Study of the electric dipole excitation of nuclei with a combination of real and virtual photon scattering

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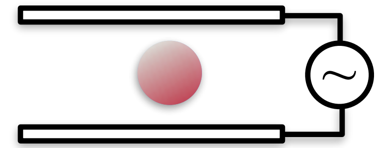
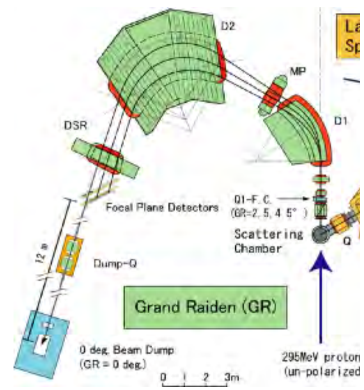
Remote Presentation from RCNP

Outline

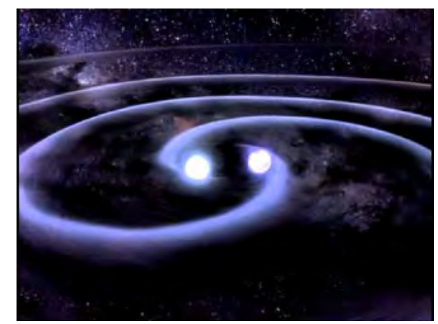
I. Electric Dipole Response of Nuclei



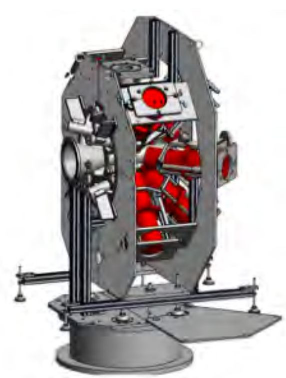
II. Experimental Methods

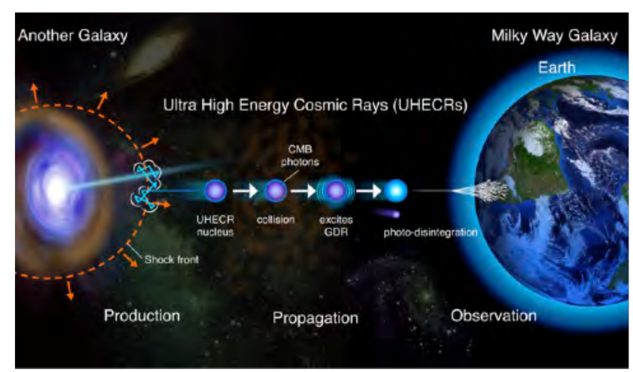


III.Physics Topics

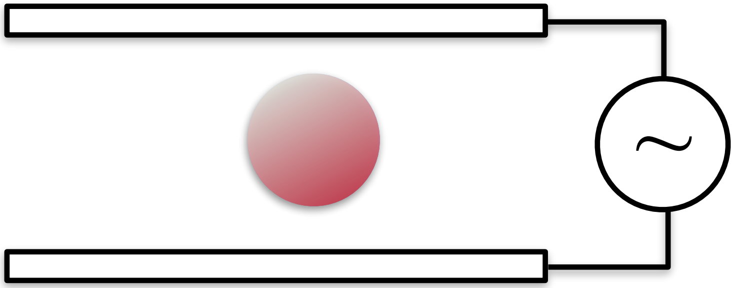


- Polarizability and Symmetry Energy
- Ultra-High-Energy Cosmic Rays
- Fine Structure of GDR



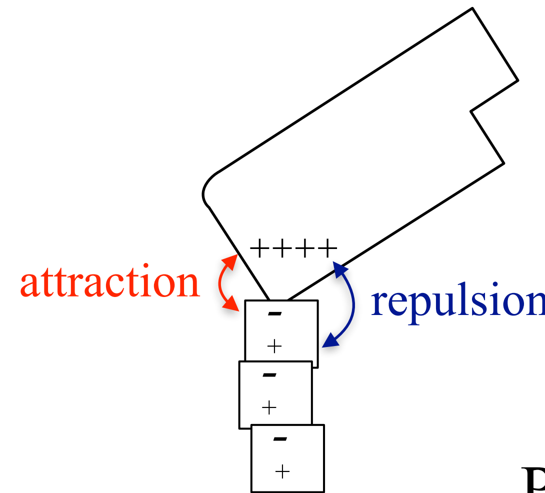


I Electric Dipole Response of Nuclei



Polarization in Static Electricity

A charged comb attracts electrical neutral papers.



Electric Polarization

Chage in the comb

⟶ induces polarization in a neutral paper

⟶ The paper is attracted by the comb.

⟶ The next paper is polarized and is attracted.

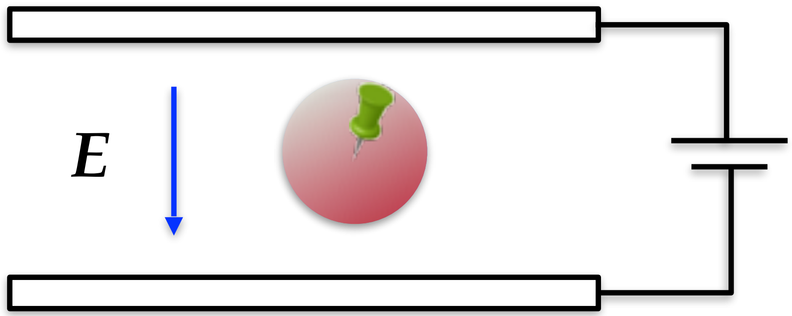
Photo from *Fundamentals of Physics, Electricity and Magnetism*, Halliday / Resnick / Walker

Static Electric Dipole Polarizability (α_D)

Electric dipole moment

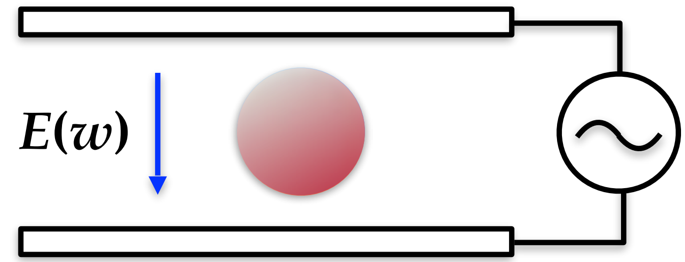
$$p = \alpha_D \times E$$

***α_D*: electric dipole polarizability**



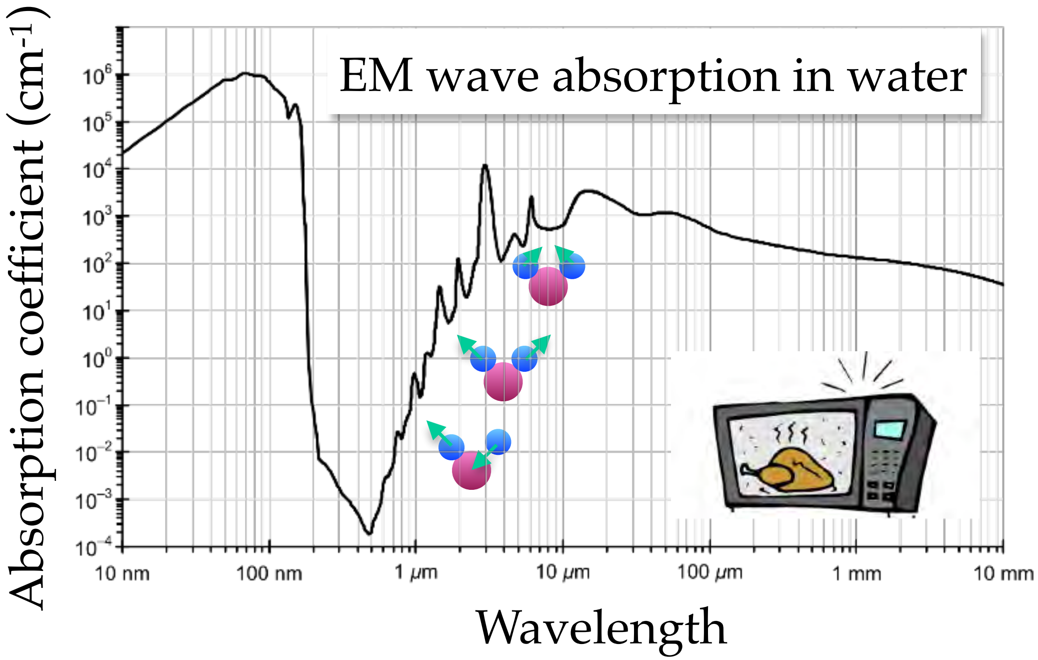
nucleus
in a static electric field
with fixing the c.m. position

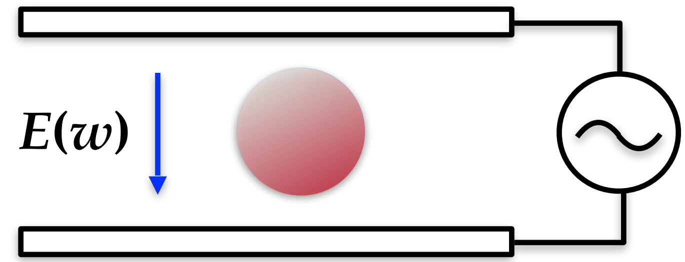
Electric Dipole Response of Nuclei



dielectric material
in an oscillating electric field

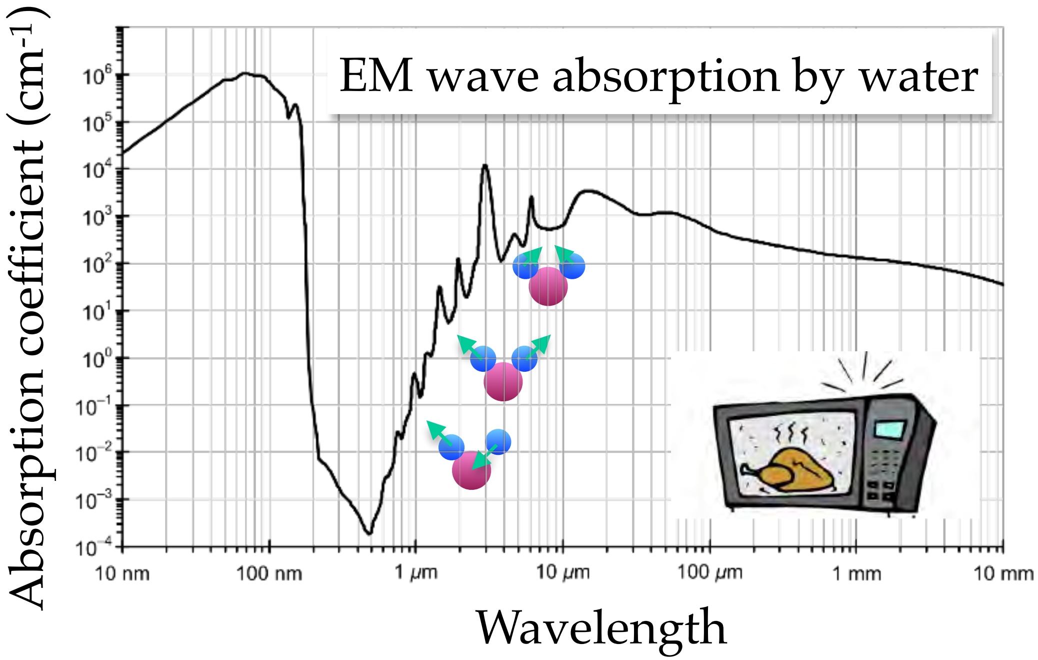
Electric Dipole Response of Nuclei

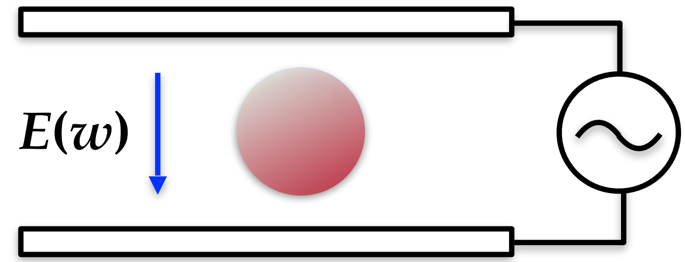




dielectric material
in an oscillating electric field

Electric Dipole Response of Nuclei



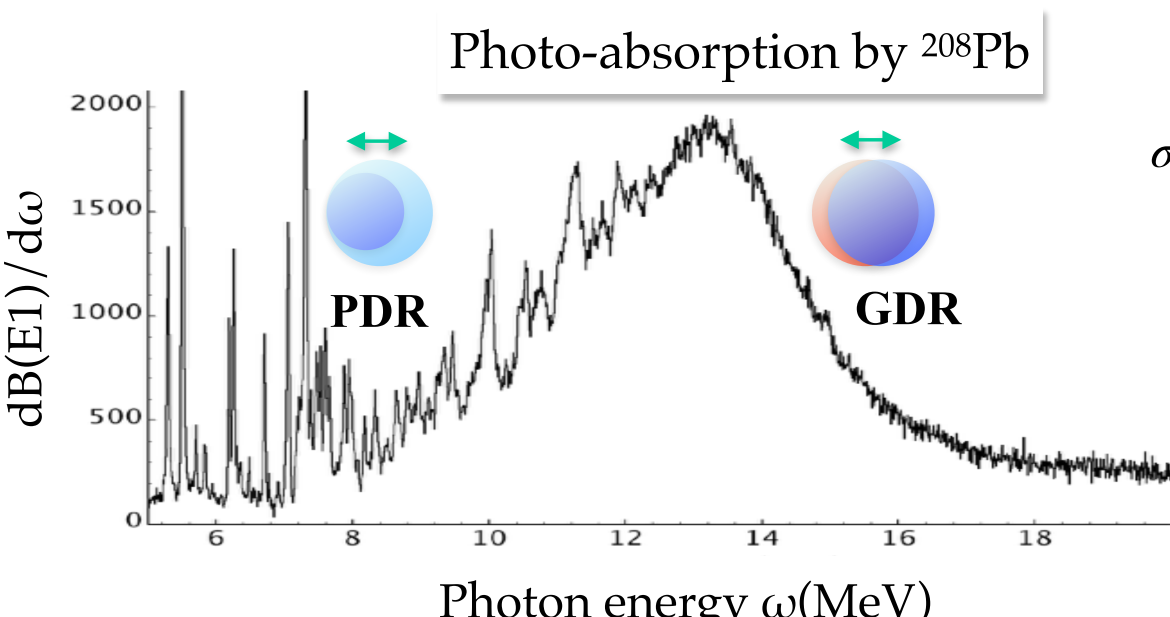


dielectric material
in an oscillating electric field

(E1) photo-absorption cross section

E1 reduced transition probability

$$\sigma_{\rm abs}^{E1} = \frac{16\pi^3\alpha\omega}{9}\frac{dB(E1)}{d\omega}$$



Inversely energy-weighted sum-rule

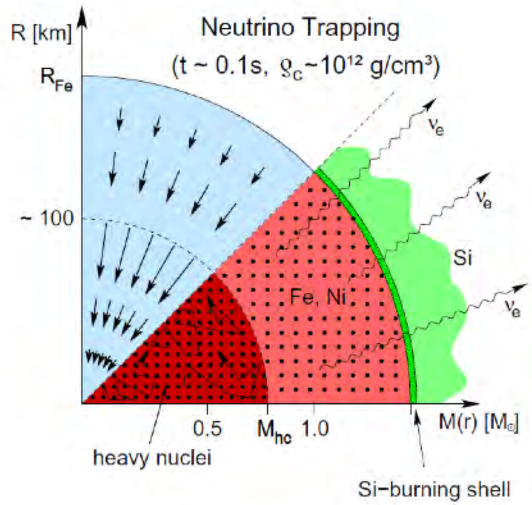
$$\alpha_D = \frac{\hbar c}{2\pi^2}\int\frac{\sigma_{\rm abs}^{E1}}{\omega^2}d\omega = \frac{8\pi}{9}\int\frac{dB(E1)}{\omega}$$

A.B. Migdal: 1944

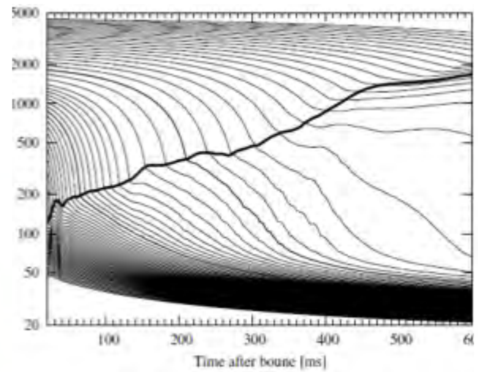
Symmetry Energy of the Nuclear EOS

is fundamental information for stellar processes

Core-collapse supernova

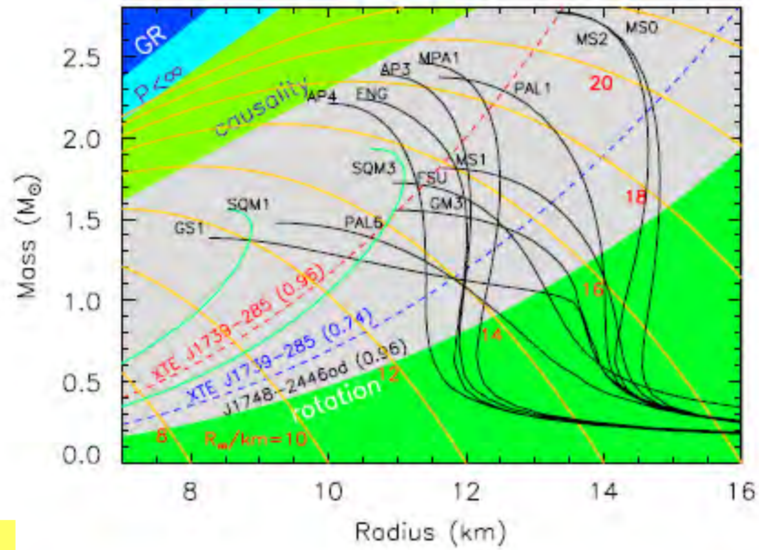


Langanke and Martinez-Pinedo



Y. Suwa et al., ApJ764, 99 (2013).

Neutron star mass vs radius



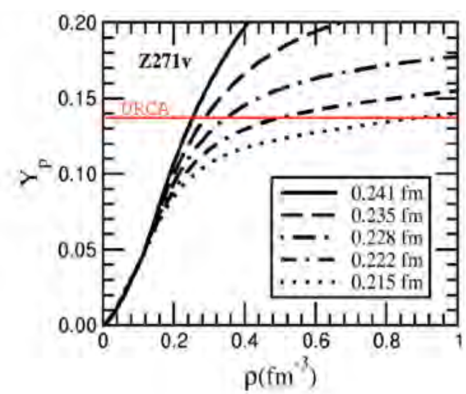
Lattimer et al., Phys. Rep. 442, 109(2007)

Nucleosynthesis

Neutron Star Merger Gravitational Wave

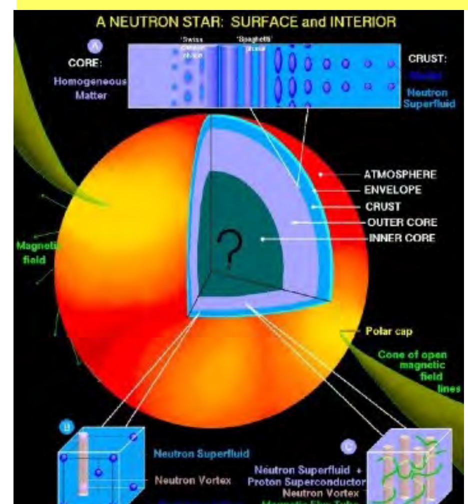
https://www.youtube.com/watch?v=IZhNWh_lFuI

Neutron star cooling



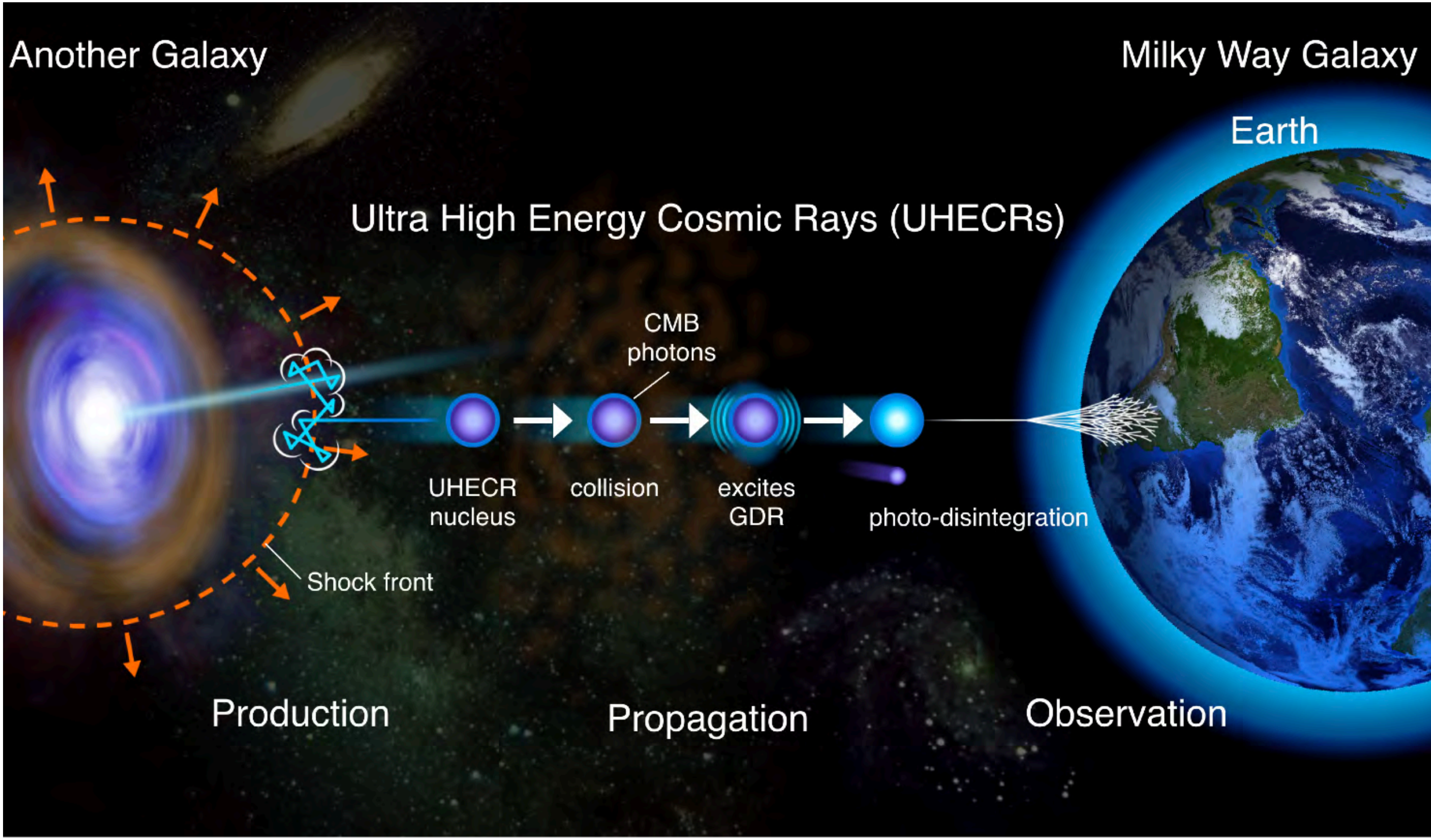
Lattimer and Prakash, Science 304, 536 (2004).

