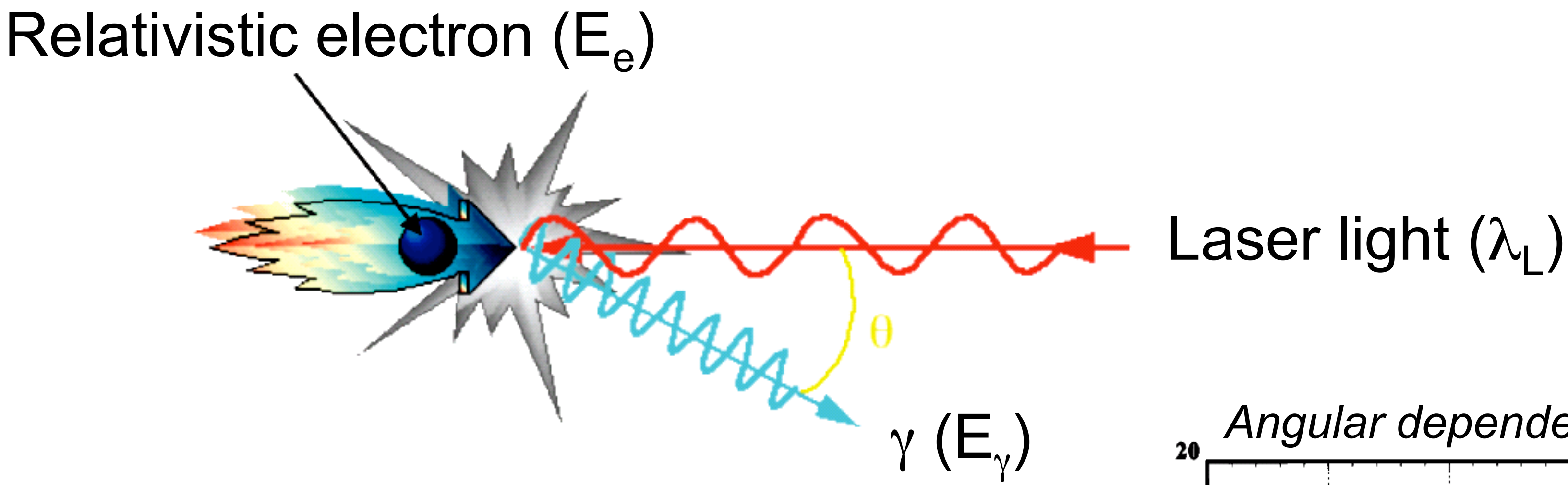


D(γ,p)n data



--- Good agreement with existing data
as well as theoretical calculations and fittings !

Laser Compton backscattering

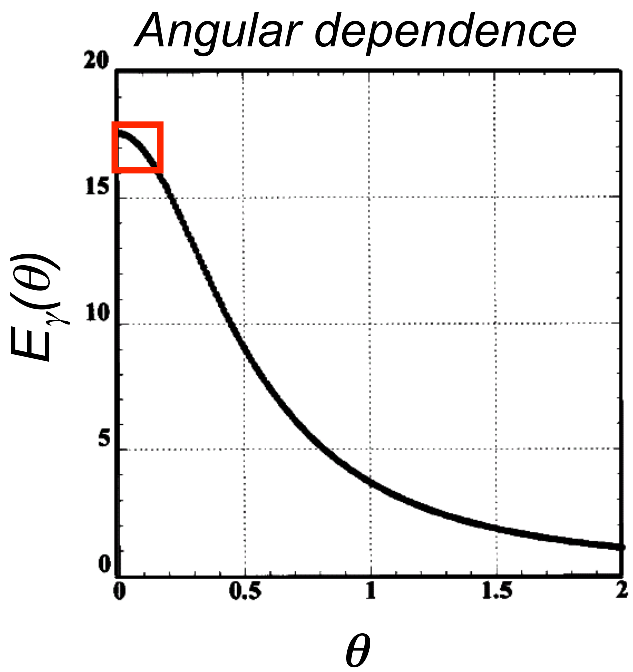


Klein-Nishina formula

$$E_\gamma = \frac{4hc}{\lambda_L} \cdot \frac{\gamma^2}{1+\gamma^2\theta^2}\ , \qquad \gamma = \frac{E_e}{m_e c^2}$$

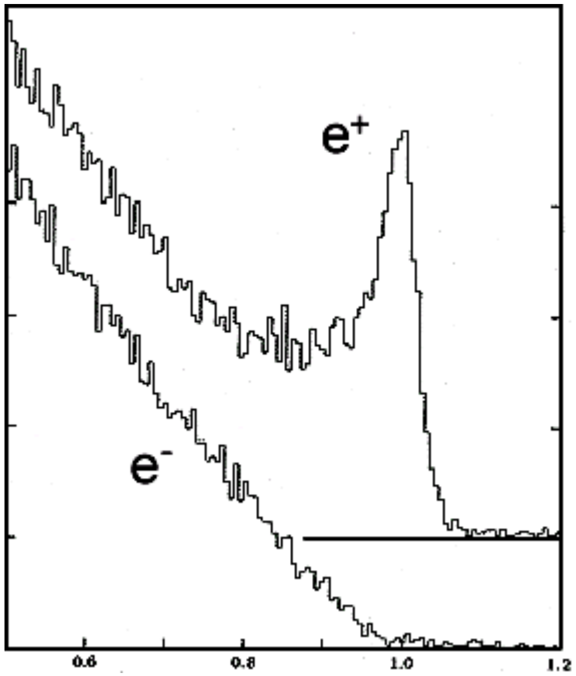
ex. λ_L=1.064μm, E_e=800MeV

⇒ E_γ = 11MeV

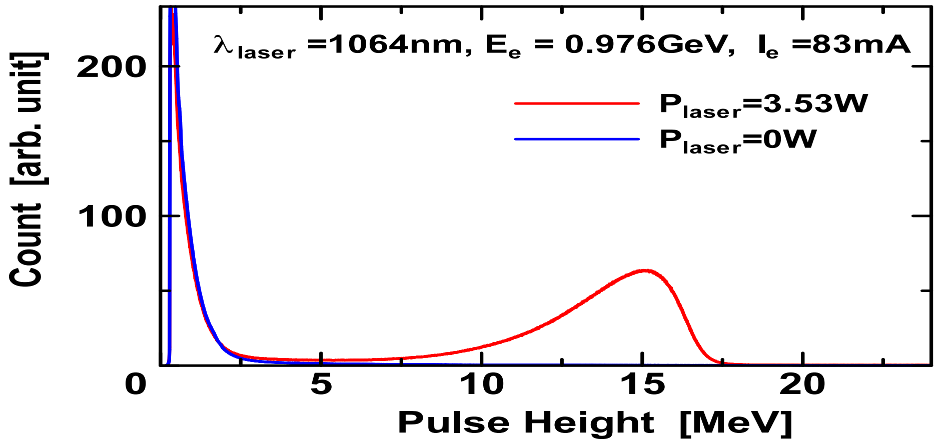


Energy distributions of γ-rays

Bremsstrahlung,
e^+e^- annihilation in flight



Laser Compton-Scattered γ
(PH spectra of GSO scintillator)



BG from low-energy component of brems.

