PANDORA Project: Photonuclear Reaction of Light Nuclei

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PANDORA Collaboration

The Workshop on Photonuclear Science in 2025
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Photo-Nuclear Reactions: Photo-absorption

A photon interacts with protons in the target nuclei

→ excites the Iso-Vector Giant Dipole Resonance (IVGDR)

$E_x \simeq 7 - 30$ MeV

IV Giant Dipole Resonance

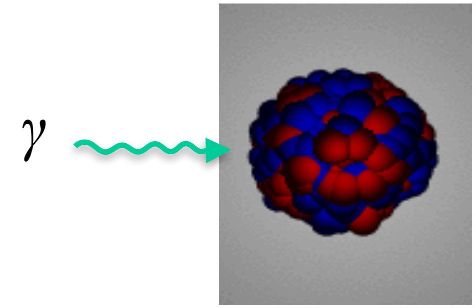

Photo-absorption cross section is dominated by the electric dipole (*E1*) excitation of nuclei.

$$\sigma_{\text{abs}} = \frac{16\pi^3}{9} \alpha E_\gamma \frac{dB(E1)}{dE_\gamma}$$

σ_{abs} : photo-absorption cross section

$B(E1)$: electric-dipole reduced transition probability

E_γ : photon-energy = nuclear excitation energy

α : fine structure constant

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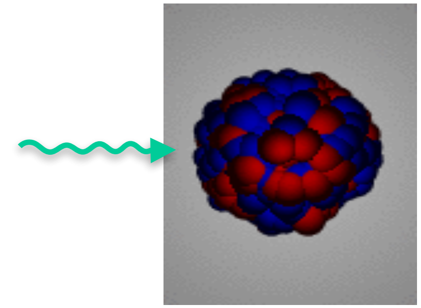

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Photo-absorption cross section of heavy nuclei

Studied since the discovery of IVGDR

Shape of IVGDR:
described by a Lorentzian for spherical nuclei

$\sigma_{\rm abs} \simeq (\gamma, xn)$ cross sections for heavy nuclei

p and other charged particle decay
negligibly small due to Coulomb barrier

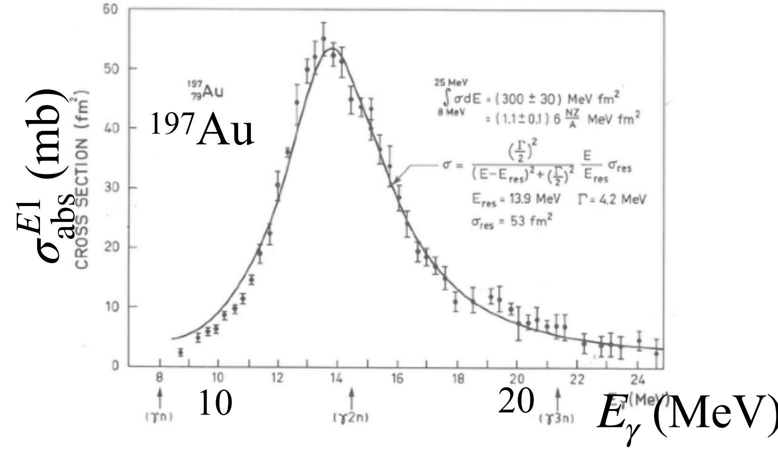
direct γ decay from IVGDR is ~1%
Beene *et al.*, PRC39, 1307 (1989)

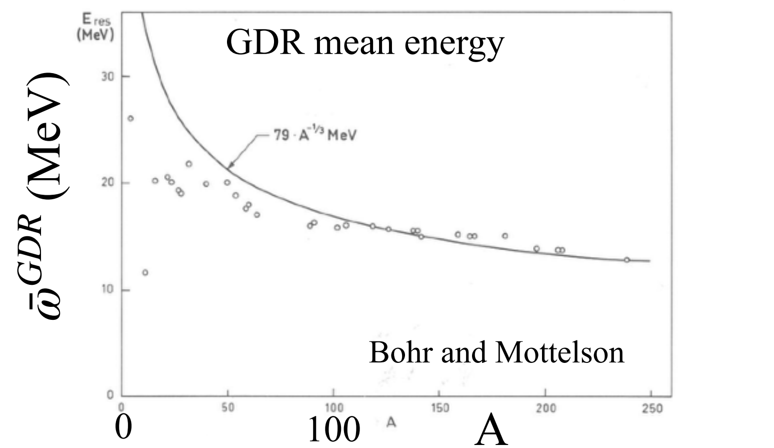
Mean energy

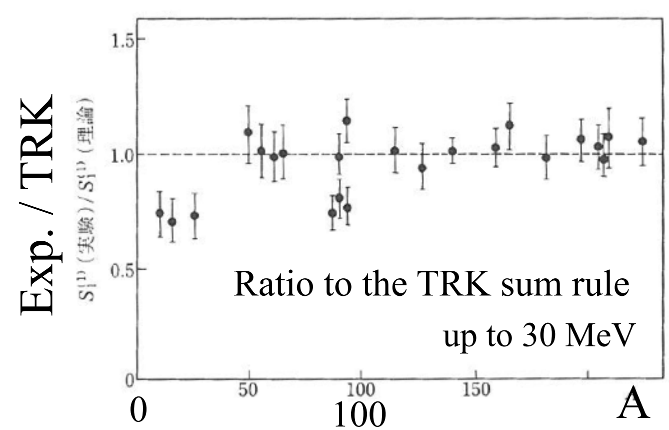
$$\bar{\omega}^{E1} = \sqrt{\frac{m_1^{E1}}{m_{-1}^{E1}}} \simeq 85A^{-1/3}\ \text{MeV}$$ A.B. Migdal: 1944

Strength: TRK Sum-Rule

$$\int \sigma_{abs}^{E1}(\omega)d\omega = \frac{2\pi e^2\hbar}{mc}\frac{NZ}{A} \simeq 60\frac{NA}{A}\ \text{MeV mb}$$







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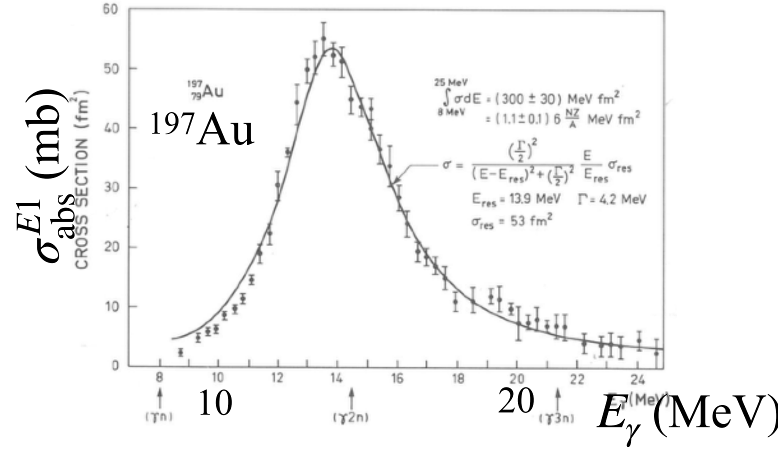

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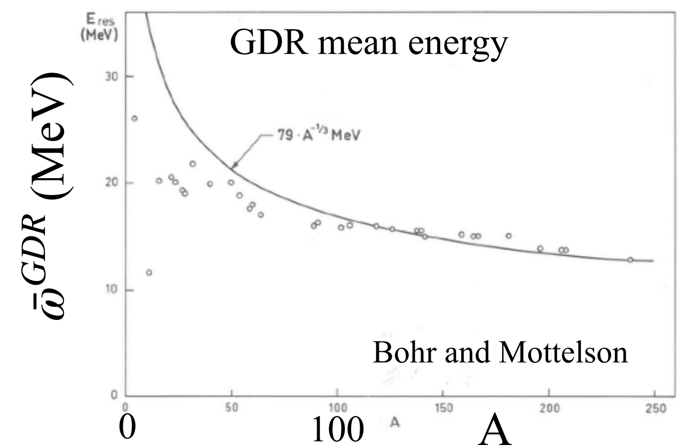

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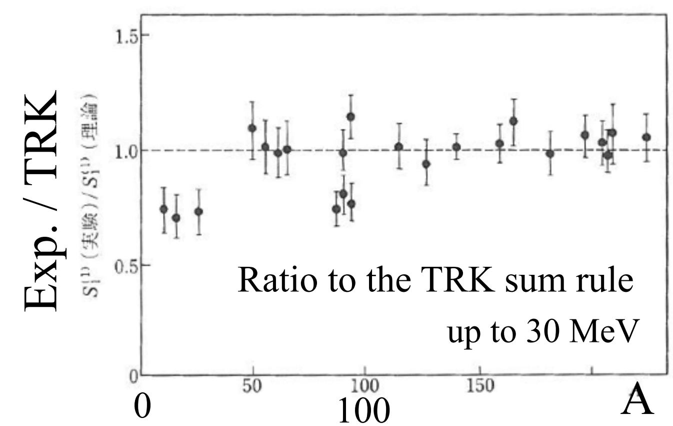


How is the case of light nuclei?

Photo-nuclear Reactions in Light Nuclei

For light nuclei

- photo-abs. c.s. $\neq$ (γ,xn) c.s.

  large branch to *p* and α emissions

- Challenges to theoretical models

  Structure

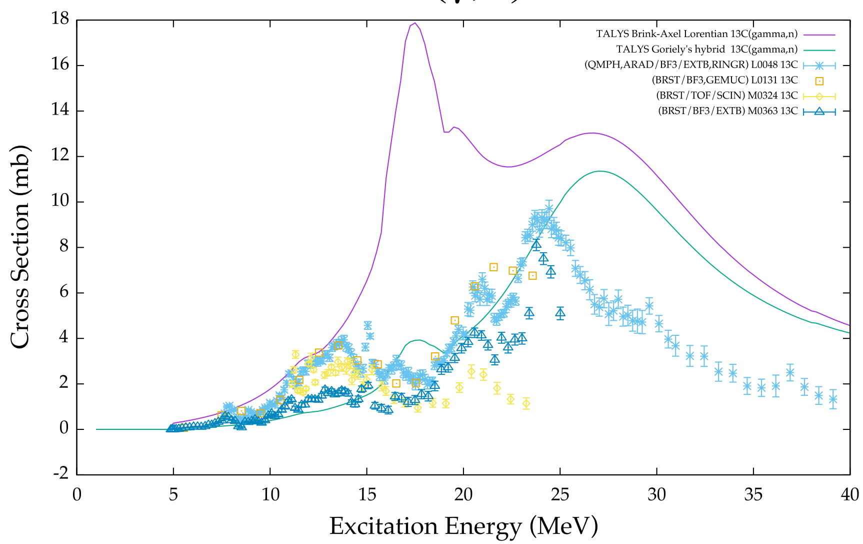
  - stronger shell effect
  - nuclear deformation
  - nucleon correlations:

    α clustering, *np* pairing, tensor correlation,...

  Decay

  - direct and pre-equilibrium decay process in addition to statistical decays
  - isospin selection rule in the α-decay process

^{13}C(γ,n)

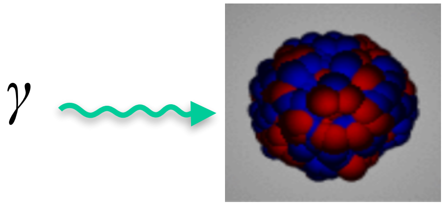


Example: ^{13}C(γ,xn) reaction data and predictions

also see the recent data from NewSUBARU PRC'24

- Lack of data especially for charged particle decays
- Large inconsistency among available data
- Poor theoretical prediction

IV Giant Dipole Resonance



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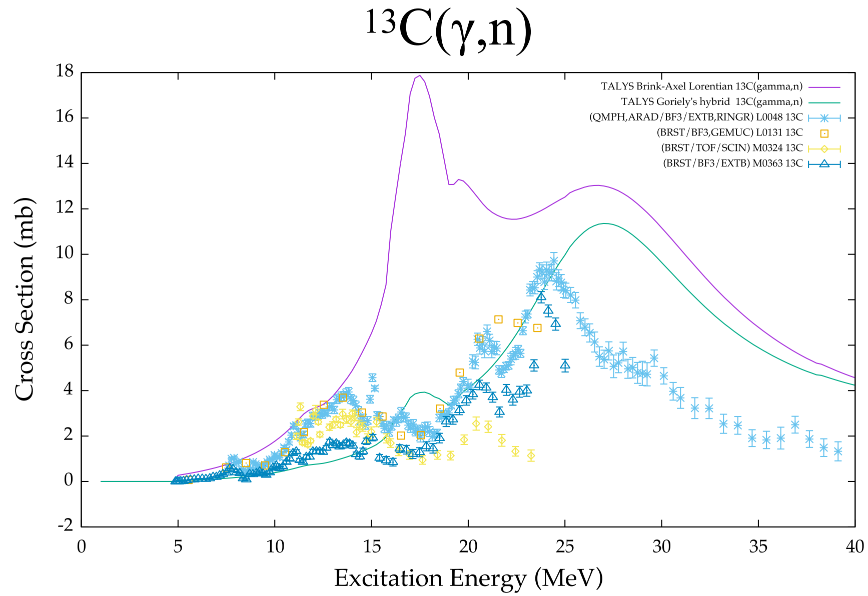
Decay calculation is important as well as the structure calculations



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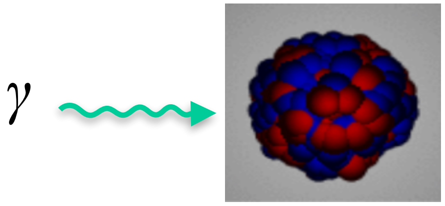

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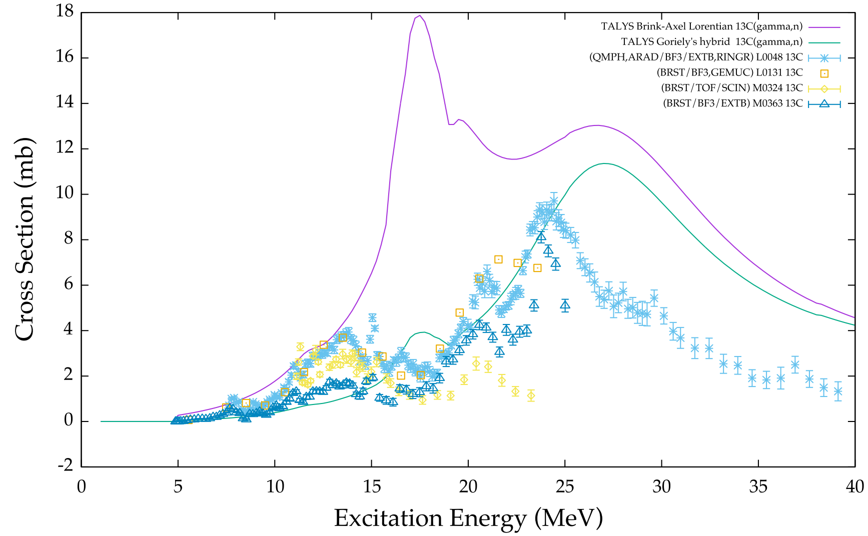