Neutron star structure

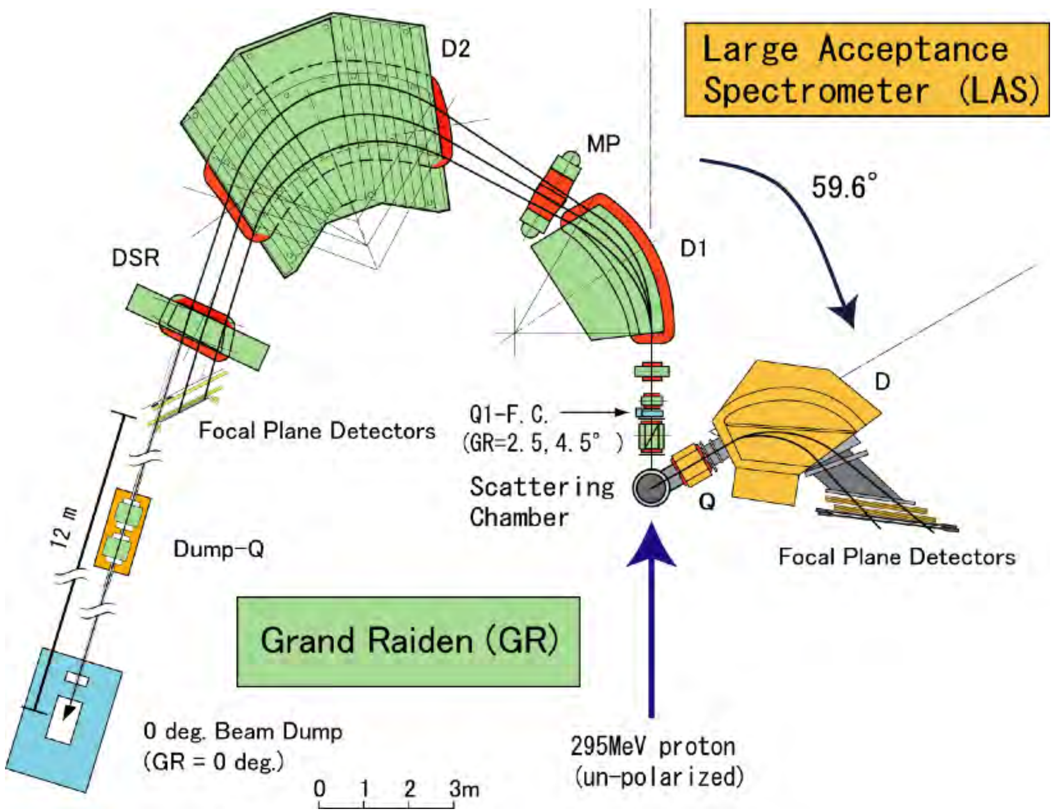


http://www.astro.umd.edu/~miller/nstar.html

Extragalactic Propagation of Untra-High-Enegy Cosmic Rays

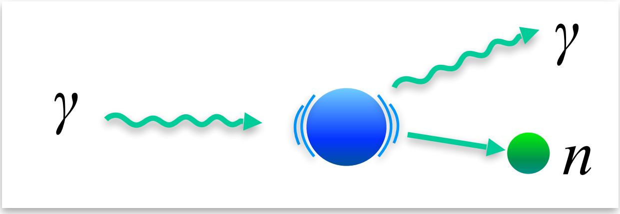


II Experimental Methods

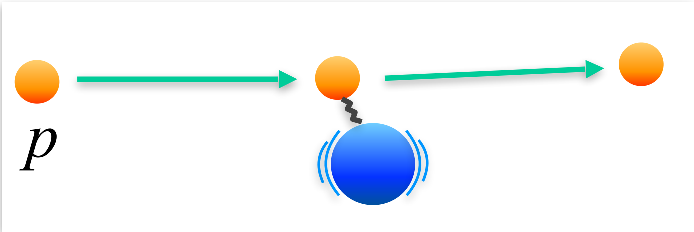


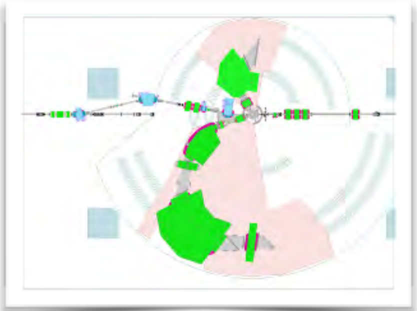
Probes for the Electric Dipole Response of Nuclei

1. Real photon absorption
   - (γ,γ’) Nuclear Resonance Fluorescence
   - (γ,n), (γ,2n), (γ,p), … photodisintegrations



2. Virtual photon excitation
   (Coulomb excitation)
   - proton inelastic scattering at 0 deg.

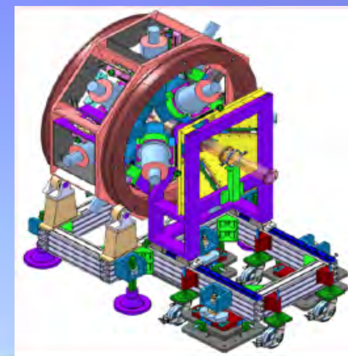




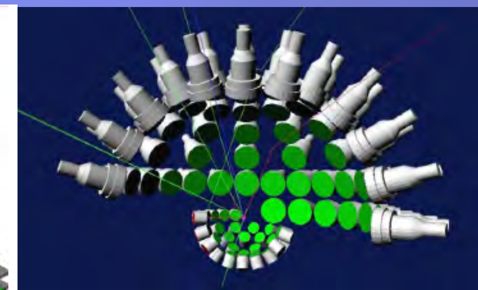
A New Photon Facility ELI-NP @ Bucharest

A photon beam from laser Compton backscattering with:

- very high intensity (10^4 photons/(s·eV))
- narrow bandwidth (down to 0.5%)
- high degree of polarization (> 99%)
- small beam diameter (mm range)



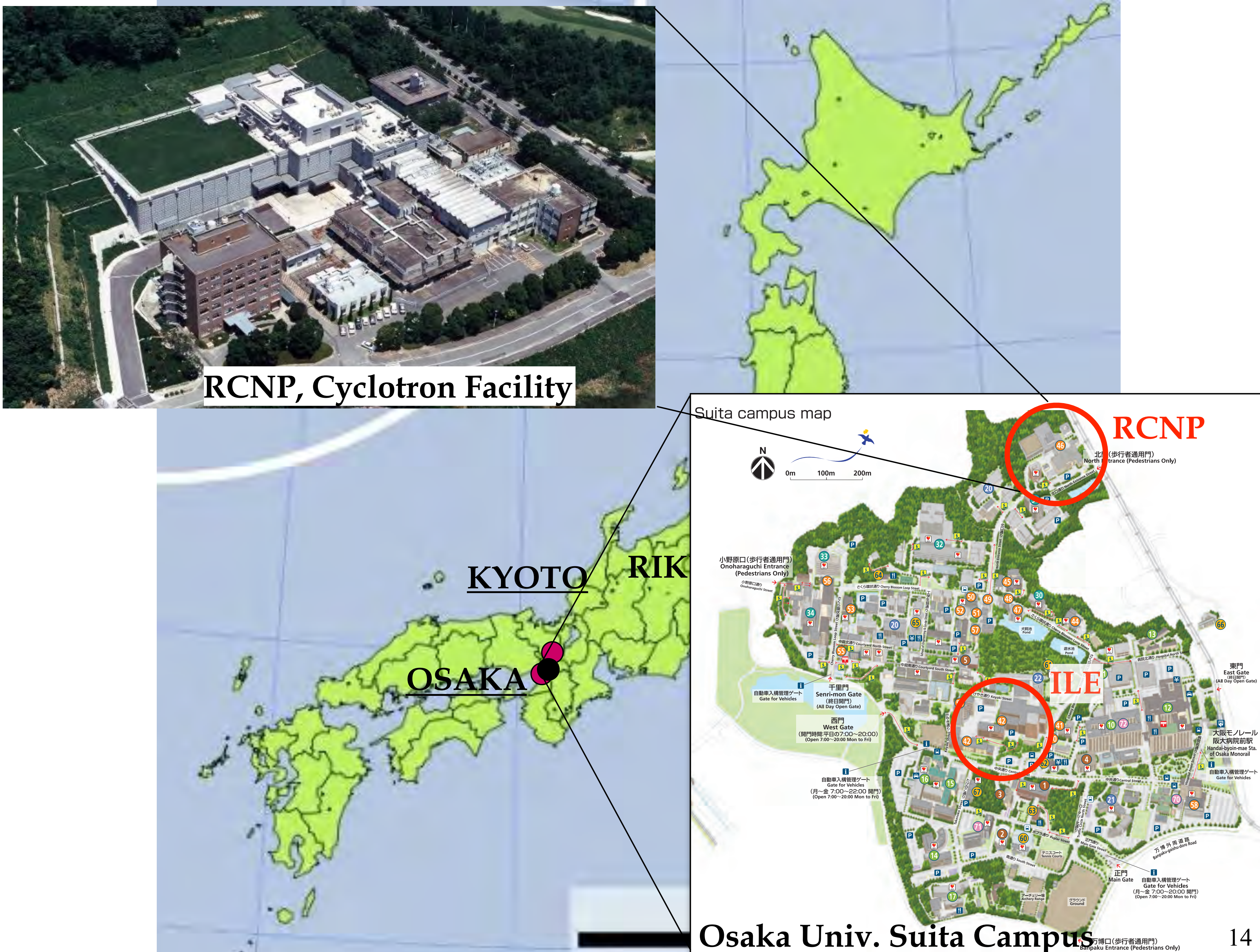
γ detectors



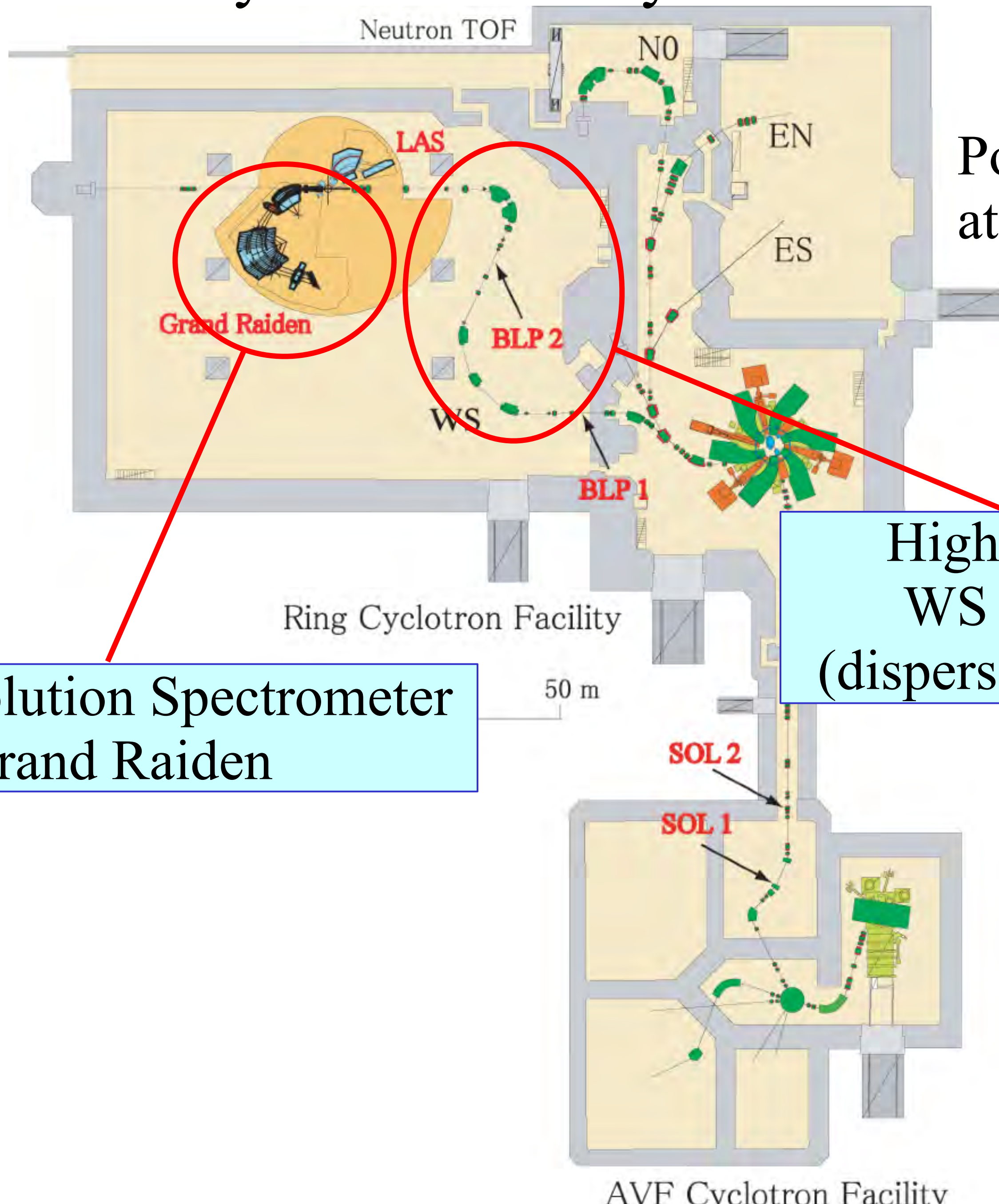
n detectors

Latest information is shown in this school.

Courtesy of D. Balabanski


RCNP, Cyclotron Facility
KYOTO
OSAKA
Suita campus map
N
0m
100m
200m
RCNP
ILE
Onoharaguchi Entrance (Pedestrians Only)
Senri-mon Gate
West Gate
East Gate
Main Gate
Osaka Univ. Suita Campus

Cyclotron Facility at RCNP



Polarized *p* beam at 295 MeV

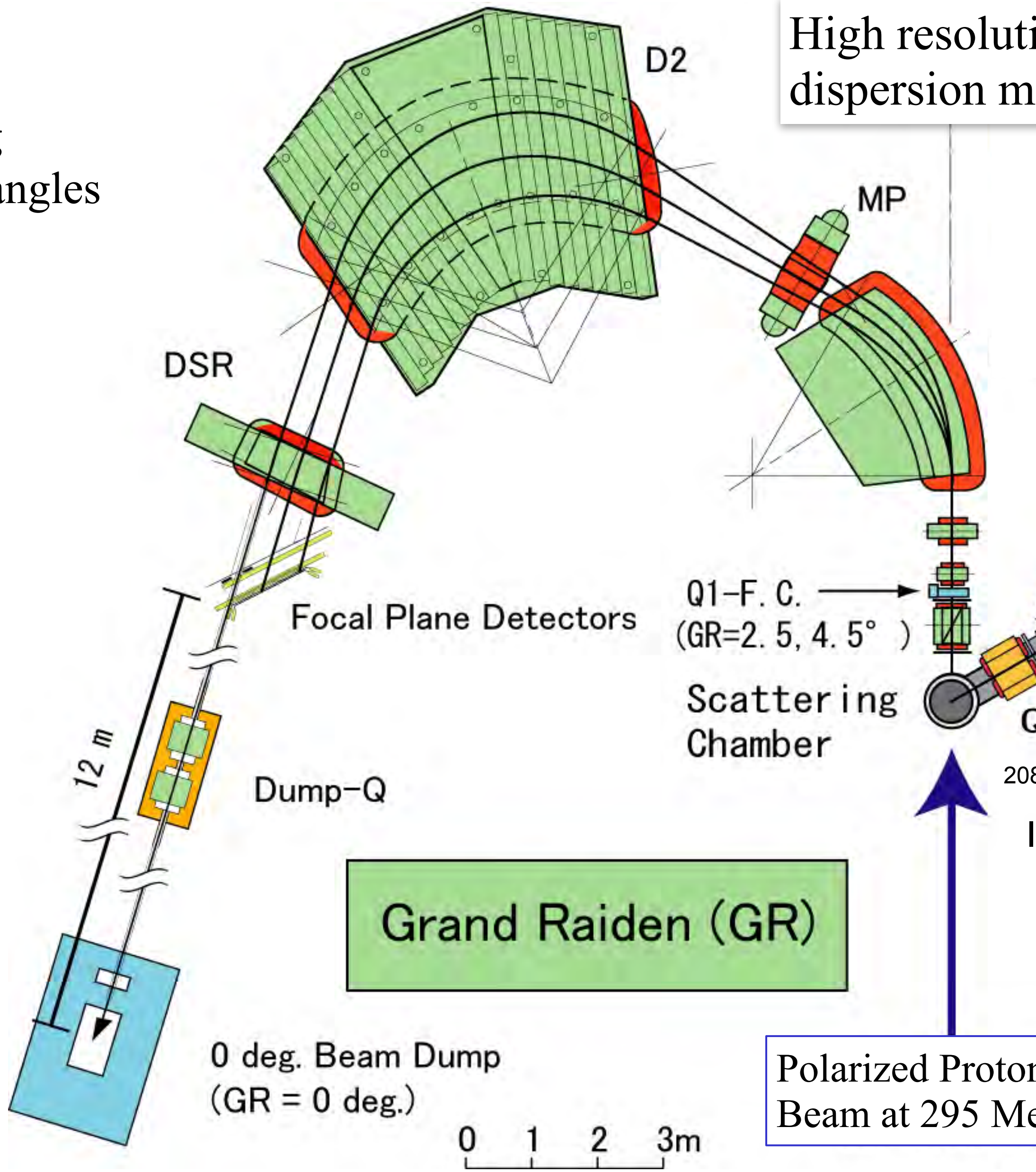
High-resolution WS beam-line (dispersion matching)

High-resolution Spectrometer Grand Raiden

High-Resolution Spectrometer "Grand Raiden"

Proton scattering
at very forward angles

High resolution of 20-30 keV:
dispersion matching.



