The Compton Slope Parameter and Neutron Skin

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MountAllison UNIVERSITY A2 mami MAINZER MIKROTRON JG|U NSERC CRSNG

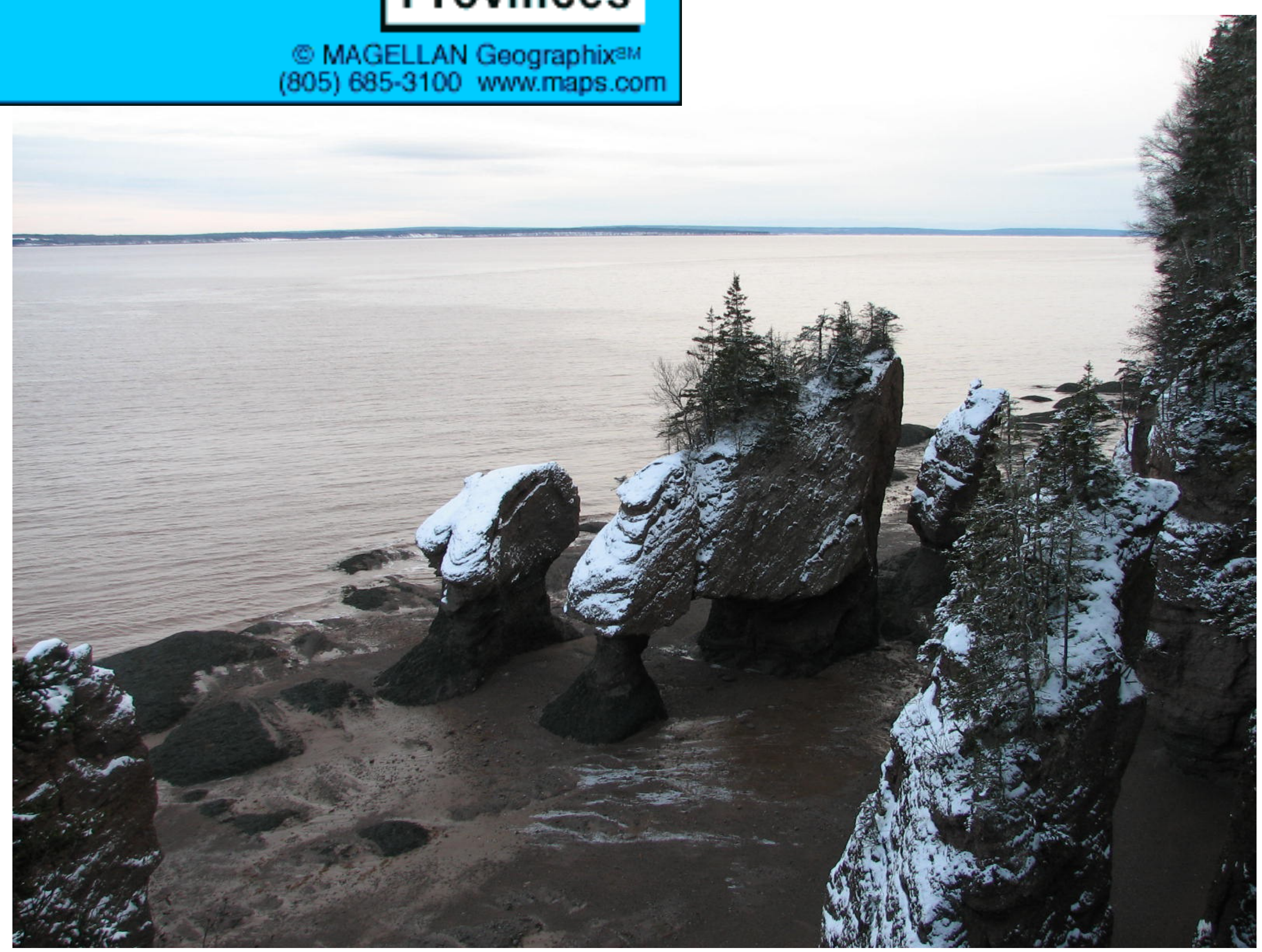
Mount Allison University

New Brunswick
CANADA

Population: 840,000
Area: 72,908 km²

English and French

Lobster, Lumber, and High Tides



Mount Allison University

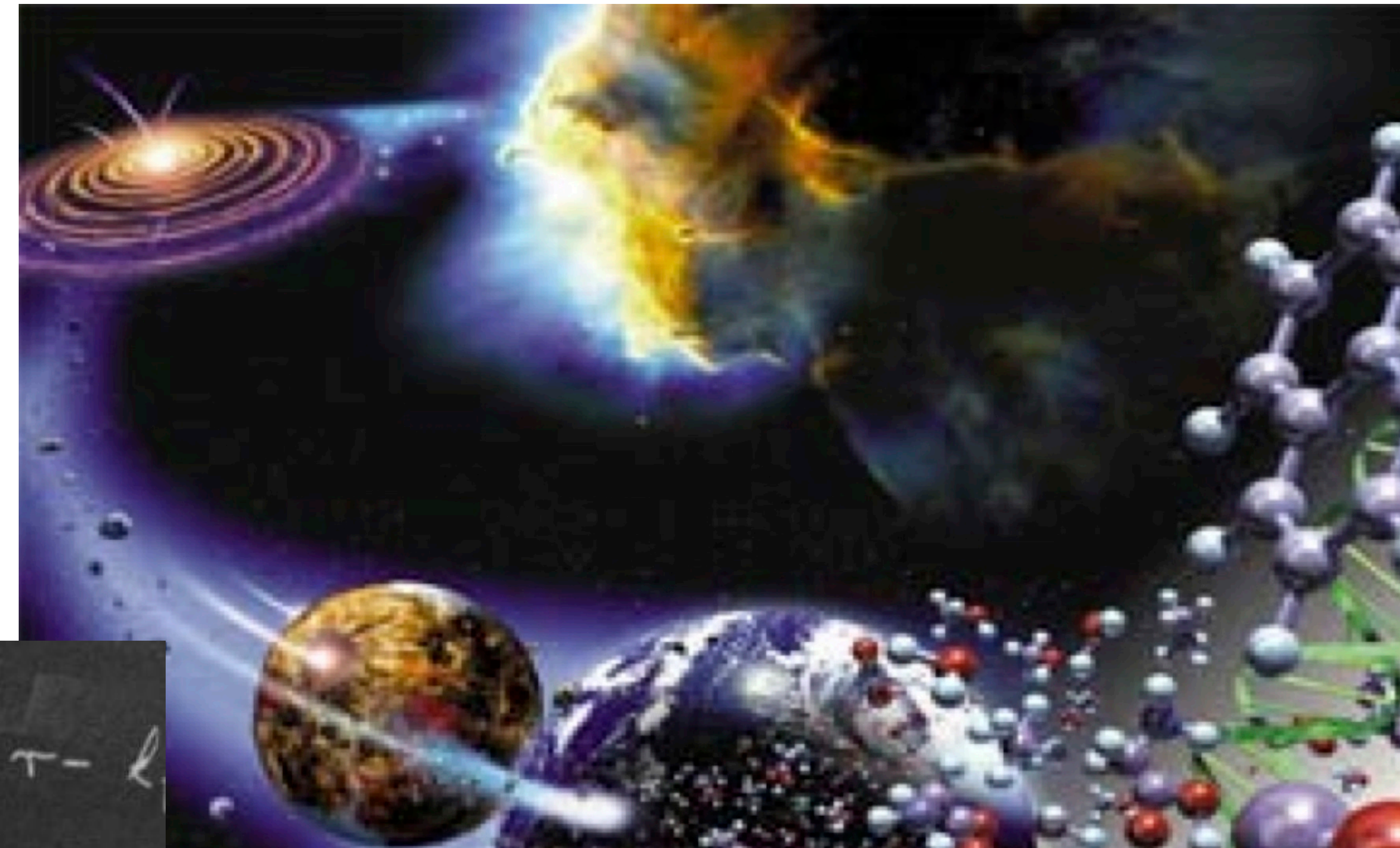
- 2,250 students
- Undergrads only

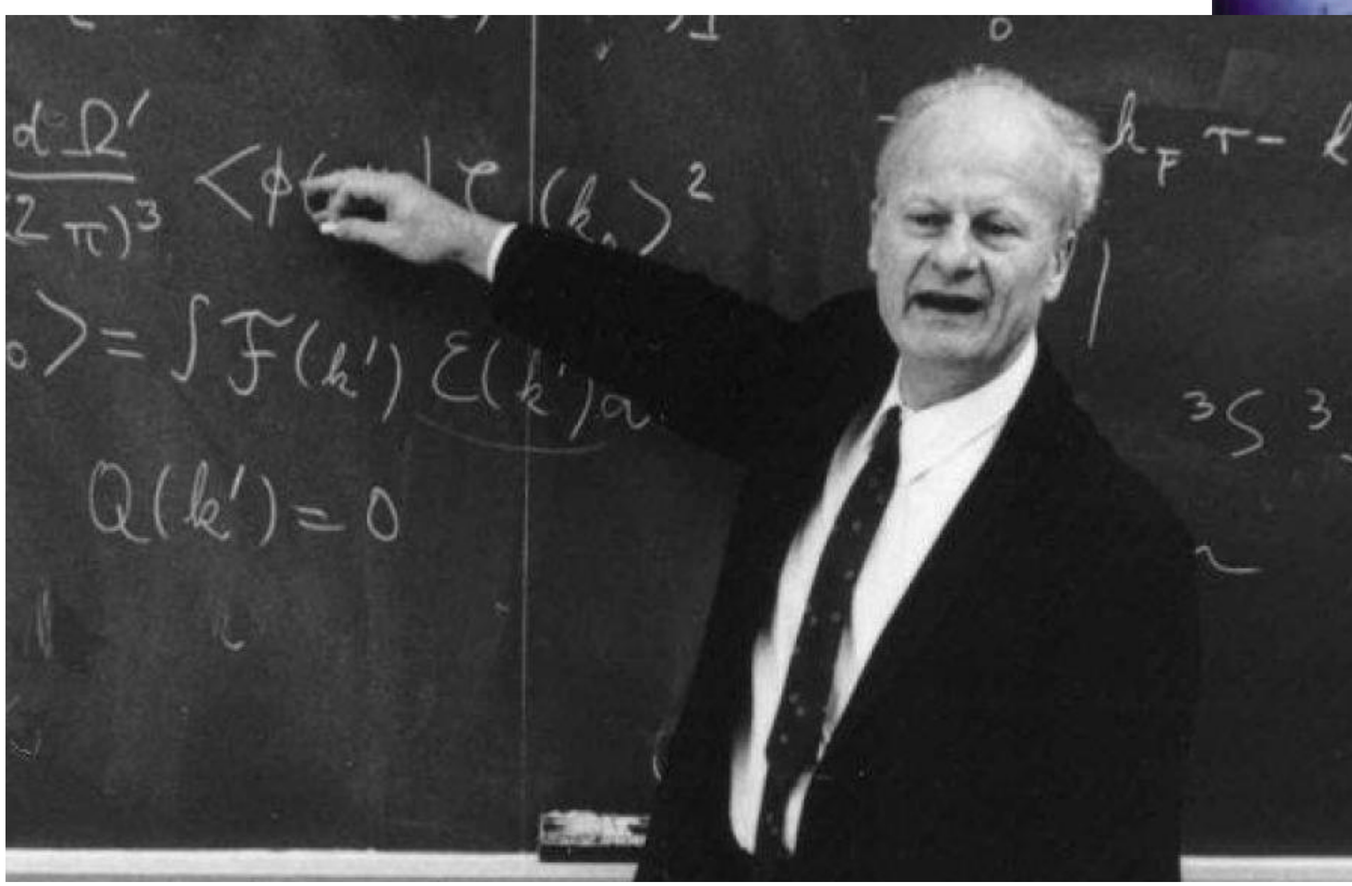
Outline

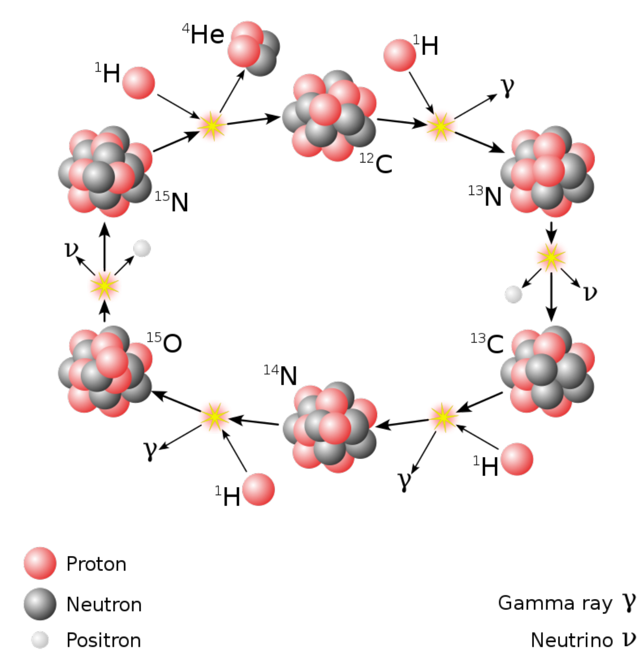
- Neutron Stars and the Nuclear Equation of State
- Nuclear Matter and Neutron Skin
- Asymmetries: PVES and BNSSA
- Compton Form Factor and Slope Parameter
- CATS Detector and A2 Hall
- Projected Results and Outlook

Disclaimer

I am NOT a nuclear astrophysicist.