(almost) no BG !!

Advantages of LCS-γ

- Quasi-monochromatic; $\Delta E/E \sim$ a few %
- Little background γ-rays; tagging not necessary
- Well-collimated; $\Delta\theta < 0.1$ mrad
- Highly polarized; linear or circular, P ~ 100%

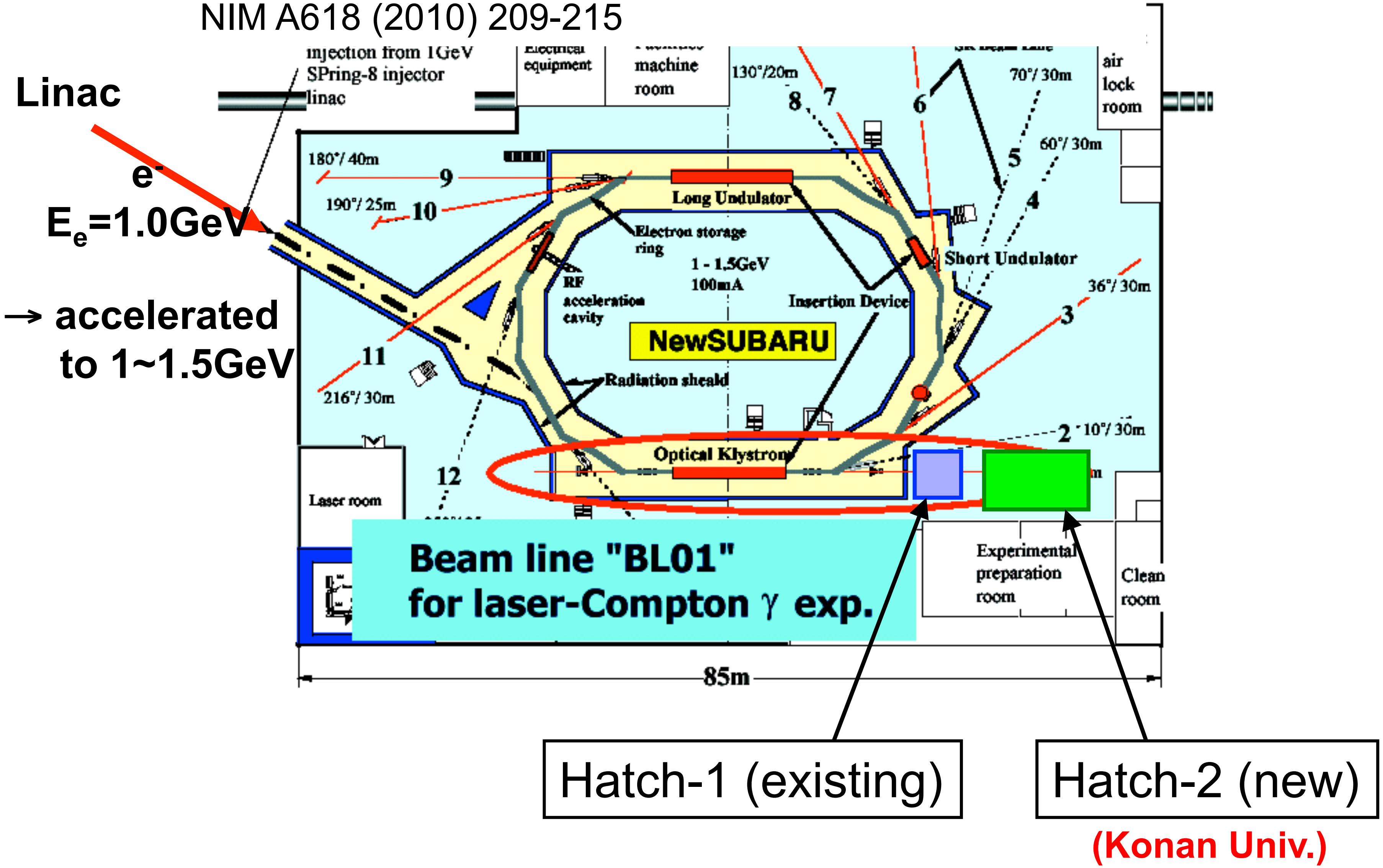
  → useful to separate E1 and M1
- Continuous or pulsed; $\Delta t < 10$ns
- Considerable intensity; $\Phi_\gamma = 10^4 \sim 10^8$ γ/s/MeV