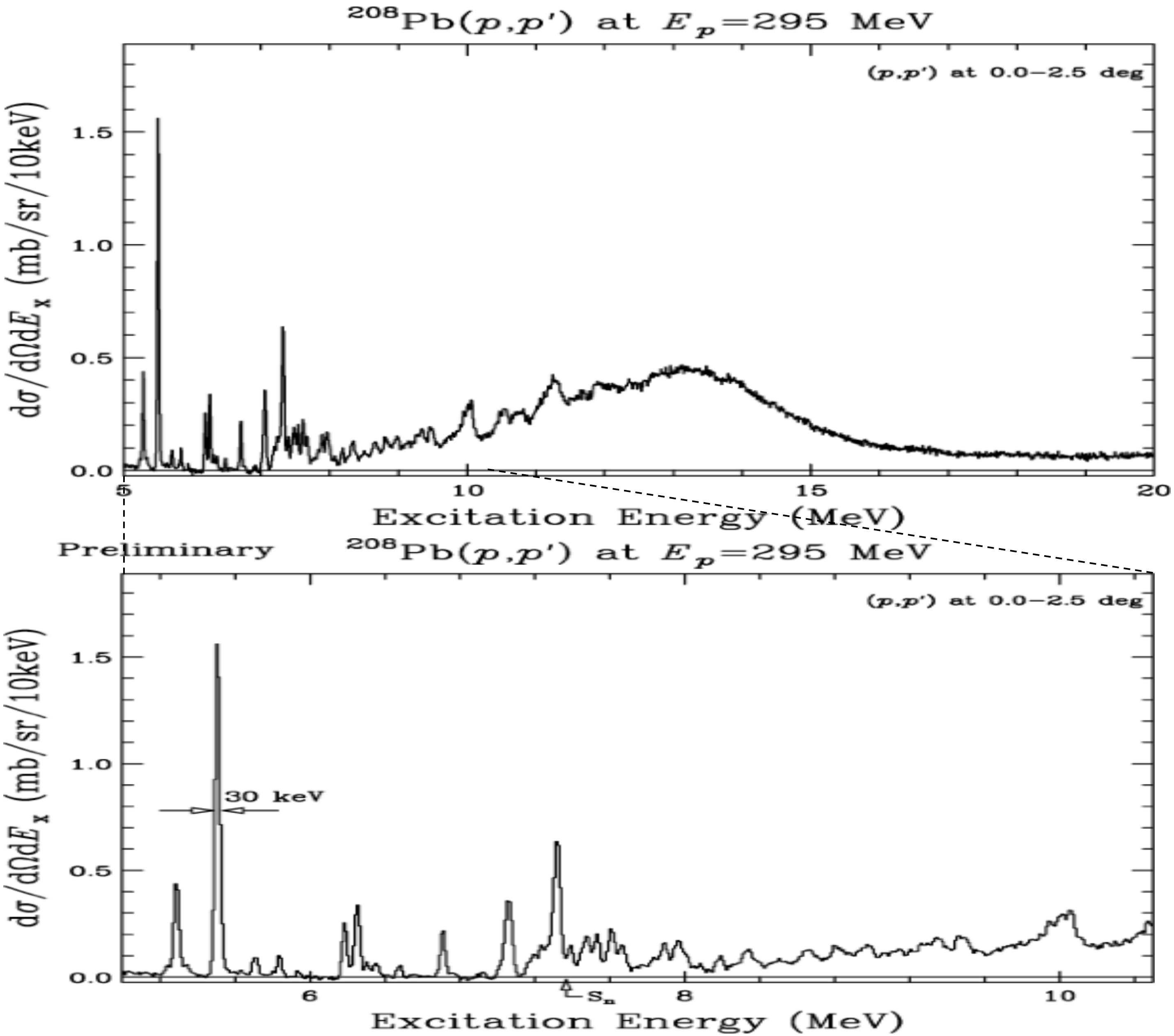
^{208}Pb target: 5.2 mg/cm^2

Intensity : 1-8 nA

Polarized Proton
Beam at 295 MeV

AT et al., NIMA605, 326 (2009)

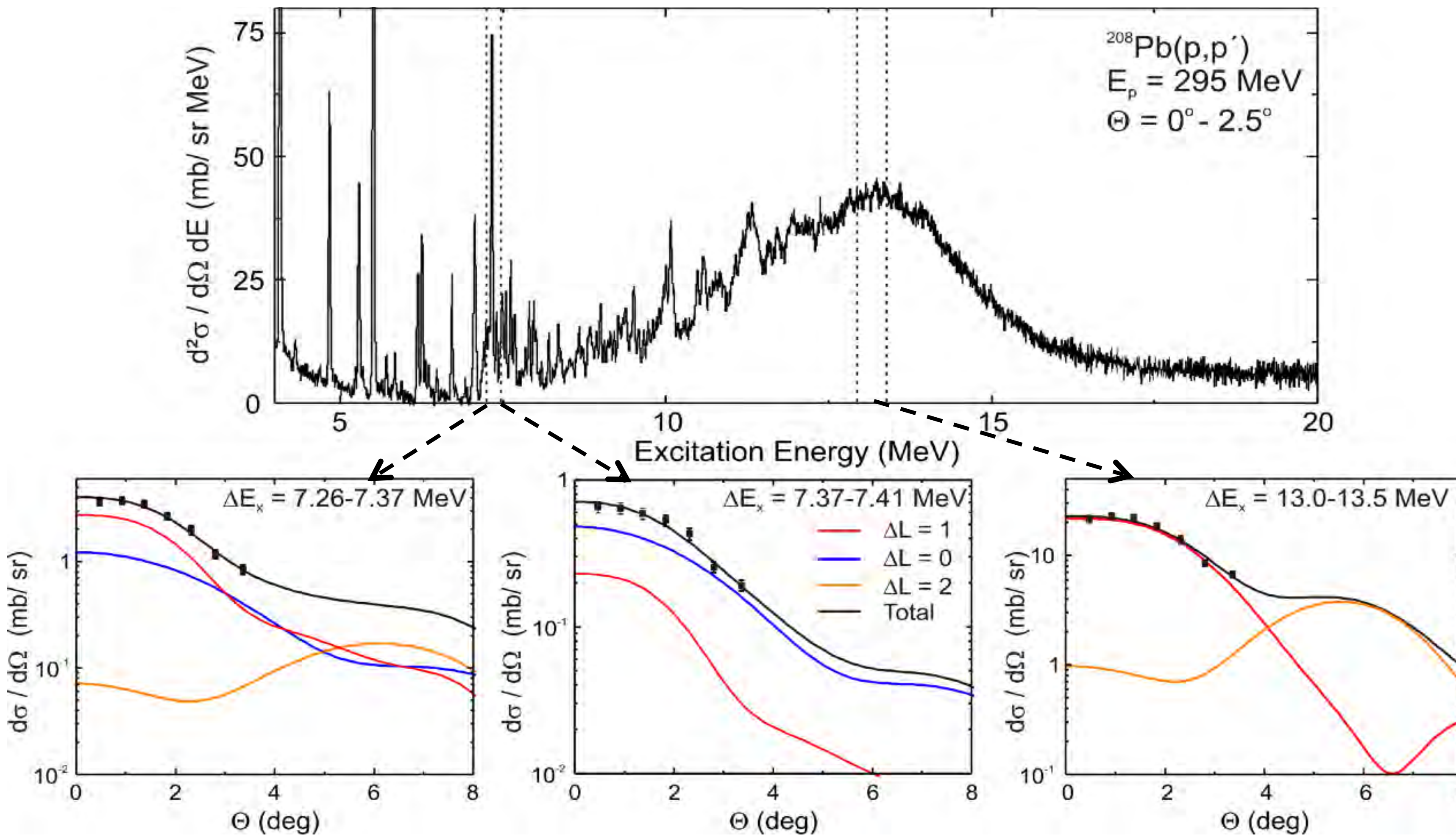
Setup for E282&E316



^{208}Pb(p,p') at E_p=295 MeV
(p,p') at 0.0−2.5 deg
dσ/dΩdE_x (mb/sr/10keV)
0.0
0.5
1.0
1.5
5
10
15
20
Excitation Energy (MeV)
Preliminary
^{208}Pb(p,p') at E_p=295 MeV
(p,p') at 0.0−2.5 deg
dσ/dΩdE_x (mb/sr/10keV)
30 keV
S_n
6
8
10
Excitation Energy (MeV)

B(E1): continuum and GDR region

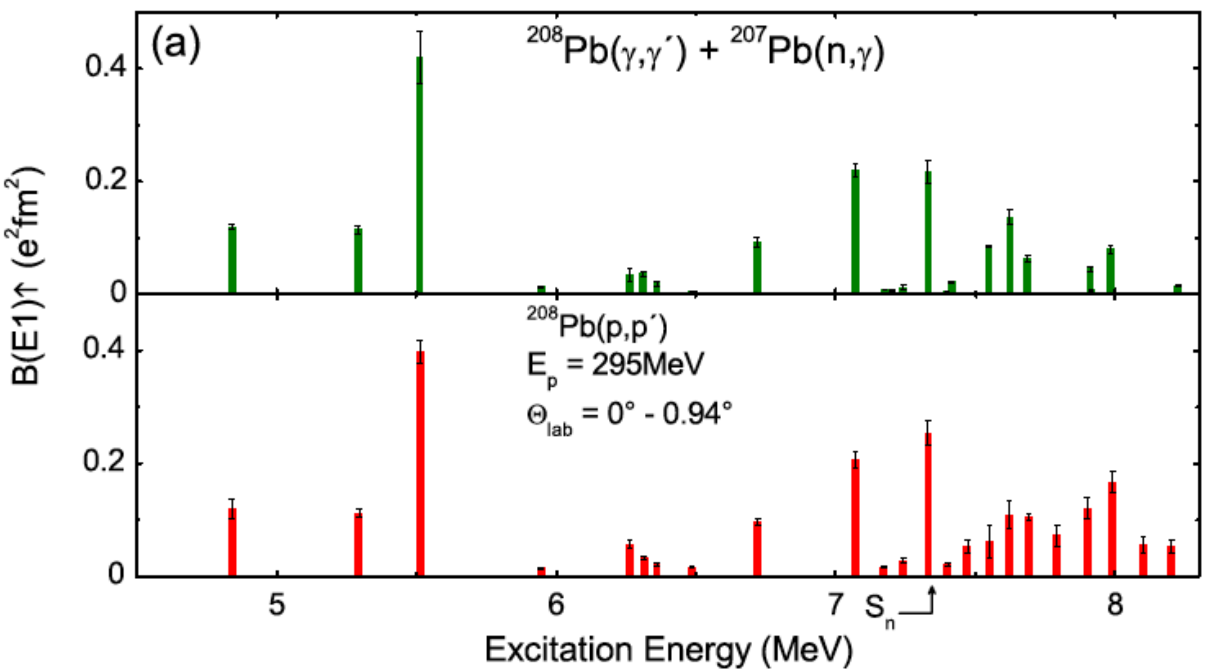
Multipole Decomposition Analysis (MDA)



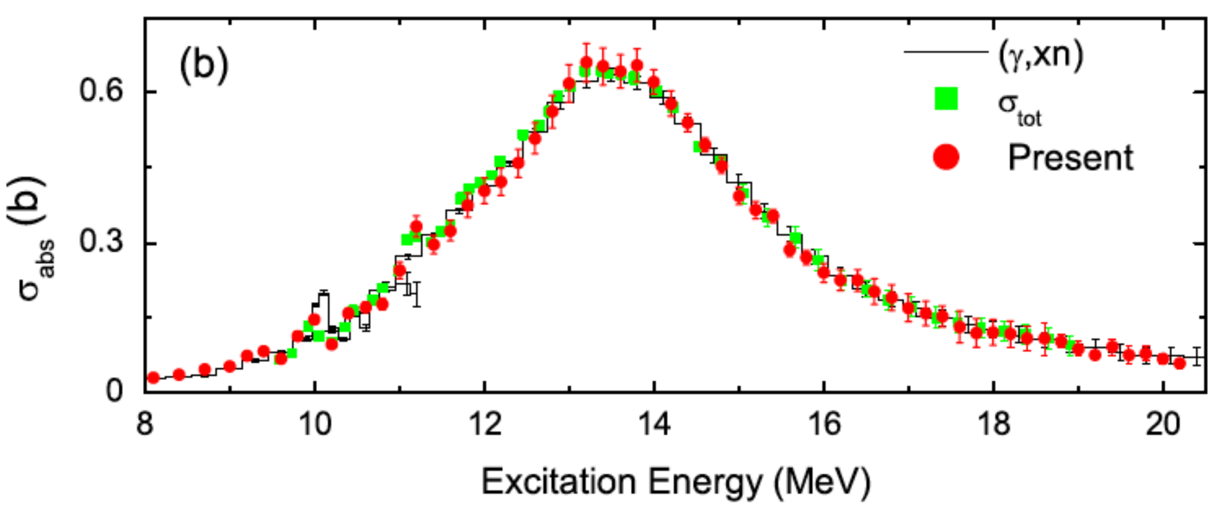
- Neglect of data for Θ>4: (p,p´) response too complex
- Included E1/M1/E2 or E1/M1/E3 (little difference)

Grazing Angle = 3.0 deg

Comparison with (γ,γ') and (γ,xn)



low-lying discrete states



GDR region

Probes for the Electric Dipole Response of Nuclei

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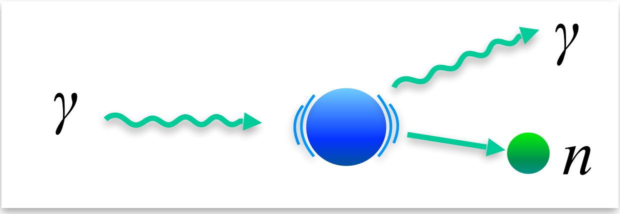
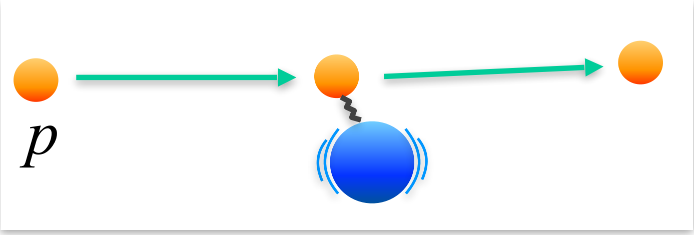
   - (γ,γ') Nuclear Resonance Fluorescence
   - (γ,n), (γ,2n), (γ,p), … photodisintegrations



a γ-beam at ELI-NP

pure EM probe by quasi-monoenergetic γ
precise absolute strength
partial strength for each decay channel including *n*
clear selection of E1 and M1 (polarized-gamma)
up to 20 MeV at ELI-NP

2. Virtual photon excitation
   (Coulomb excitation)
   - proton inelastic scattering at 0 deg.

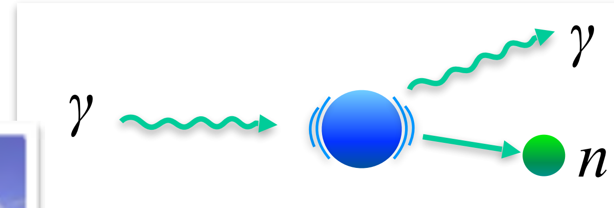


a proton beam at RCNP
and iThemba LABS

dominantly electric excitation: req. decomposition
E_x distribution is obtained in one shot
sensitive to the total strength
up to 32 MeV at RCNP

Probes for the Electric Dipole Response of Nuclei

1. Real photon absorption
   - (γ,γ') Nuclear Resonance Fluorescence
   - (γ,n), (γ,2n), (γ,p), … pho



a γ-beam at ELI-NP

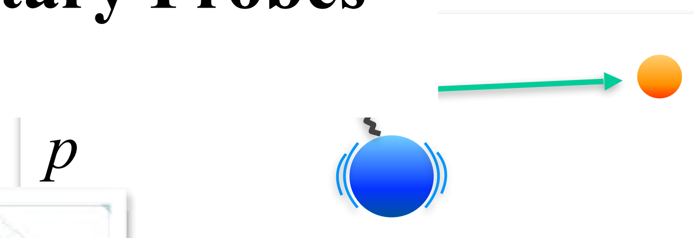
uasi-monoenergetic γ

ngth

partial strength for each decay channel including *n*

Complementary Probes

2. Virtual photon
   (Coulomb excitation)
   - proton inelastic scattering a



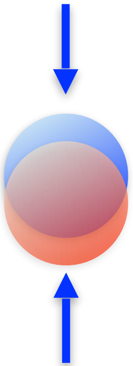
a proton beam at RCNP and iThemba LABS

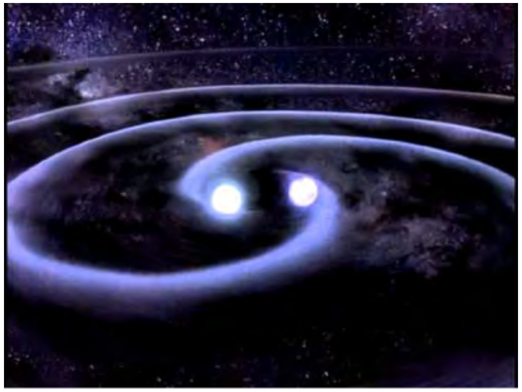
The best data can be obtained by combining the two methods.

CNP

III Physics Topics

Polarizability and Symmetry Energy





Nuclear Equation of State (EOS)
at zero temperature

Nuclear EOS neglecting Coulomb

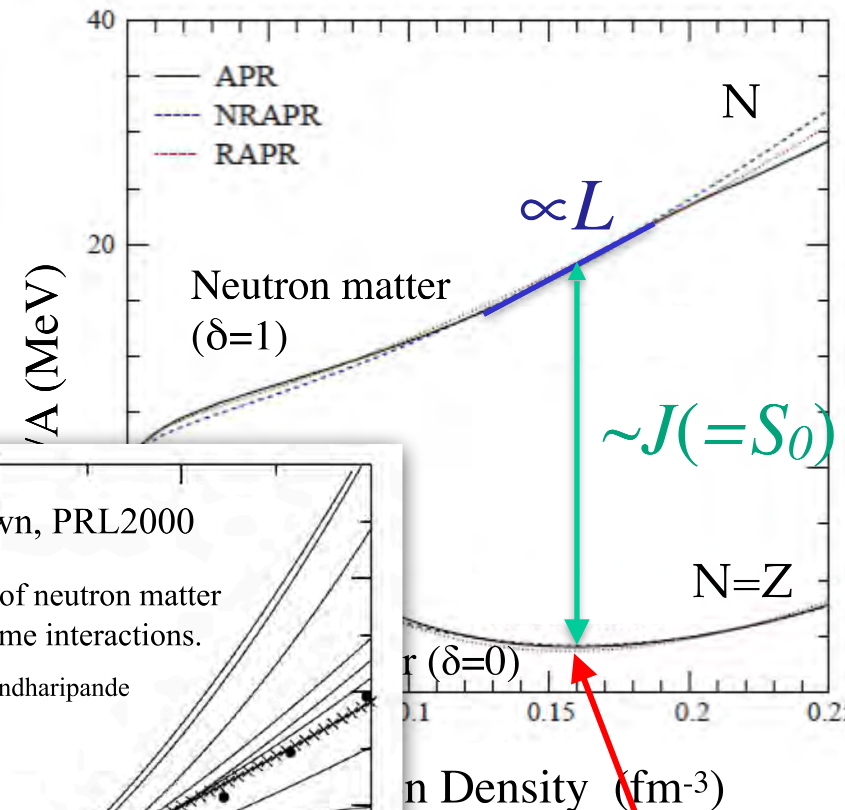
$$\frac{E}{A}(\rho,\delta)=\frac{E}{A}(\rho,0)+S(\rho)\delta^2+\cdots$$

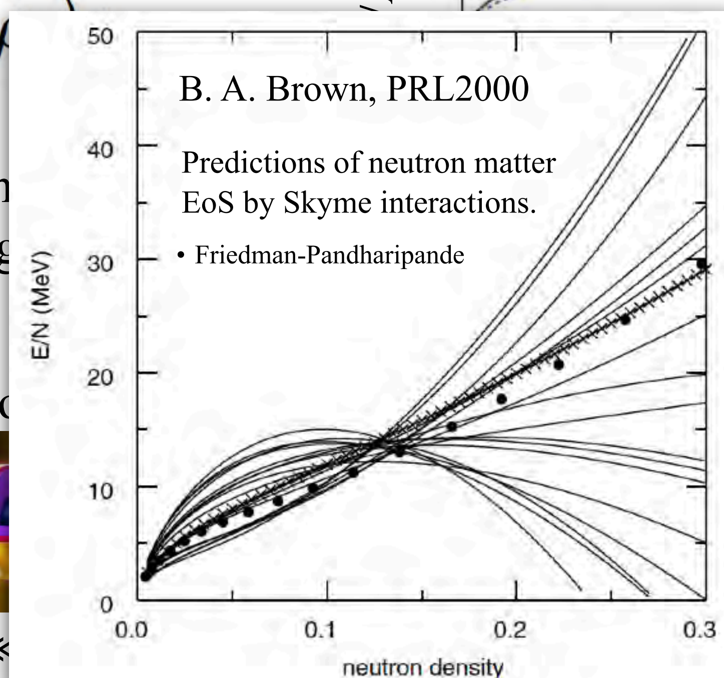
$$\delta\equiv\frac{\rho_n-\rho_p}{\rho_n+\rho_p}$$ Asymmetry parameter

Symmetry energy

$$S(\rho)=J+\frac{L}{3\rho_0}(\rho-\rho\ldots$$

⇔ difference between *p*-*n* ch
how the system energy chang
are replaced by the neutrons

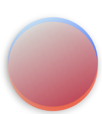




Saturation Density ρ_0

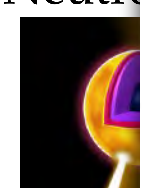
~0.16 fm^{-3}

Nucleus



$Z\lesssim N$

Neutr



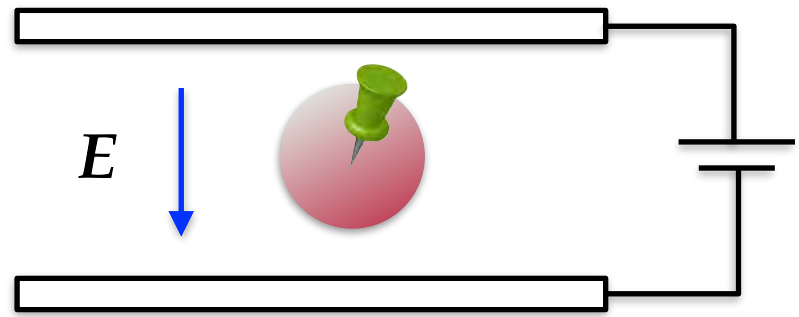
Z≪

Static Electric Dipole Polarizability (α_D)

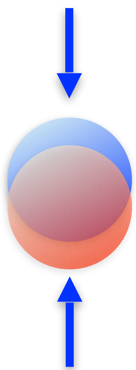
Electric dipole moment

$$p = \alpha_D \times E$$

α_D: electric dipole polarizability



nucleus
in a static electric field
with fixing the c.m. position



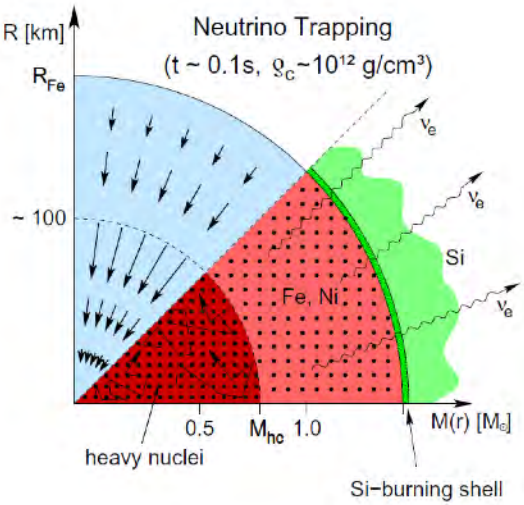
The **restoring force** originates from the **symmetry energy.**

Electric dipole polarizability (EDP) is sensitive to the symmetry energy below the nuclear saturation density.