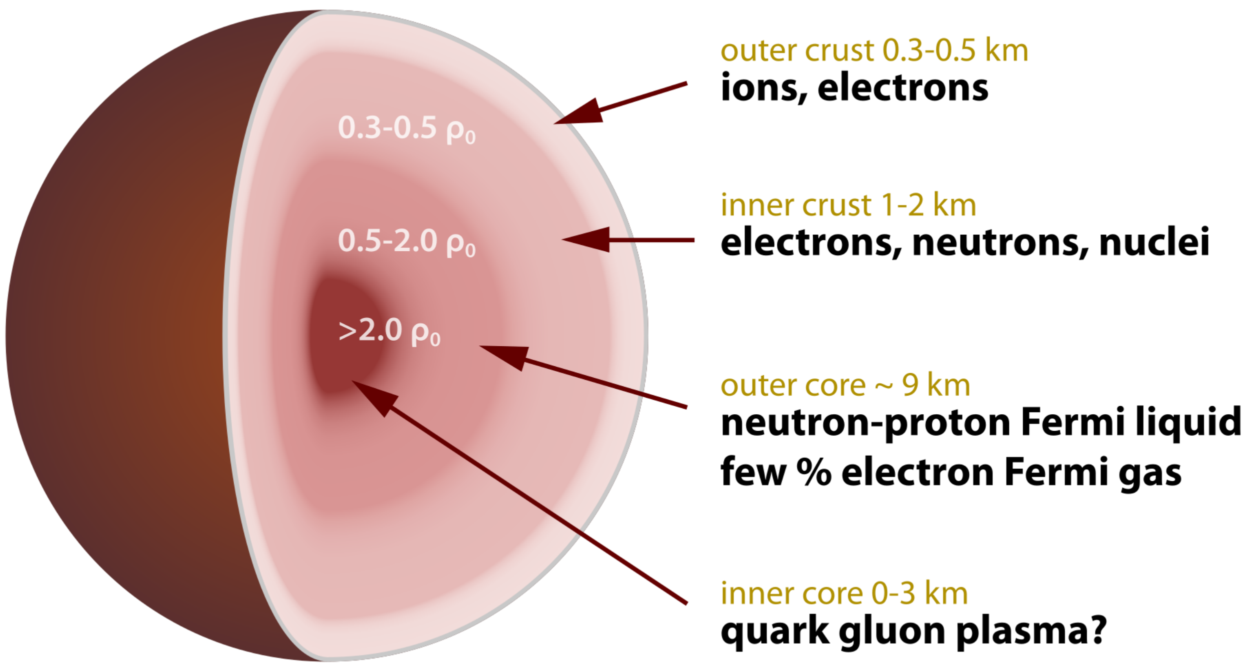


Related Presentations

- A. Obertelli
- S. Guillot
- A. Arcones
- W. Weise
- J. Lattimer

- N. Kozyrev
- A. Esser

Neutron Stars

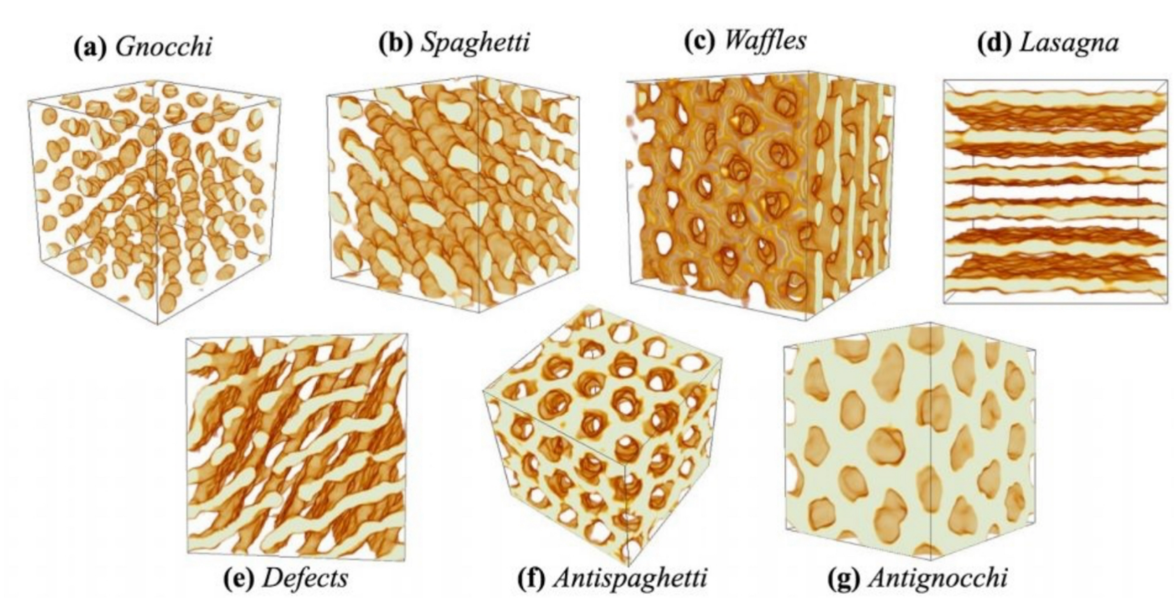


Fascinating astrophysical bodies.

Densest massive objects in the universe.

Properties determined by the nuclear Equation of State (EoS)

Crust of neutron stars may even contain the hardest substance in the universe, the so called **Nuclear Pasta...**



Physics is governed by a combination of **General Relativity** and **Nuclear Physics**.

Still much to learn!

Nuclear Equation of State

$E(\rho, \delta) = E(\rho,0) + S(\rho)\delta^2$ determines the basic properties of neutron stars

- mass
- radius
- cooling behaviour

$\rho = \rho_n + \rho_p$ total density of n and p

$$\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$ Relative asymmetry parameter

$S(\rho)$ Symmetry energy → energy cost of n-p asymmetry

Neutron skin $R_{\text{skin}} = R_n - R_p$ is strongly correlated with slope of $S(\rho)$ via

$$L = 3\rho_0 \left. \frac{dS(\rho)}{d\rho} \right|_{\rho=\rho_0}$$

where ρ_0 is the nuclear saturation density

Neutron Distribution in Nuclear Matter

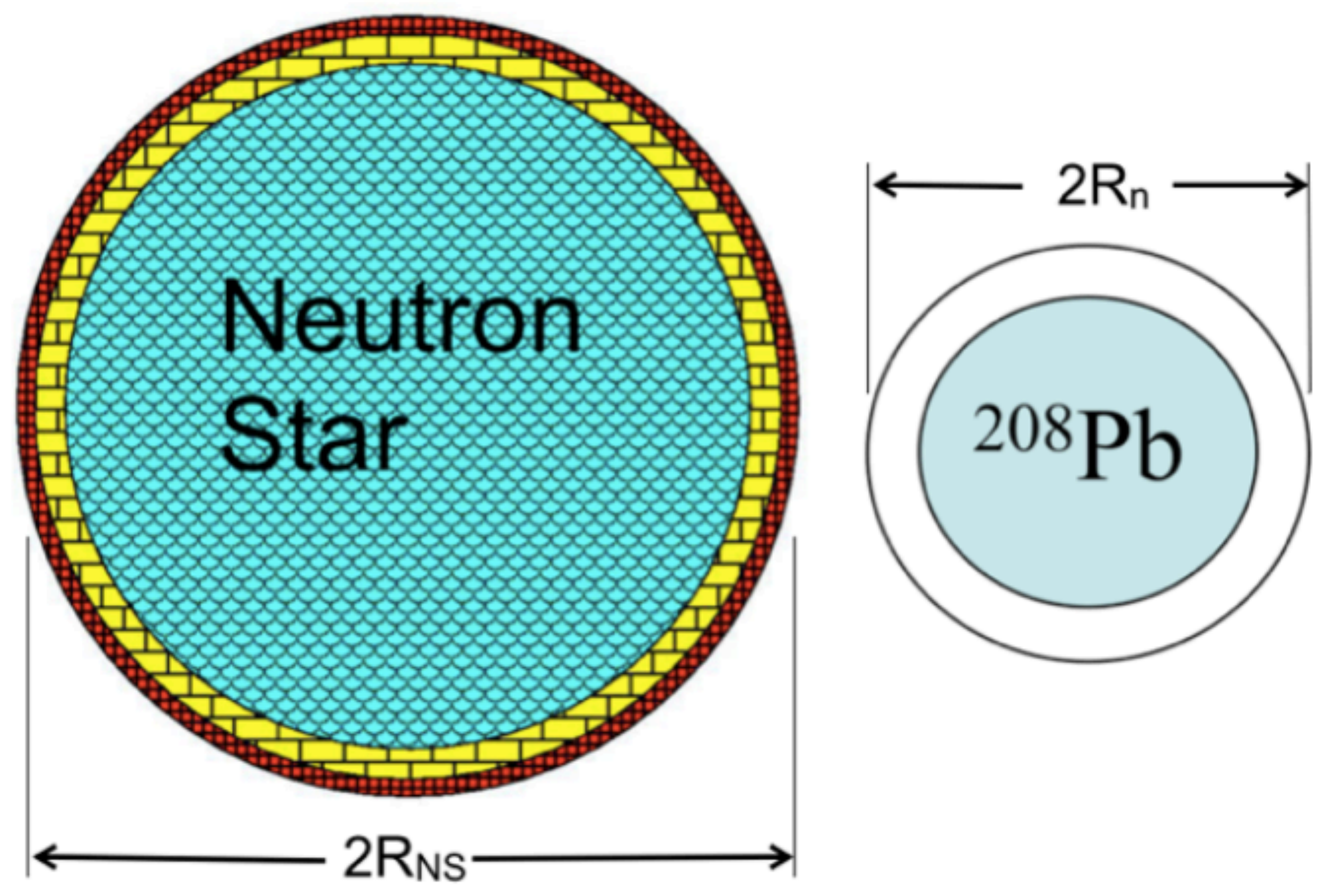
How can we study neutron stars and their properties here on Earth?

→ Neutron-rich nuclear matter!

Neutron star is 18 orders of magnitude larger than a ^{208}Pb nucleus.

↓

Same interactions, same Equation of State.