NewSUBARU

Lab. of Adv. Sci. and Tech. for Industry,
University of Hyogo, Japan

NewSUBARU/LCS-γ source

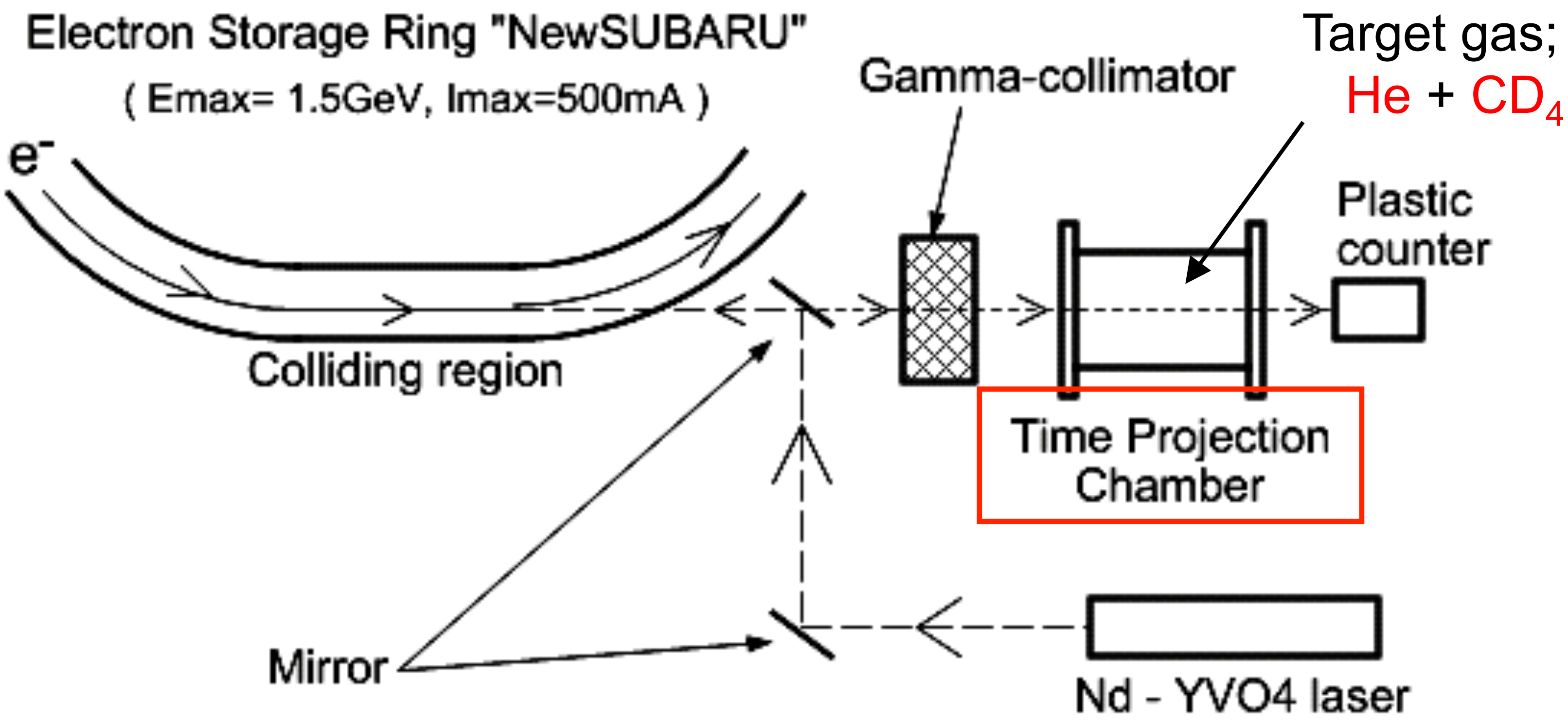
K. Horikawa, S. Miyamoto, S. Amano, T. Mochizuki,
NIM A618 (2010) 209-215



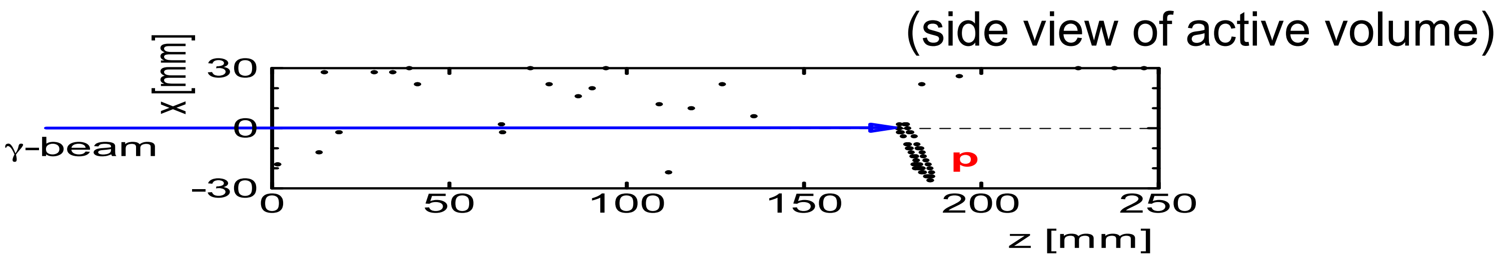
Experiment with quasi-monochromatic γ at NewSUBARU

Laser Compton-scattered γ-ray :

E_γ = 1.6 ~ 40MeV, Φ_γ ~4×10^4 /sec, FWHM=4~5%, P~100%



Candidate of D(γ,n)p event



Event ID:

- Single track
- Vertex on beam axis
- Pulse height corresponding to proton dE/dx

^{7}Li, ^{11}B production by ν-spallations

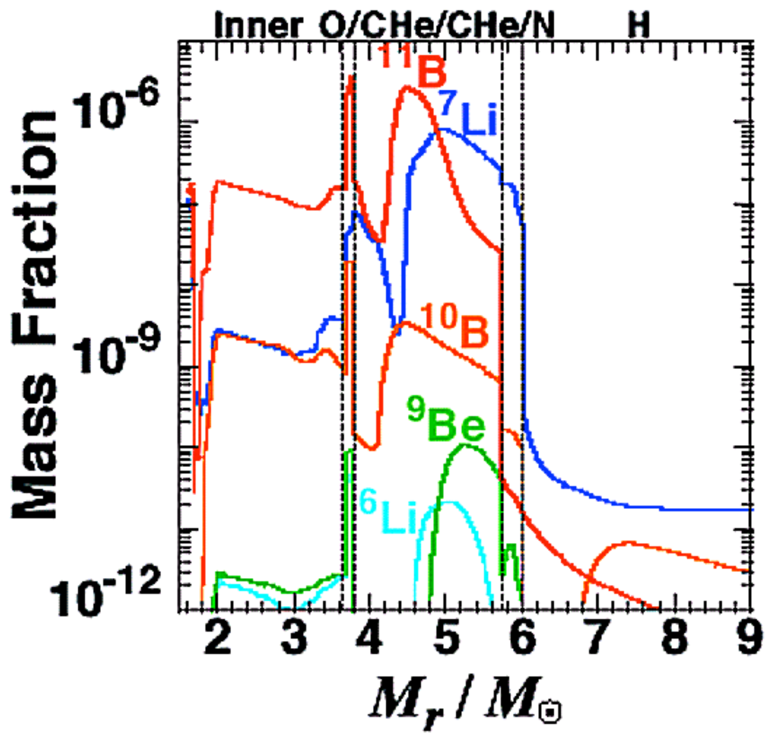
Woosley et al., Woosley & Weaver, Rauscher et al., Yoshida et al.