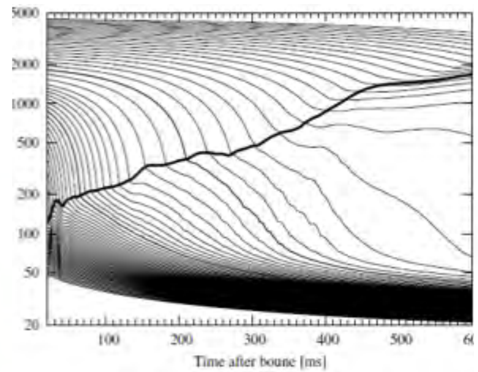
Symmetry Energy of the Nuclear EOS

is fundamental information for stellar processes

Core-collapse supernova

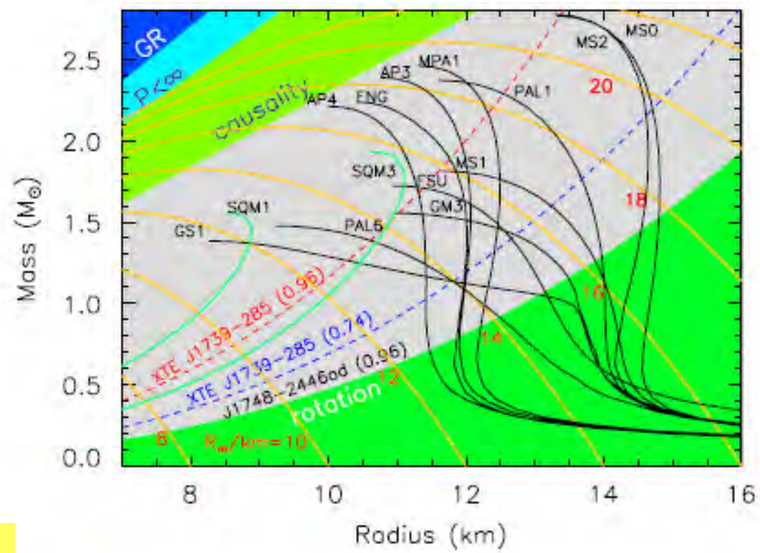


Langanke and Martinez-Pinedo



Y. Suwa et al., ApJ764, 99 (2013).

Neutron star mass vs radius



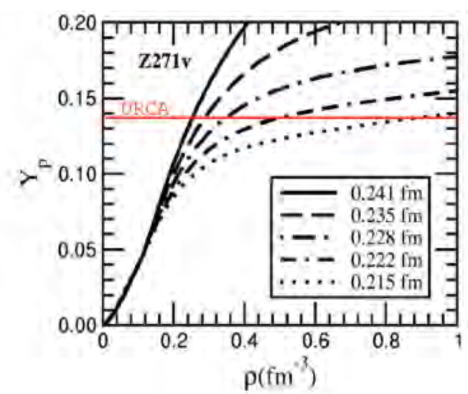
Lattimer et al., Phys. Rep. 442, 109(2007)

Nucleosynthesis

Neutron Star Merger
Gravitational Wave

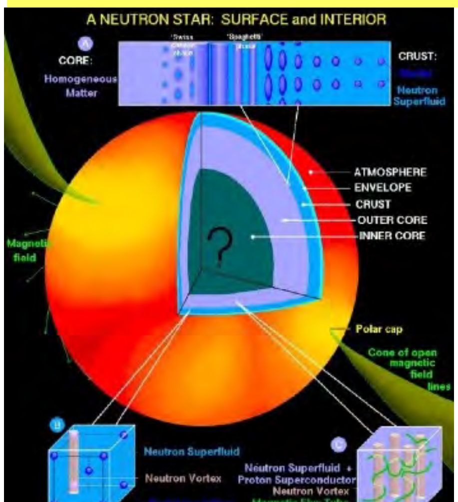
https://www.youtube.com/watch?v=IZhNWh_lFuI

Neutron star cooling



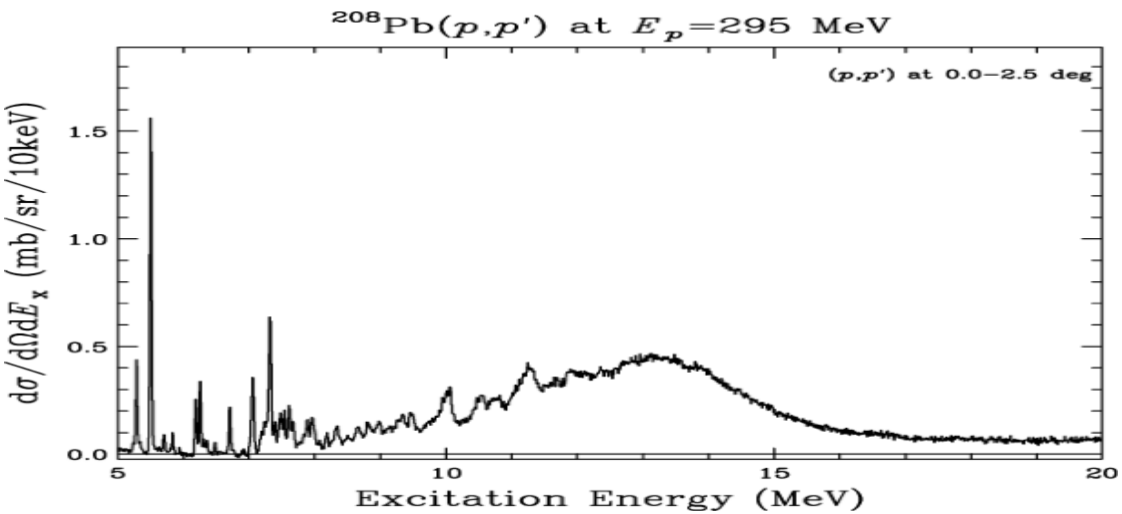
Lattimer and Prakash, Science 304, 536 (2004).

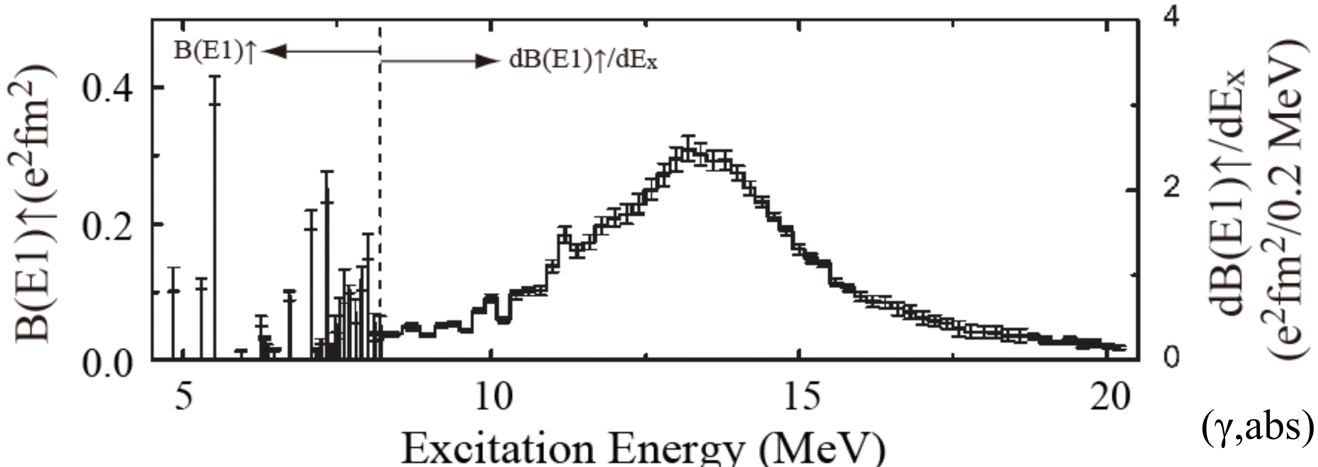
Neutron star structure



http://www.astro.umd.edu/~miller/nstar.html

Electric Dipole Polarizability: ^{208}Pb, ^{120}Sn

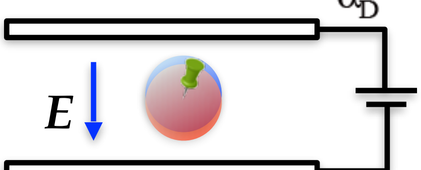




(γ,abs) at Mainz

E_x	0 – 10	10 – 20	20 – 130 MeV
α_D	2.7	16.2	1.2 fm³

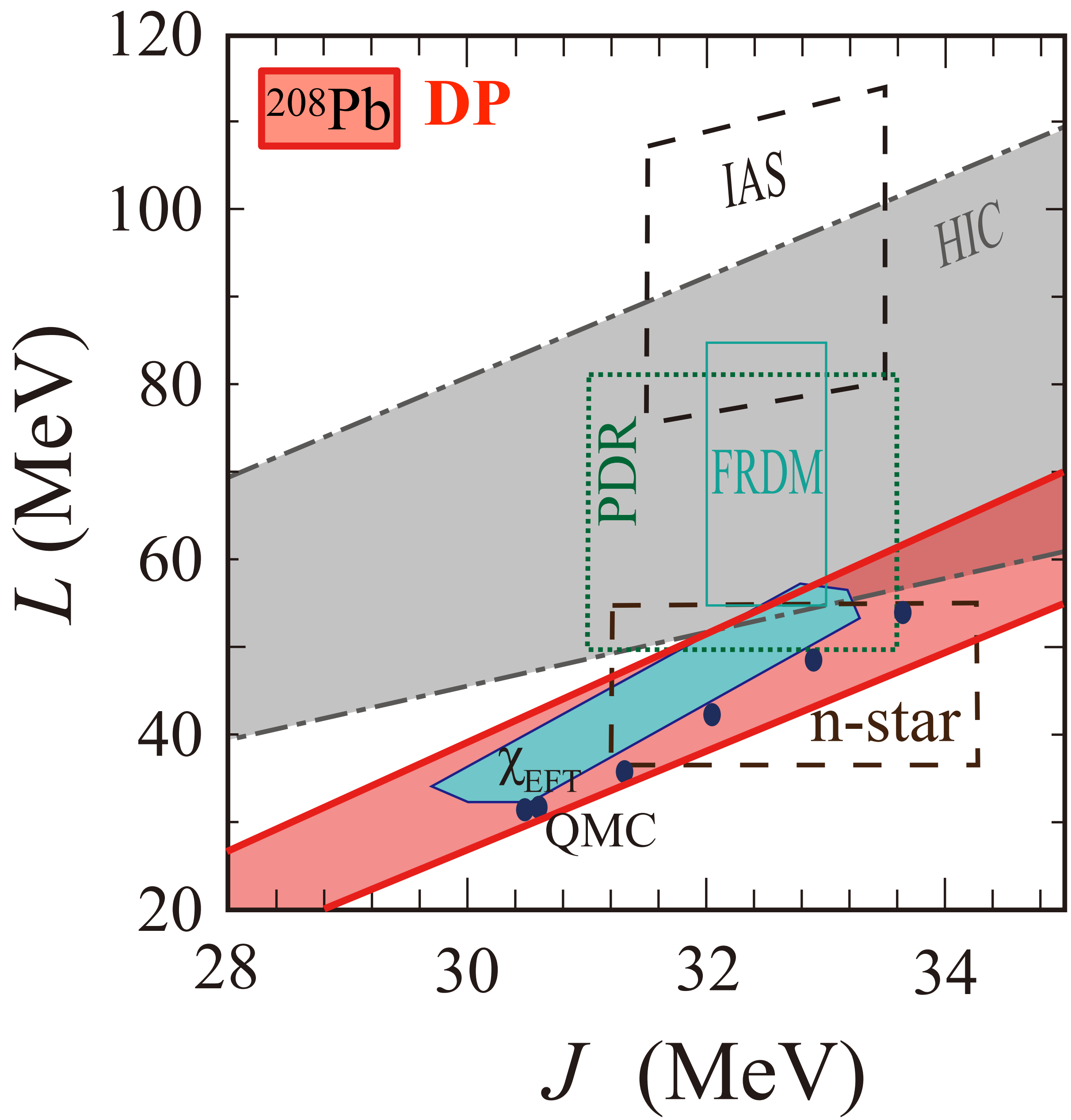
total 20.1±0.6 fm³



$$\alpha_D = \frac{8\pi}{9} \int \frac{dB(E1)}{\omega}$$

AT et al., PRL107, 062502(2011)

Constraints on Symmetry Energy (*J* and *L*)



Tsang PRC2012

HIC: Heavy Ion Collision Analysis
Tsang PRL2009

IAS: Isobaric Analog State Energy
Danielewicz&Lee NPA2009

PDR: Pygmy Dipole Resonance in
^{132}Sn, ^{68}Ni, Carbone PRC2010

FRDM: Finite Range Droplet Model
Moller PRL2012

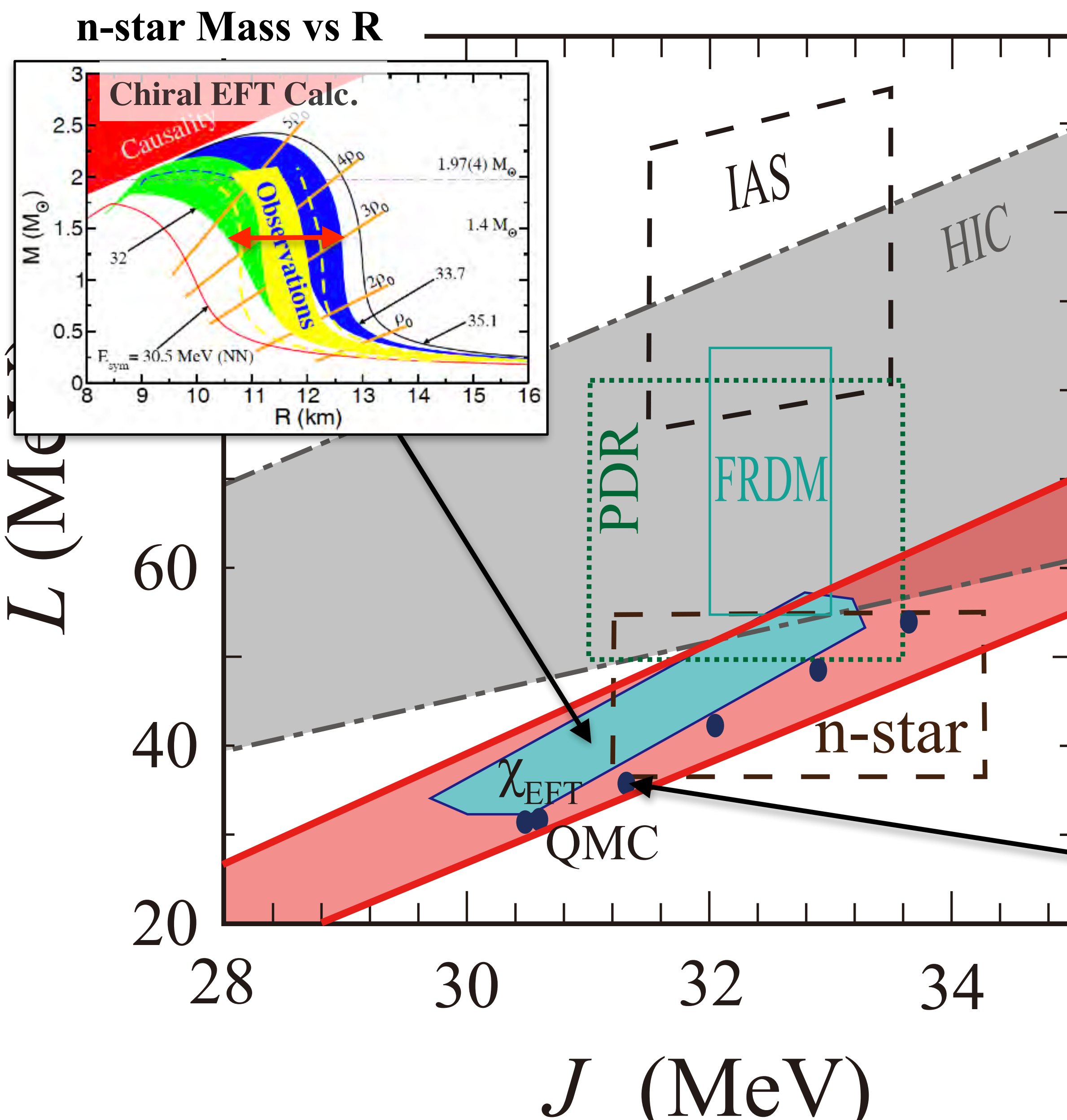
n-star: Quiescent Low-Mass X-ray Binaries, Stainer PRL2012

χ_{EFT}: Chiral Effective Field Theory,
Tews PRL2013

QMC: Quantum Monte-Carlo Calc.
Gandolfi, EPJA50, 10(2014).

DP: Dipole Polarizability
^{208}Pb AT PRL2011

Constraints on Symmetry Energy (J and L)



Tsang PRC2012

HIC: Heavy Ion Collision Analysis
Tsang PRL2009

IAS: Isobaric Analog State Energy
Danielewicz&Lee NPA2009

PDR: Pygmy Dipole Resonance in
^{132}Sn, ^{68}Ni, Carbone PRC2010

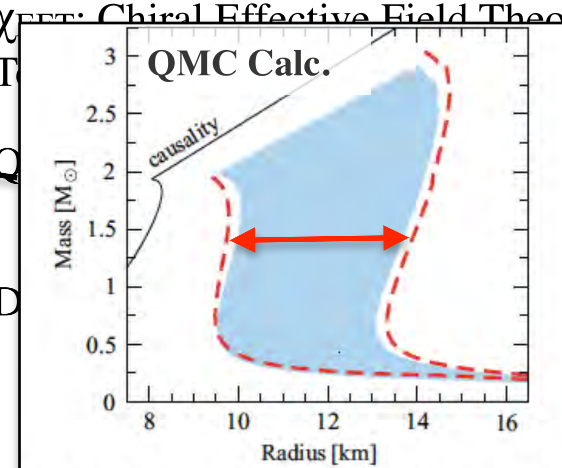
FRDM: Finite Range Droplet Model
Moller PRL2012

n-star: Quiescent Low-Mass X-ray
Binaries, Stainer PRL2012

χ_{EFT}: Chiral Effective Field Theory,
T

Q c.

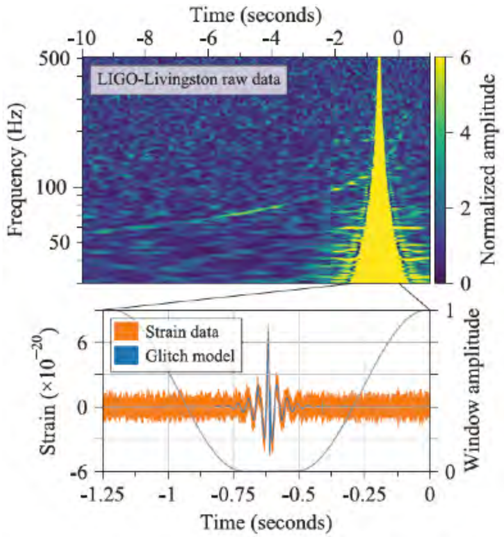
D

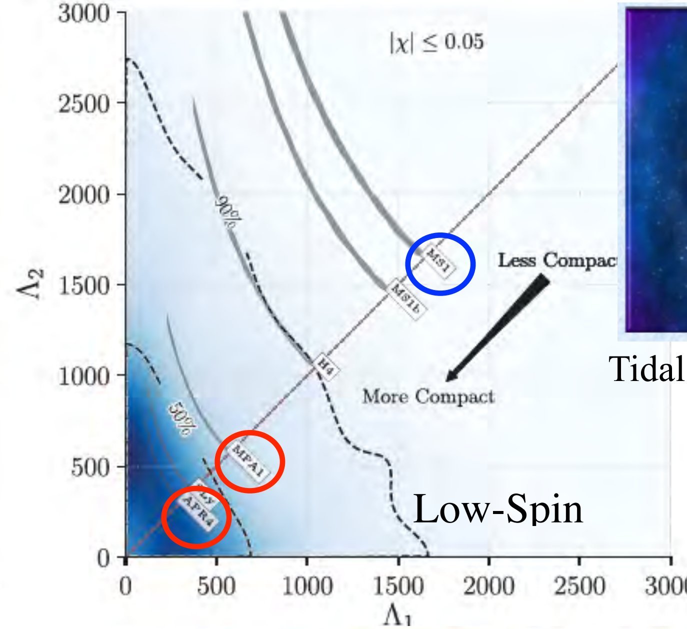


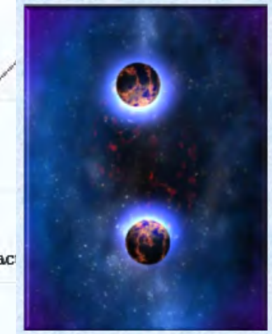
Neutron Star Merger GW170817

GW170817, PRL119, 161101(2017)

LIGO







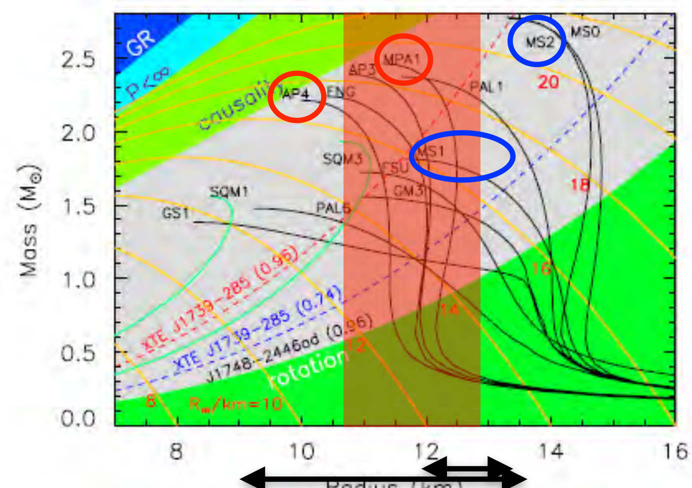
Tidal Deformation

$12.00 < R^{1.4} < 13.45$ km

E.R. Most et al., PRL120, 261103(2018)

$9.0 < R^{1.4} < 13.6$ km

I. Tews et al.,

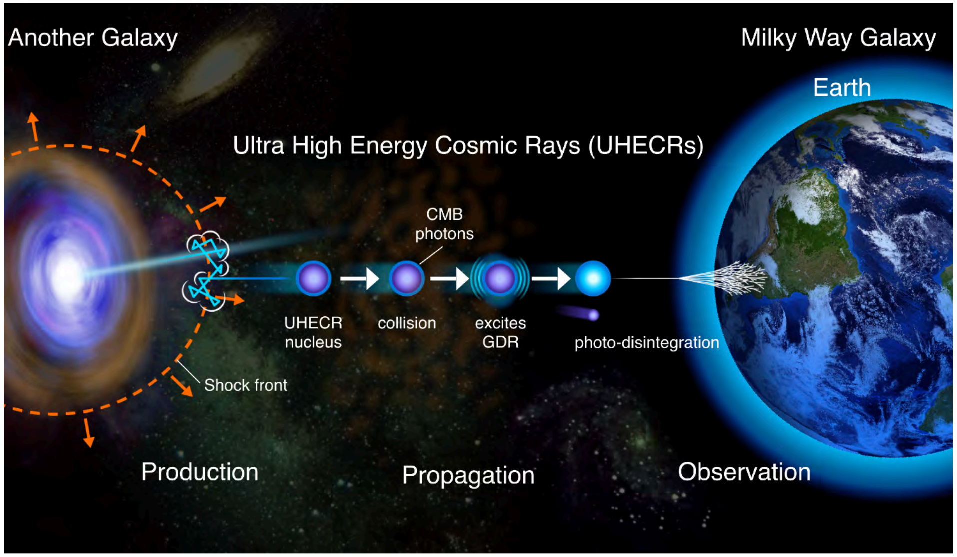


N-star merger GW analysis is giving constraints on the nuclear EOS that are consistent with the study of atomic nuclei.