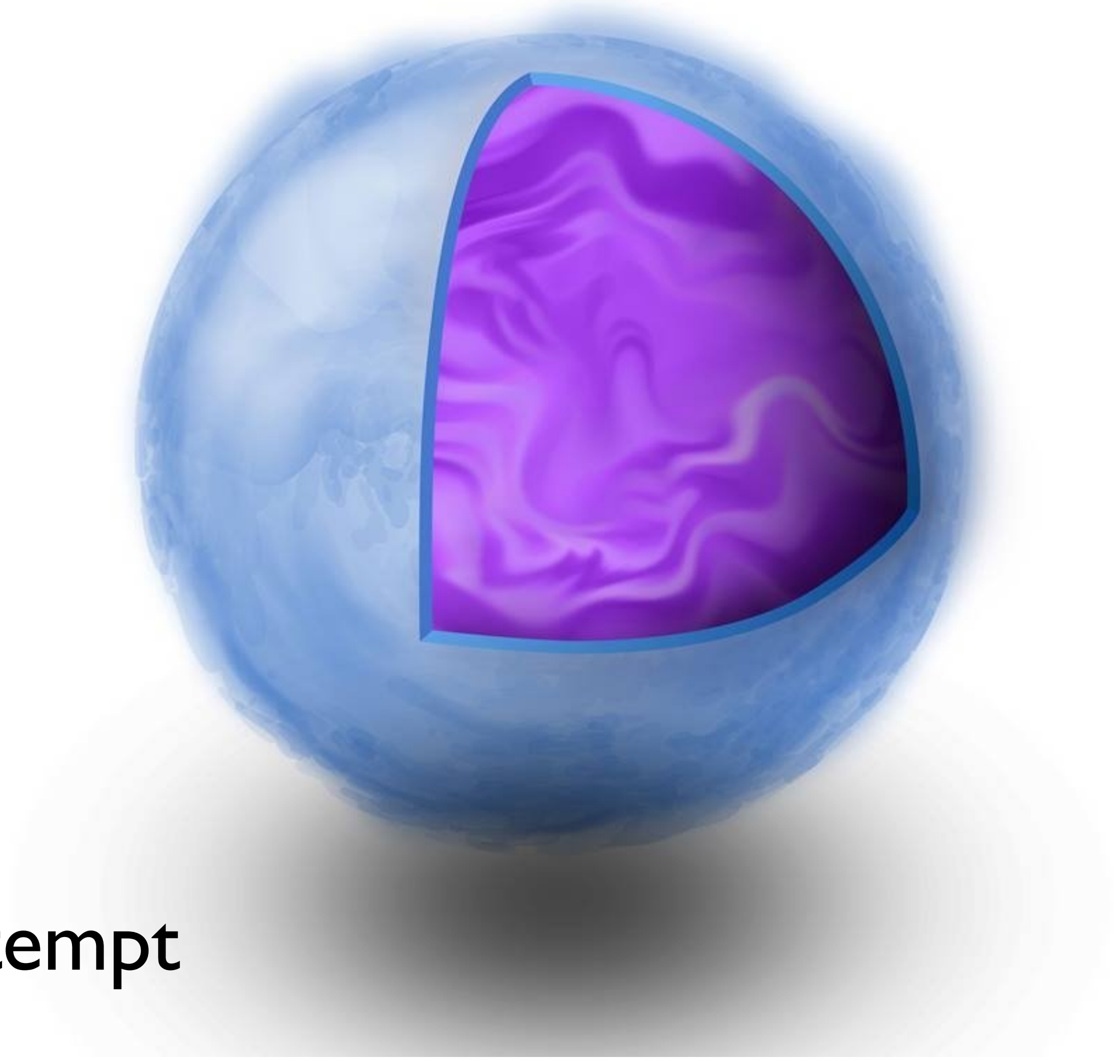
Measure the neutron skin of a heavy nucleus such as ^{208}Pb

Neutron Skin

Neutron-rich region near the surface of a heavy nucleus.

Can be quantified by $R_{\text{skin}} = R_n - R_p$
where R_n, R_p are the r.m.s. radii

$$R_{n/p} = \sqrt{\langle r^2_{n/p} \rangle}$$

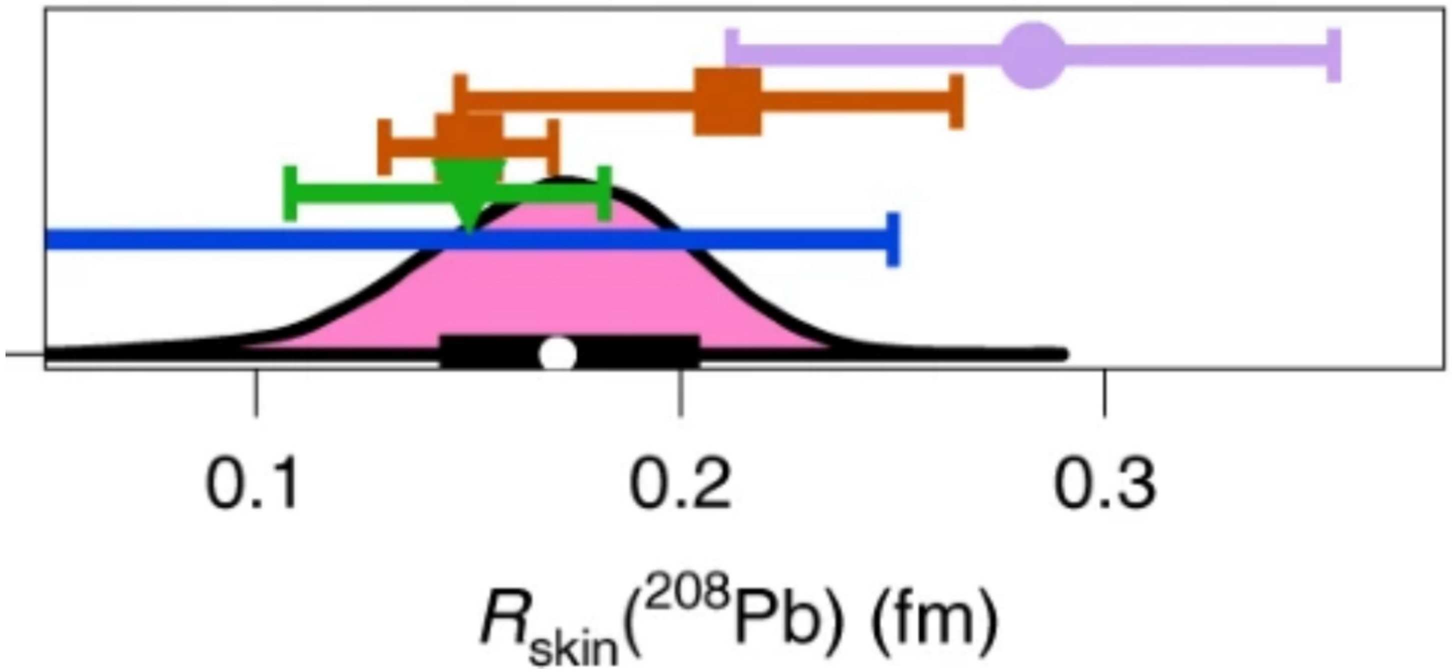


Many techniques have been used to attempt measurement of R_n over the years:

- Hadron-scattering experiments
- Electric dipole polarizabilities
- Pygmy dipole resonances
- Coherent π^0 production from heavy nuclei

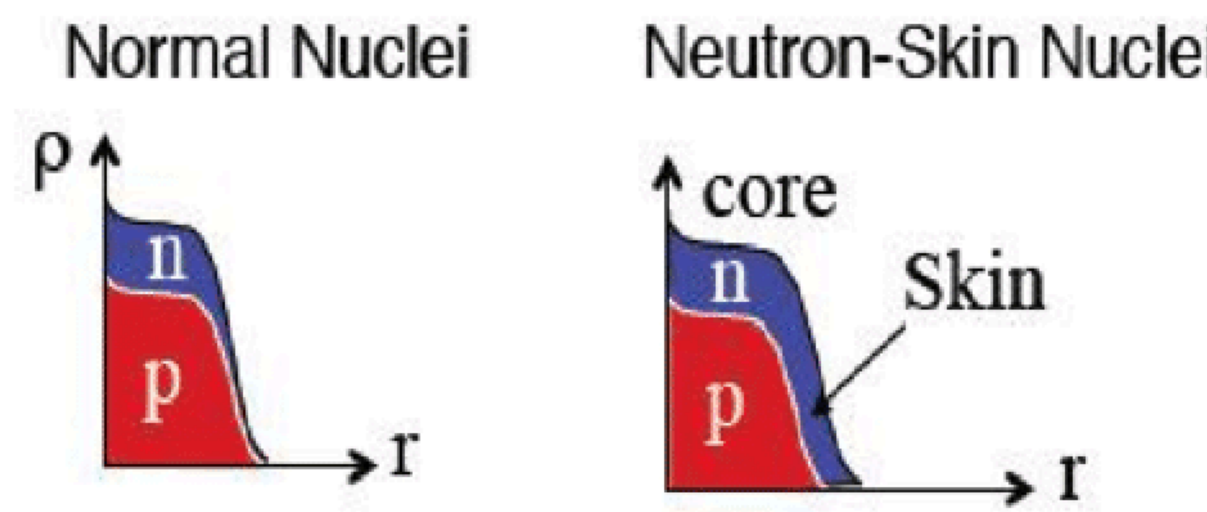
^{208}Pb Measurements

Hu et al., Nature Physics **18**, 1126 (2022).



Pi0 Photoproduction
Proton elastic scattering
Antiprotonic atoms
Electroweak
Gravitational Waves

$$R_{\text{skin}} = R_n - R_p$$

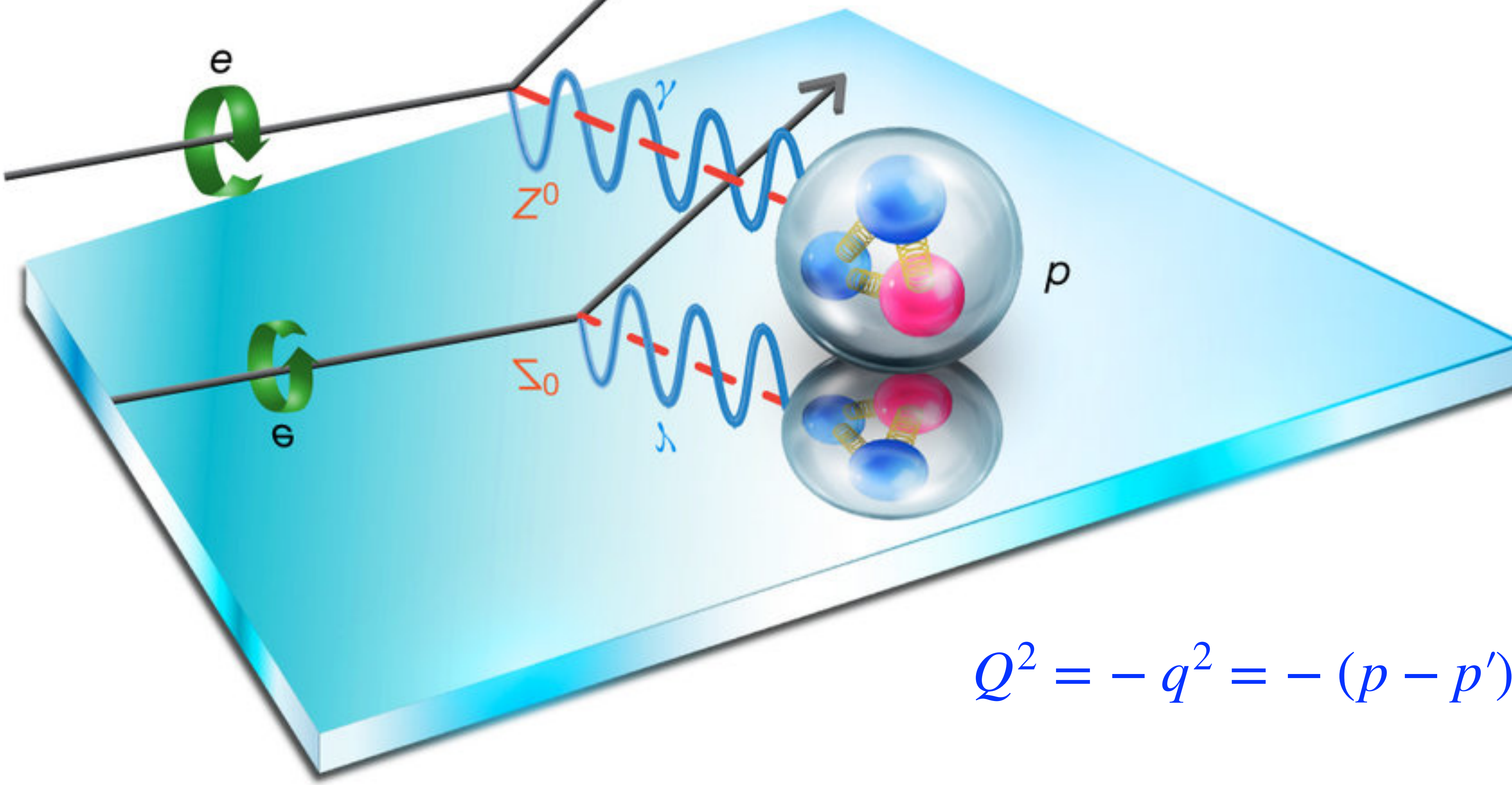


R_p well known from elastic electron scattering, although we are apparently still a bit puzzled…