$^4He(\nu,\nu'p)^3H(\alpha,\gamma)^7\mathbf{Li}(\alpha,\gamma)^{11}\mathbf{B}$

$^4He(\nu,\nu'n)^3He(\alpha,\gamma)^7Be(e^-,\nu_e)^7\mathbf{Li}$

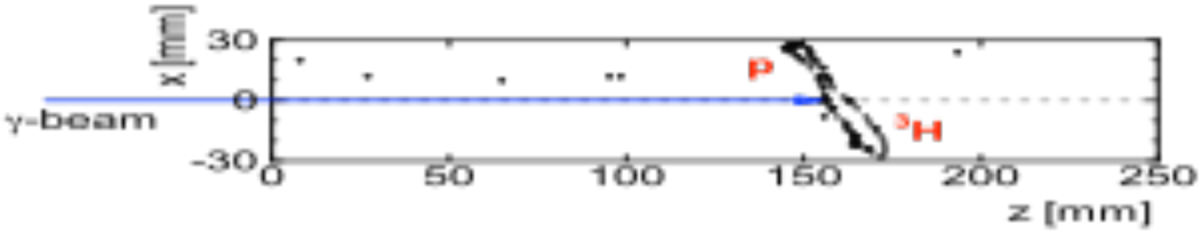
$^{12}C(\nu,\nu'p)^{11}\mathbf{B}$

$^{12}C(\nu,\nu'n)^{11}C(e^-,\nu_e)^{11}\mathbf{B}$

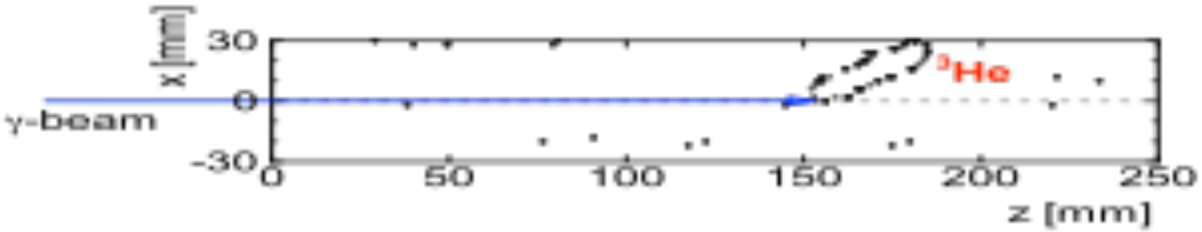


Yoshida, Kajino et al.,
PRL96, 091101 (2006)