Further constrains are anticipated both from nuclear physics experiments and from gravitational wave observations.

III Physics Topics

Extragalactic Propagation of Ultra High-Energy Cosmic Rays

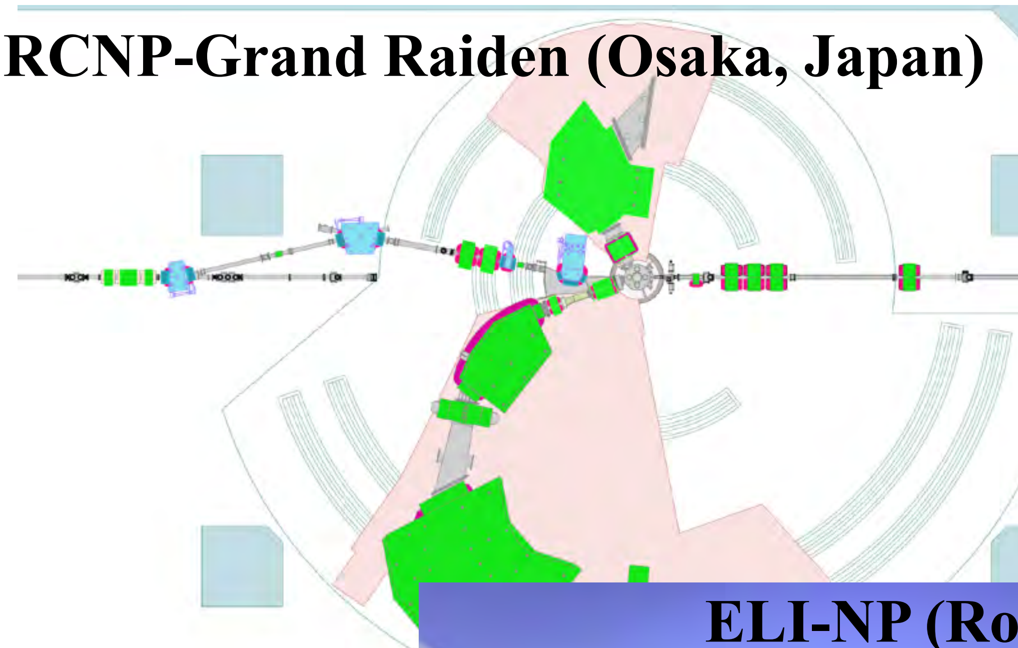


PANDORA Project

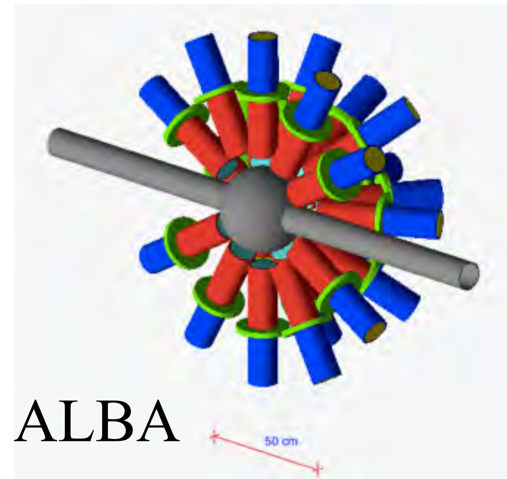
Photo-**A**bsorption of **N**uclei and **D**ecay **O**bservation for **R**eactions in **A**strophysics

Joint project among three experimental facilities with nuclear theories and astrophysical simulations

RCNP-Grand Raiden (Osaka, Japan)

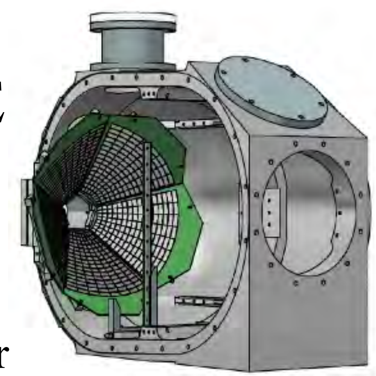


iThemba LABS South Africa



CAKE

decay charge particle detector array

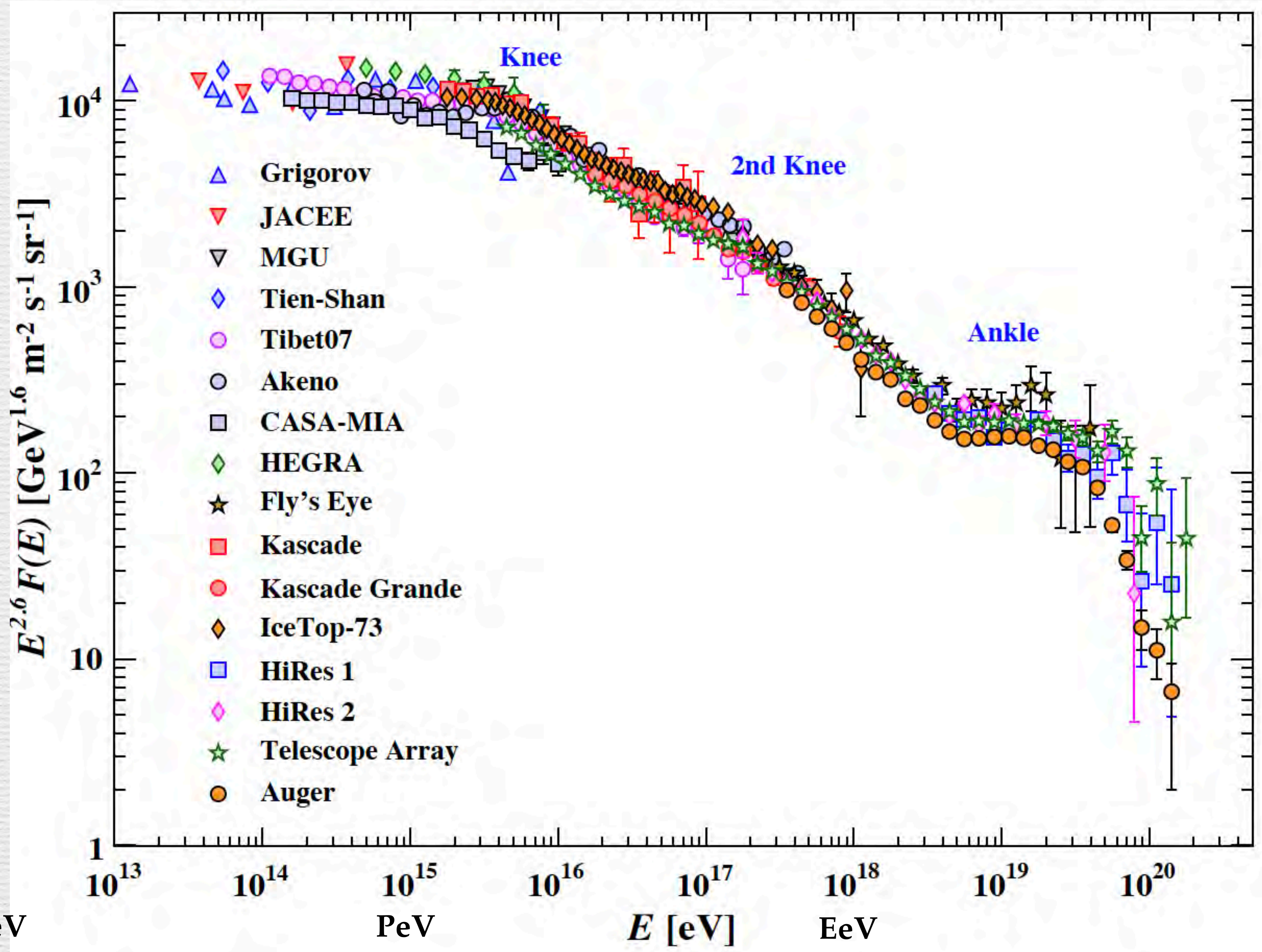


ELI-NP (Romania)

complementary experimental techniques

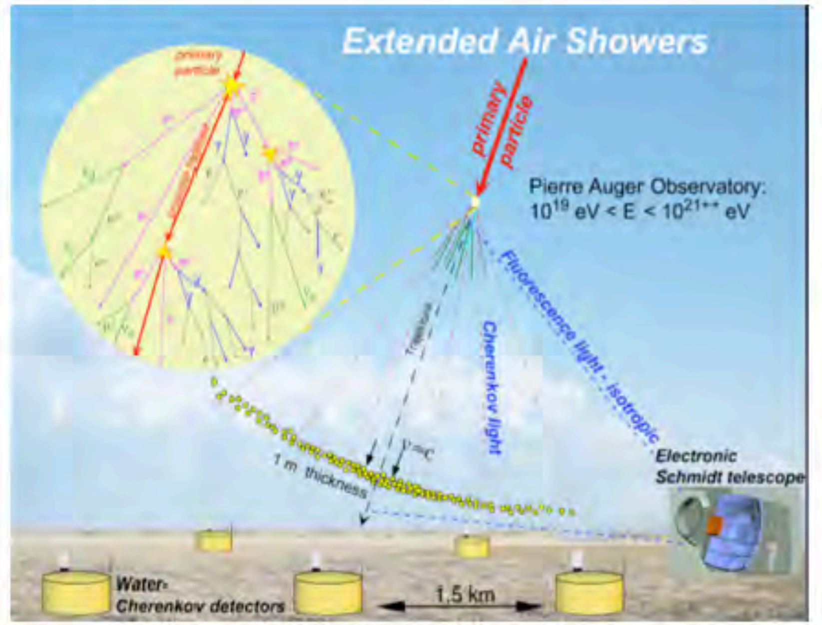
(Ultra-)High-Energy Cosmic Rays

[PDG2018]



Observation of UHECRs

Pierre Auger Observatory (Southern Hemisph.)
Telescope Array (Northern Hemisphere)



Hadronic process

primarily produces mesons (π or K)

p(A) +A → π, K, and nuclear fragments

$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}\ (\overline{\nu_{\mu}})$

$\pi^0 \rightarrow 2\gamma$

$\gamma \rightarrow e^+ + e^-$

$e^{\pm} + A \rightarrow e^{\pm} + A + \gamma$

Electromagnetic Shower

Auger

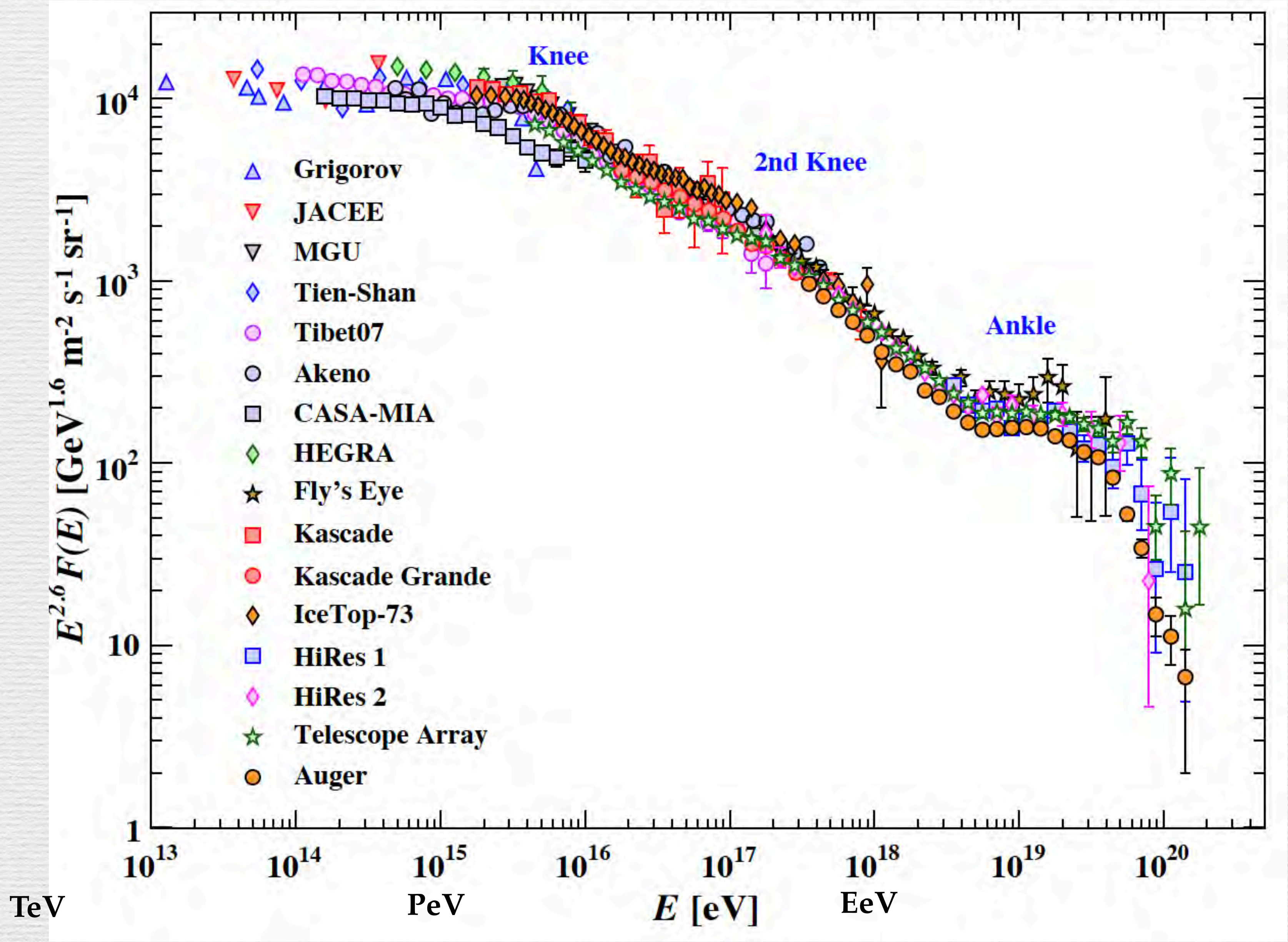
1600 Surface Detectors in 3000 km^2

24 Fluorescence Detectors at 4 sites

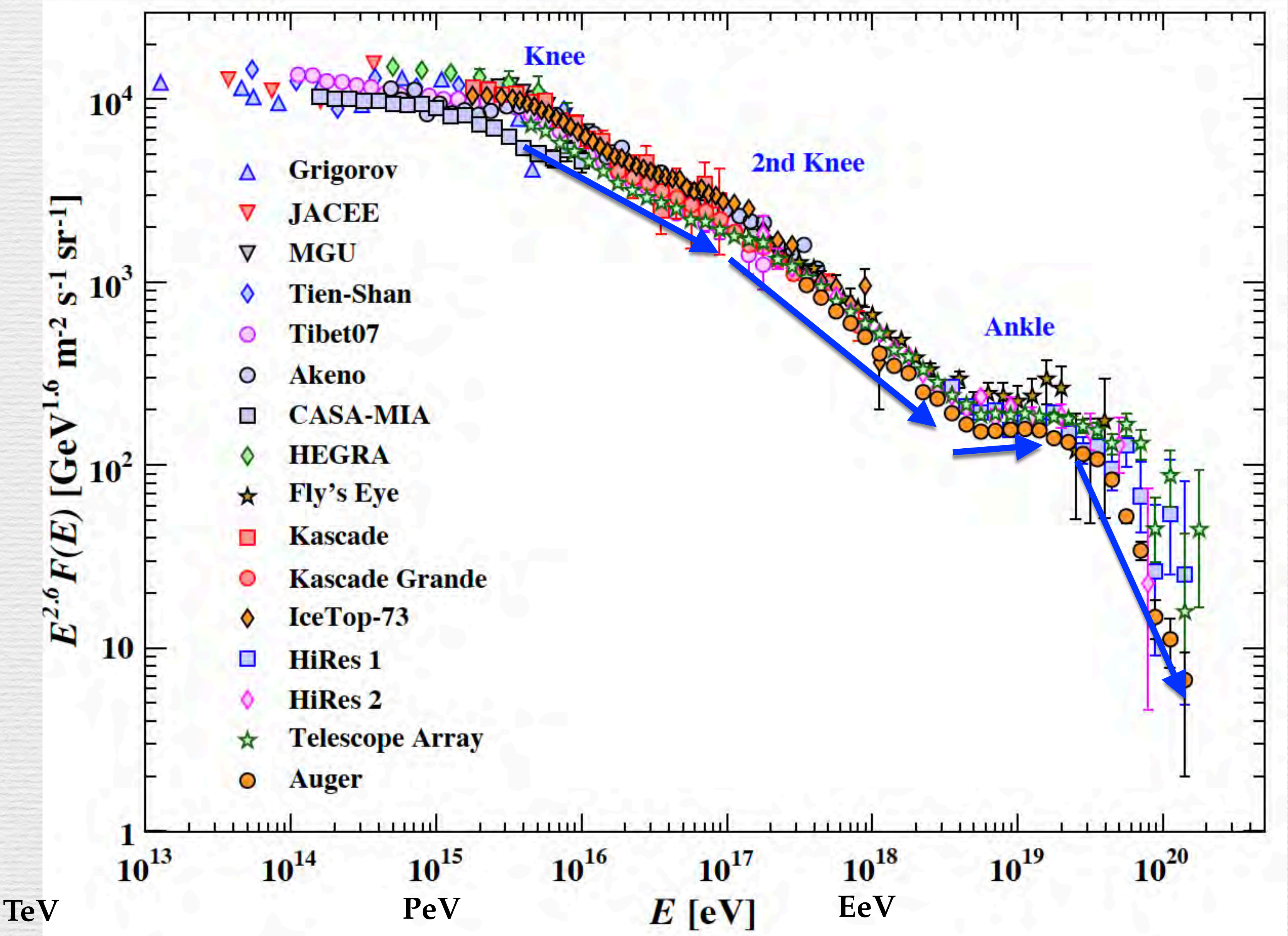
above 10^{19} eV, ~1 particles/km^2/year

[mol18]

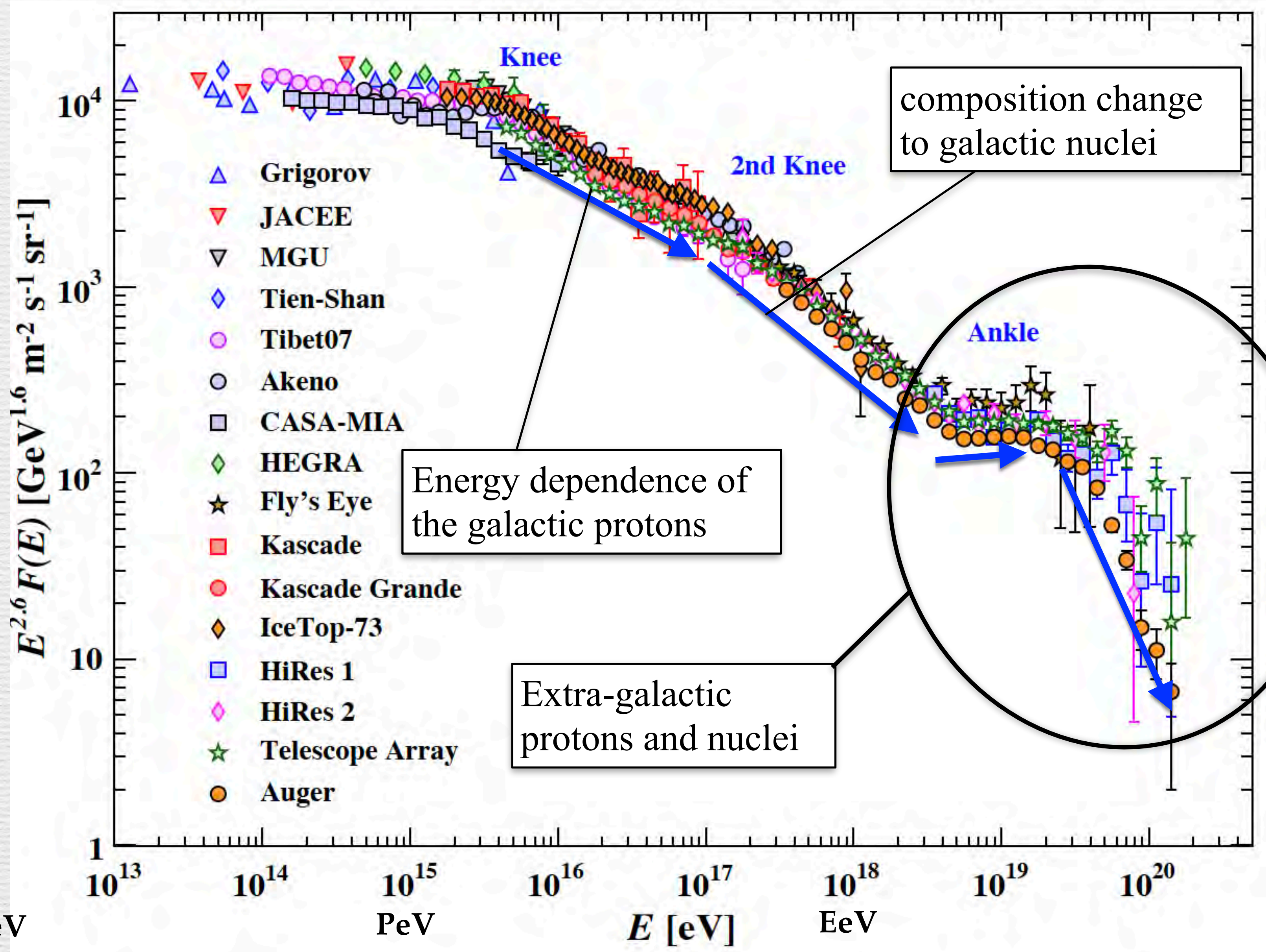
Ultra-High-Energy Cosmic Rays (UHECRs) [PDG2018]