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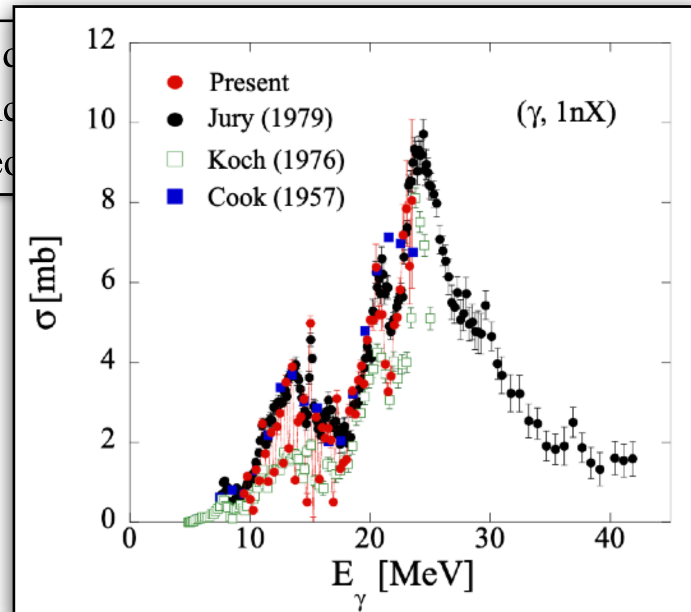
- Poor theo



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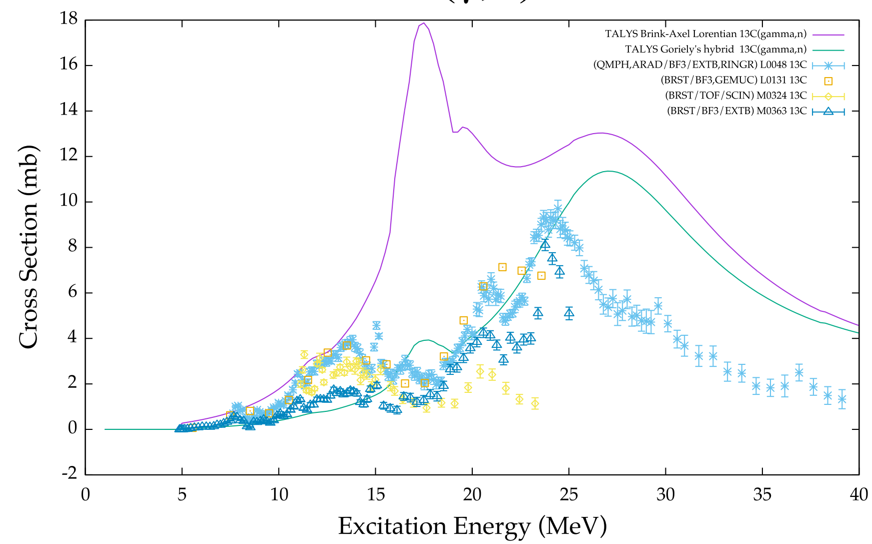

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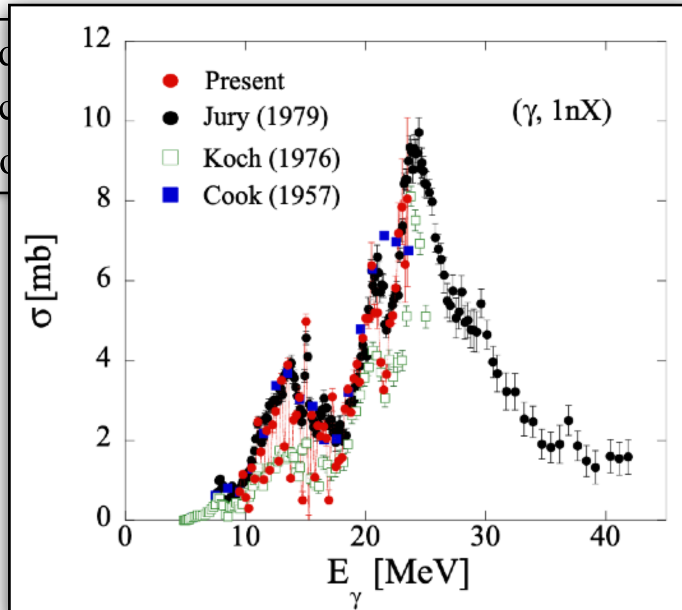
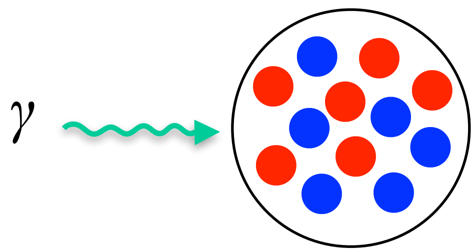
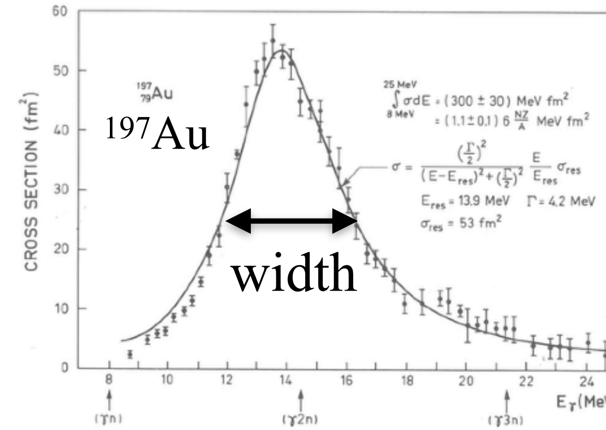


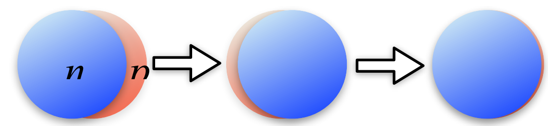
Damping of a nuclear collective excitation IVGDR

spreading of an ordered motion to a random motion



time





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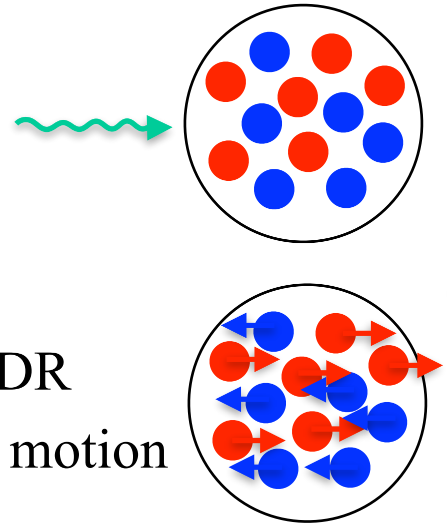
γ

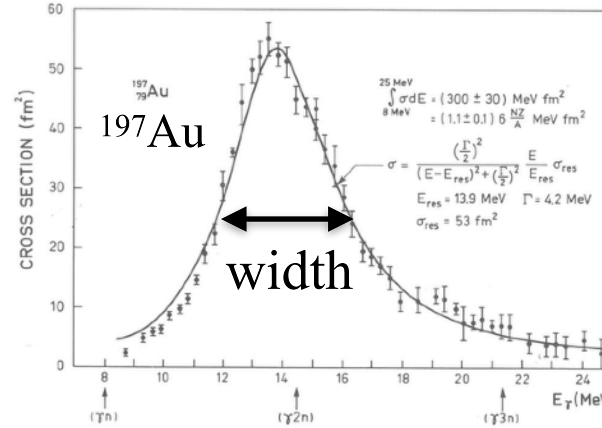


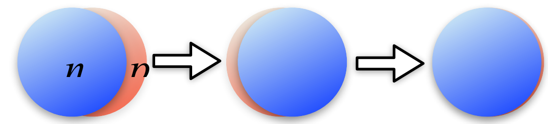
spreading

IVGDR

collective motion

time





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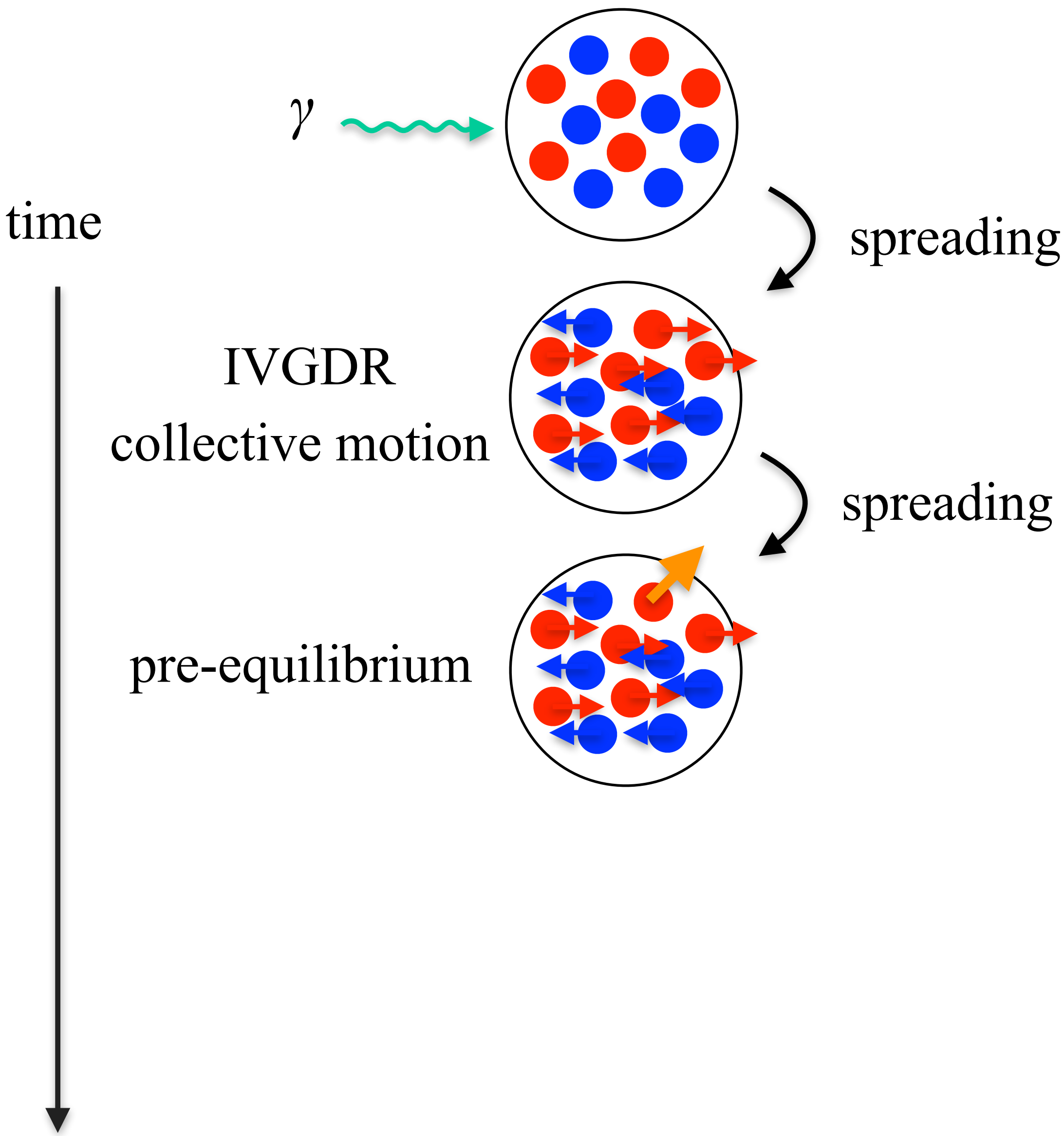

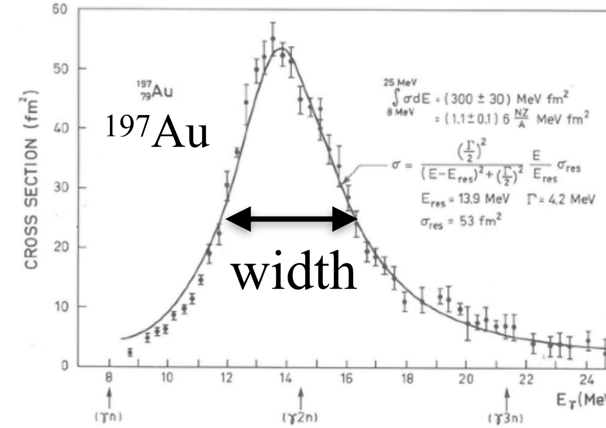

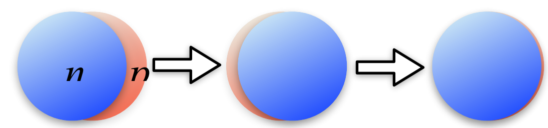

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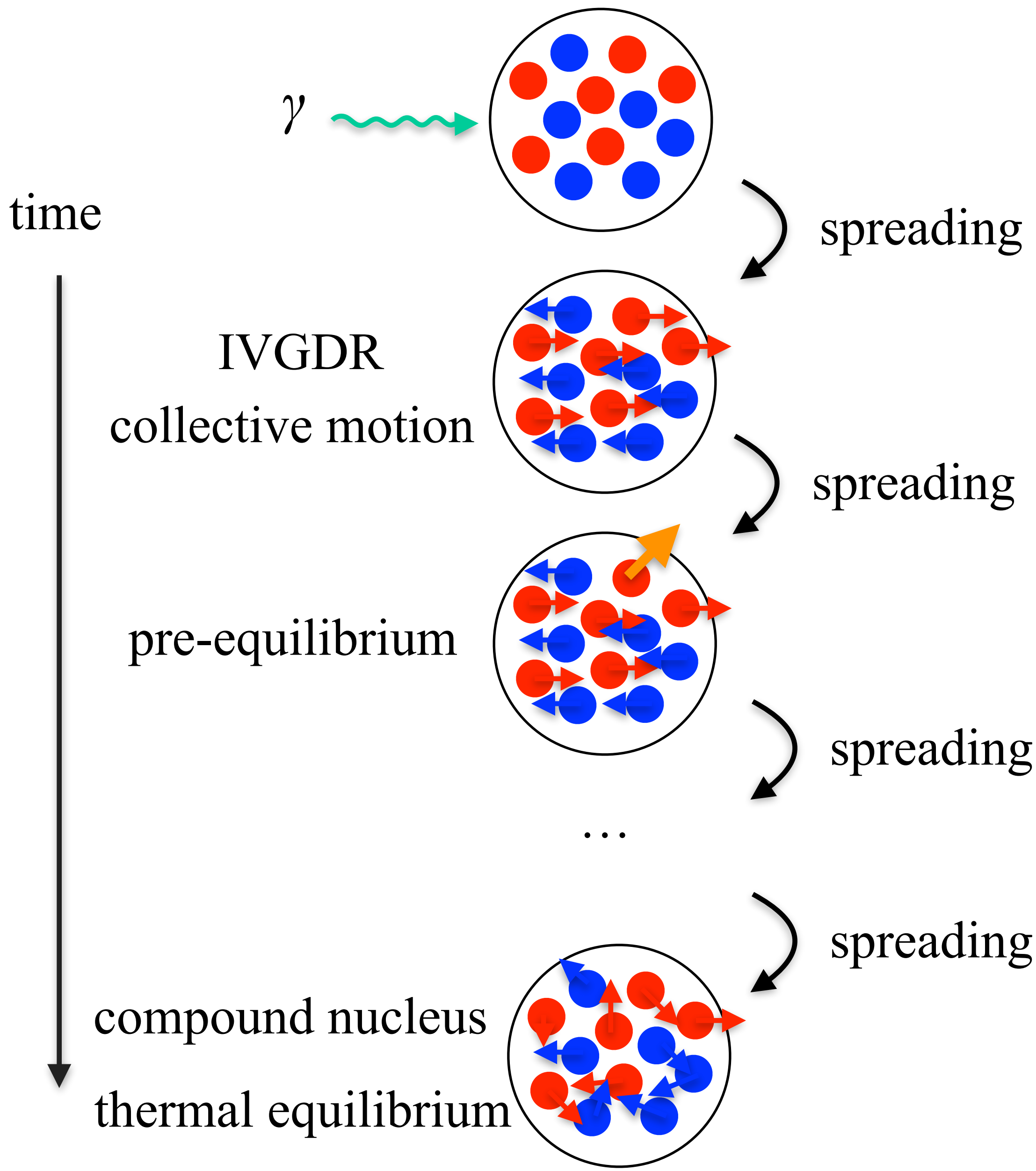