$^4He(\gamma,p)^3H$, $^4He(\gamma,n)^3He$



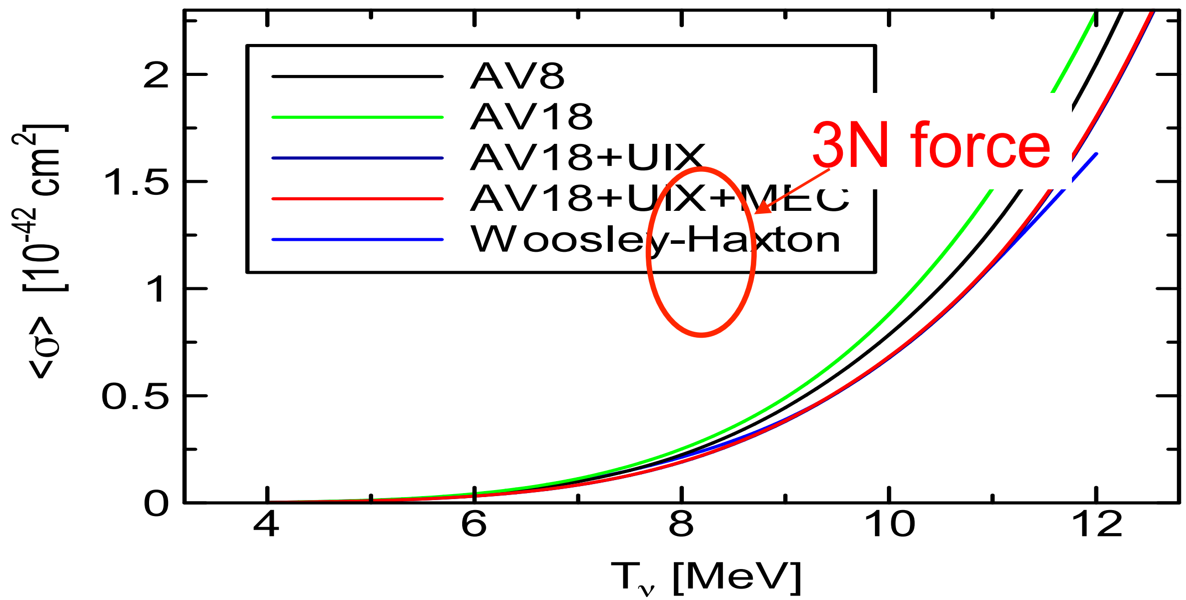
$^4He(\gamma,p)^3H$



$^4He(\gamma,n)^3He$

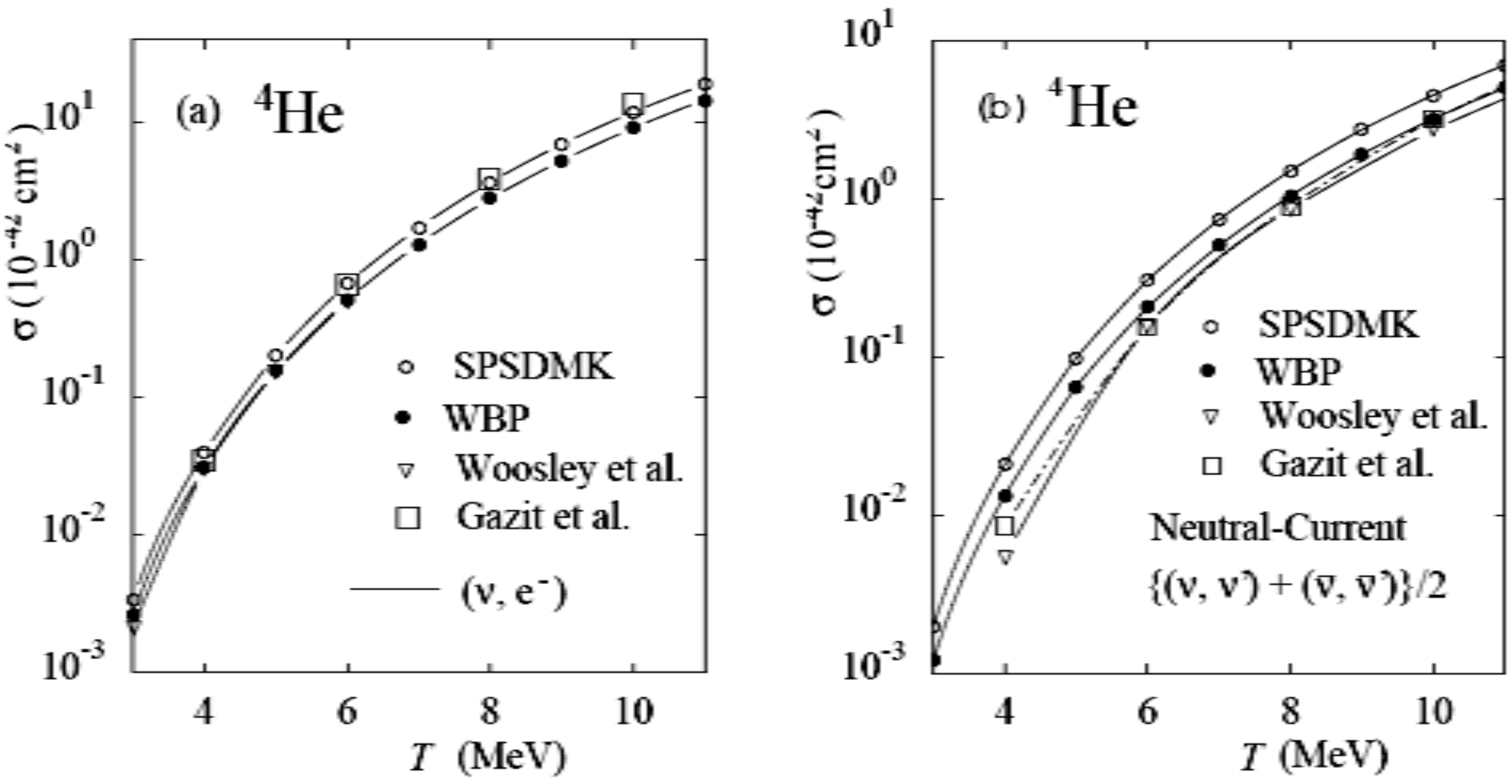
ν+^{4}He; “ab initio” calculation

Gazit & Barnea (2007), Lorentz-Integral Transform method



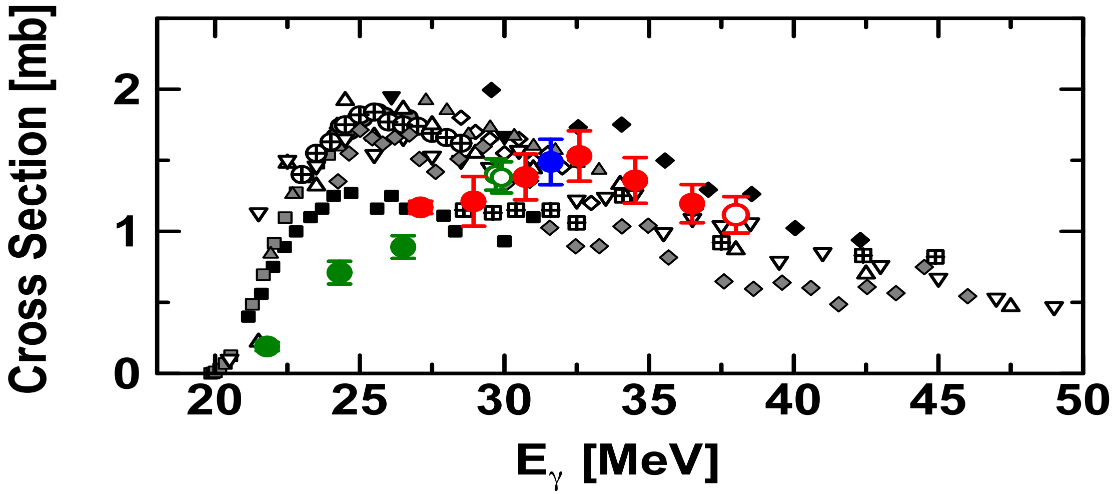
ν+^{4}He; shell-model calculation

T. Suzuki et al., PR C74 034307 (2006)



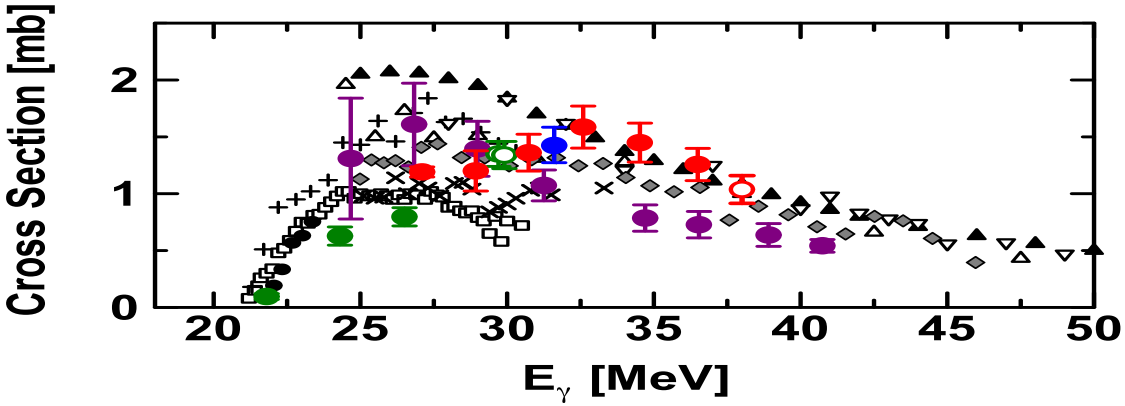
(ν,e$^-$) (ν,ν')

$^{4}He(\gamma,p)^{3}H$



- ●○ RCNP-AIST2005 (PRC72, 044004) ; λ=351nm (3rd), E_e=0.8GeV
- ● RCNP-NewSUBARU; λ=532nm (2nd), E_e=0.97GeV
- ● RCNP-NewSUBARU; λ=1064nm (fund.), E_e≤1.46GeV
- ○ RCNP-NewSUBARU; λ=532nm (2nd), E_e=1.06GeV

$^{4}He(\gamma,n)^{3}He$



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- ○ RCNP-NewSUBARU; λ=532nm (2nd), E_e=1.06GeV
- ● Lund 2005-2007 (PRC75, 014007) ; tagged photons