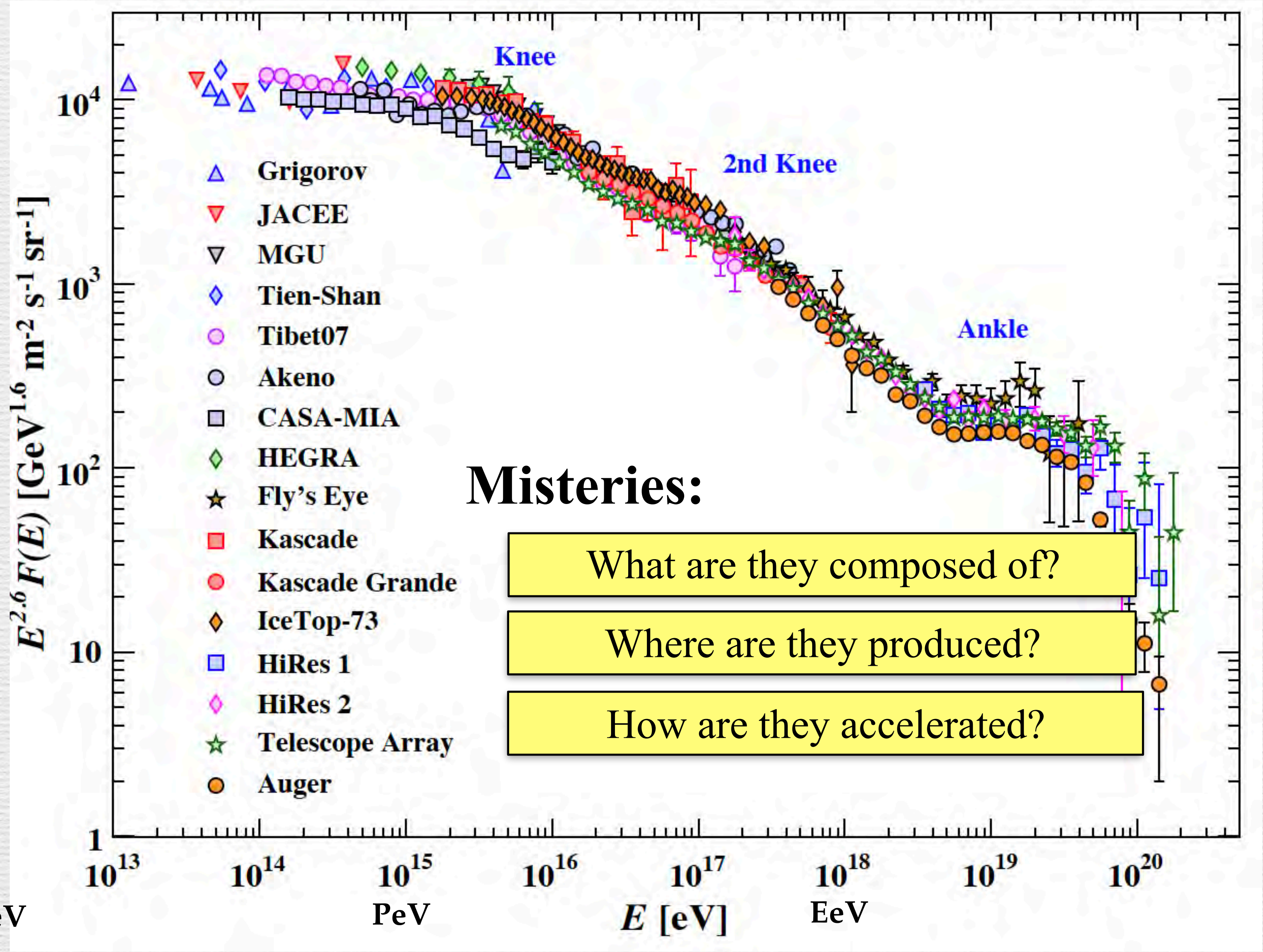
Ultra-High-Energy Cosmic Rays (UHECRs) [PDG2018]



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



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



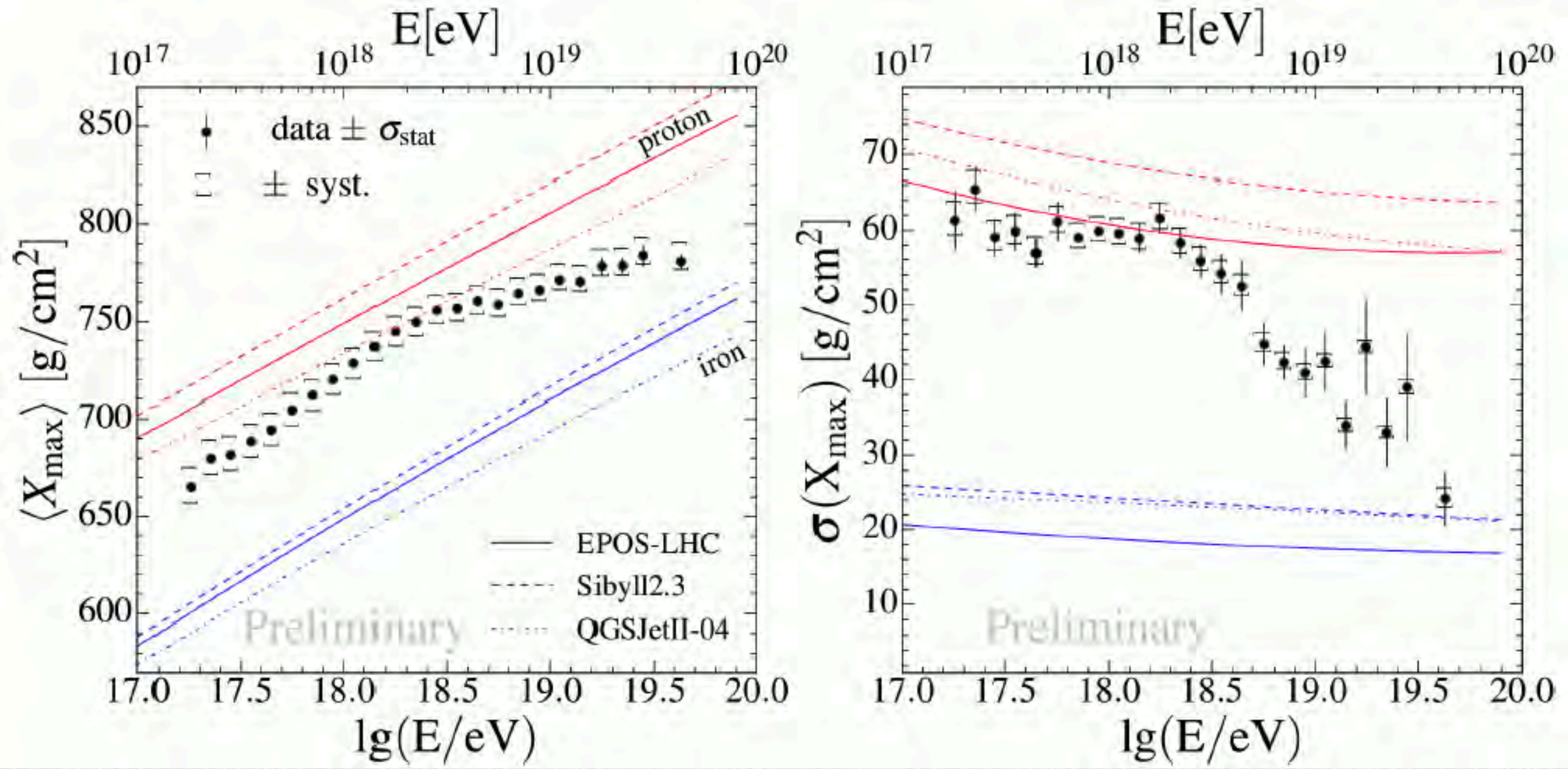
Misteries:

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

Mass Composition

[gor18]

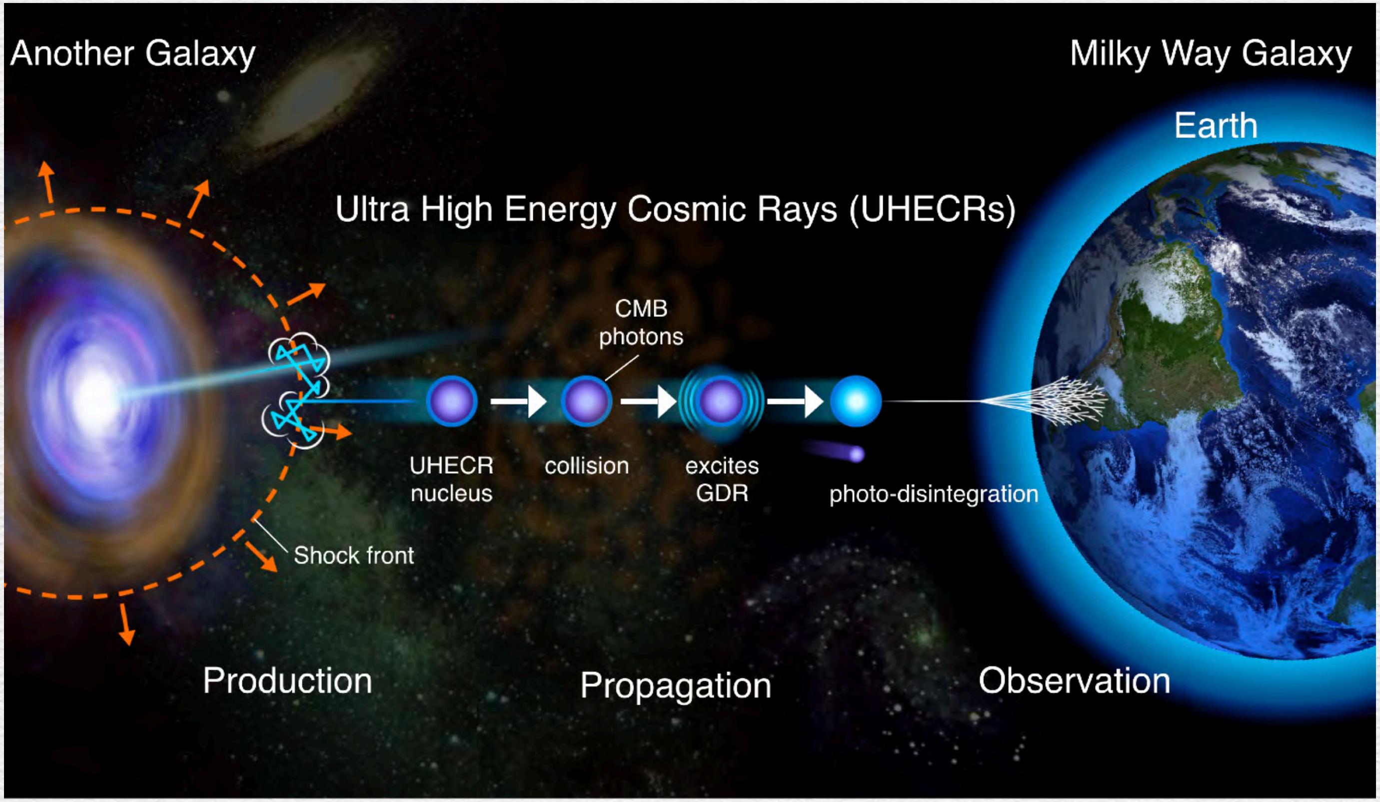
Pierre Auger Observatory



The fraction of proton increases up to $10^{18.3}$ eV and then decreases.

Heavier mass nuclei are becoming dominating the composition at the highest energy.

Extragalactic Propagation of UHECR Nuclei



Cosmic Microwave Background (CMB)

WMAP

T=2.73 K

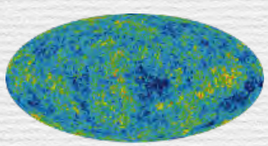


Photo-nuclear reactions determine the allowed travel distance of UHECRs nuclei and their composition/ energy modification in extra-galactic propagation.

GZK cut-off

Photo-disintegration Pass of ^{56}Fe

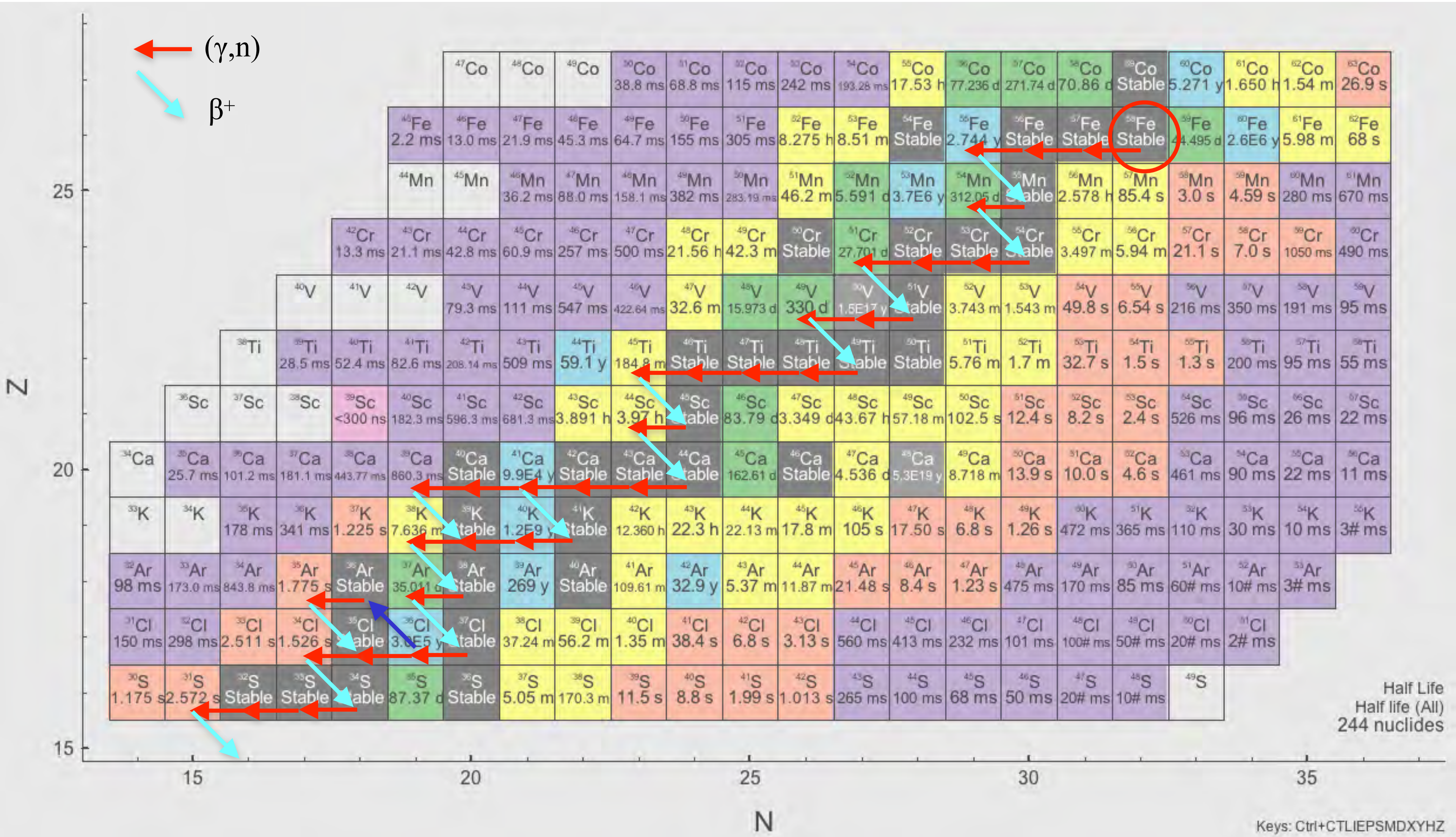
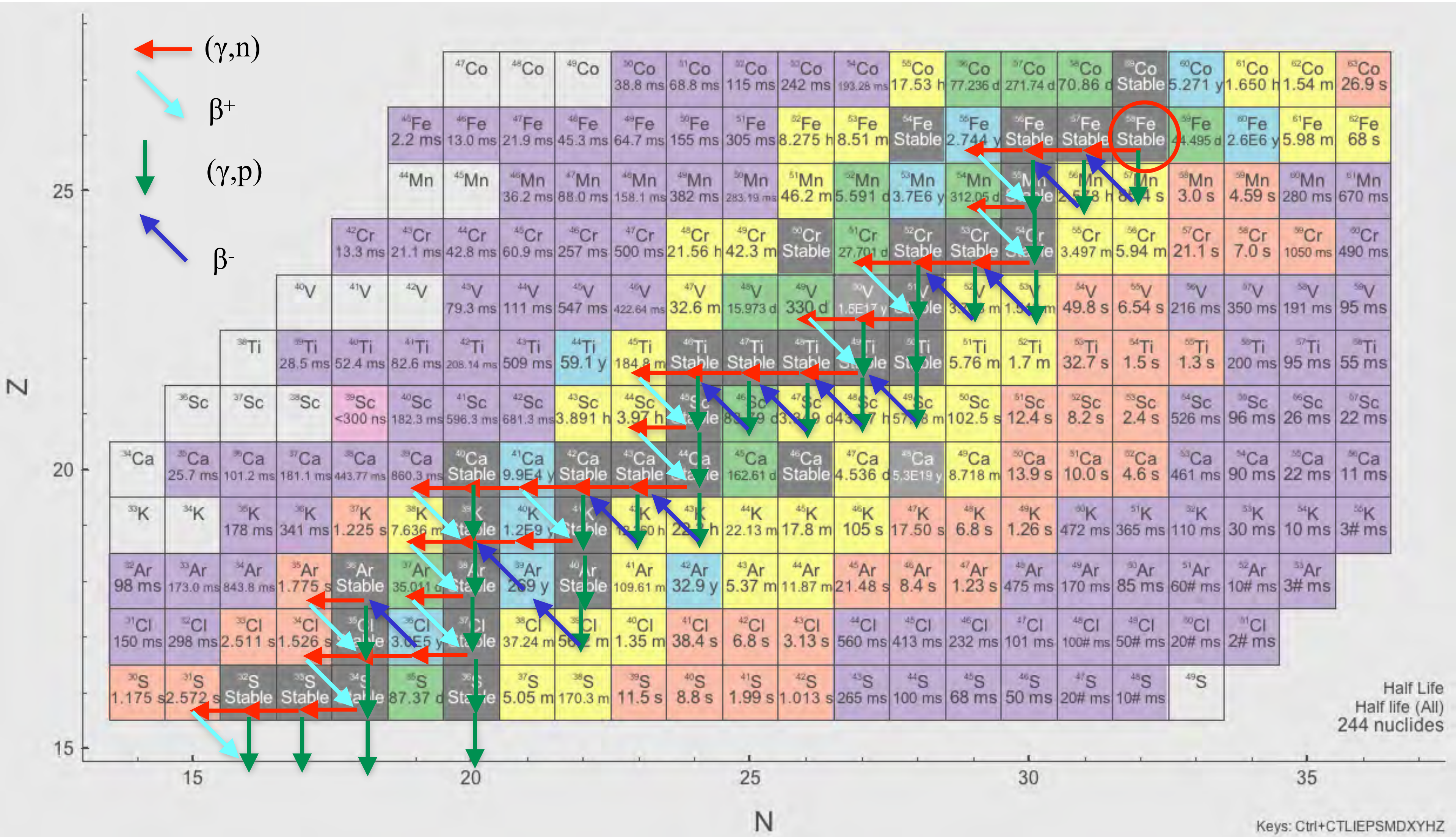