Parity Violating Electron Scattering (PVES)

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx 10^{-6}$$

Very small asymmetries!



$$Q^2 = -q^2 = -(p - p')^2$$

Parity Violating Electron Scattering (PVES)

Most accurate way to measure the neutron skin.

Very clean compared to most other techniques.

Model independent.

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{Q_W F_W(Q^2)}{Z F_{ch}(Q^2)}$$

Use precise measurements of A_{PV} and $F_{ch}(Q^2)$ to get the weak charge density, $F_W(Q^2)$.

Neutron weak charge is much larger than proton weak charge.

Measuring $F_W(Q^2)$ gives you a good idea of neutron density in the nucleus.

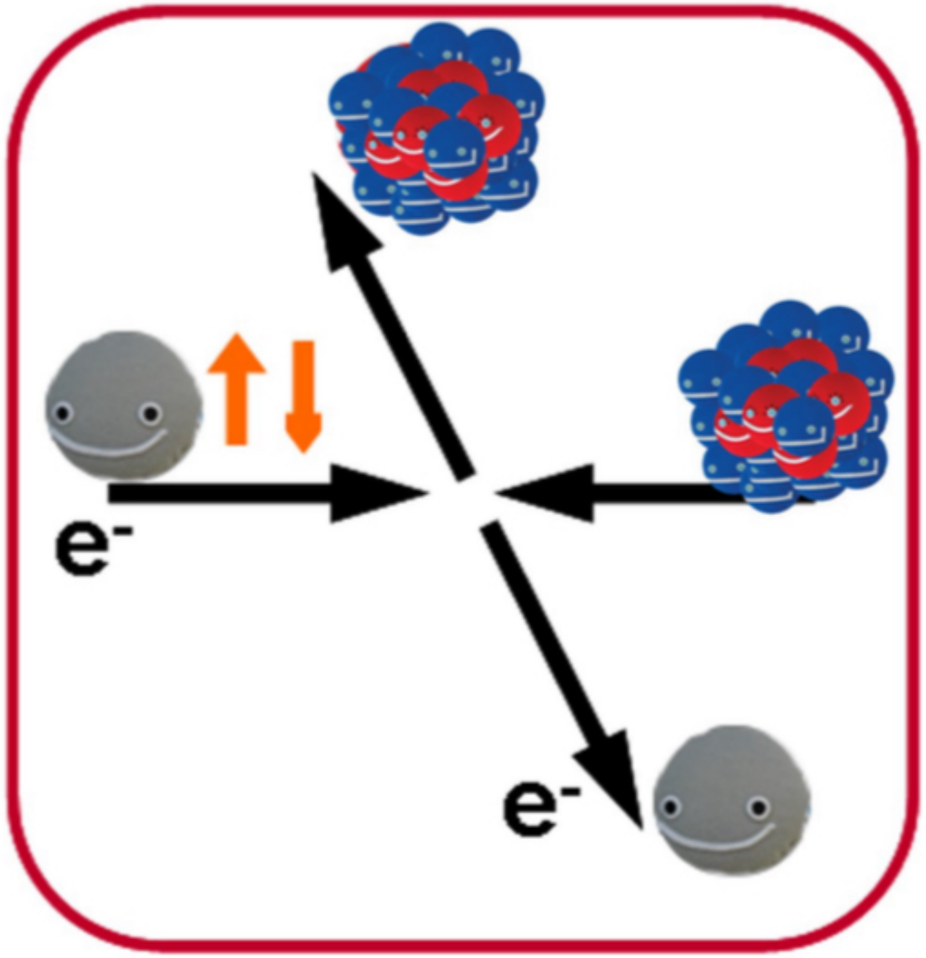
Competing Asymmetries

To measure precise PVES asymmetries, one needs a good handle on the systematic errors.

One of the main errors comes from the Beam Normal Single-Spin Asymmetry (**BNSSA**).

It is extremely difficult to polarize your electron beam 100% in the direction of the beam.

There exists a small normal component, *with a pretty big asymmetry…*



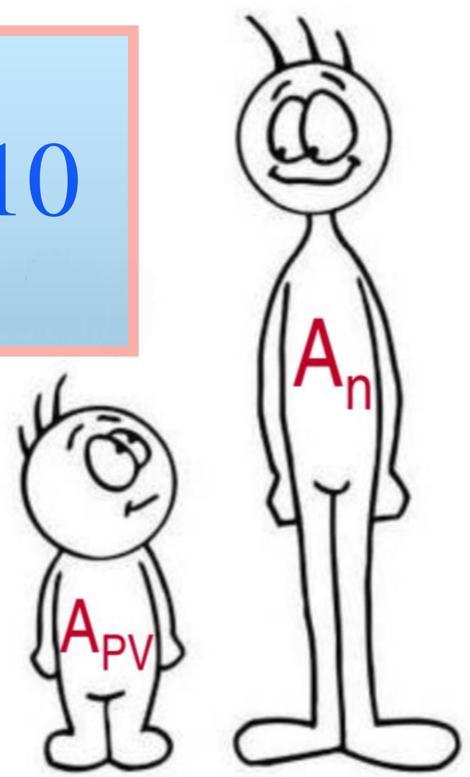
Beam-Normal Single-Spin Asymmetry (BNSSA)

Electrons are polarized transverse (normal) to their direction of motion.

Resulting asymmetry $A_n = \dfrac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$

As opposed to the usual longitudinal asymmetry used in PVES.

$$\frac{A_n}{A_{PV}} \approx 10$$



Can introduce a significant systematic error in PVES if the e^- beam has a even a small transverse polarization component.

"False" asymmetry in PVES!

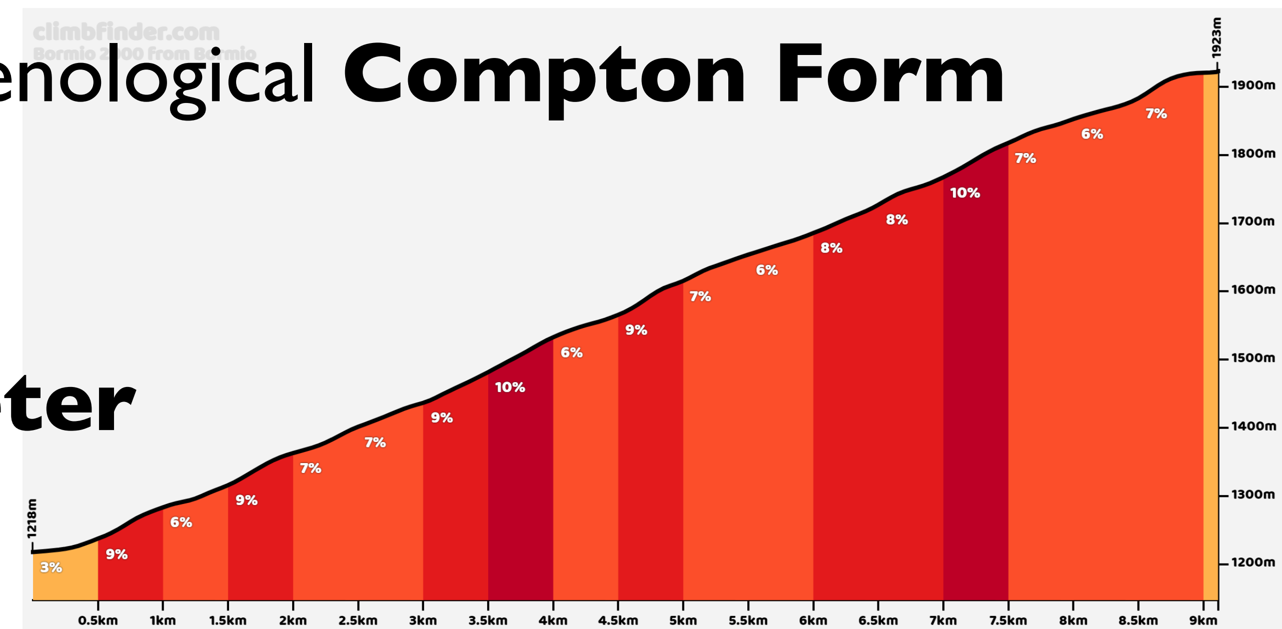
Theoretical Treatment of the BNSSA

Gorchtein and Horowitz, PRC **77**, 044606 (2008).

$$A_n = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \propto g_N(Q^2) \propto e^{-BQ^2/2}$$