^{7}Li, ^{11}B production by ν-spallations

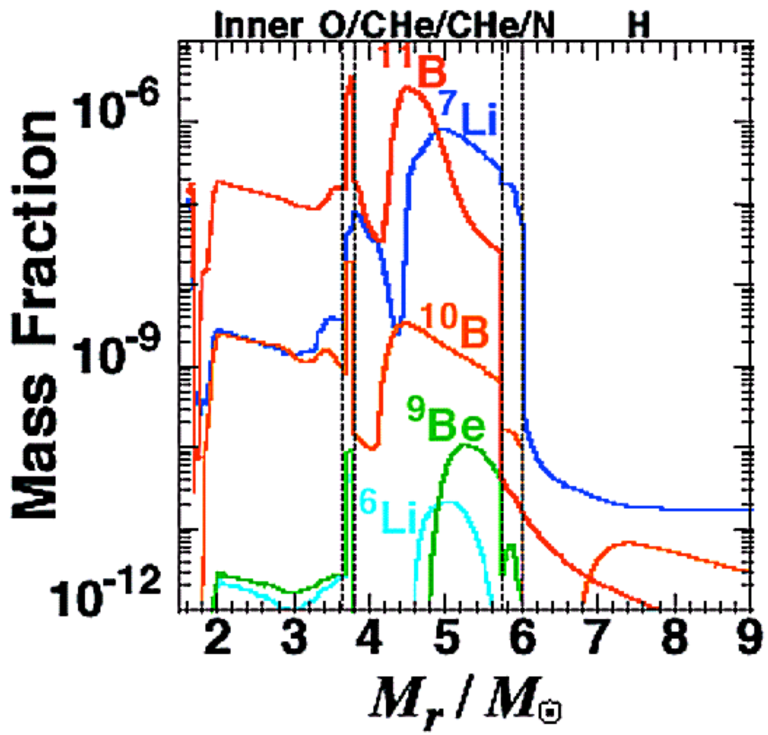
Woosley et al., Woosley & Weaver, Rauscher et al., Yoshida et al.

$^{4}He(\nu,\nu'p)^{3}H(\alpha,\gamma)^{7}\mathbf{Li}(\alpha,\gamma)^{11}\mathbf{B}$

$^{4}He(\nu,\nu'n)^{3}He(\alpha,\gamma)^{7}Be(e^{-},\nu_{e})^{7}\mathbf{Li}$

$^{12}C(\nu,\nu'p)^{11}\mathbf{B}$

$^{12}C(\nu,\nu'n)^{11}C(e^{-},\nu_{e})^{11}\mathbf{B}$

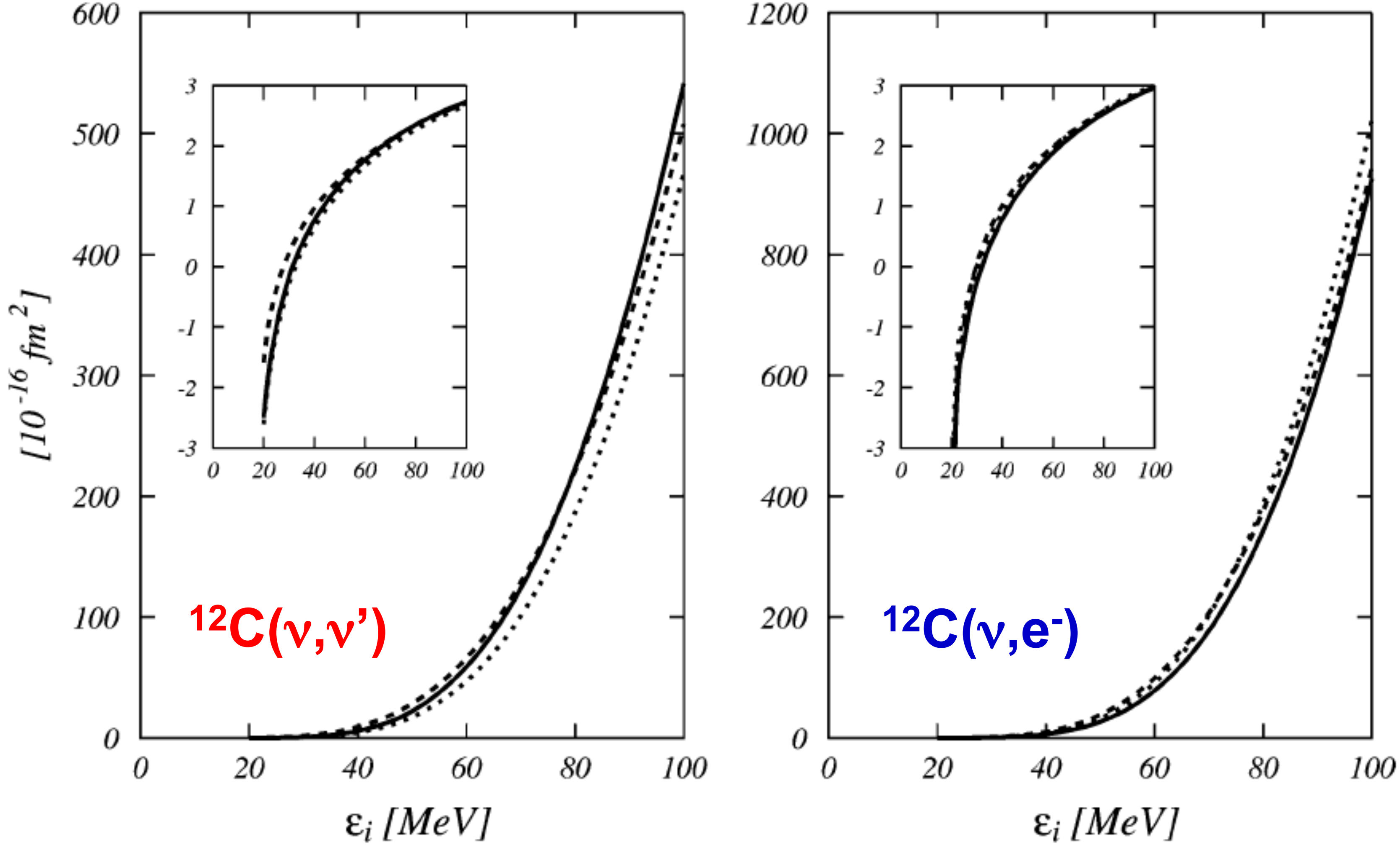


Yoshida, Kajino et al., PRL96, 091101 (2006)

