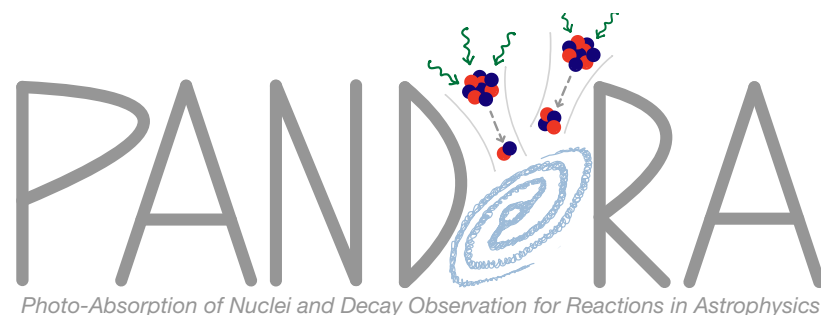


原子核の電磁応答と光核反応

民井 淳

大阪大学核物理研究センター



PANDORA Collaboration

1

東北大学セミナー(集中講義), 東北大学, 2026年9月29日

Outline

- Photo-Nuclear Reaction

E1 Polarizability, Pygmy&Toroidal Excitation

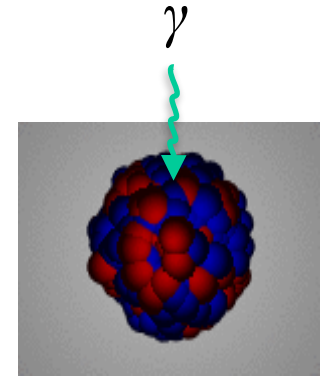
- Photo-nuclear reaction of light nuclei (PANDORA)
- Ultra-High-Energy Cosmic Rays
- PANDORA Experiment@RCNP

Photonuclear Reaction

Photo-nuclear Reaction / Excitation of IV GDR

Oscillating electric field induced by an incident photon

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



IVGDR

Photo-absorption cross section: dominated by electric dipole ($E1$) excitation

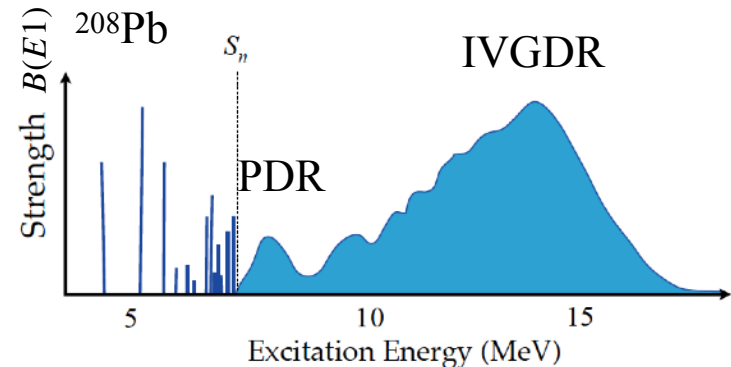
$$\sigma_{\text{abs}} \simeq \sigma_{\text{abs}}^{E1} = \frac{16\pi^3}{9} \alpha E_\gamma \frac{dB(E1)}{dE_\gamma}$$

σ_{abs} : photo-absorption cross section

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

E_γ : photon-energy = nuclear excitation energy

α : fine structure constant



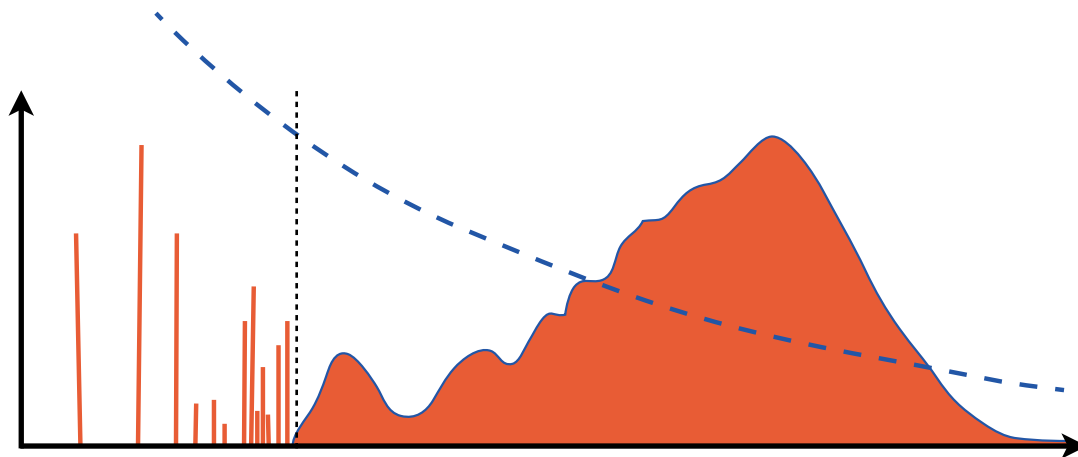
Stable double magic nuclei, E1 response

Fundamental $\longleftrightarrow$ Exotic

“Exotic Nuclear Physics Conf.”