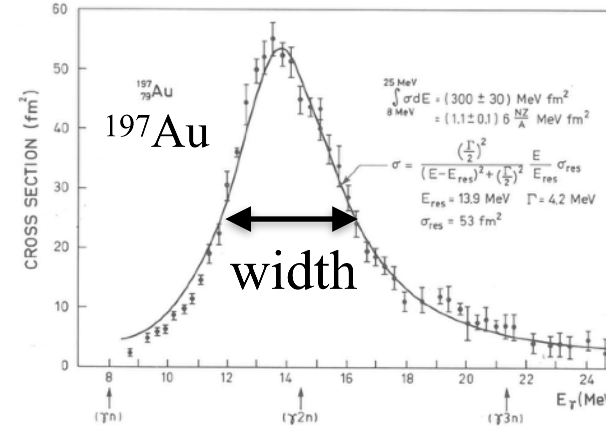

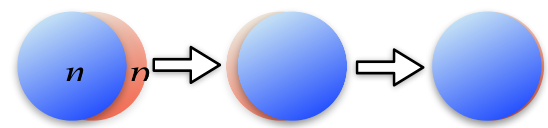

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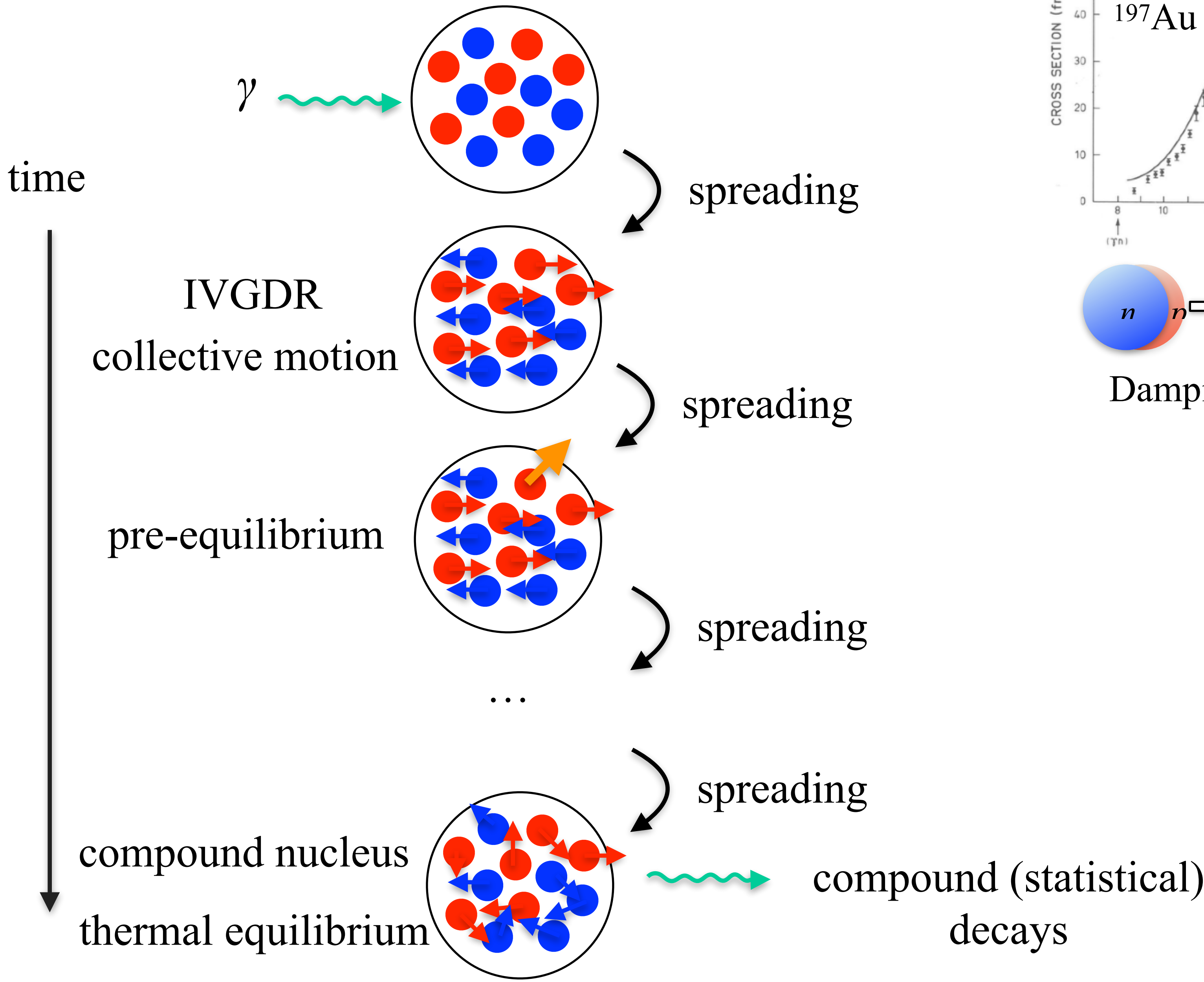

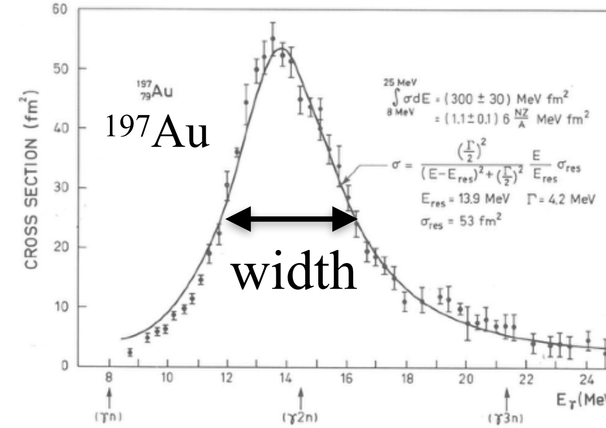

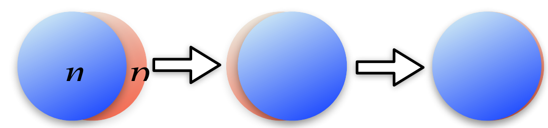

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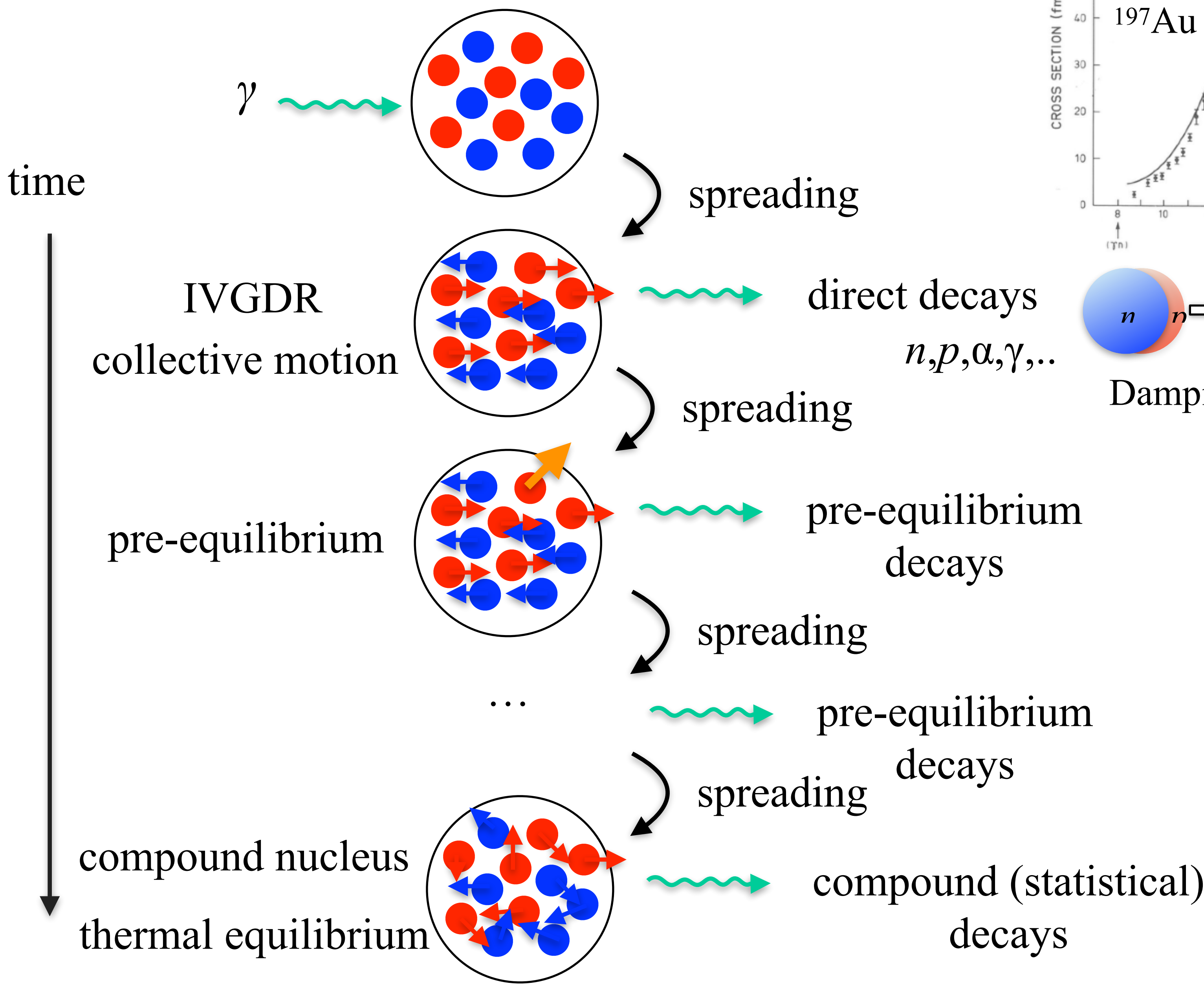

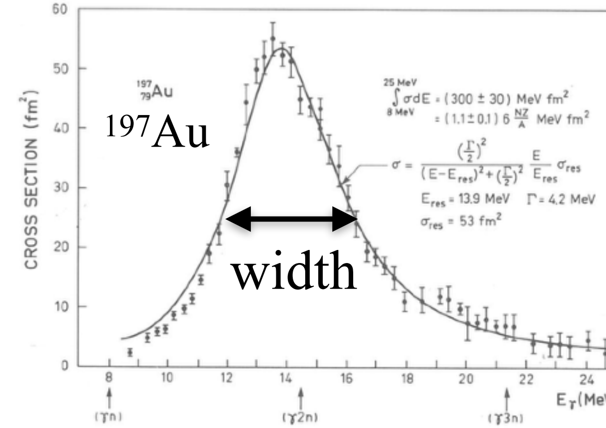

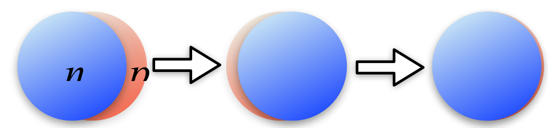

Damping of IVGDR

PANDORA Project: Photo-Nuclear Reactions of Light Nuclei (A<60)

Photo-nuclear reaction of light stable nuclei is important for

- Nuclear structure/reaction studies
- Astro-nuclear physics, particle physics, detector response
- Applications
  - Radiation shield, decommissioning, reactions in nuclear reactors
  - Photo-activation analysis, nondestructive inspection
  - γ-imaging、CT-diagnostics、biological effects
  - Homeland security、inspection of fission or explosive material
  - Medical RI production by photo-irradiation
  - Nuclear reaction/gamma radiation in thunder volts

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99.99999% of the elements in the universe is made of nuclei below A=60

Photo-nuclear reaction on ^{12}C and ^{16}O is not determined well

Oxygen (^{16}O) forms 65% of the human body weight (30% of Earth)

Carbon (^{12}C) forms 18% (0.02%)

Potential biological radiation effect!

α-decay of IVGDR in ^{12}C or ^{16}O is not well measured.