Continuum RPA

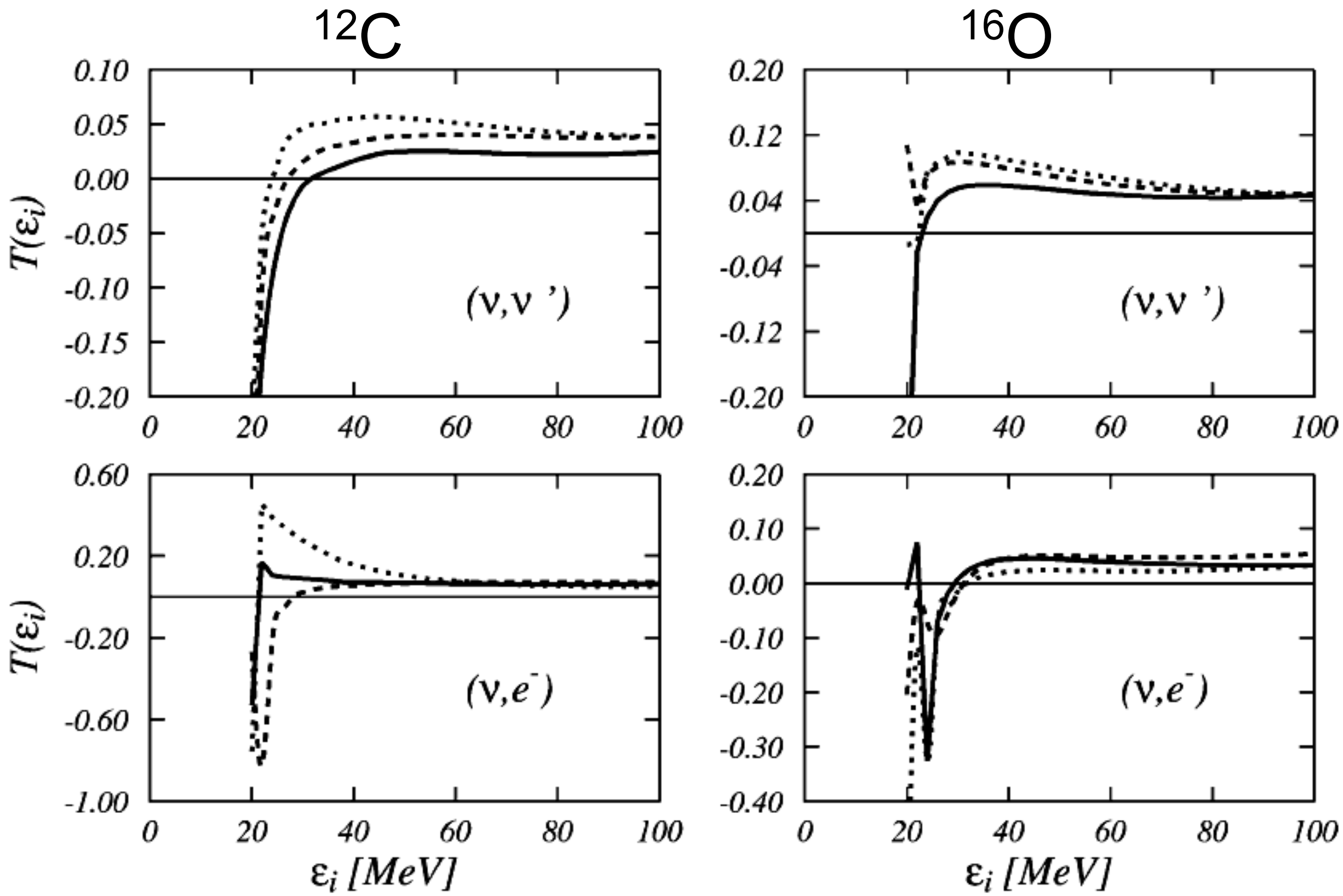
A. Botrugno and G. Co',
Nucl. Phys. A761 (2005) 200

Nuclear potential
- LM1: muonic-^{208}Pb (solid line)
- LM2: ^{12}C spin response (dashed line)
- PP : polarization potential (dotted line)



CRPA with Final State Interaction

Relative magnitude of FSI effect: $$T(\varepsilon_i) = \frac{\sigma^{CRPA}(\varepsilon_i) - \sigma^{CRPA+FSI}(\varepsilon_i)}{\sigma^{CRPA}(\varepsilon_i) + \sigma^{CRPA+FSI}(\varepsilon_i)}$$