Note: $Q^2 = -t$

$g_N(Q^2)$ is the phenomenological **Compton Form Factor** for nucleus N



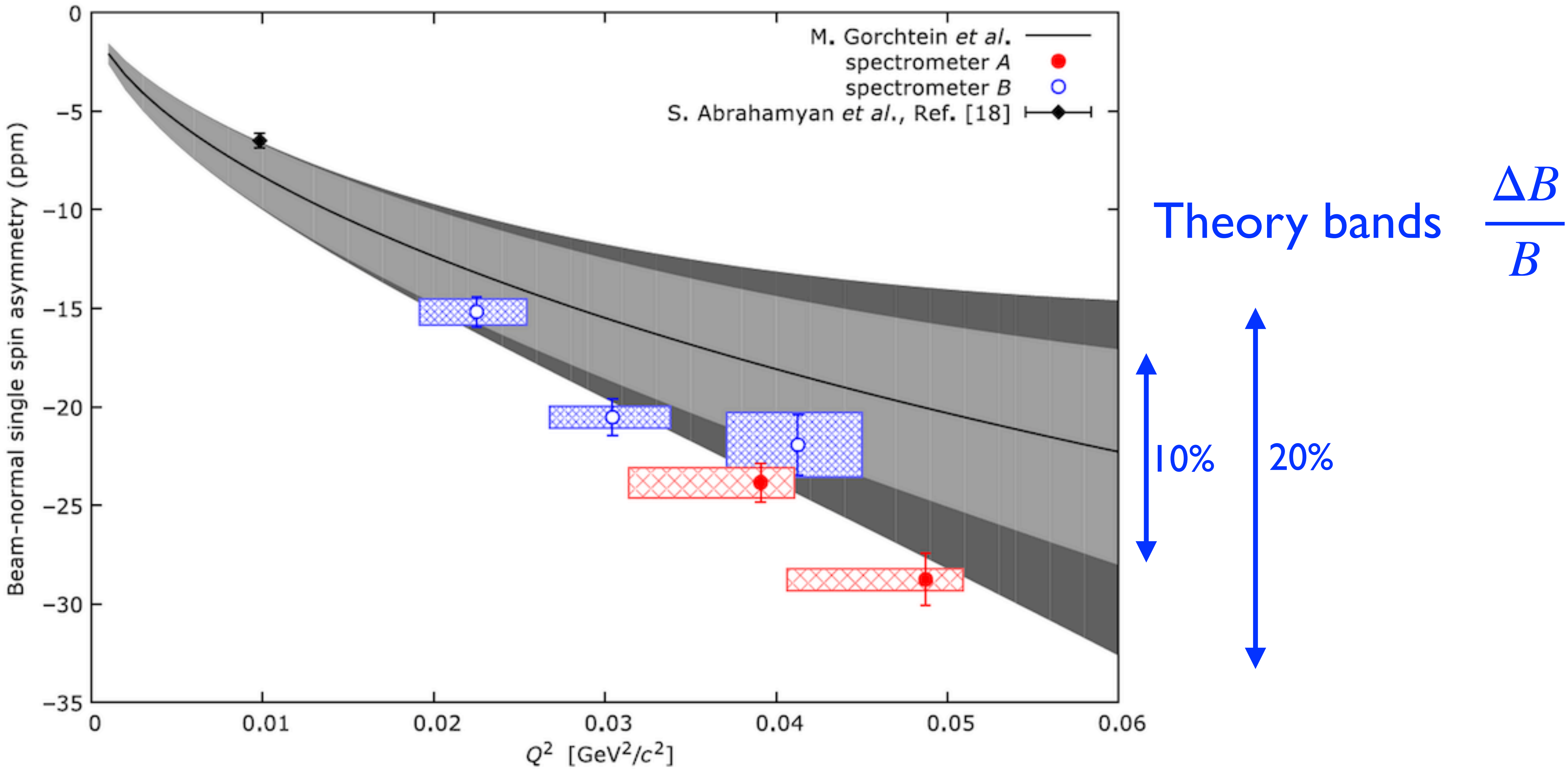
B is the **Compton Slope Parameter**

Not well known for complex nuclei!

Assumptions about B introduce an error of at least **10-20%** in the theoretical calculations of A_n.

Proper understanding of A_n of requires more accurate determination of B.

Beam-Normal Asymmetry on ^{12}C

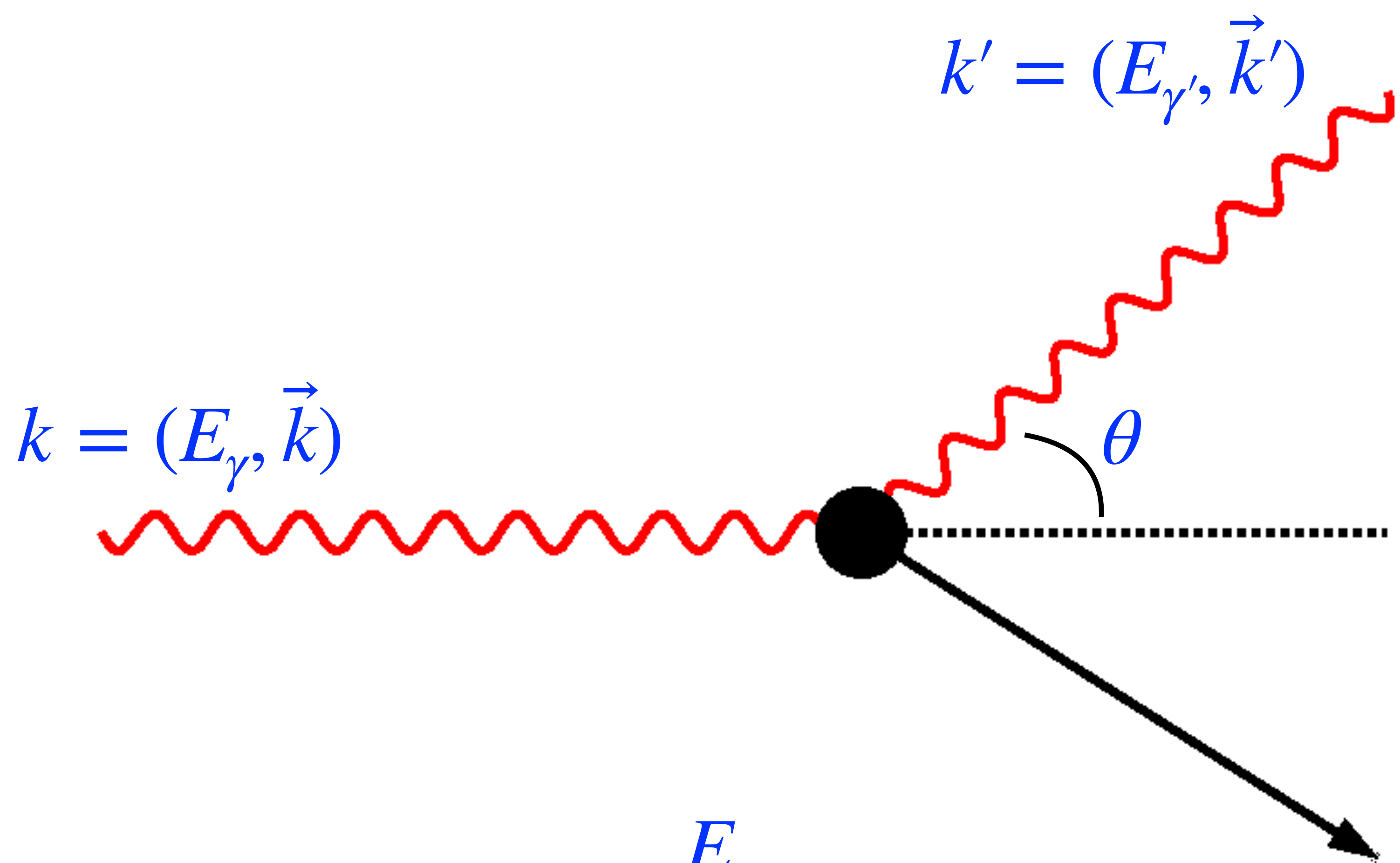


Gorchtein and Horowitz, PRC **77**, 044606 (2008)
A. Esser et al., PRL **121**, 022503 (2018)
S. Abrahamyan et al., PRL **109**, 192501 (2012)

Experimental data:
A1 @ Mainz
PREX/HAPPEX @ JLab

Start with an "easy" nucleus, then move to heavier nuclei.

Compton Scattering Kinematics



Compton Formula $$E_{\gamma'} = \frac{E_\gamma}{1 + \frac{E_\gamma}{M}(1 - \cos\theta)}$$

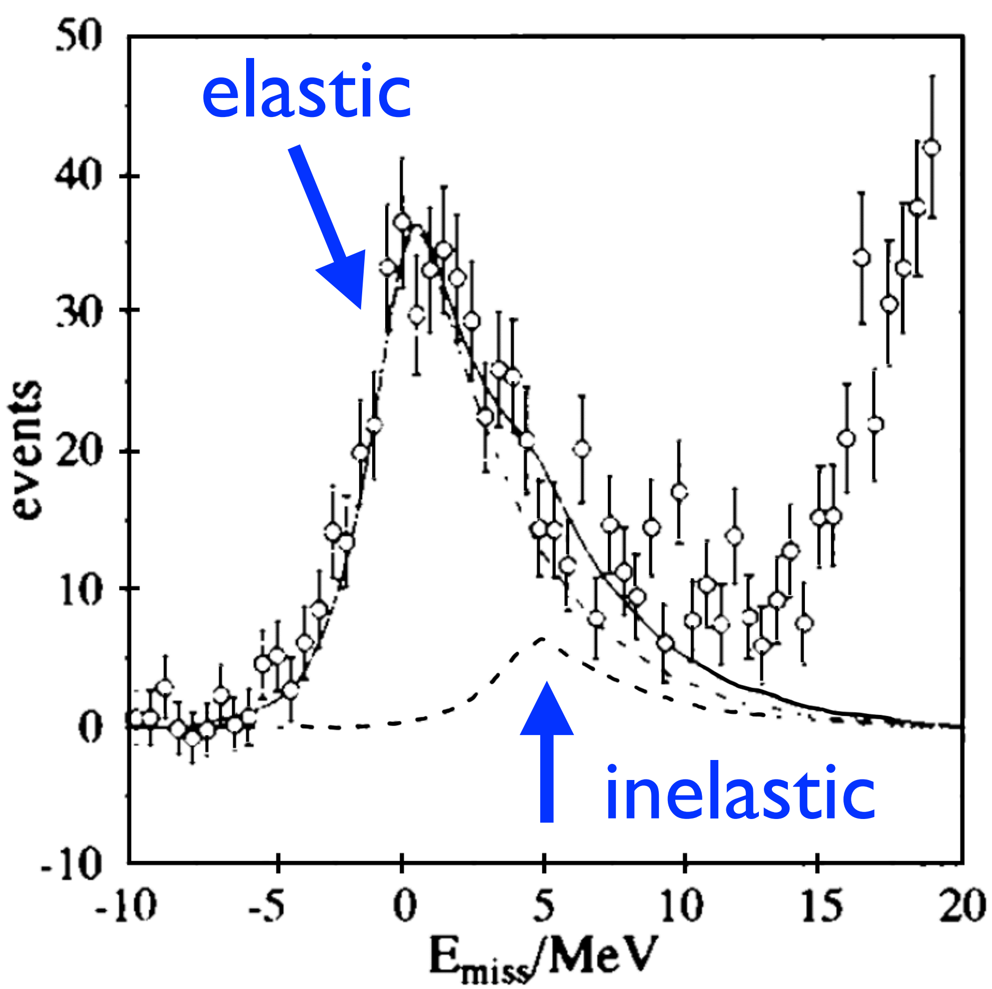
Mandelstam $$t = -Q^2 = q^2 = (k - k')^2 = -2E_\gamma E_{\gamma'}(1 - \cos\theta)$$

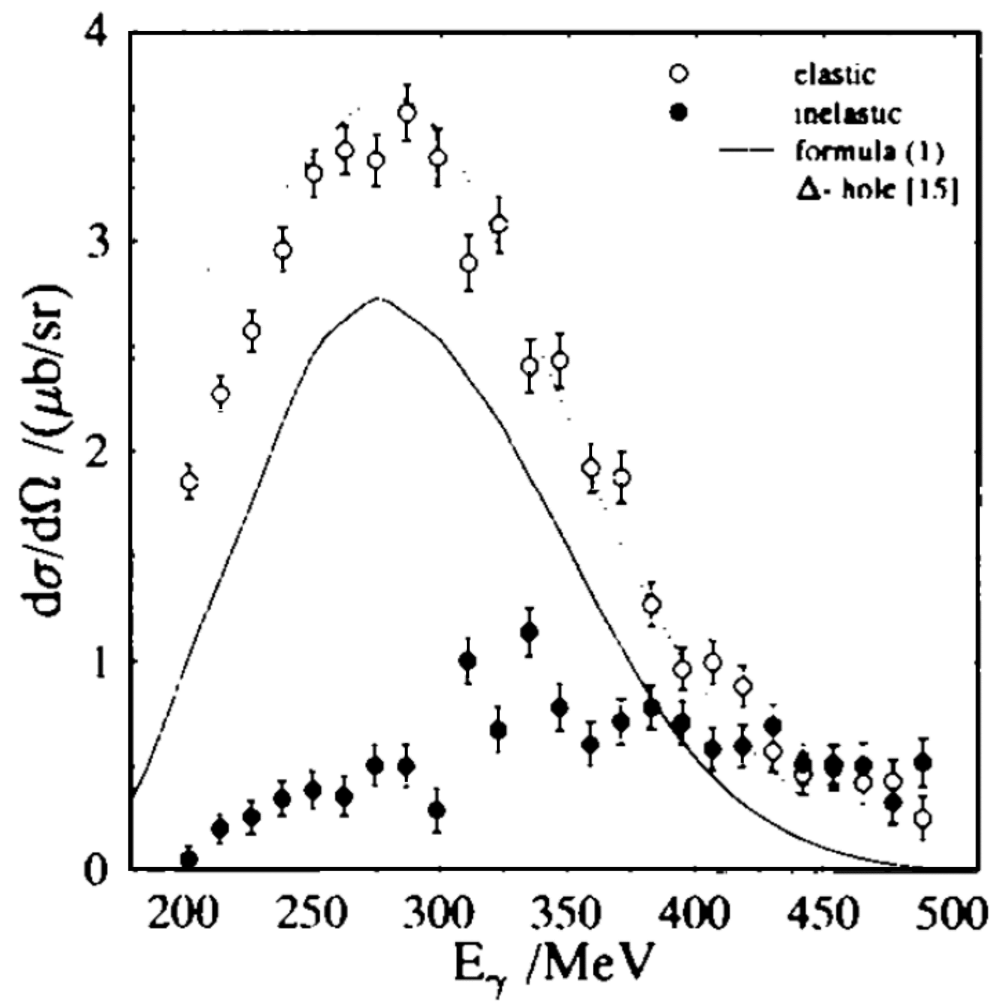
Compton Scattering on ^{12}C - Previous Results