※^{16}O (^{12}O) isotopic abundance: 99.8 (98.9)%

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$$^{16}\mathrm{O}(T=0) + \gamma \rightarrow {}^{16}\mathrm{O}*(\mathrm{IVGDR}: T=1) \nrightarrow {}^{12}\mathrm{C}(T=0) + \alpha(T=0)$$

isospin forbidden decay

requires implementation of isospin-symmetry breaking by Coulomb interaction

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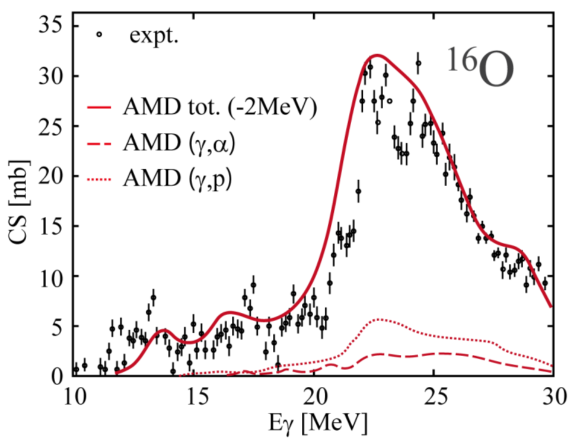
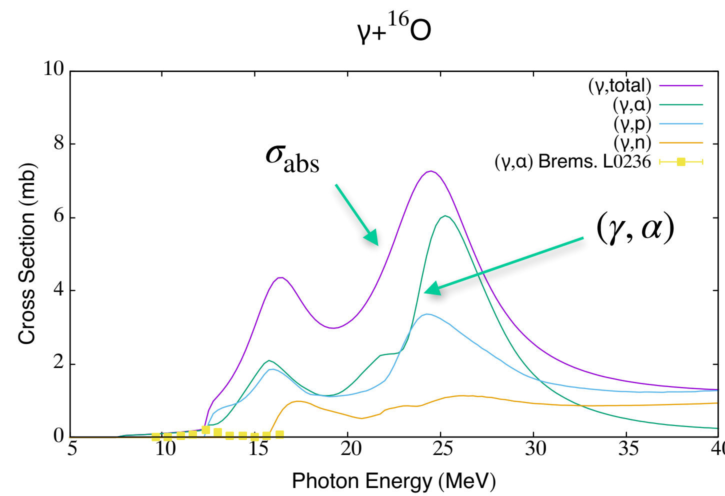


prediction by AMD

M. Kimura et al.,



calculation with TALYS
(default parameters)

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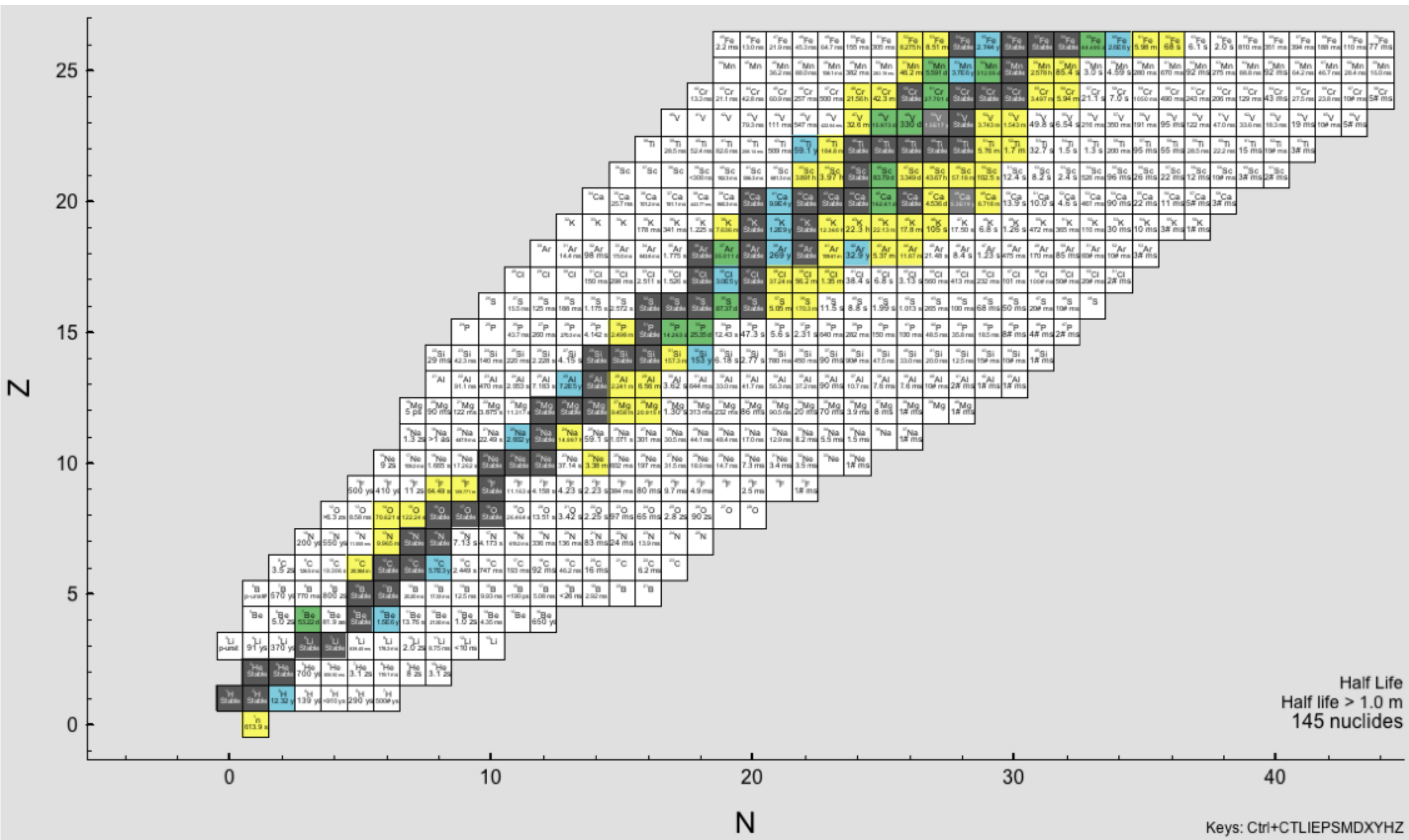
Systematic Measurement on Photo-Absorption C.S. and n,p,α,γ decays for light stable nuclei

- E1 excitation strength distribution
- n, p, α, γ decay branching ratios
- from light to A~60 for stable nuclei



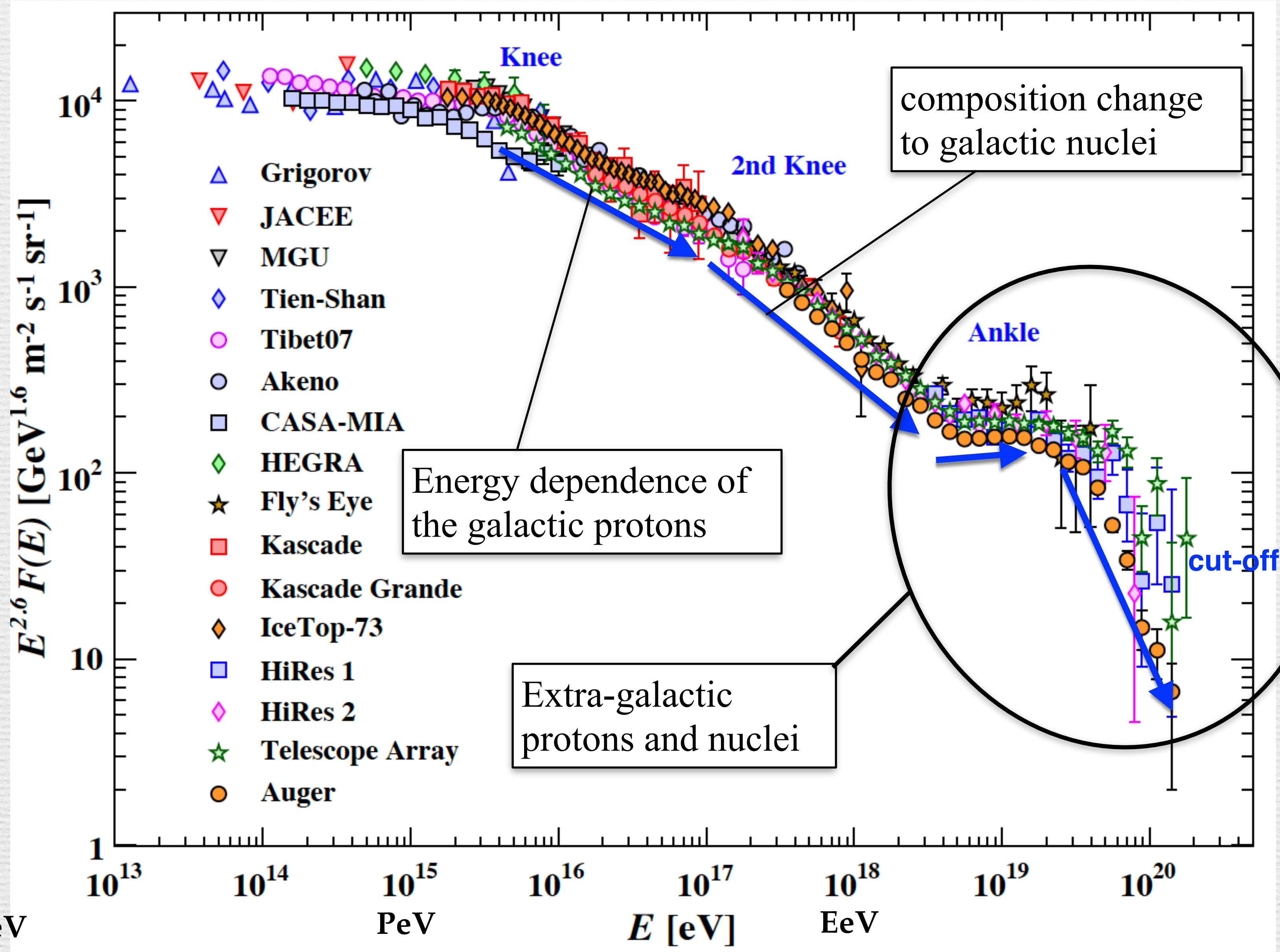
PANDORA Project

Photo-**A**bsorption of **N**uclei and **D**ecay **O**bservation for **R**eactions in **A**strophysics

Motivations

- Intergalactic propagation of ultra-high energy comic rays (UHECRs)
- Nuclear Structure
  - electric dipole strength distribution: PDR, GDR, EDP
  - decay mechanism
  - gamma-decay of GR: damping mechanism
  - alpha-clustering structure
- Nuclear-astrophysics and nucleosynthesis
- Neutral-current neutrino detection in large volume neutrino detectors
- Applications

Ultra-High-Energy Cosmic Rays (UHECRs) [PDG2018]



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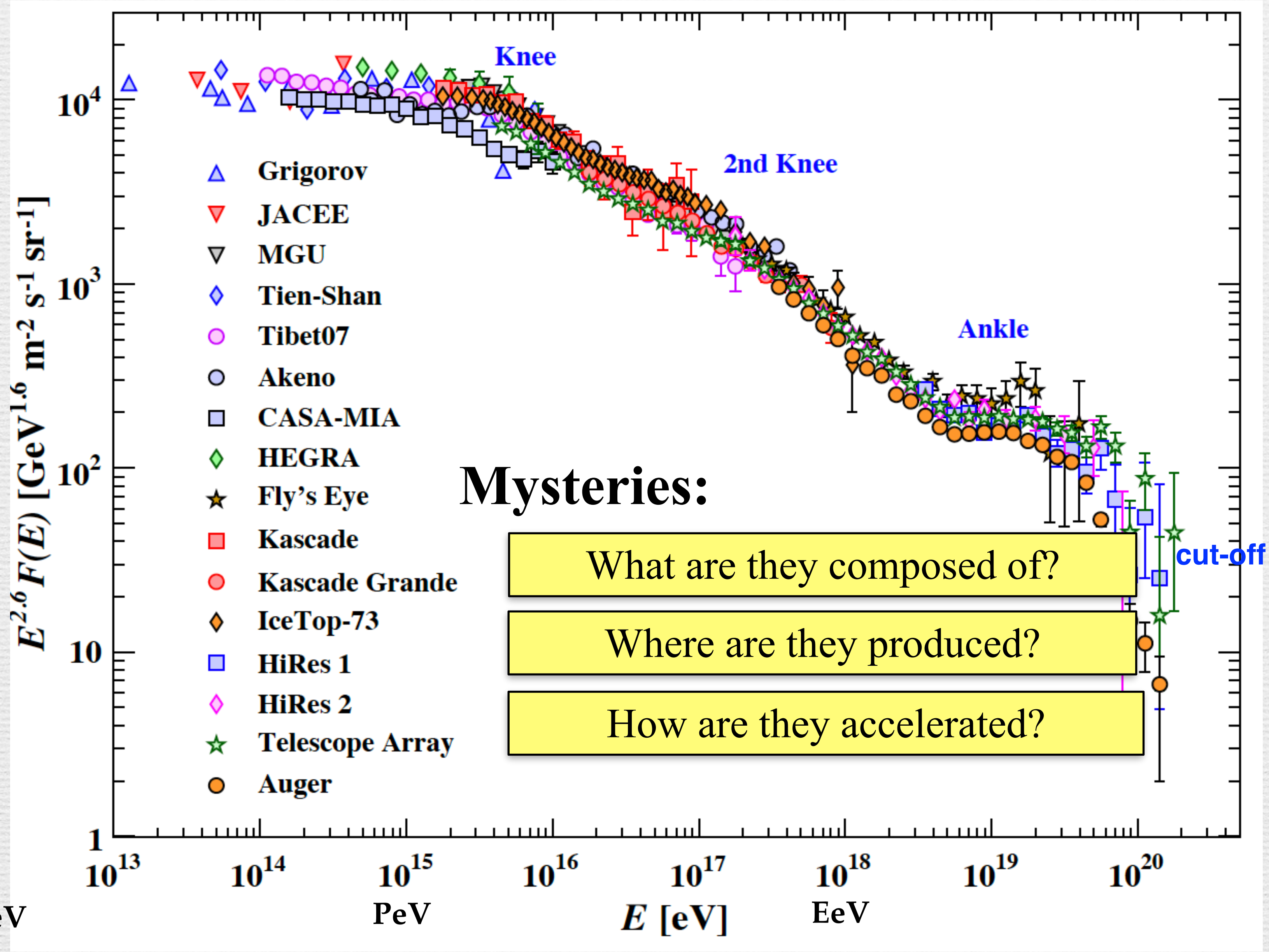
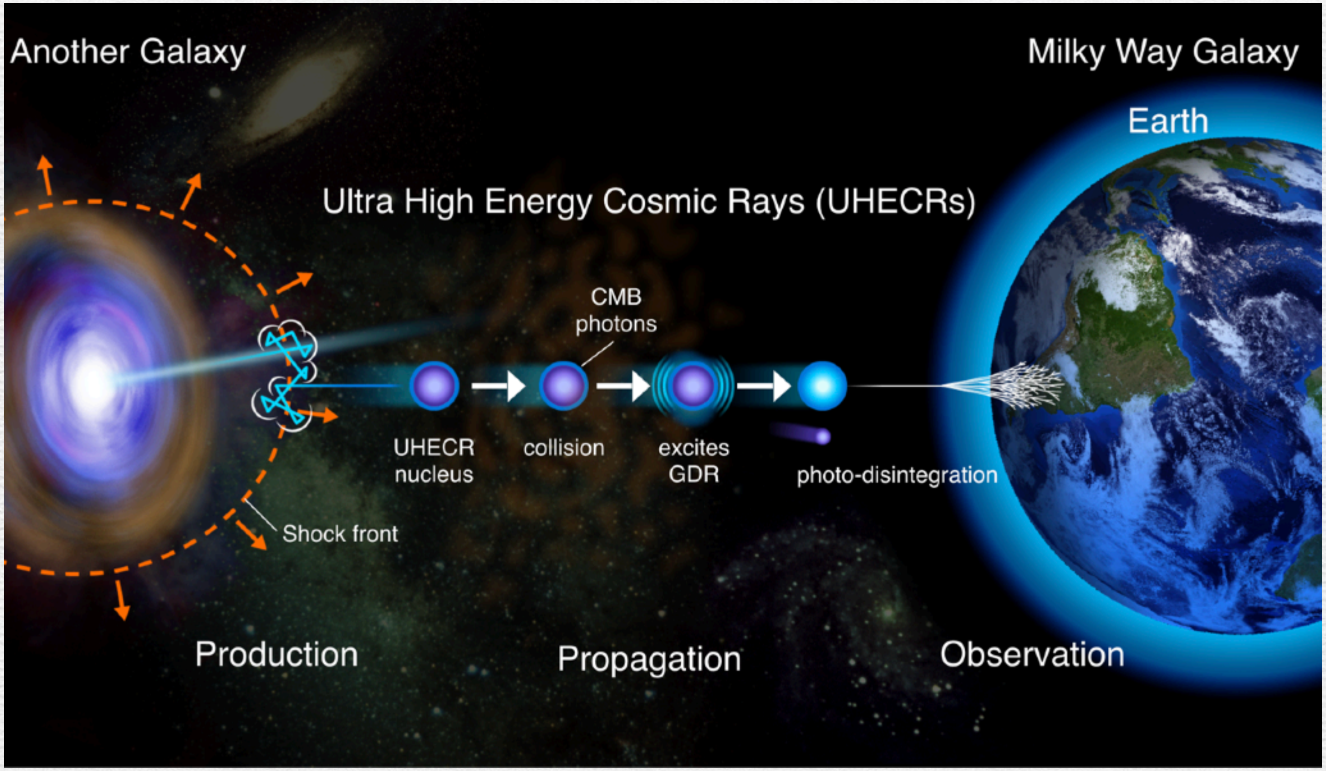