“least exotic = exotic”

E1 Polarizability



Static Electric Dipole Polarizability (α_D)

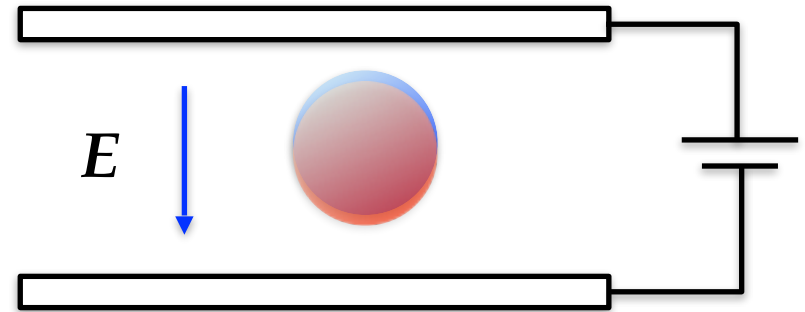
Electric dipole moment

$$p = \alpha_D \times E$$

α_D : electric dipole polarizability



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



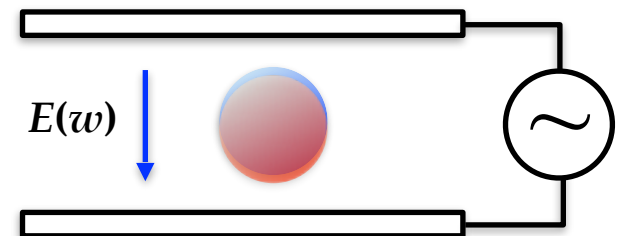
nucleus

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

Inversely energy-weighted sum-rule of B(E1)

$$\alpha_D = \frac{8\pi e^2}{9} \int \frac{dB(E1)}{E_x}$$

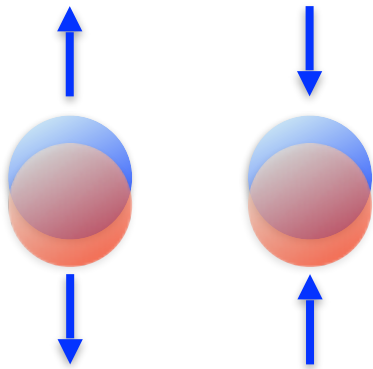
first order perturbation calc. A.B. Migdal: 1944
dielectric theorem



Symmetry Energy (J and L parameters)

Keys to Understand the Neutron Matter Equation of State (EOS)

Electric Force Symmetry Energy



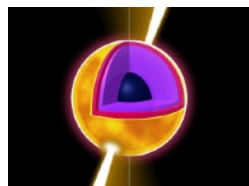
α_D is determined by the balance between the two.