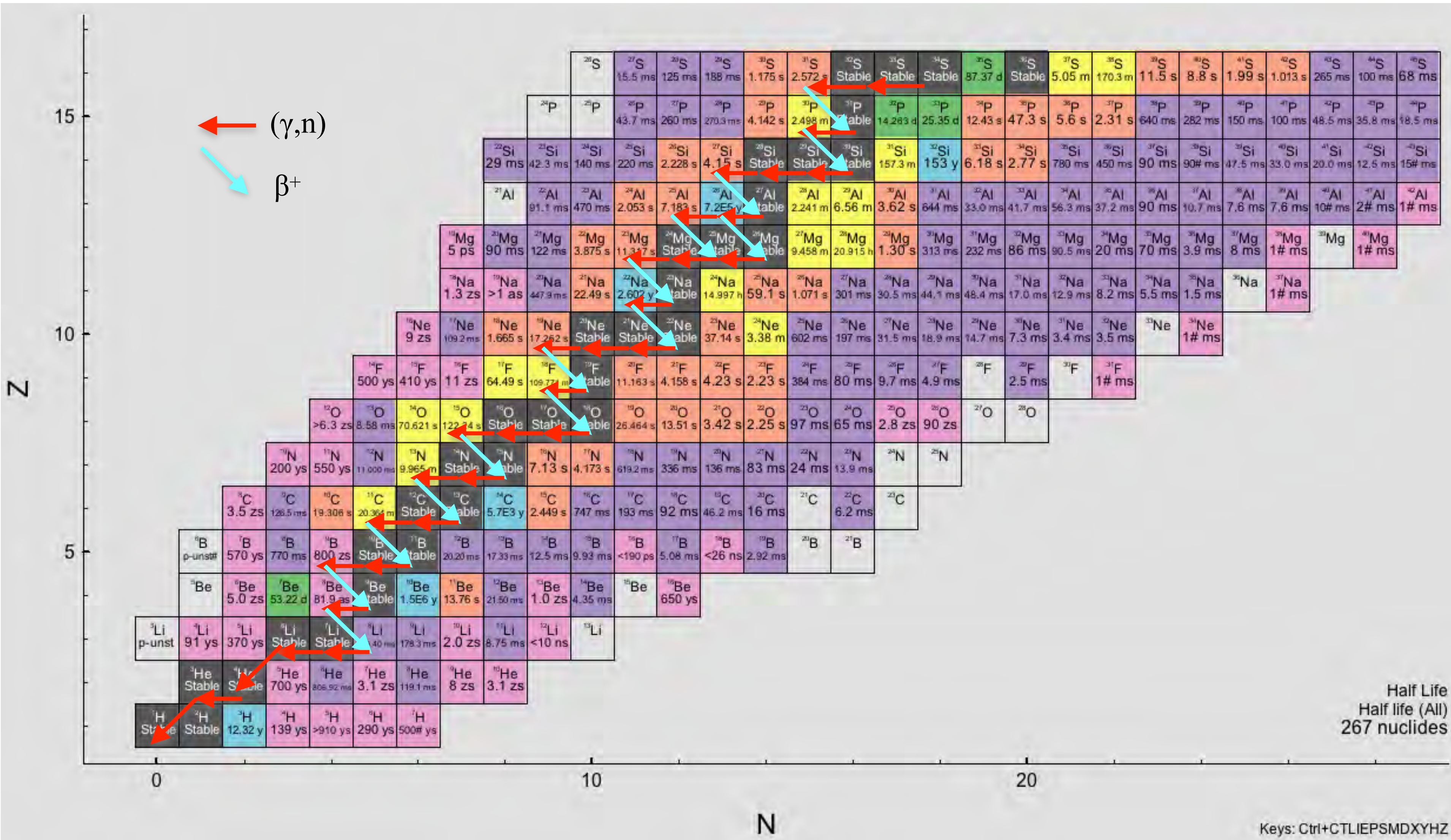
Photo-disintegration Pass of ^{56}Fe



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

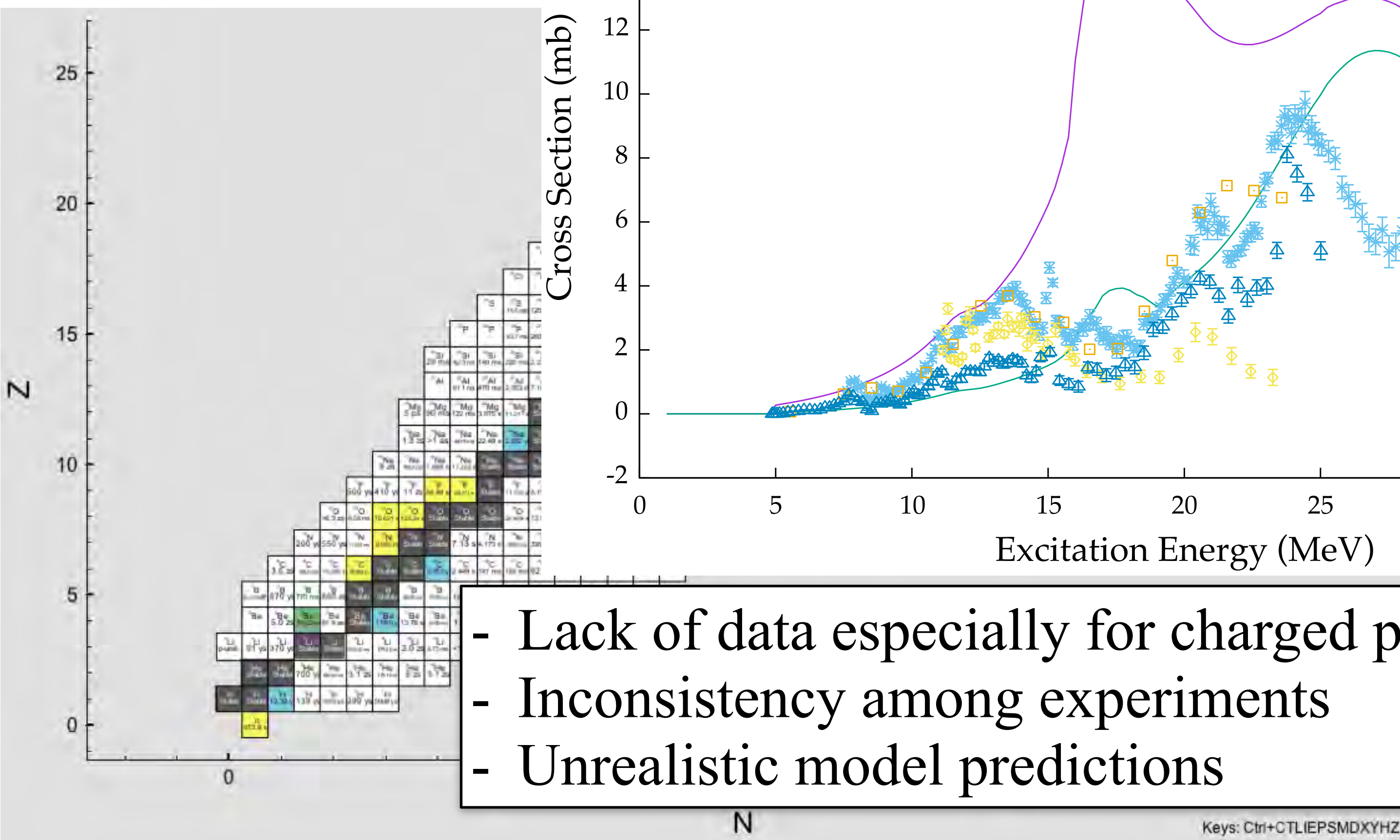
Several unstable nuclei also contribute.

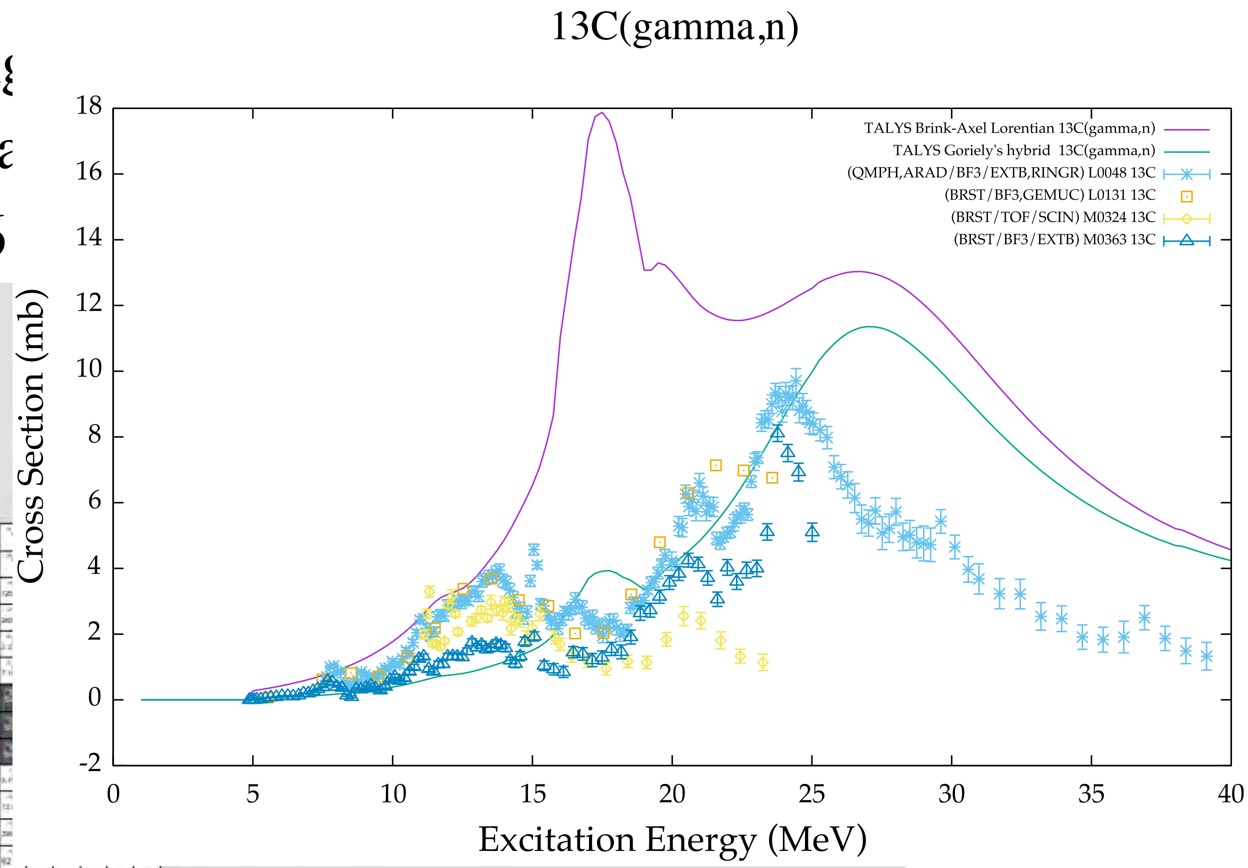
Photo-disintegration Pass of ^{56}Fe



Systematic Measurement on Photo-Absorption C.S. and n,p,α,γ decays for light to A~56 stable nuclei

- E1 excitation stren
- n, p, α, γ decay bra
- from light to A~56

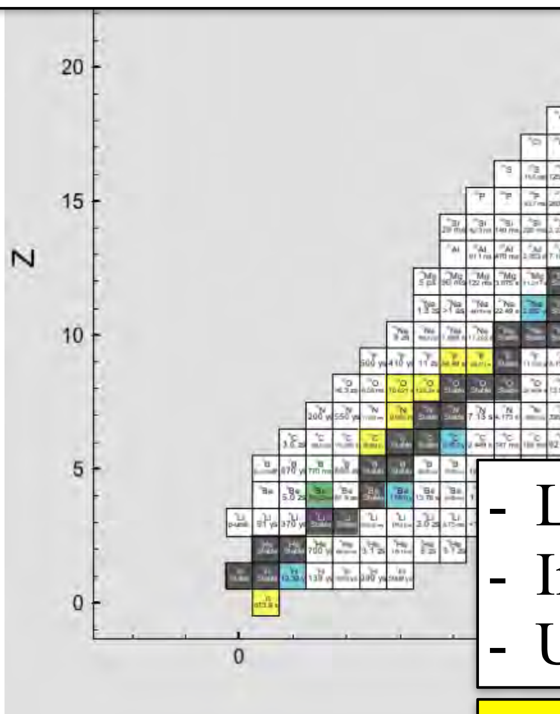


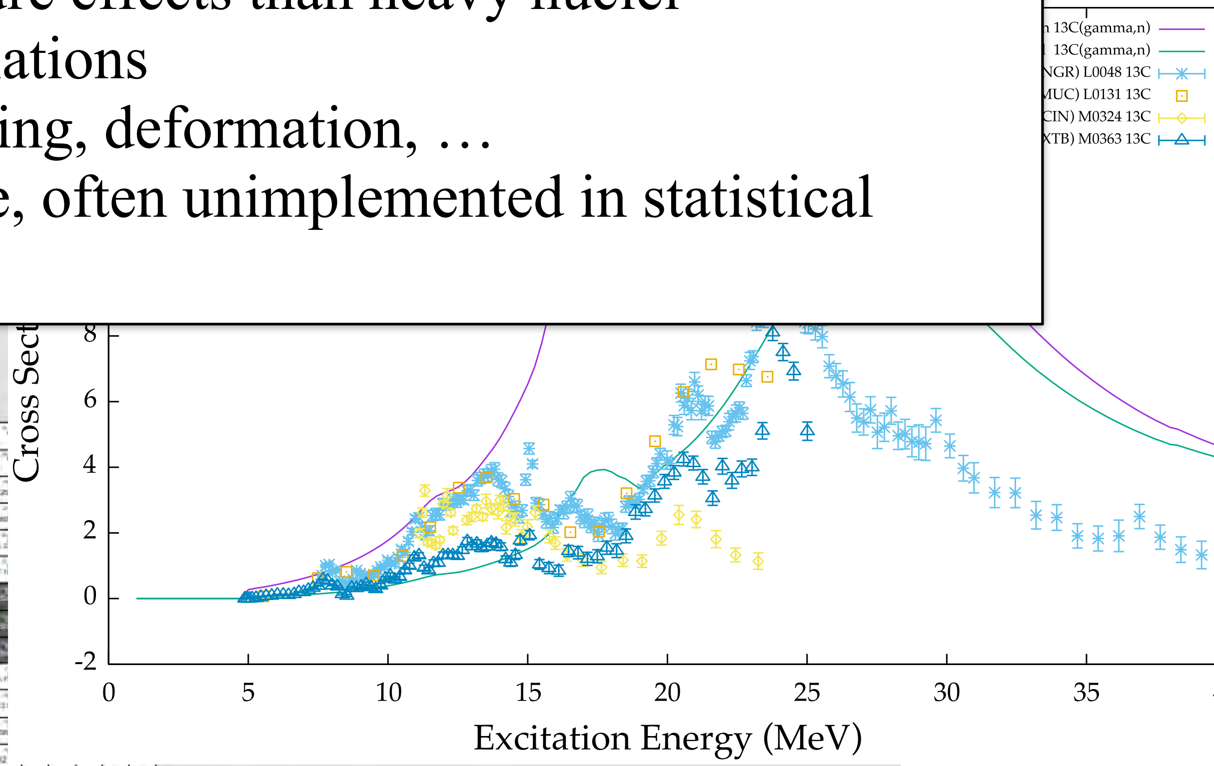


- Lack of data especially for charged particle decays
- Inconsistency among experiments
- Unrealistic model predictions

Systematic Measurement on Photo-Absorption C.S. and n,p,α,γ decays for light to A~56 stable nuclei

difficulties in theoretical modeling of light-medium mass nuclei
- stronger shell structure effects than heavy nuclei
- many-nucleon correlations
  α-clustering, *np*-pairing, deformation, …
- isospin selection rule, often unimplemented in statistical calculations.





- Lack of data especially for charged particle decays
- Inconsistency among experiments
- Unrealistic model predictions

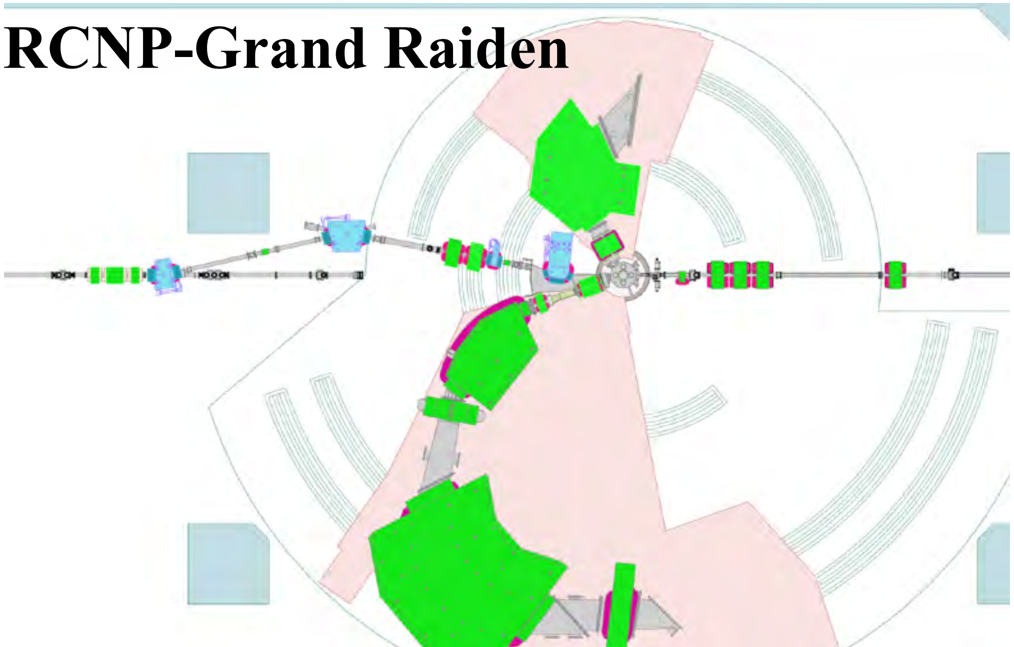
We need good systematic data and reliable models!

PANDORA Project

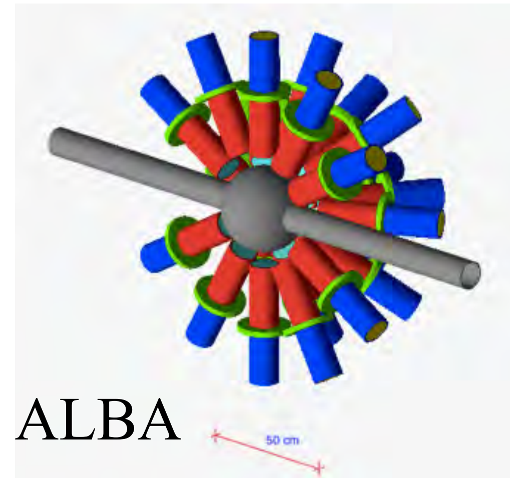
Photo-**A**bsorption of **N**uclei and **D**ecay **O**bservation for **R**eactions in **A**strophysics

Systematic Measurement on E1 Strength Distribution and n,p,α,γ decays up to A~56

RCNP-Grand Raiden



iThemba LABS

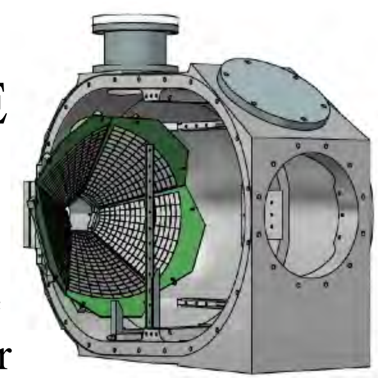


ALBA

Combination of experiments with complementary devices.

ELI-NP

CAKE



decay charge particle detector array

Experiment combining three complementary facilities

Virtual Photon Exp.

RCNP 2022-

Total strength distribution up 32 MeV

γ-decay

multipole decomp. analysis (ang. dep. and polarization transfer)

Osaka Univ.
A. Tamii, N. Kobayashi, T. Sudo, Z. Yang, T. Furuno, M. Murata, A. Inoue, H. Mori

iThemba LABS 2021-

Total strength distribution up 24 MeV

p,α,γ-decays

multipole decomp. analysis (ang. dep.)

iThemba LABS, Univ. Witwatersland, Stellenbosh Univ.
L. Pellegri, R. Neveling, F.D. Smit, J.A.C. Bekker, S. Binda, H, Jivan, T. Khumal, M. Wiedeking, K.C.W. Ki, P. Adsley, L.M. Donaldson, E. Sideras-Haddado, K.L. Malatji, S. Jongile, A. Netshiya

Real Photon Exp.

ELI-NP 2023-

absolute c.s.

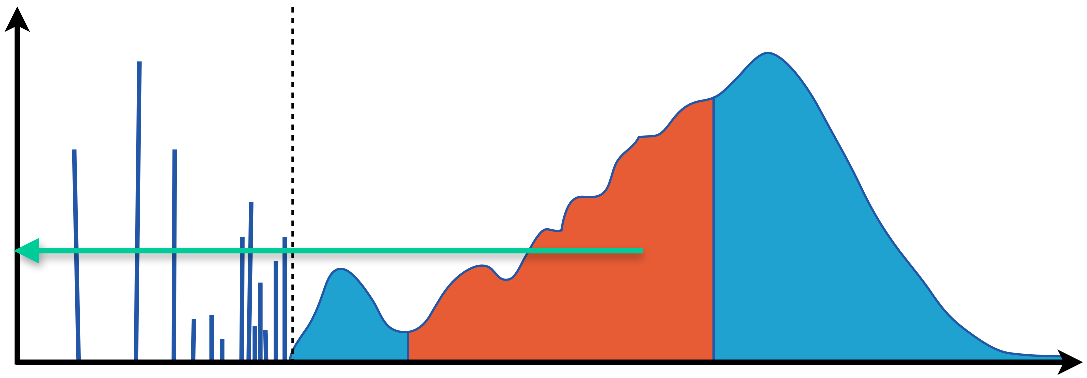
model independent separation of E1 and M1

n,p,α,γ-decays up to 20 MeV

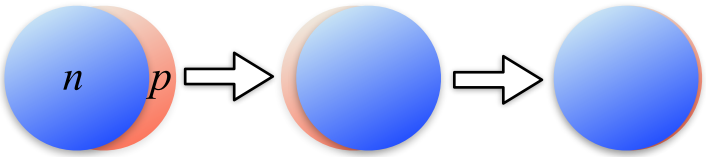
ELI-NP
P.-A. Söderström, D. Balabanski, L. Capponi, A. Dhal, T. Petruse, D. Nichita, Y. Xu

III Physics Topics

Fine Structure of the Giant Dipole Resonance
Damping mechanism and the Nuclear Level Density



Damping Mechanism of Collective Excitations (IVGDR)