Mysteries:

- What are they composed of?
- Where are they produced?
- How are they accelerated?

Intergalactic Propagation of UHECR Nuclei

Greisen, Zatzepin, and Kuzmin (GZK) Cut-off



Cosmic Microwave Background (CMB)

WMAP

T=2.73 K

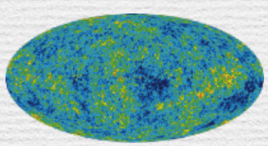


Photo-nuclear reactions determine the maximum travel distance of UHECR nuclei and their composition/energy evolution.

GZK cut-off

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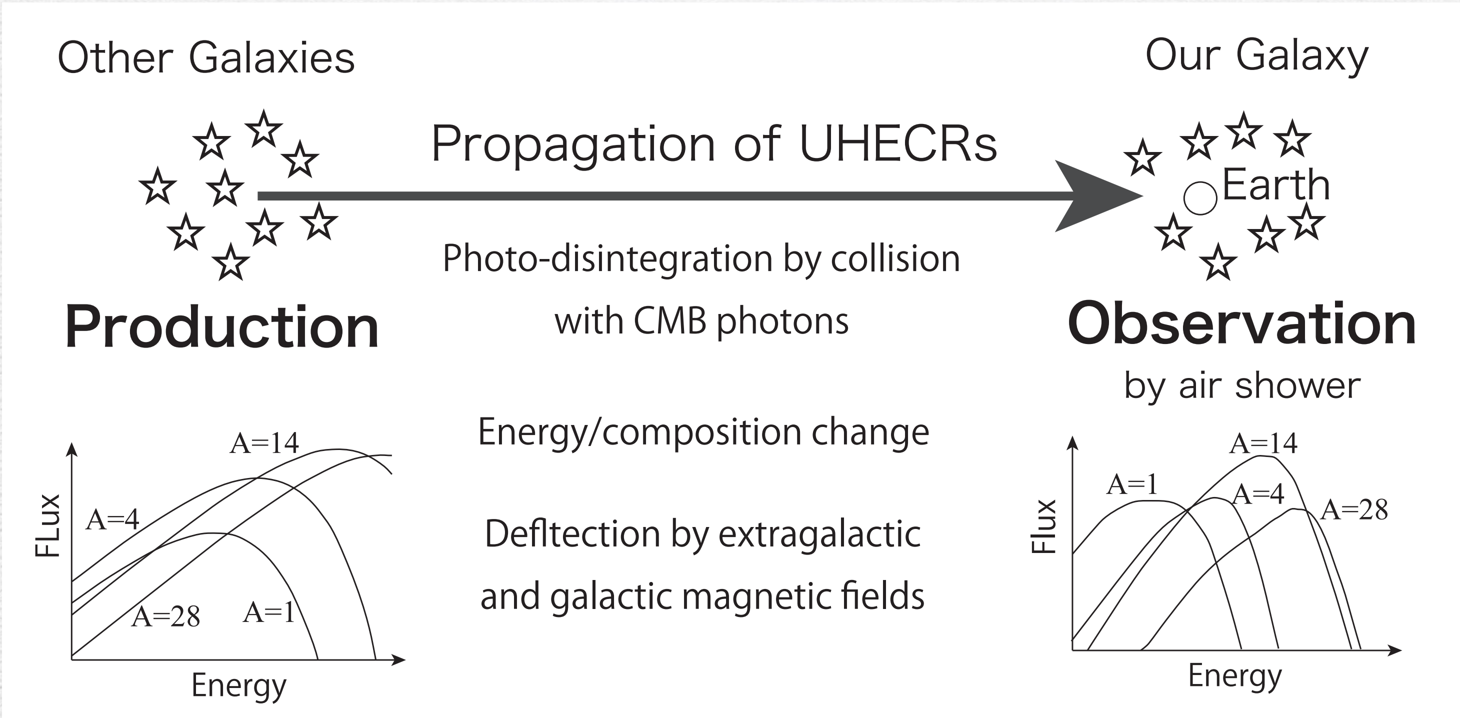

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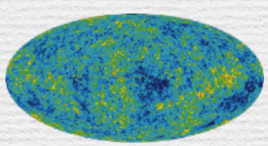

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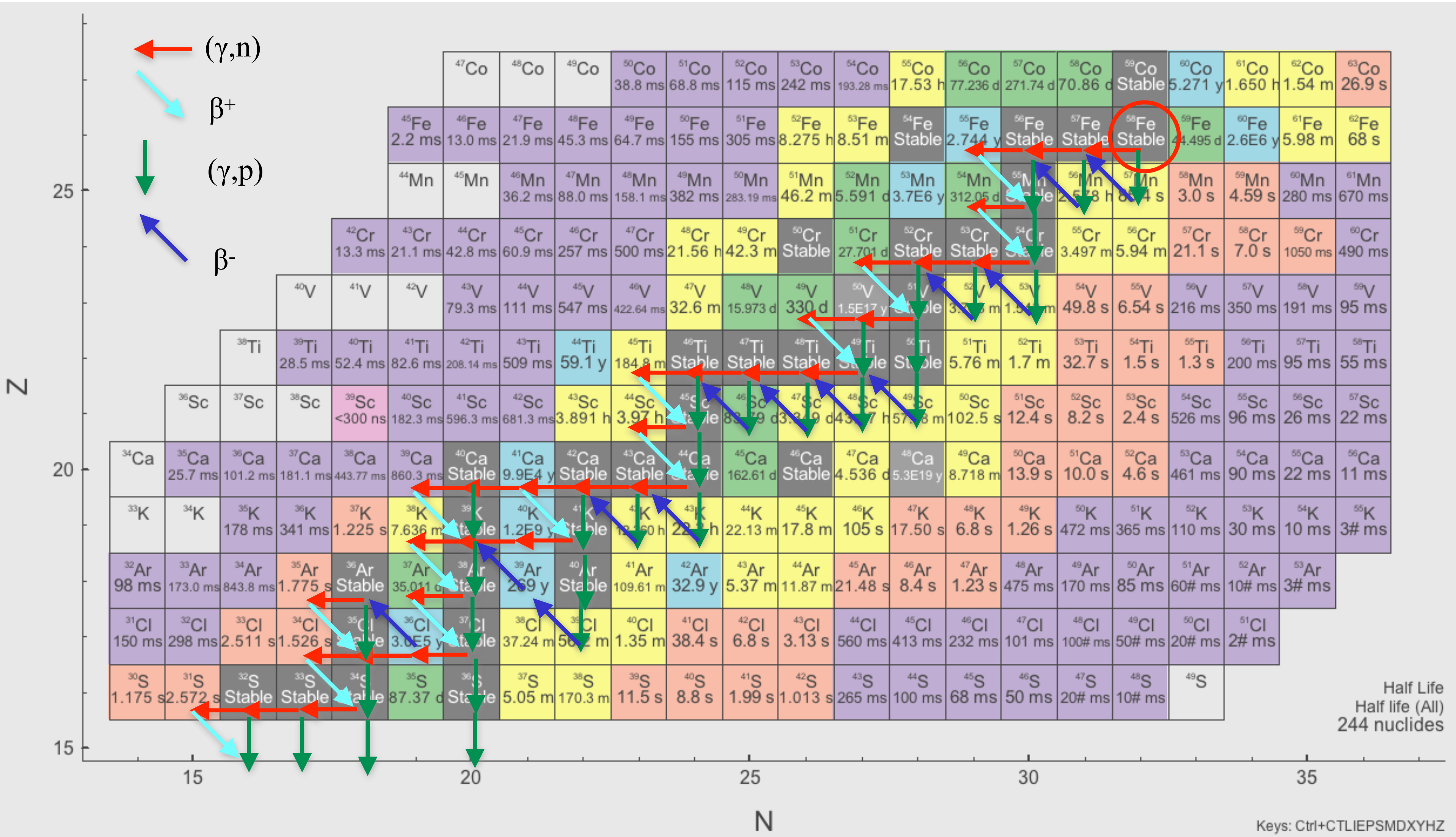
Photo-disintegration Pass of ^{56}Fe



(γ,xn), (γ,α) reactions also take place.

Several unstable nuclei also contribute.

PANDORA Project: Organization

Nuclear Experiment

RCNP	*Osaka Univ.* **A. Tamii**, N. Kobayashi, **Y. Sasagawa**, **Y. Suzuki, Y. Irie**, W.H. Guo, et al.
ELI-NP	*ELI-NP* **P.-A. Söderström**, D. Balabanski, **A. Gavrilescu**, Asli Kusoglu, et al.,
iThemba LABS	*iThemba LABS, Univ. Witwatersland, Stellenbosh Univ.* **L. Pellegri**, R. Neveling, **J.A.C. Bekker**, et a.,
TU-Darmstadt	P. von Neumann-Cosel, N. Pietralla, J. Isaak, J. Kleemann, M. Spall, et al.
U. Milano/INFN	A. Bracco, F. Camera, F. Crespi, O. Wieland, et al.
Shanghai	H. Utsunomiya, H. Wang, et al.
U. Oslo	S. Siem, A. Görgen , K.C.W. Li, et al.,

Nuclear Theory

AMD	**M. Kimura,** Y. Taniguchi, H. Motoki
NRFT	**E. Litvinova**, P. Ring, H. Wibowo
RPA/DFT	RPA by **T. Inakura,** QPM by **N. Tsoneva**
TALYS	**S. Goriely**, **E. Khan**
Large Scale Shell Model	**Y. Utsuno, N. Shimizu** K. Sieja, O.L. Noan
Reaction/Decay	K. Ogata, **F. Minato**

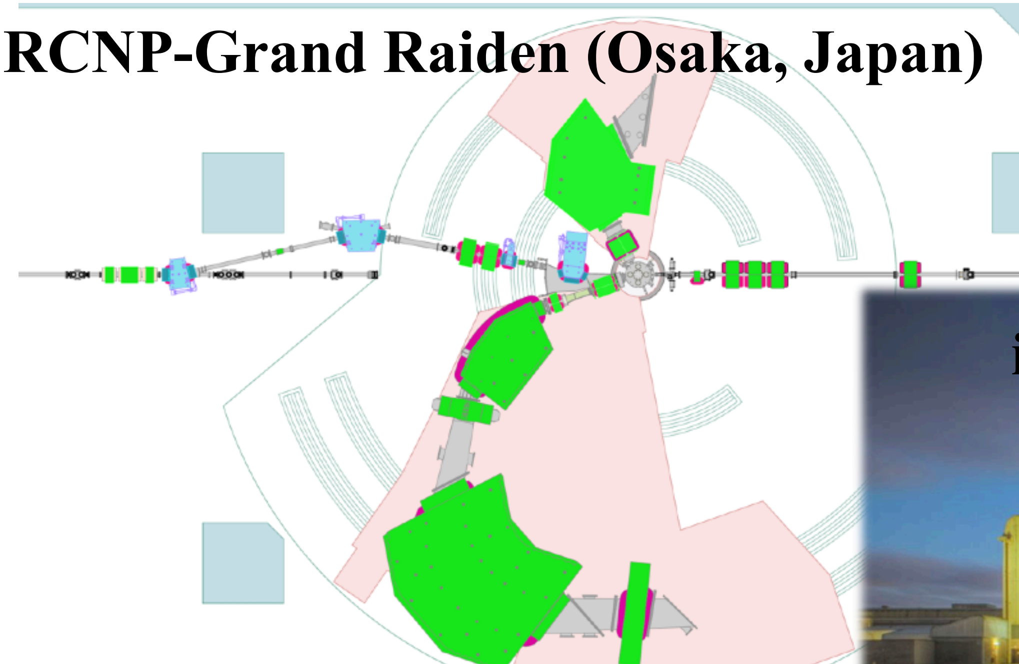
UHECR Theory

Propagation and production	**D. Allard**, B. Baret, I. Deloncle, J. Kiener, E. Parizot, V. Tatischeff **S. Nagataki**, **E. Kido**, J. Oliver, H. Haoning

PANDORA project: experimental facilities

Photo-**A**bsorption of **N**uclei and **D**ecay **O**bservation for **R**eactions in **A**strophysics

White paper: AT et al.,. Euro. Phys. J. A **59**, 208 (2023)