F. Wissman et al., PLB **335**, 119 (1994).

$E_\gamma = 200 - 500\,\text{MeV}$ $\Delta x = 5\,\text{cm}$ $T = 30\,\text{hours}$

$\theta_{\gamma'} = 40^\circ$ $\Delta\Omega = 23\,\text{msr at } 0.978\,\text{m}$





CATS detector in the A2 Hall at MAMI

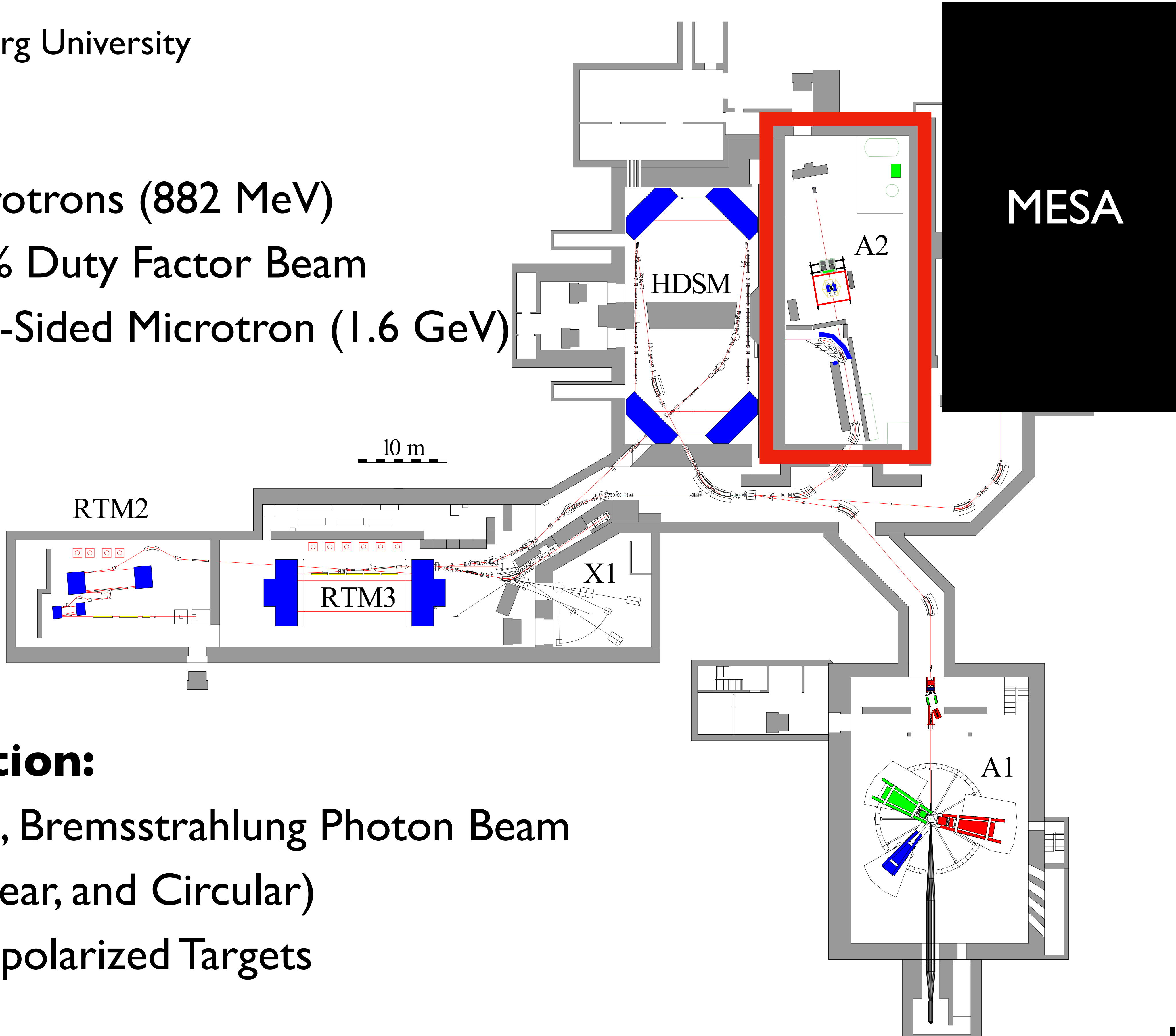
The Mainz Microtron (MAMI)

Johannes Gutenberg University
Mainz, Germany

3 Race-Track Microtrons (882 MeV)

High-Quality 100% Duty Factor Beam

Harmonic Double-Sided Microtron (1.6 GeV)



A2 Collaboration:

High-Flux, Tagged, Bremsstrahlung Photon Beam

(Unpolarized, Linear, and Circular)

Polarized and Unpolarized Targets

Experimental Configuration in the A2 Hall

$E_{e^-} = 1.6\,\text{GeV}$

$E_\gamma = 200 - 1000\,\text{MeV}$

$\theta_{\gamma'} = 20°$

$\epsilon_{\text{tag}} \approx 0.30$

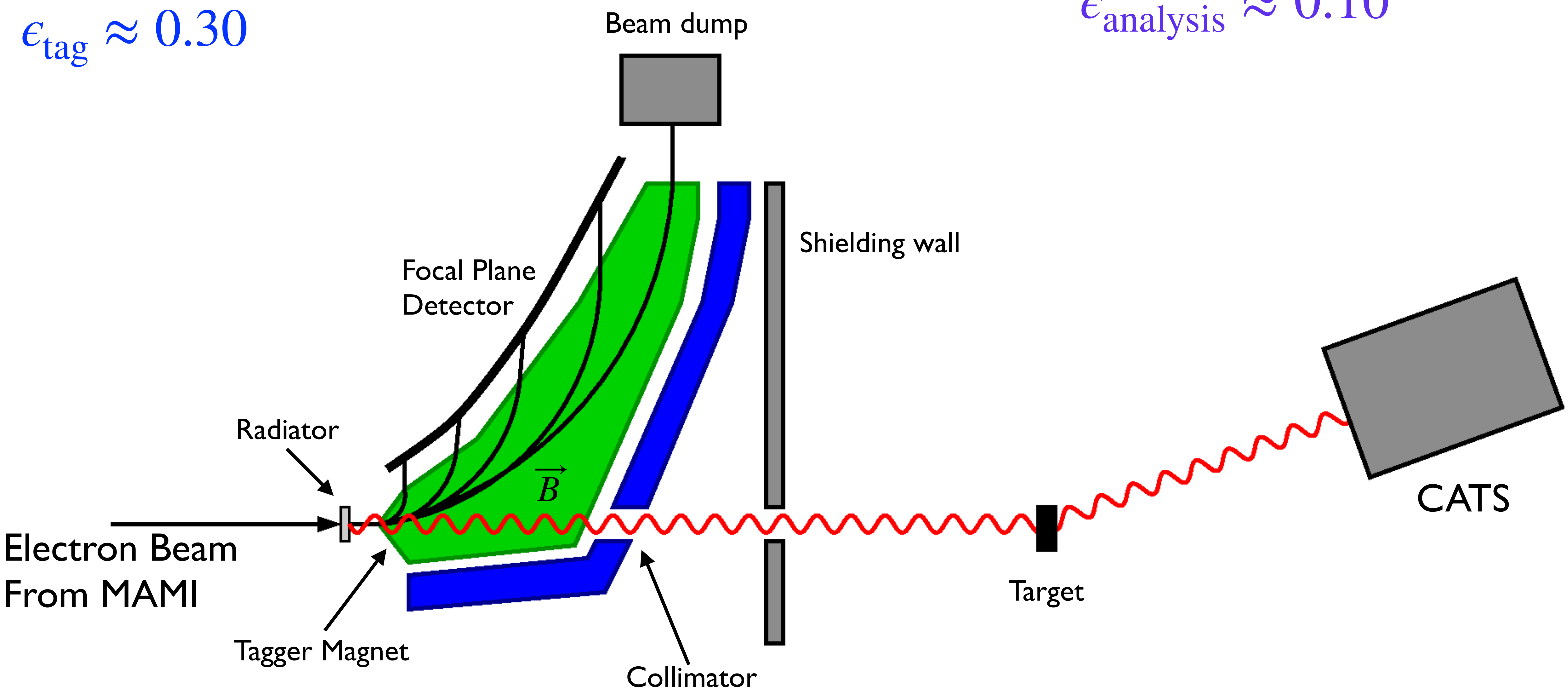
$\Delta x = 5\,\text{cm} = 4 \times 10^{-7}\,\mu\text{b}^{-1}$