Damping of IVGDR

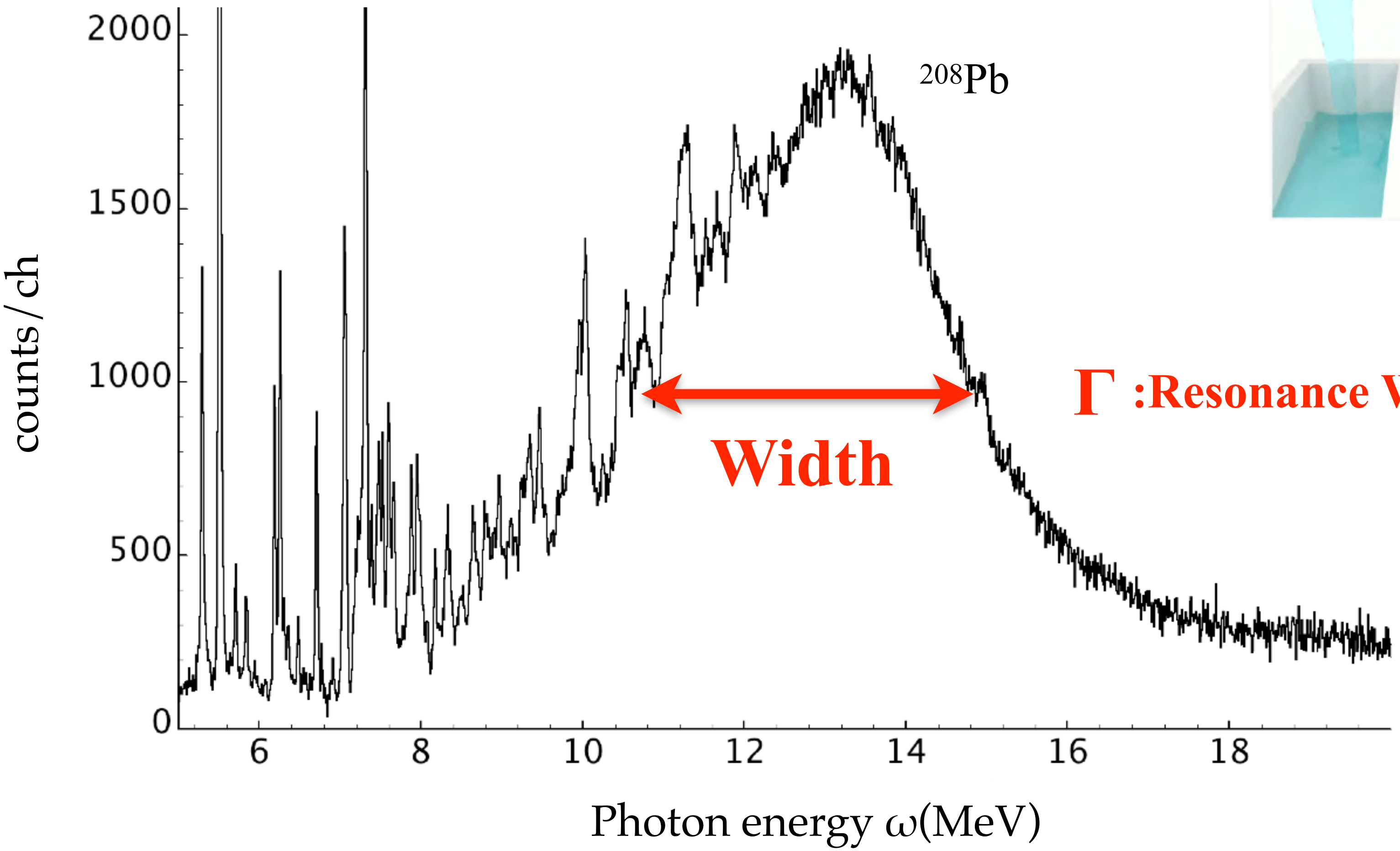
Macroscopically

IVGDR: relative dipole oscillation between *p* and *n*

Damping: due to viscosity between the p and n fluids

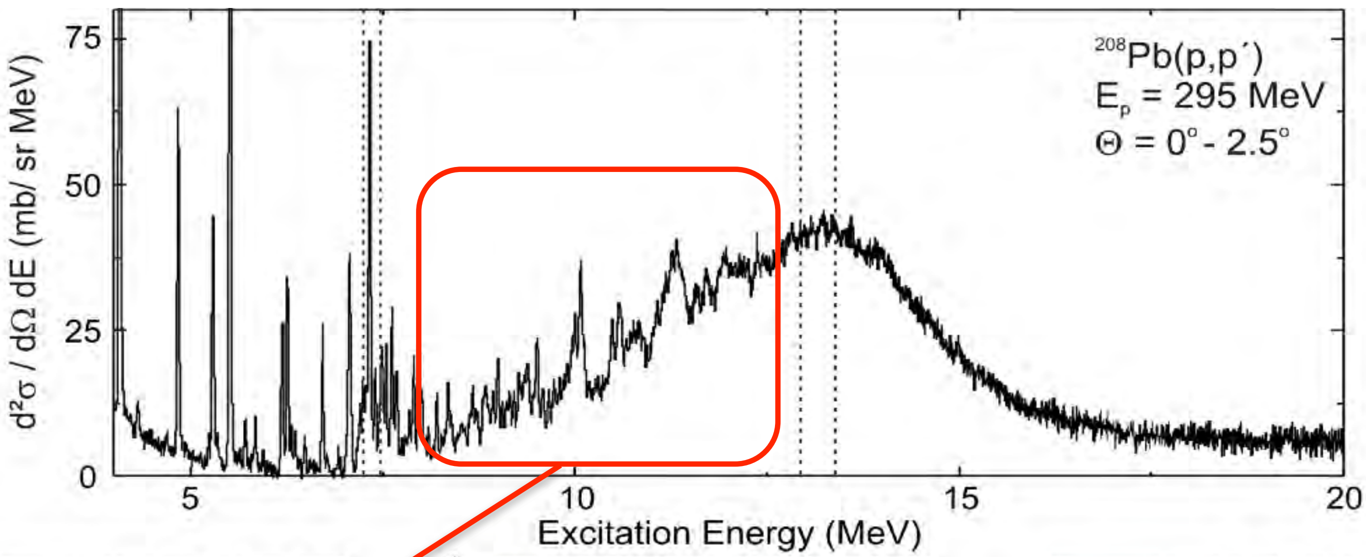
see e.g. J. Wambach, Rep. Prog. Phys.'88

wikipedia



Γ :Resonance Width

Fine Structure of the GDR



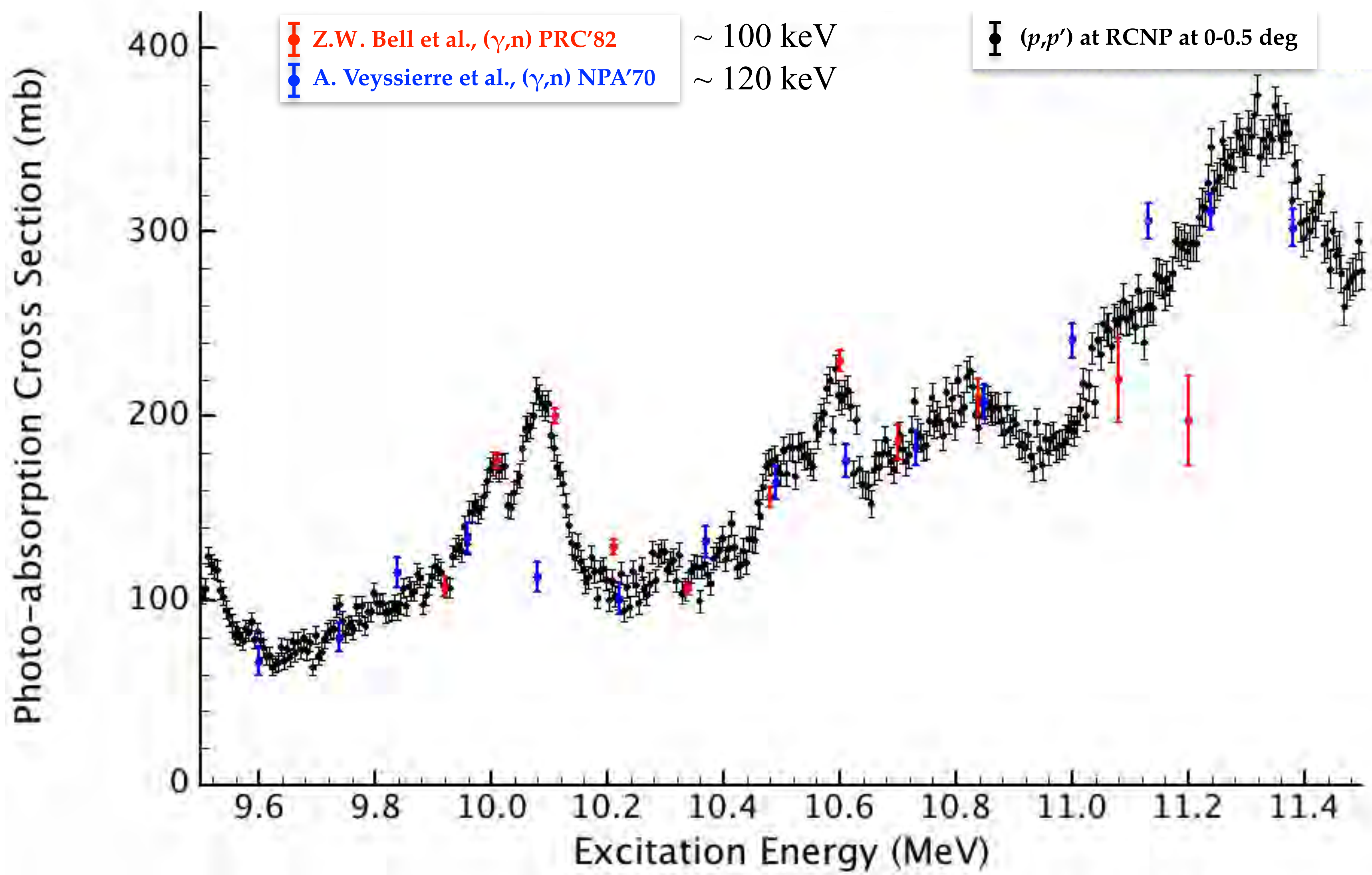
Fine structure of the GDR is clearly observed.

→ Energy dissipation and damping

Gamma decay measurement of the GDR will be one of interesting probes to study the damping mechanism of the GDR.

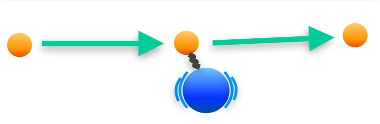
See e.g. J. Beene et al., PRC41, 920 (1990)

Fine Structure of the GDR



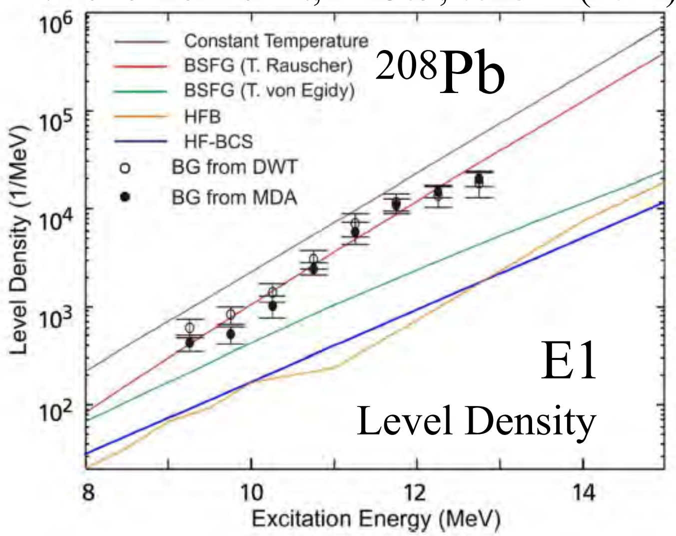
20-30 keV resolution is required.

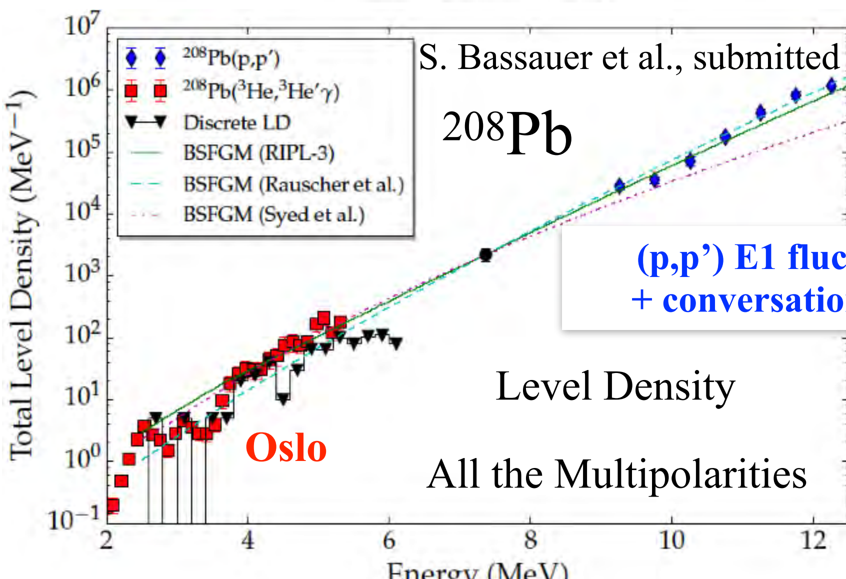
Nuclear Level Densities



extracted by fluctuation analysis using auto-correlation function

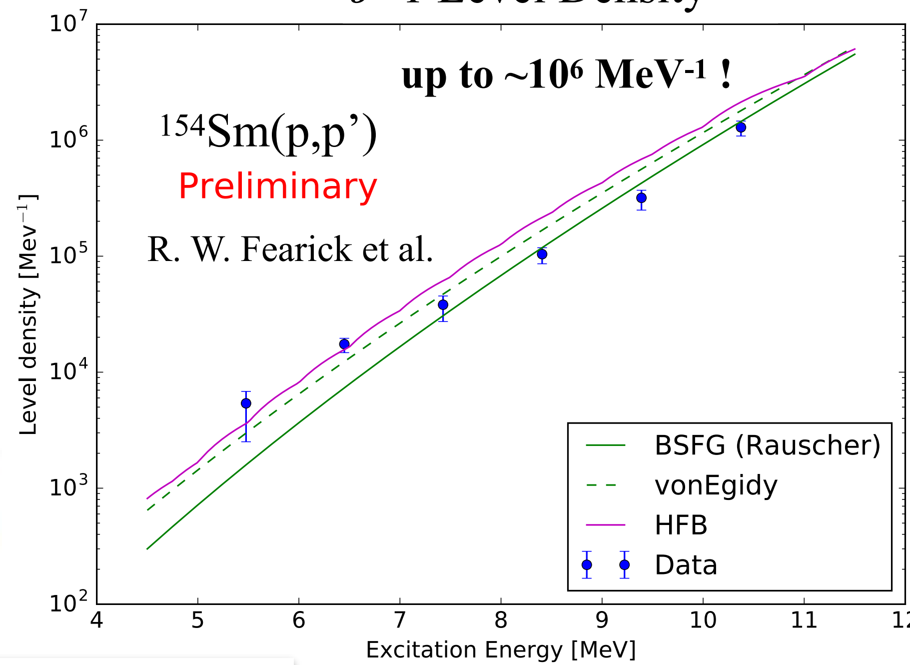
I. Poltoratska et al., PRC89, 054322 (2014)





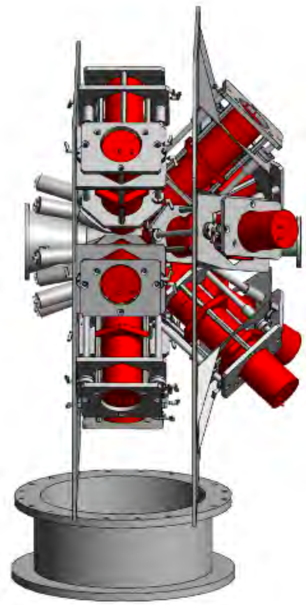
(p,p') E1 fluctuation analysis
+ conversation to total (theo.)

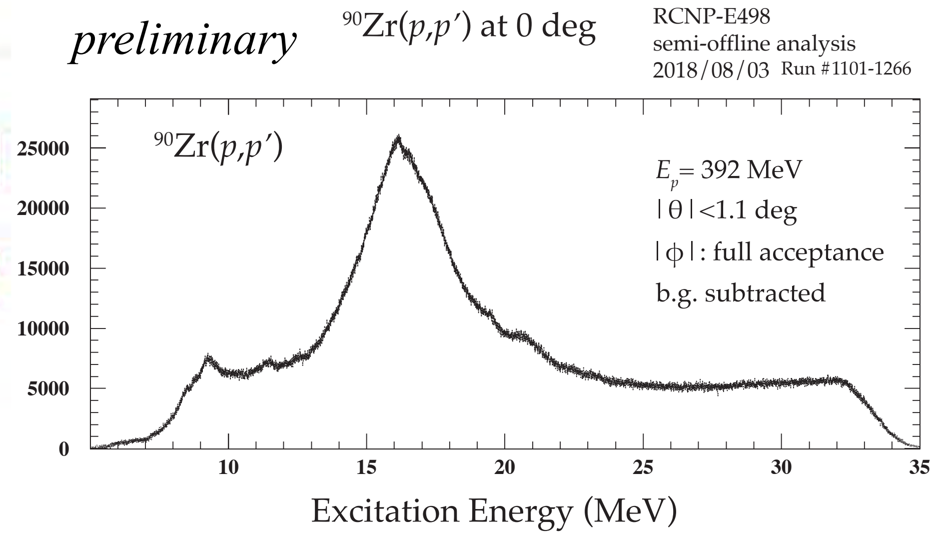
J=1 Level Density

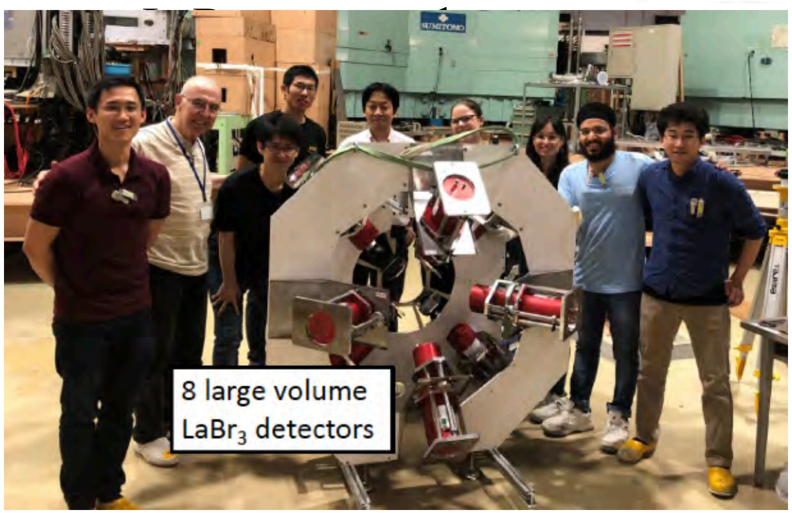


Level density of states can be extracted from high-resolution data

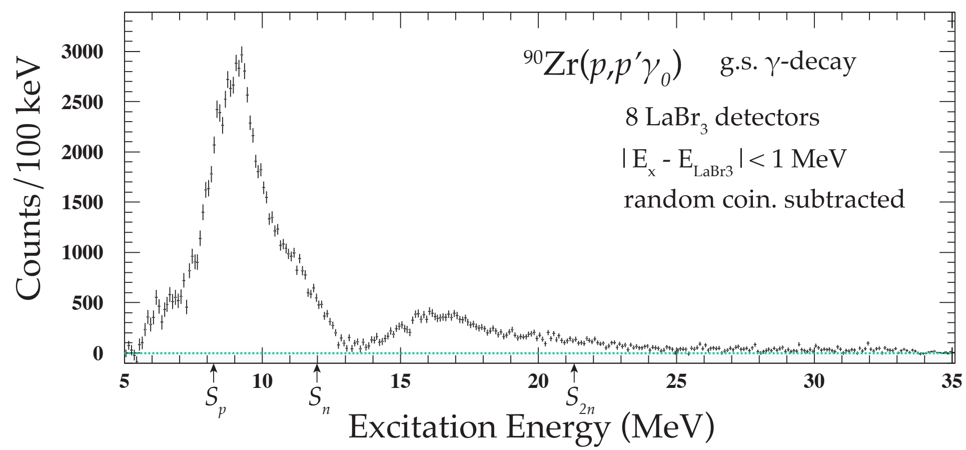
Damping Mechanism of the GDR in ^{90}Zr
(July 2018 at RCNP)



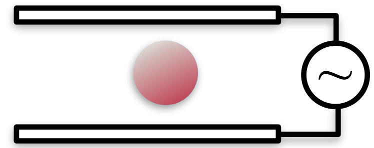


A part of the E498 collaborators
in collaboration with ELI-NP



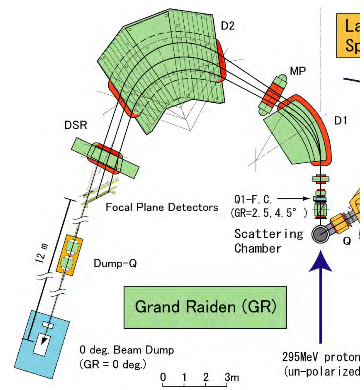
further analysis is in progress

Summary

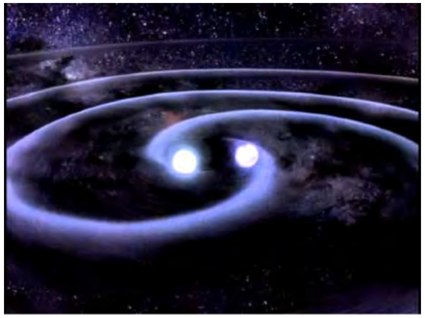


I. Electric Dipole Response of Nuclei

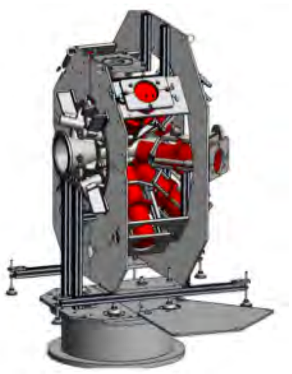
II. Experimental Methods

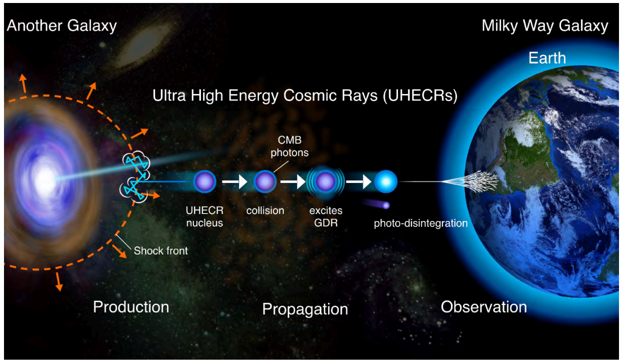


III. Physics Topics



- Polarizability and Symmetry Energy
- Ultra-High-Energy Cosmic Rays
- Fine Structure of GDR





Thank you

for your attention