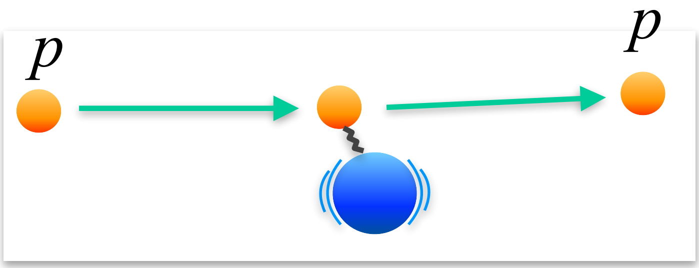
Experiments at three facilities
with complementary techniques

Joint project of experimental nuclear physics, theoretical nuclear physics and particle astrophysics

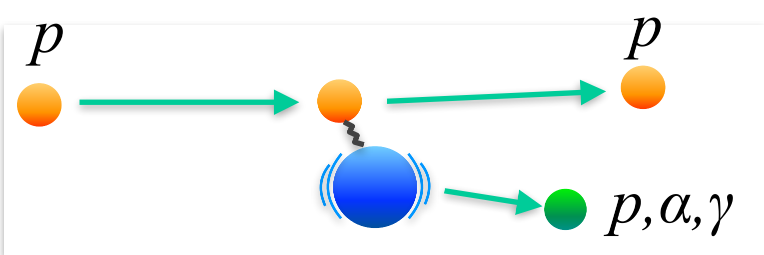
Probing Photo-Nuclear Response of Nuclei

Virtual photon excitation by proton scattering (RCNP, iThemba)

- Missing mass method
  with proton Coulomb excitation

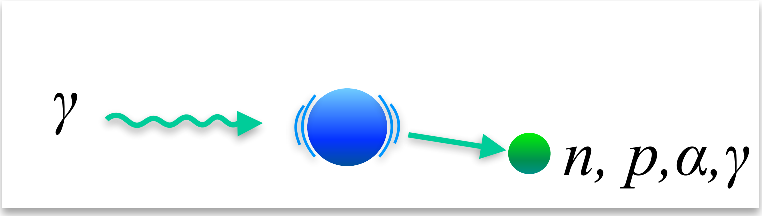


- better for the total c.s.
  and for the c.s. distribution
  larger cross sections
  applicable to p,α,γ decays



Real photon excitation (ELI-NP, Shanghai)

- Gamma-beam by laser-Compton
  scattering with an electron beam



- individual decay channels
  better for absolute normalization
  applicable also for *n* decays

Virtual Photon Excitation by Proton Scattering at 0°

RCNP

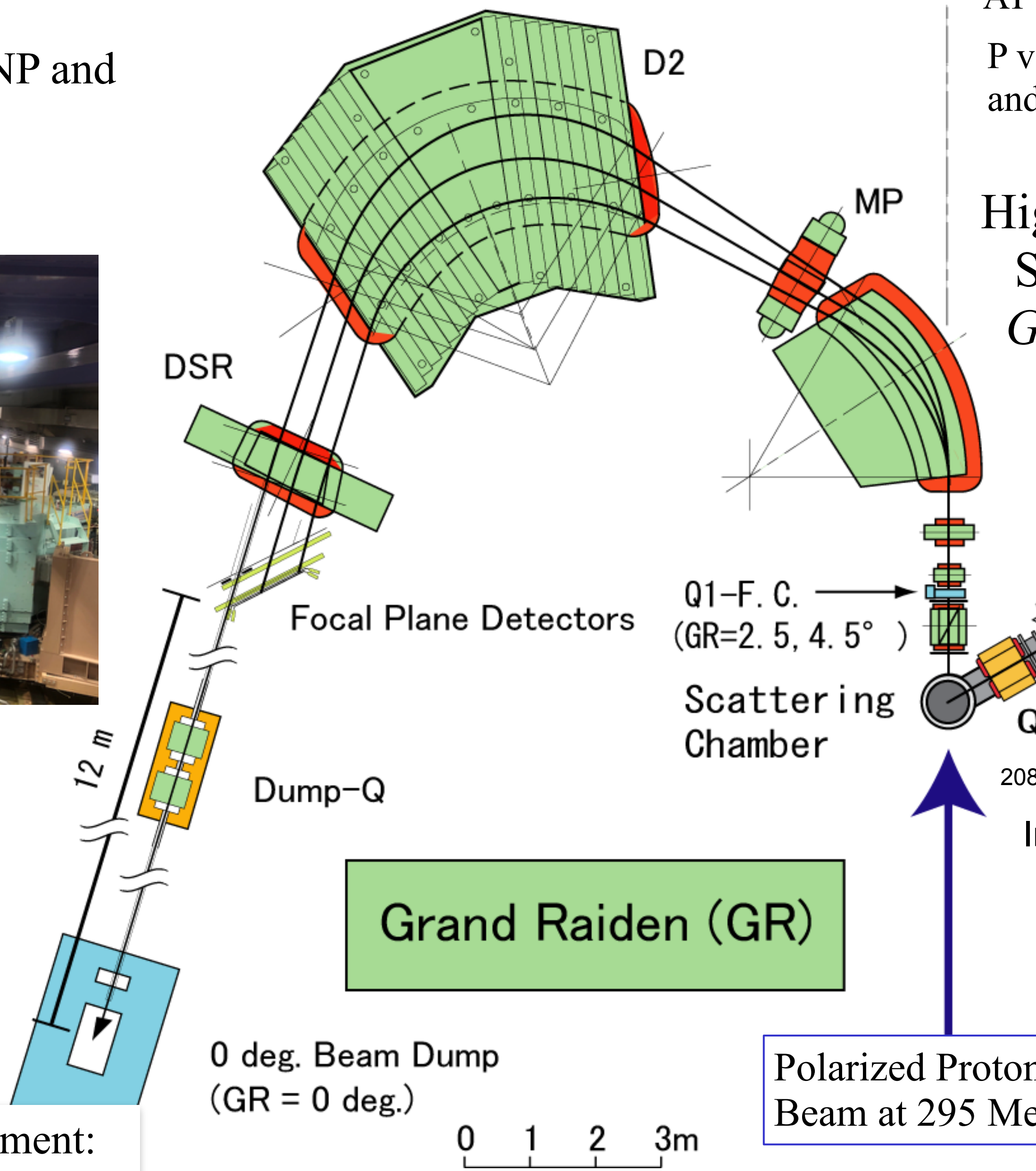
Applicable at RCNP and iThemba LABS

AT et al., NIMA2009

P von Neumann-Cosel and AT EPJA2019

High-Resolution Spectrometer *Grand Raiden*

Proton scattering at very forward angles



^{208}Pb target: 5.2 mg/cm^2

Intensity : 1-8 nA

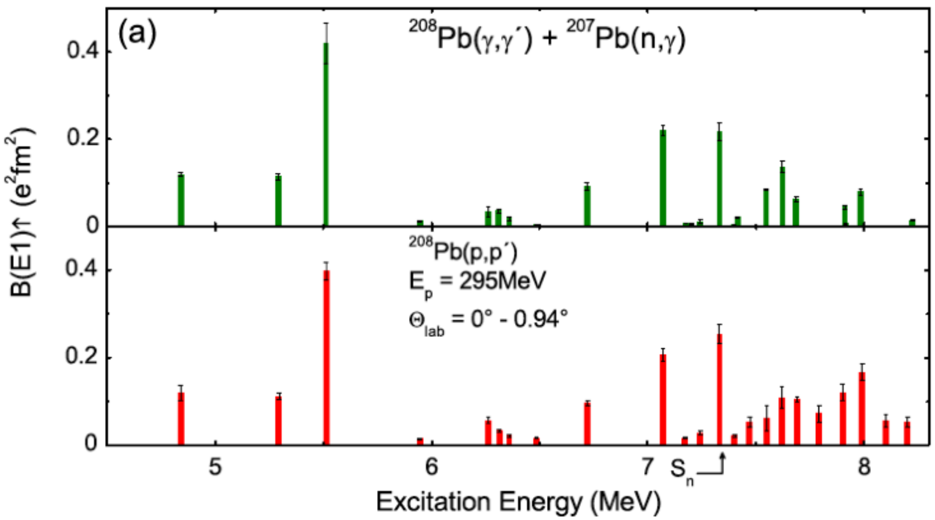
Polarized Proton Beam at 295 MeV

High resolution measurement: 20 keV by dispersion matching.

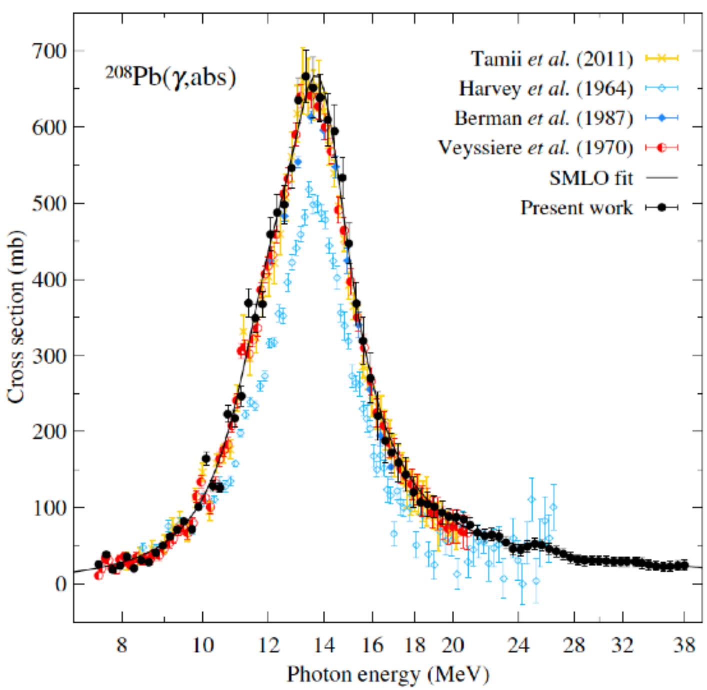
Proton beam data in comparison with (γ,γ') and (γ,xn)

^{208}Pb

AT et al., PRL2011



low-lying
discrete states



GDR region

(p,p') at RCNP

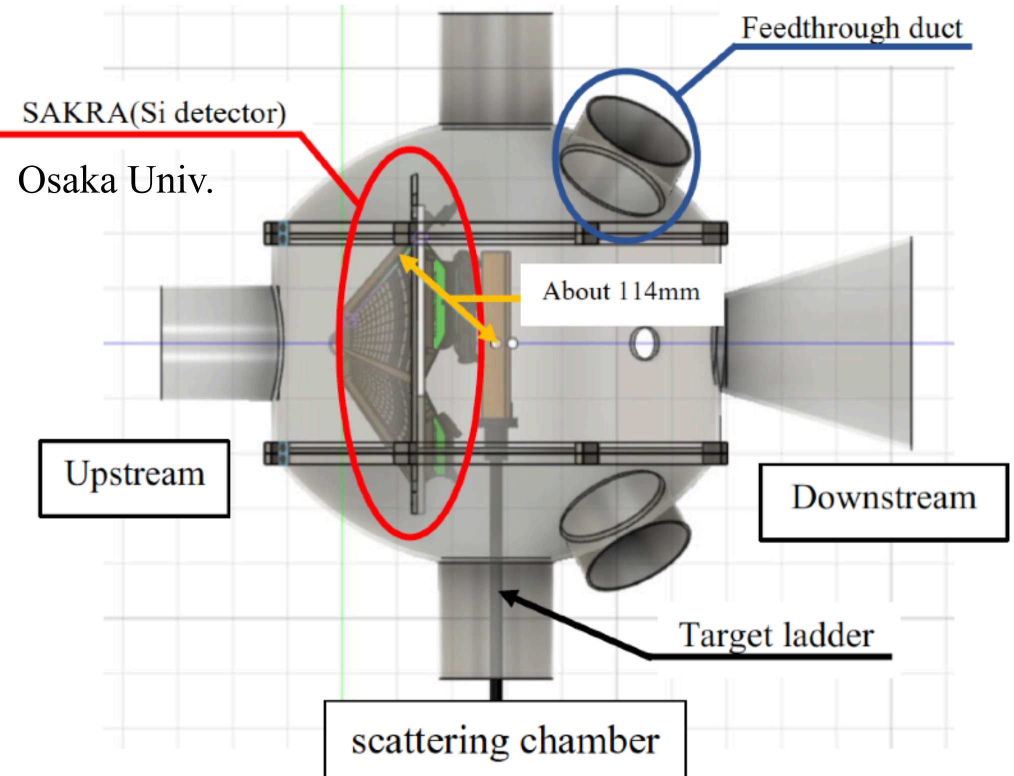
AT et al., PRL2011

(γ,xn) at NewSUBARU

I. Gheorghe et al, PRC2024

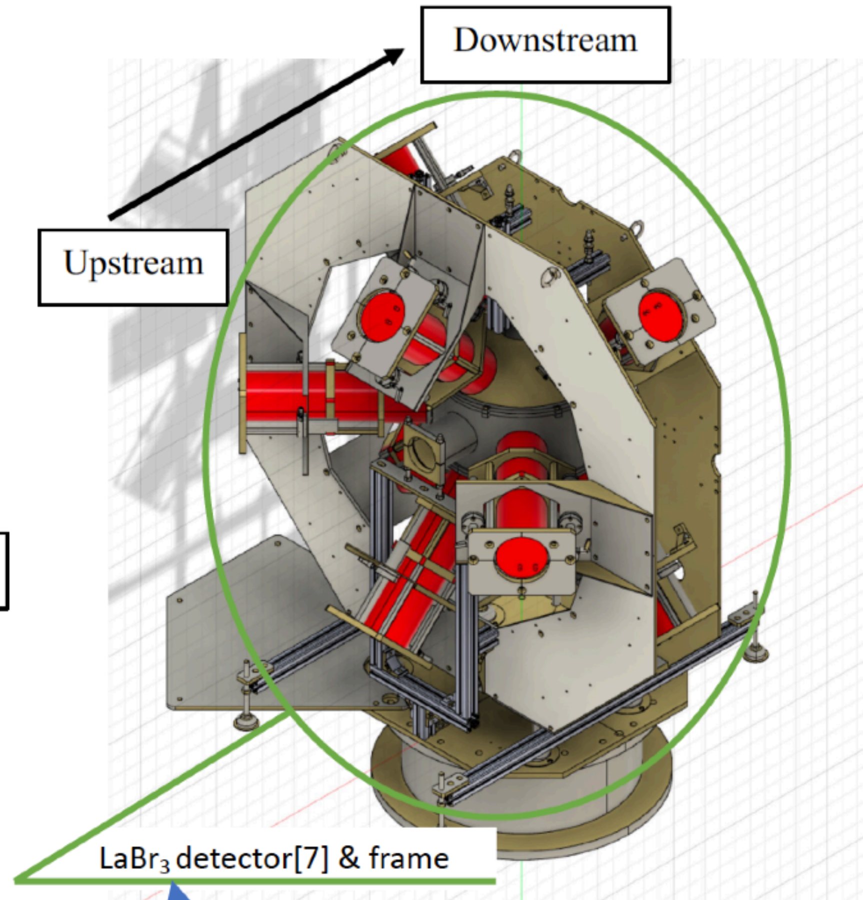
The first PANDORA experiment at RCNP, Oct. 2023