$\Delta E_{\gamma'} = 40\,\text{MeV}$

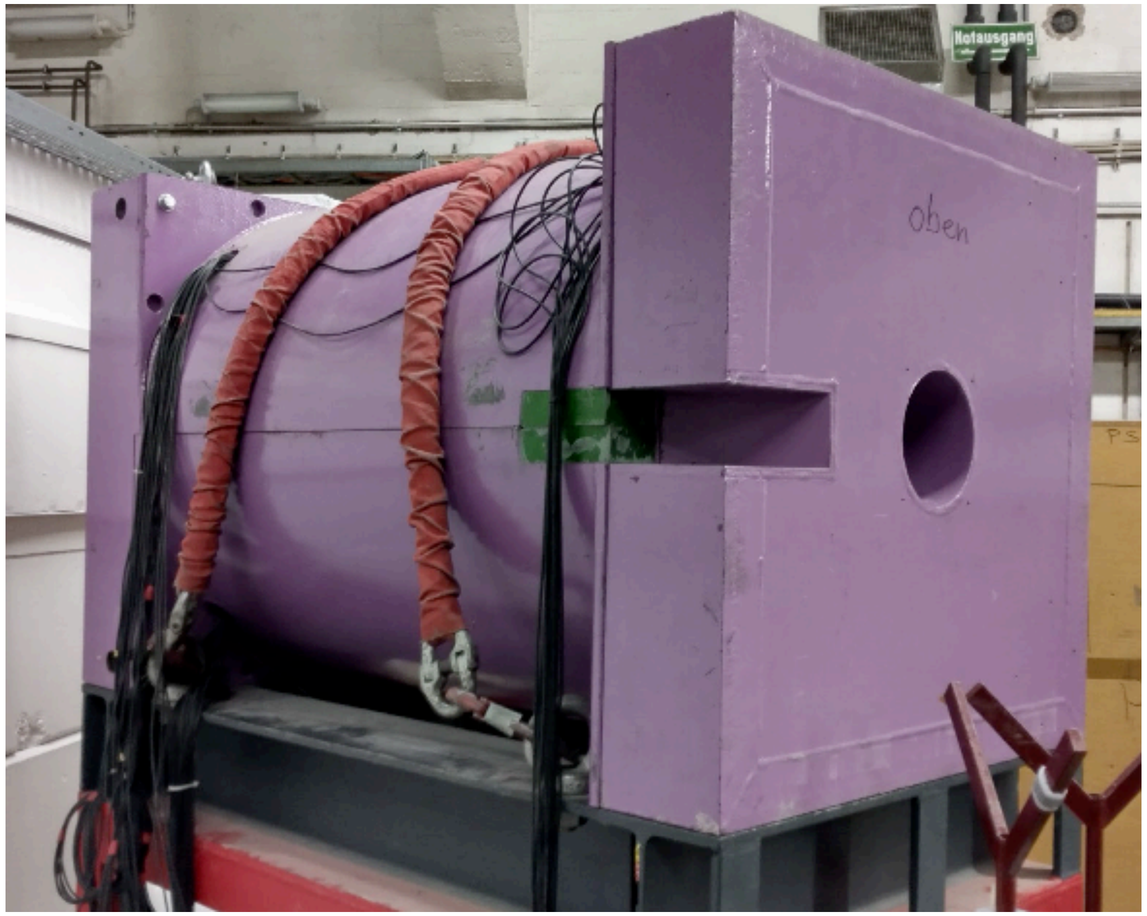
$T = 200\,\text{hours}$

$\epsilon_{\text{det}} = 0.0002 - 0.006$

$\epsilon_{\text{analysis}} \approx 0.10$

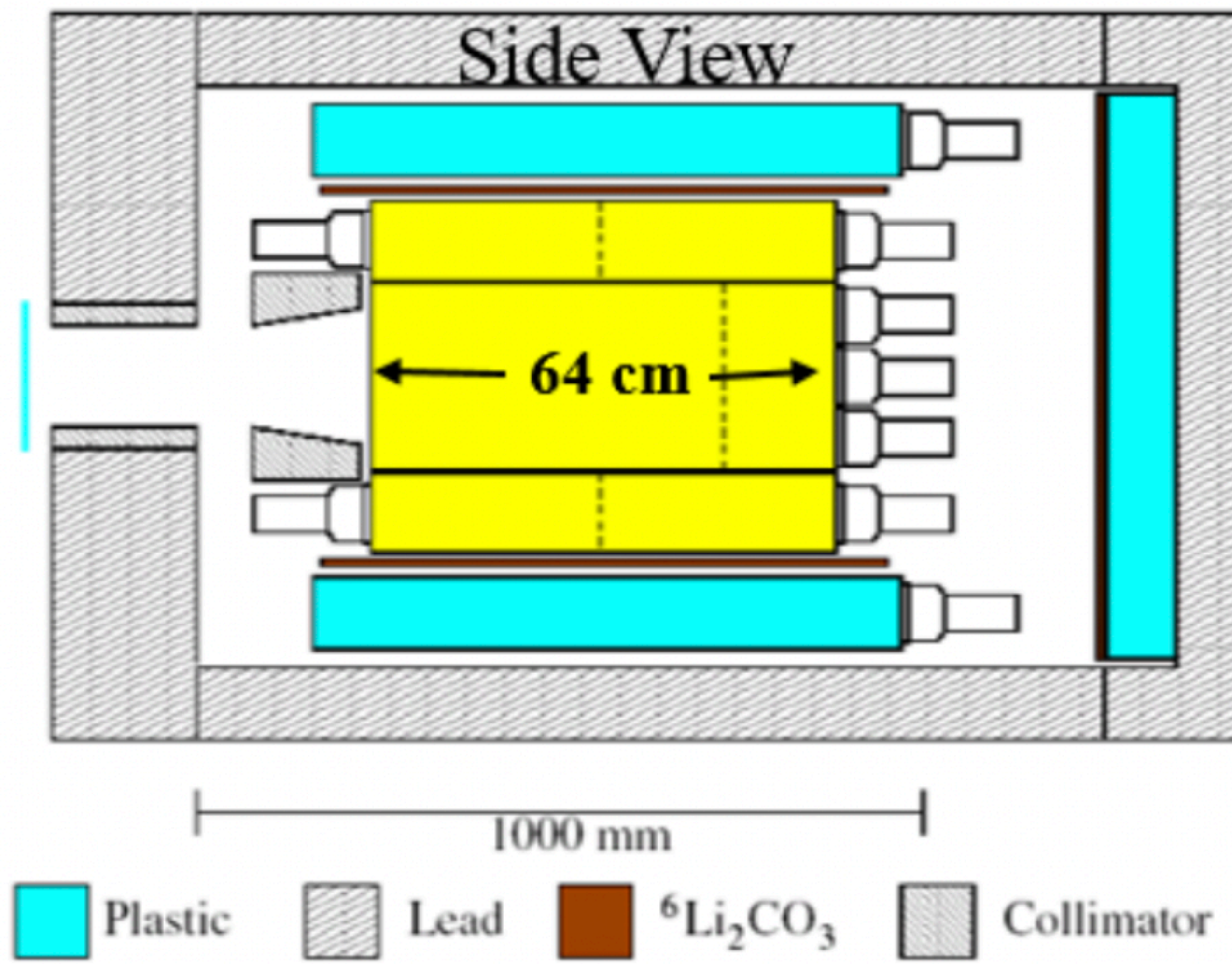


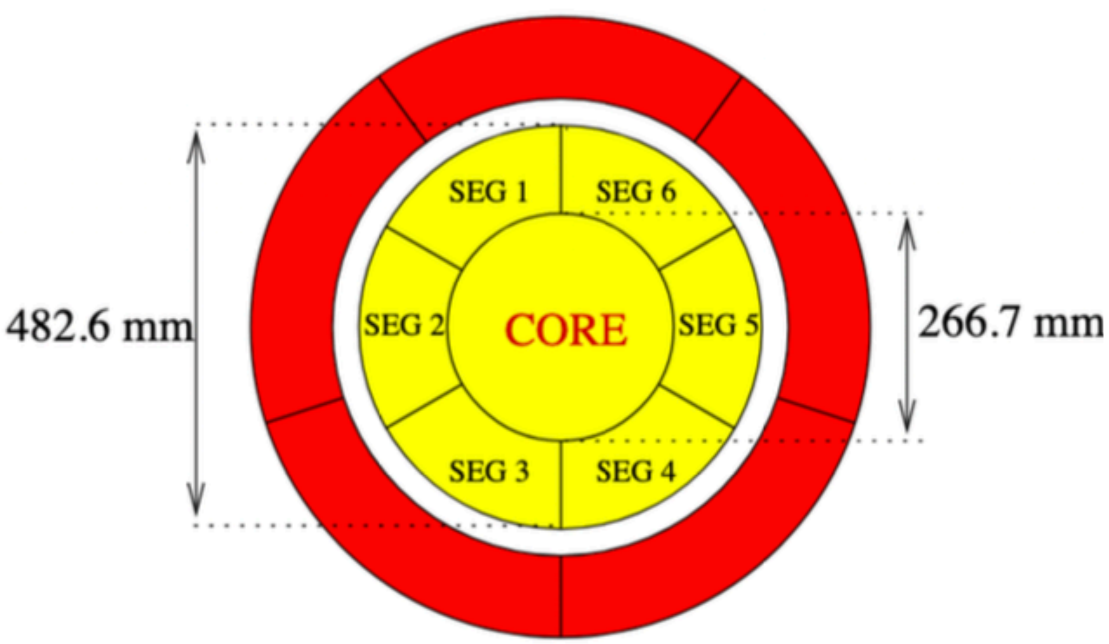
CATS NaI(Tl) Detector



FWHM $\Delta E/E \approx 1.5\,\%$

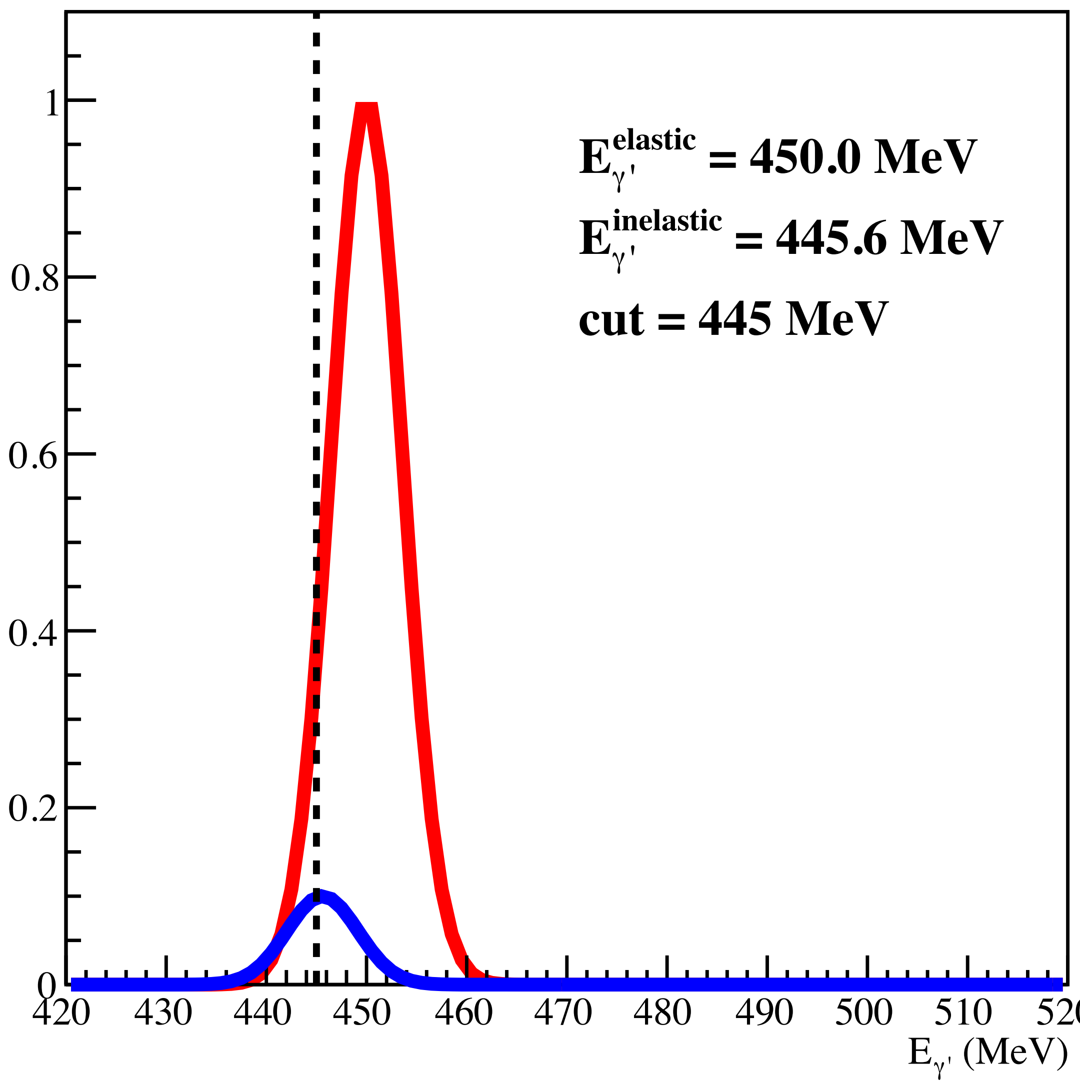
$\Delta\Omega = 10\,\text{msr at}\,1\,\text{m}$