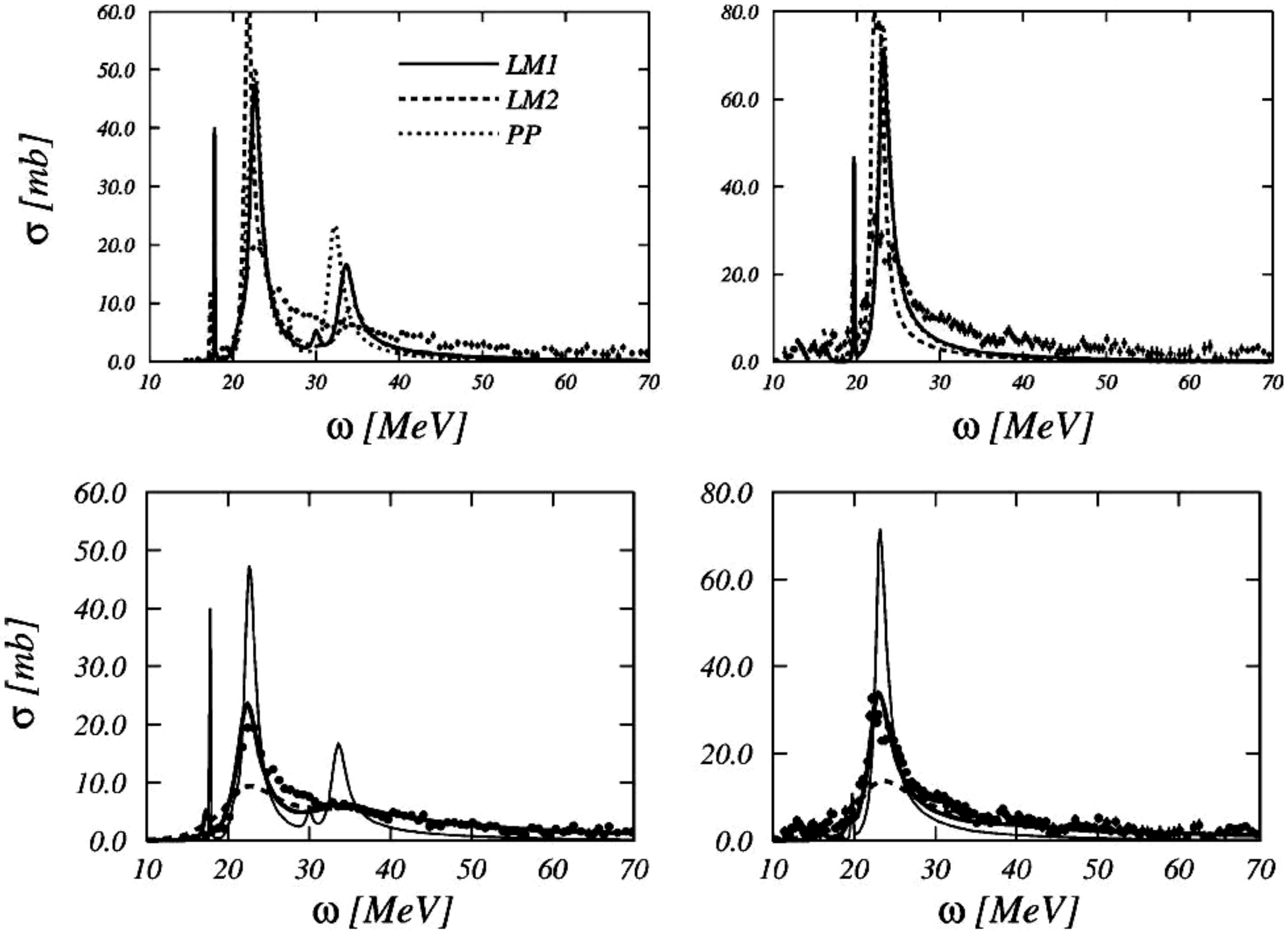
Photoabsorption

Nuclear potential
- LM1: muonic-^{208}Pb
- LM2: ^{12}C spin response
- PP : polarization potential

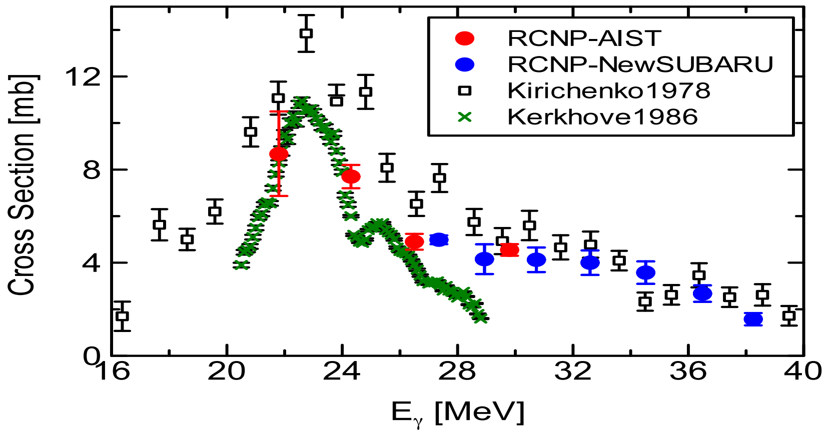
^{12}C(γ,abs) ^{16}O(γ,abs)

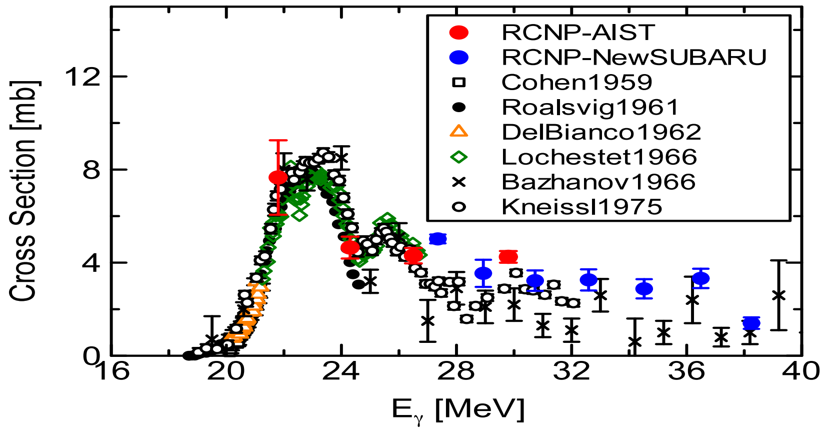
CRPA

CRPA+FSI



$^{12}C(\gamma,p)^{11}B$, $^{12}C(\gamma,n)^{11}C$

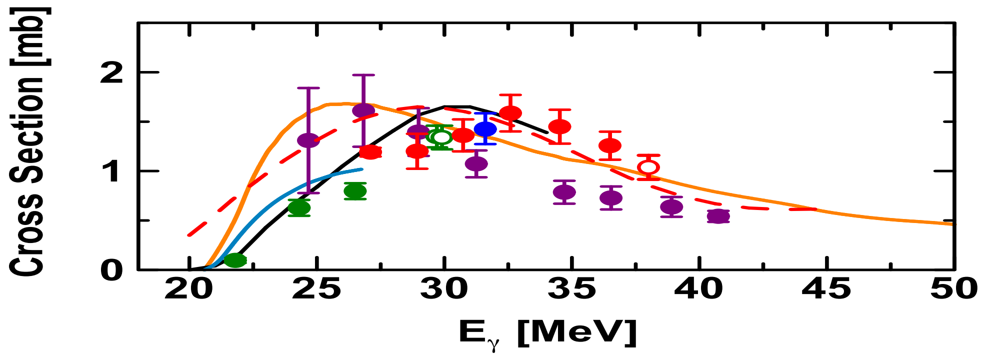




Summary

- Since H_{EM} and H_W^{NC} have analogous forms, photon can be, in principle, used as a probe for ν-A interactions.
- But the photonuclear reaction cross sections are not direct analog of those for ν-A interactions.
- But they can be connected to each other through common theoretical models.
- Data of total cross sections as well as differential cross sections from threshold up to ~80MeV are quite useful to test those models. → **LCS-γ**
- β-decay and μ-capture provide another important inputs for calculations.

Comparison with theory : $^4He(\gamma,n)^3He$



●○ RCNP-AIST

●●○ RCNP-NewSUBARU

● Lund 2005-2007

Trento (Effective Interaction Hyperspherical Harmonics)

Bonn (Faddeev-AGS)

Londergan-Shakin (Coupled Channel Shell Model)

Horiuchi, Suzuki (Cluster model)

ν-^{4}He weak interaction operators

- Allowed transitions
  - Fermi type --- no contribution to T=0 nucleus
  - Gamow-Teller type: $0^+0 \rightarrow 1^+1$

- First-forbidden transitions
  - Dipole (E1) type: $0^+0 \rightarrow 1^-1$
  - Spin-dipole (SD) type: $0^+0 \rightarrow \lambda^-1$ (λ = 0, 1, 2)

ν-^{4}He multipole strength

Gazit & Barnea 2004