Detector setup at Grand Raiden Spectrometer



Features

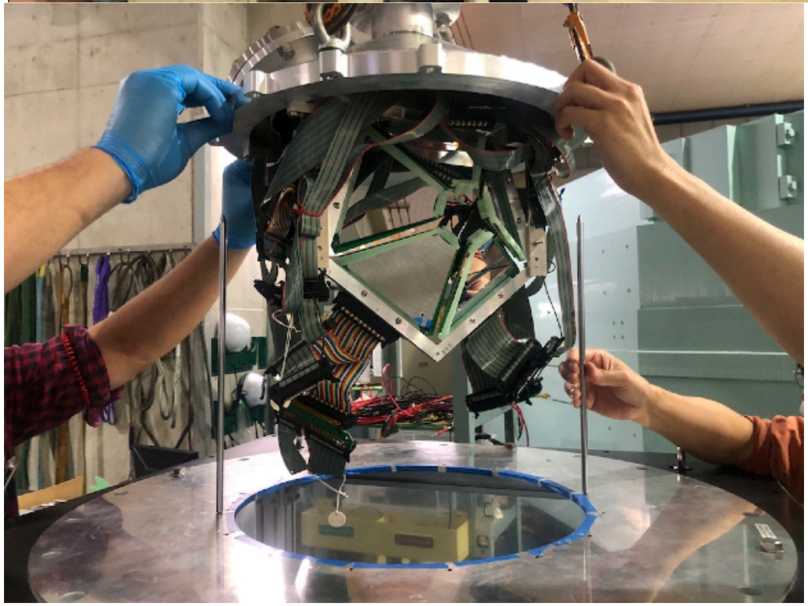
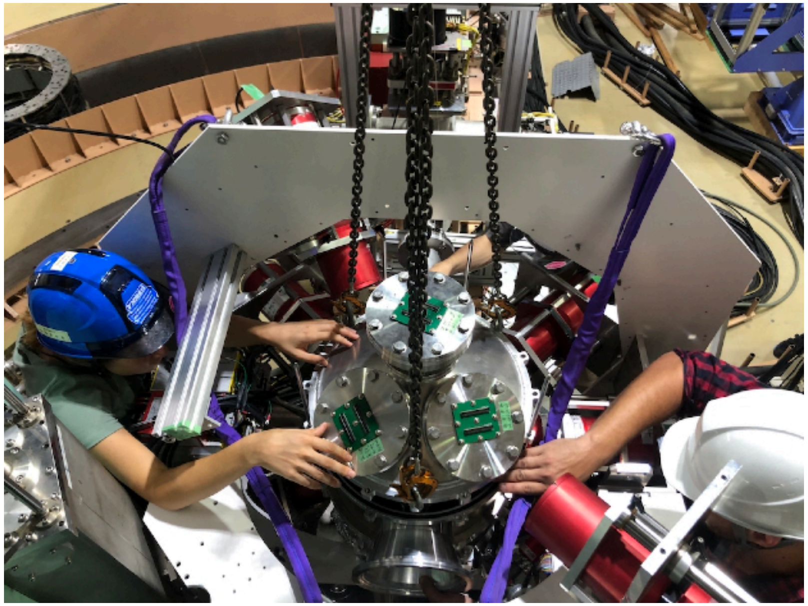
- Near Spherical shape
  → To bring the detector closer
- SAKRA mounted on lid
  →For easy SAKRA evacuation



This $LaBr_3$ detectors belongs to the Milan Group.

Experimental setup, September 2023



Targets

Measurements on 10-20 nuclei in ~10 years
with theoretical model developments

σ_{abs} distribution and decay branching ratios in 10% accuracy

Candidate target nuclides

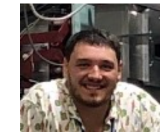
- ^{12}C, ^{16}O, and ^{27}Al — first cases, alpha decay, reference target
- ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B — light nuclei
- (^{20}Ne), ^{24}Mg, ^{28}Si, ^{32}S, (^{36}Ar), ^{40}Ca — N=Z nuclei, α-cluster effect, deformation
- ^{26}Mg, ^{48}Ca, ^{56}Fe — N>Z nuclei
- ^{13}C, ^{14}N, ^{51}V — odd and odd-odd nuclei
- (γ,xn) on ^{18}O, ^{48}Ca, ^{64}Ni

Measured in 2023

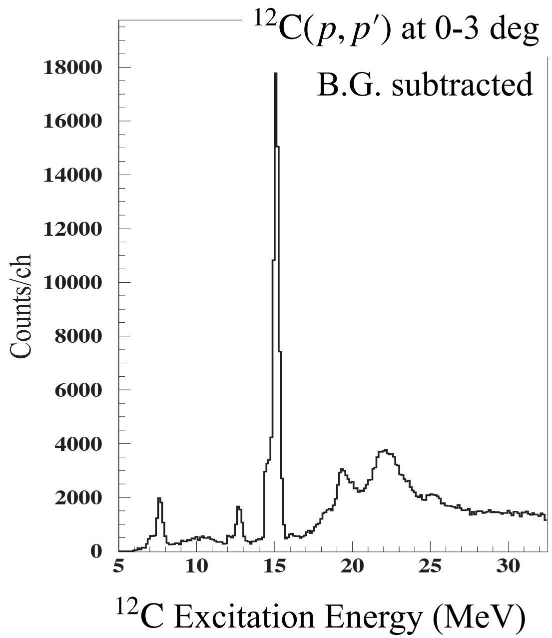
- (red box) photo-abs. c.s. + charged particle decay + gamma
- (green box) photo-abs. c.s. + gamma

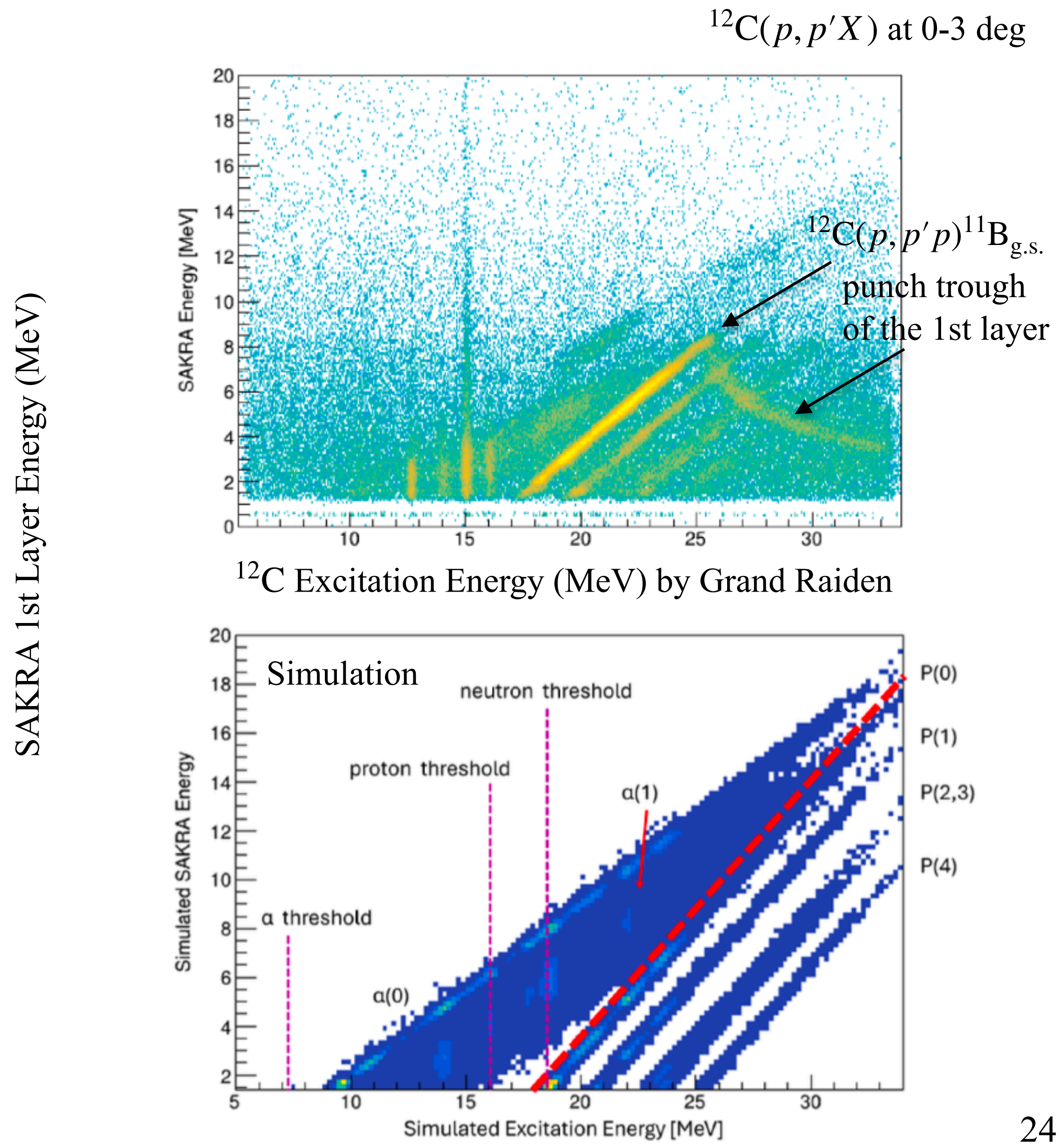
(dotted box) planned in Oct 2025

Preliminary data from E563

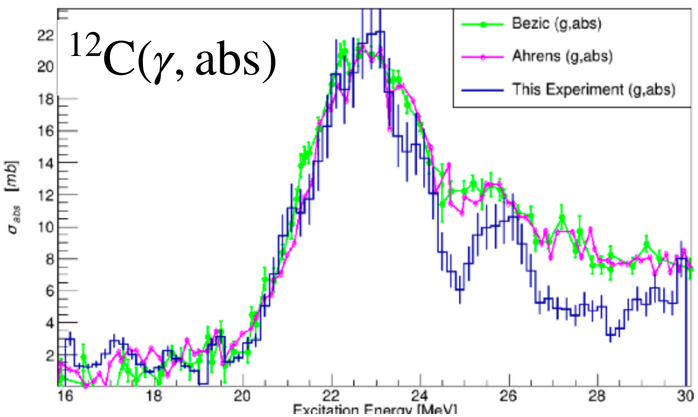


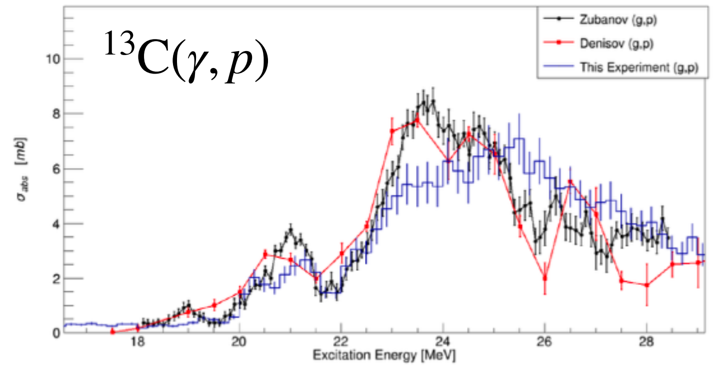
Data analysis by J.A.C. Bekker



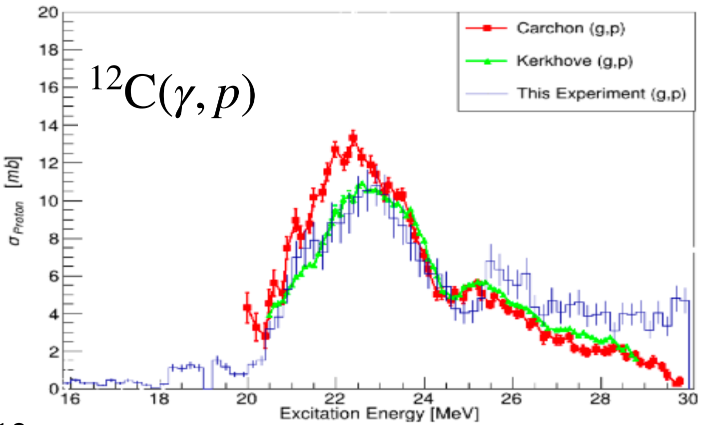


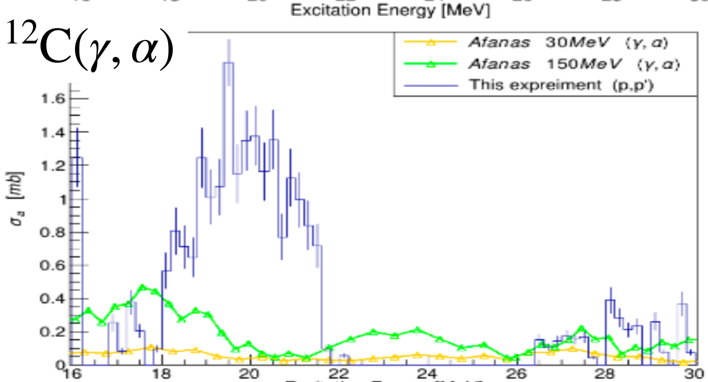
Preliminary Cross Sections





J.A.C. Bekker (SA)





— This experiment

Summary

- The photo-absorption c.s. and the decay branching ratios will be systematically measured up to A~60 in the PANDORA project.
- The photo-nuclear reaction data are important for developing nuclear structure/decay models and for understanding the inter-galactic propagation of UHECRs.
- Virtual photon excitation method by proton scattering has been applied at RCNP (will be at iThemba LABS), and real photon excitation by LCS gamma-ray facilities.
- The first PANDORA experiment was carried out at RCNP out in 2023. The second experiment is scheduled in Oct 2025.