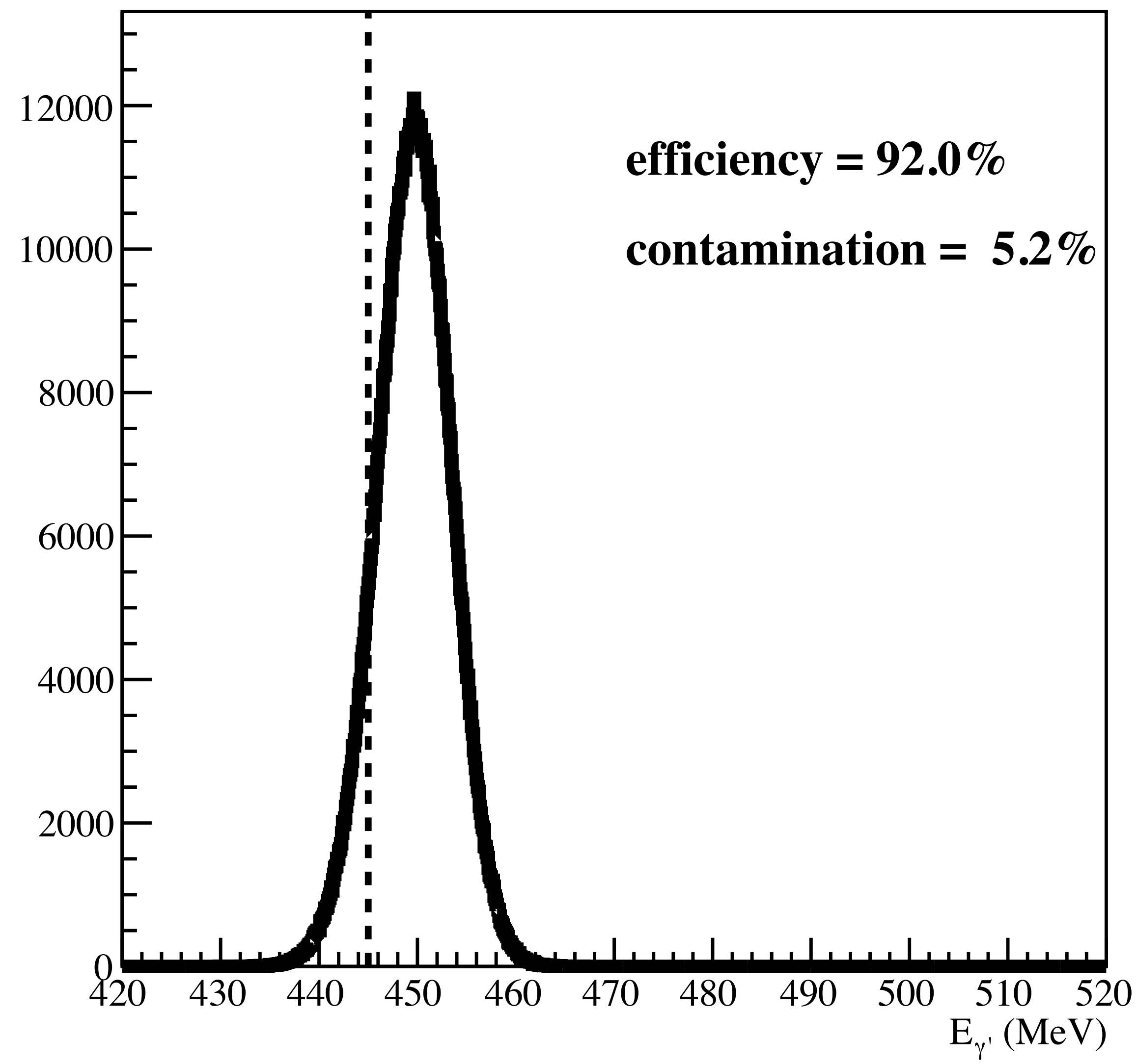




CATS Large-Volume NaI(Tl) Detector

Excellent Energy Resolution $\frac{\Delta E}{E} = 1.5\ \%$

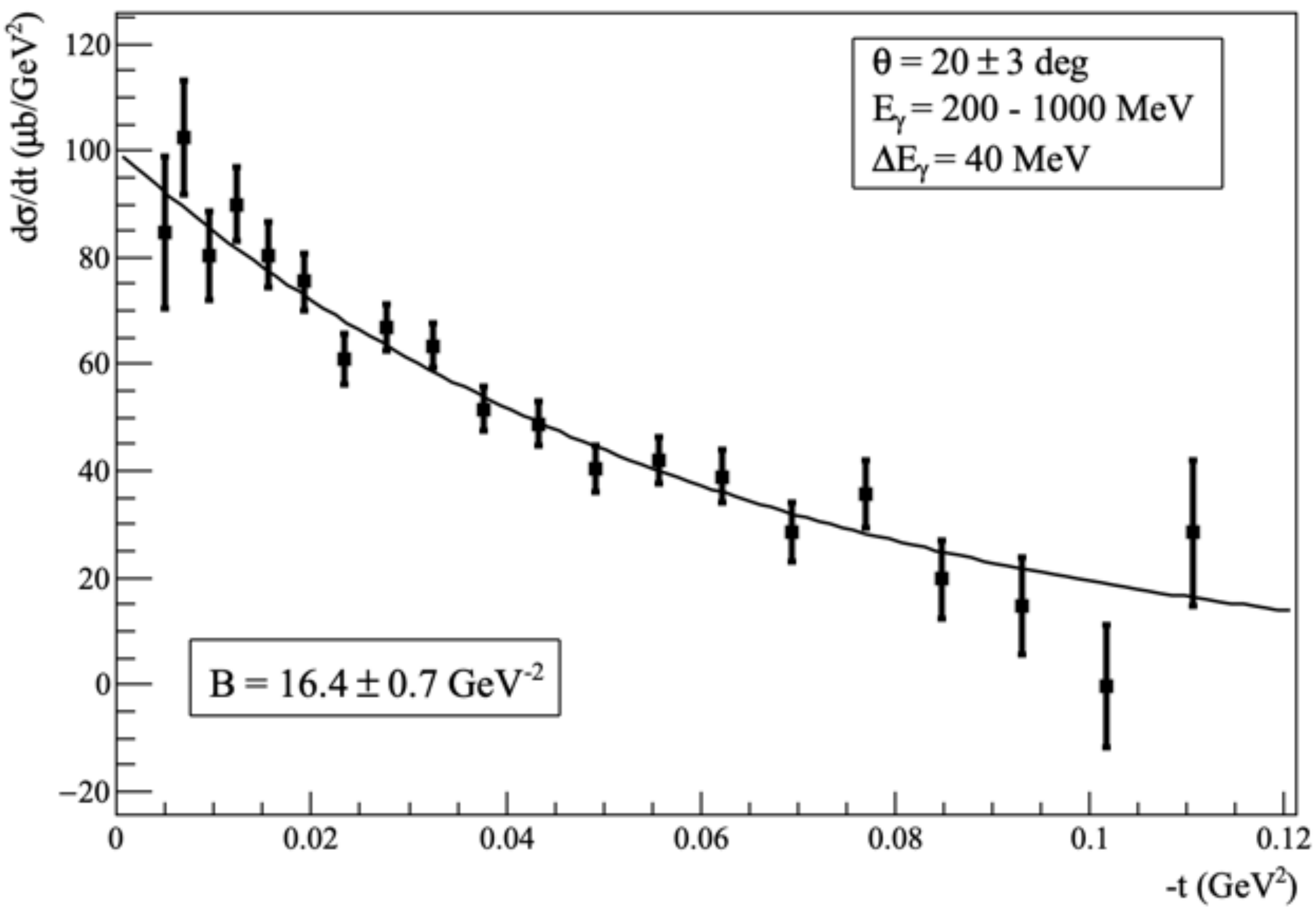




Inelastic/elastic strength taken from Wissman et al.

Projected Results with CATS in A2@Mainz

$$\frac{d\sigma}{dt} \text{ vs } -t$$



$$\frac{\Delta B}{B} \approx 5\,\%$$

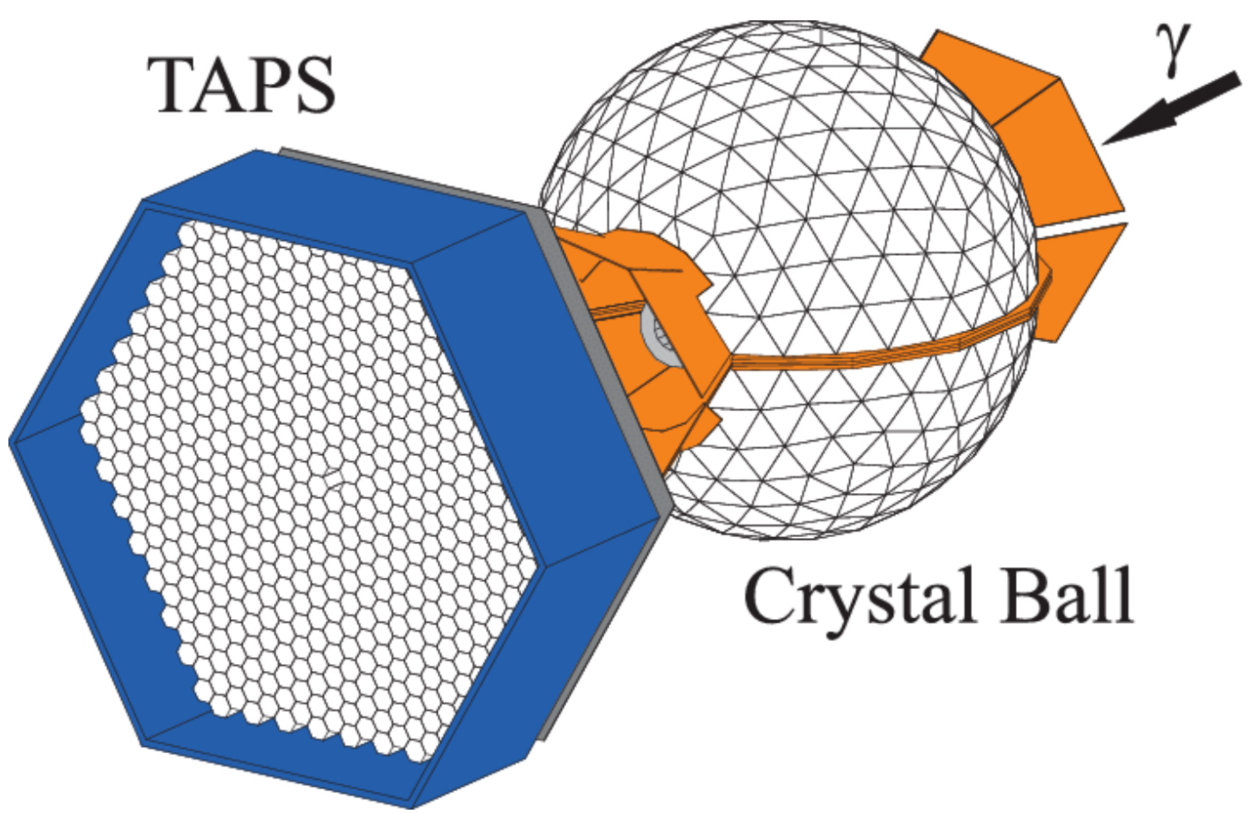
$$\frac{d\sigma}{dt} \approx \left[\frac{d\sigma}{dt}\right]_{t=0} \times e^{Bt}$$

Data points have been smeared by 1σ

200 hours of running

Next Step: Replace CATS with CB-TAPS

- 4π detector.
- Measure the decay photons as well.
- Veto inelastic events completely.
- Eliminate need for high-resolution NaI.
- Test feasibility with ^{12}C.
- Measure heavier nuclei as well.



Outlook

1. Measure coherent Compton scattering from ^{12}C with CATS in A2.
2. Test feasibility of detecting 4.4-MeV decay photons from $^{12}C^*$ using CB-TAPS.
3. Use same technique with ^{208}Pb.

Special Thanks To:

Concettina Sfienti
Michaela Thiel for slides and inspiration.
Chuck Horowitz

For more experimental details on the Mainz A_n measurements and the MREX program, refer to presentations by **N. Kozyrev** and **A. Esser**.

QUESTIONS?