Thank you for the support from r-EMU

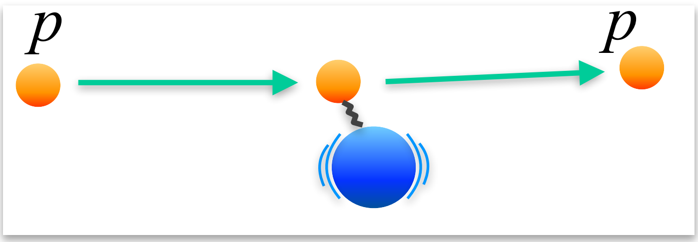
Backup Slides

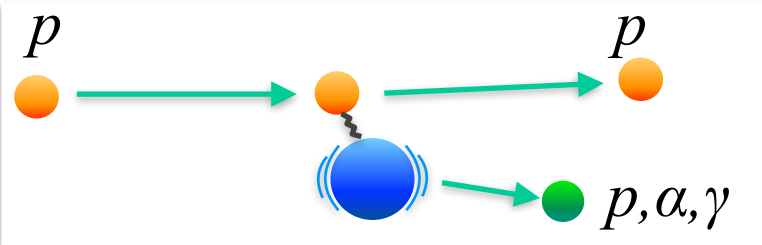
Measurement of the Photo-Nuclear Reaction and decay branching ratios by proton scattering

Virtual photo-excitation by proton scattering at forward angles

- Missing mass method
  with proton Coulomb excitation

- applicable for p,α,γ decays

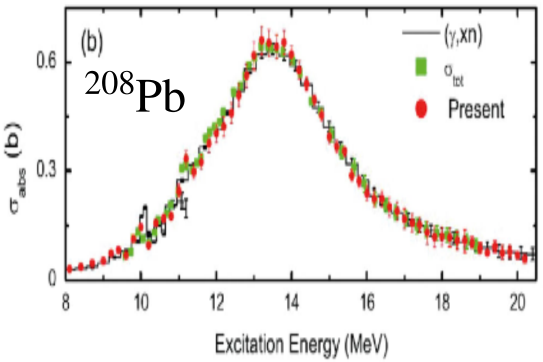




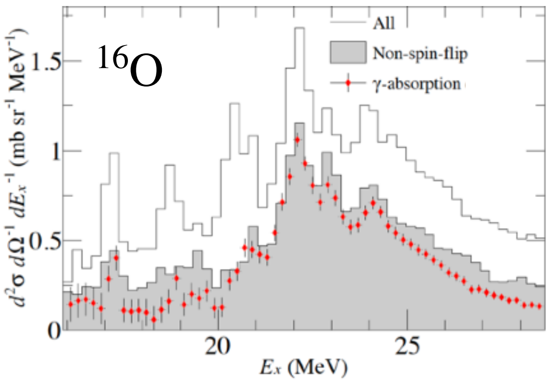
Multipole-decomposition analysis of the angular distribution to extract *E1*.

P. von Neumann-Cosel and AT, EJPA'19

AT et al., NIMA'09



AT et al., PRL'11



T. Sudo et al., RCNP-E398

UHECR spectrum after their extragalactic propagation

Assuming :

(i) a uniform distribution of extragalactic sources

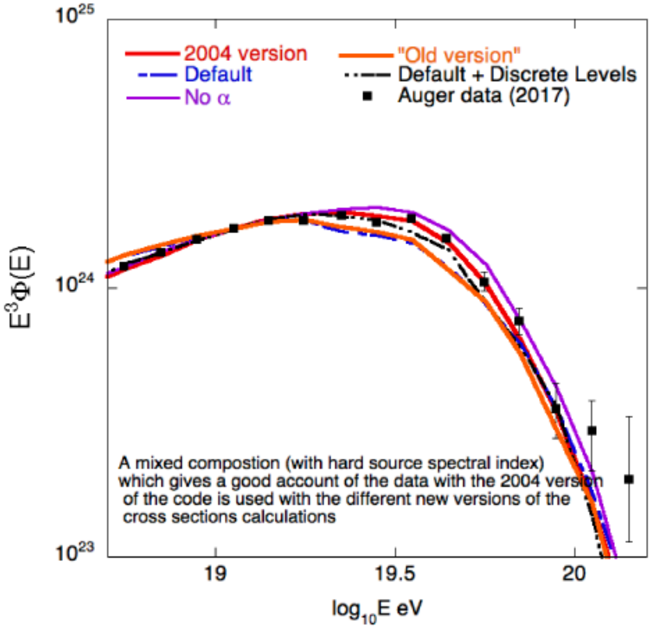
(ii) standard candle sources emitting a power law spectrum of UHECRs (i.e $N(E) \sim E^{-\beta}$)

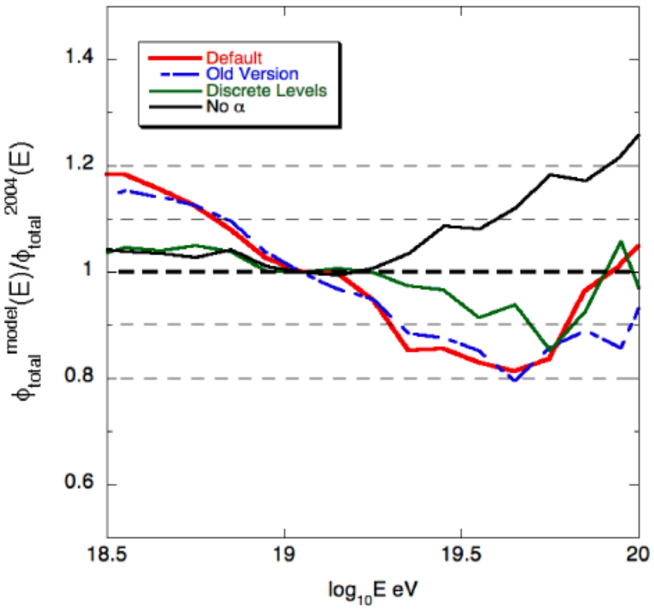
A set of parameters which allows a satisfactory reproduction of the UHECR spectrum and composition are (for the code used in Allard et al., 2005) :

(i) a source spectral index β=0.61

(ii) a low maximum energy at the sources $E_{max}(Z)=Z\times4.10^{18}$eV where Z is the charge of the nucleus

(iii) relative abundances : H=0.1, He=0.15, CNO=0.68, Si=0.07, Fe=0.002 (NB : no astrophysical motivations)





* The spectrum with the "No α" settings is quite harder than the other —> slower photodisintegration

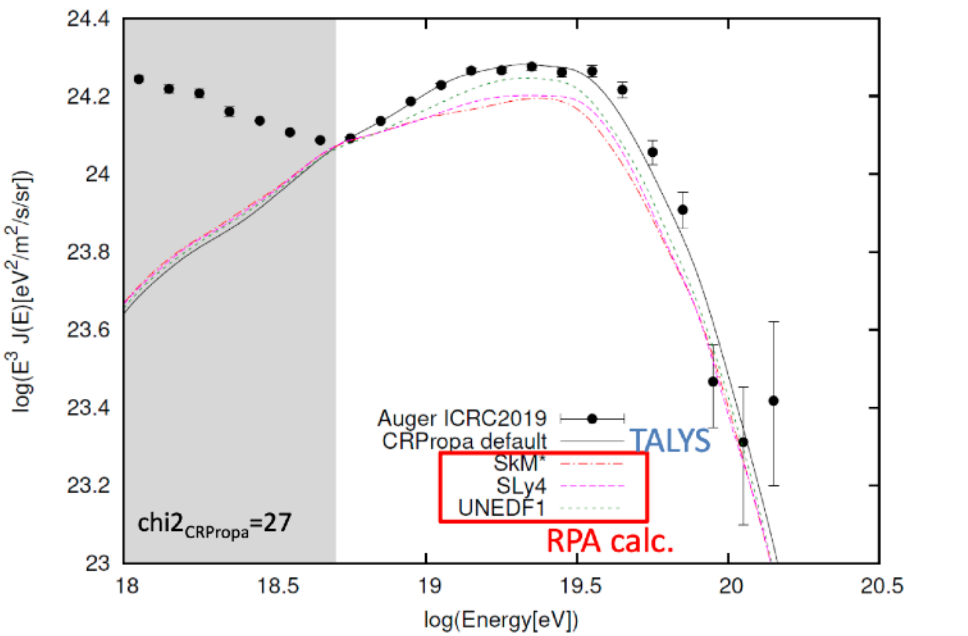
* "Discrete Levels" settings and the 2004 version are quite close to each other

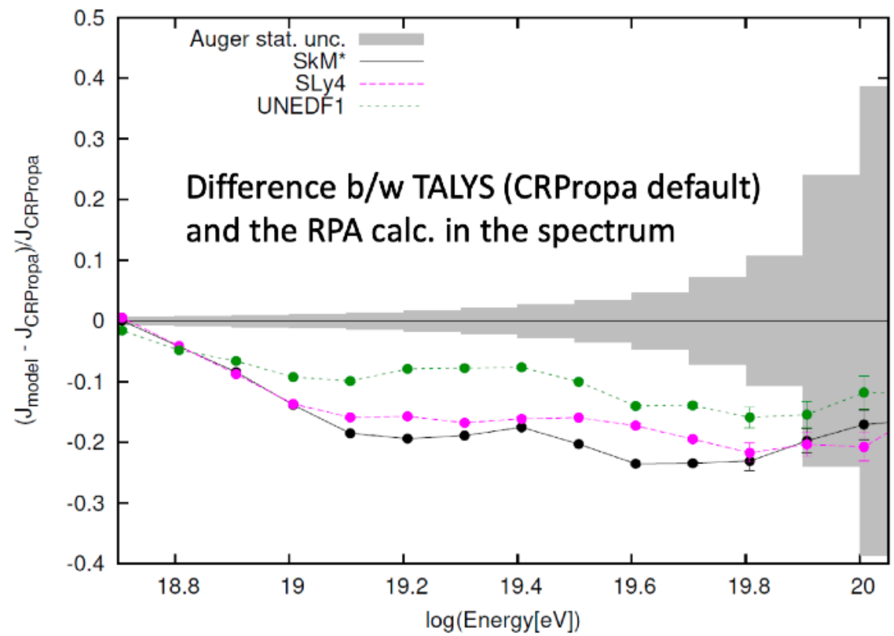
* The "default" and "old settings" are softer

Why is that so ?

—> channels involving α particles in light nuclei (e.g,(γ,α), (γ,n+α), …), see next slides

Comparison of the simulated spectral shape



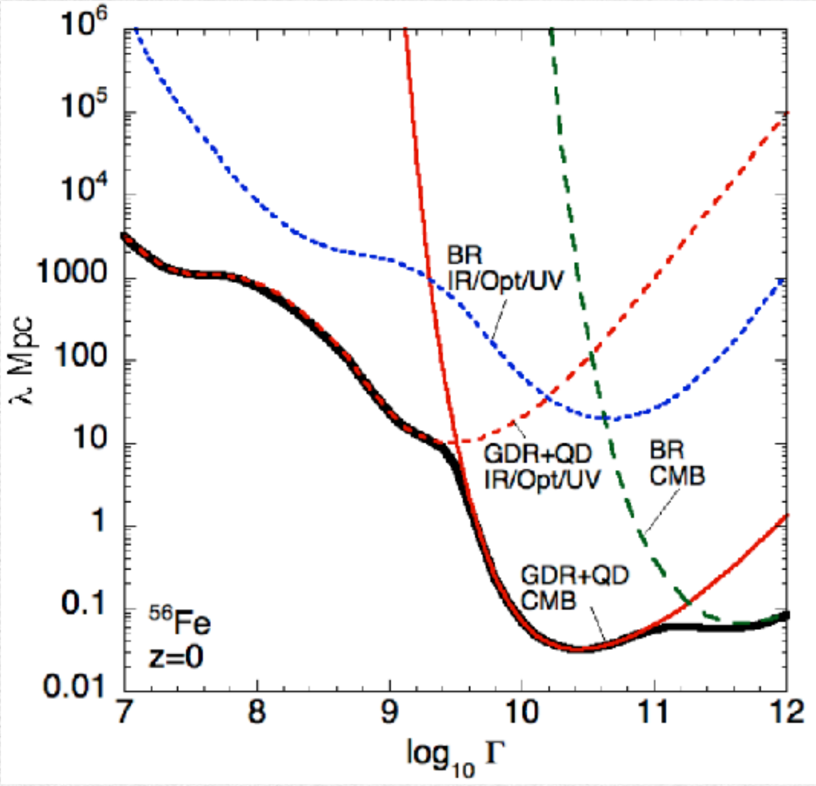


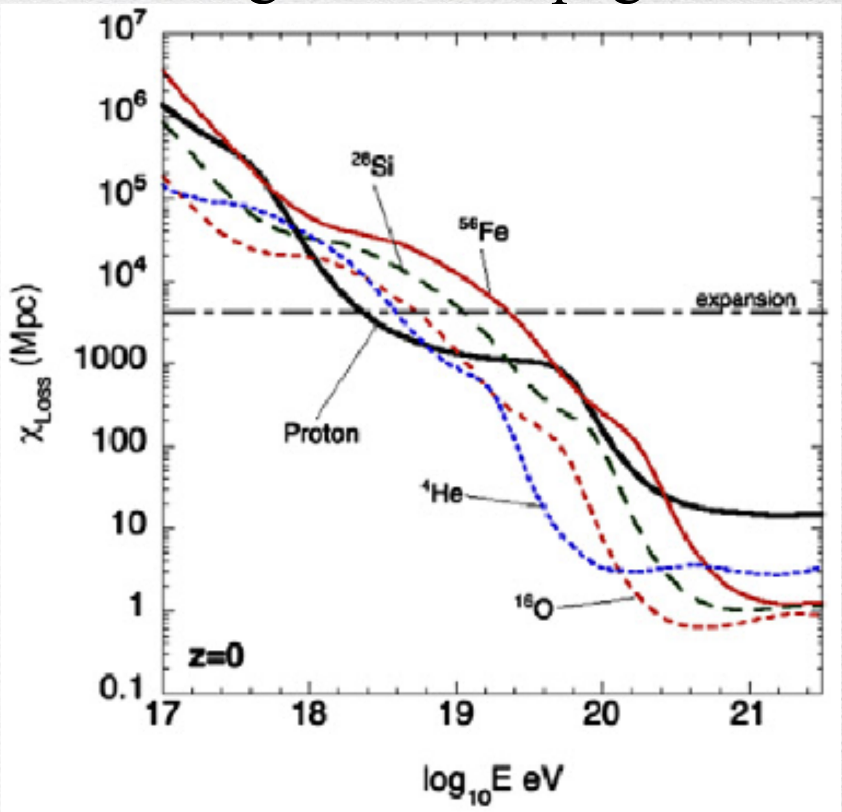
The RPA implies lower cutoff rigidity than TALYS mainly because of the difference in the GDR peaks. This is the opposite effect to the PSB model.

The difference: more than the statistical uncertainty of the experimental data.

E. Kido et al., Astropart. Phys. 2023

Energy Loss Process of UHECRs in Extragalactic Propagation





Refinements of the theoretical model in [kha05]

[ste99]

Unfortunately, photodisintegration cross section data are incomplete. For many reaction channels, $\sigma(\epsilon)$ data do not exist. Also, integrated cross section strengths are not available for all of the exclusive channels. The most complete compilation of the world's GDR cross section data exists in the 15 volumes of Fuller & Gerstenberg (1983). In these volumes GDR cross section data for ^{56}Fe, for example, are given only for the (γ, pX) channel and the inverse channels (α, γ) and (p, γ).