Nucleus



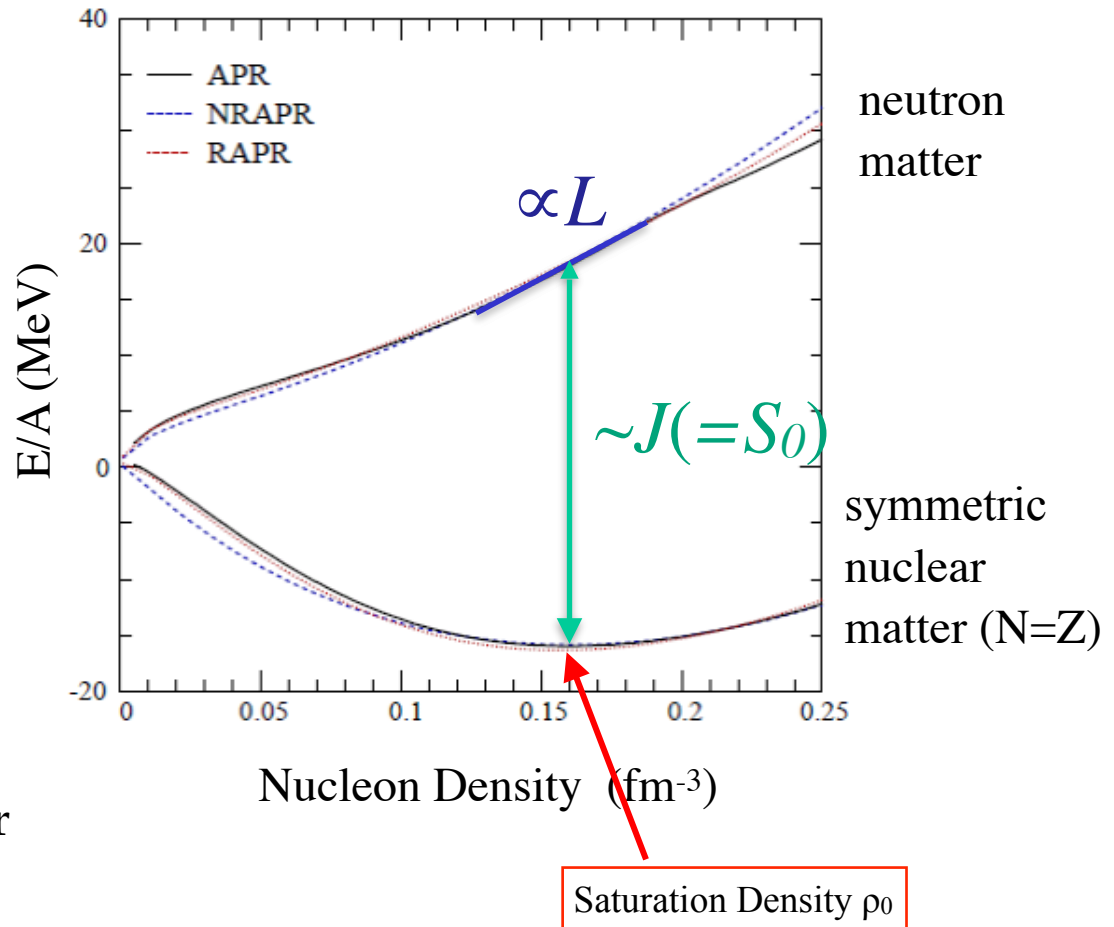
$Z \approx N$

Neutron Star



$Z \ll N$

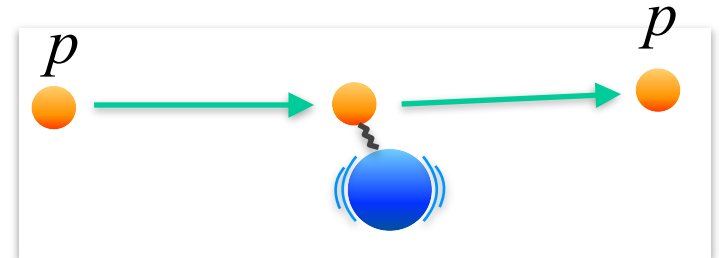
Nuclear Equation of State



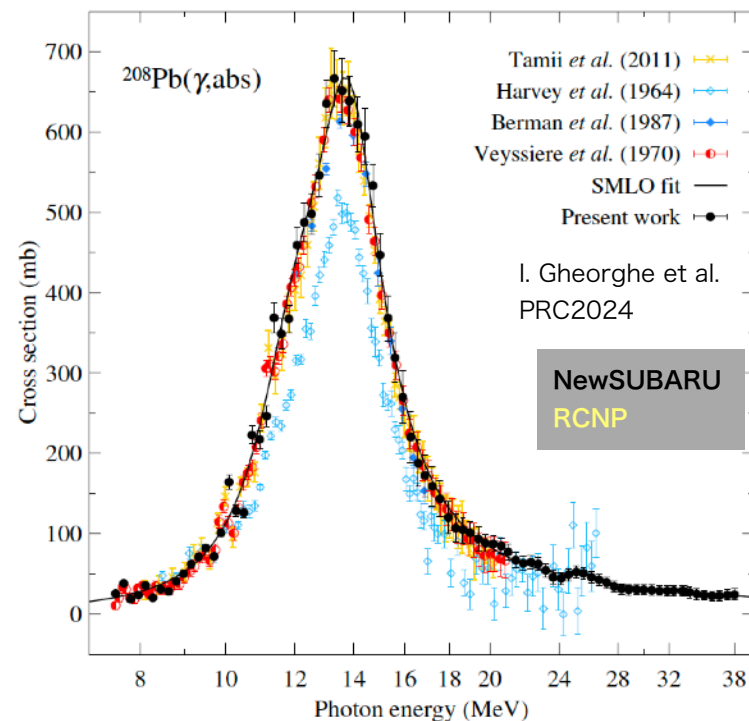
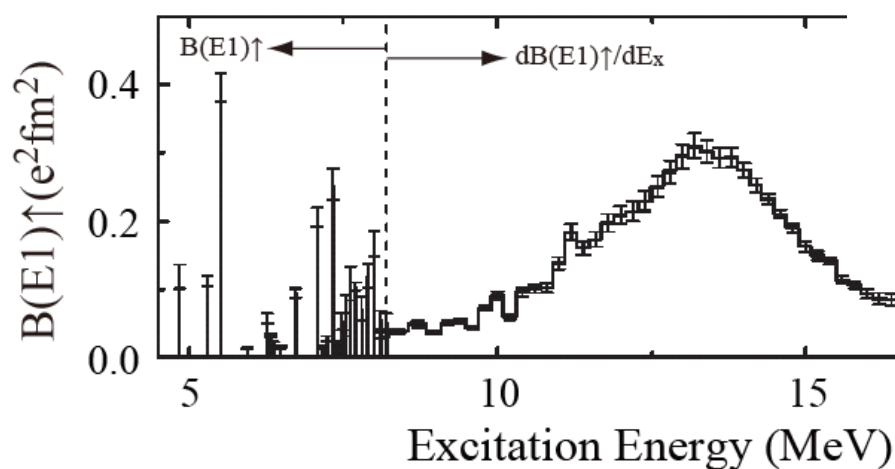
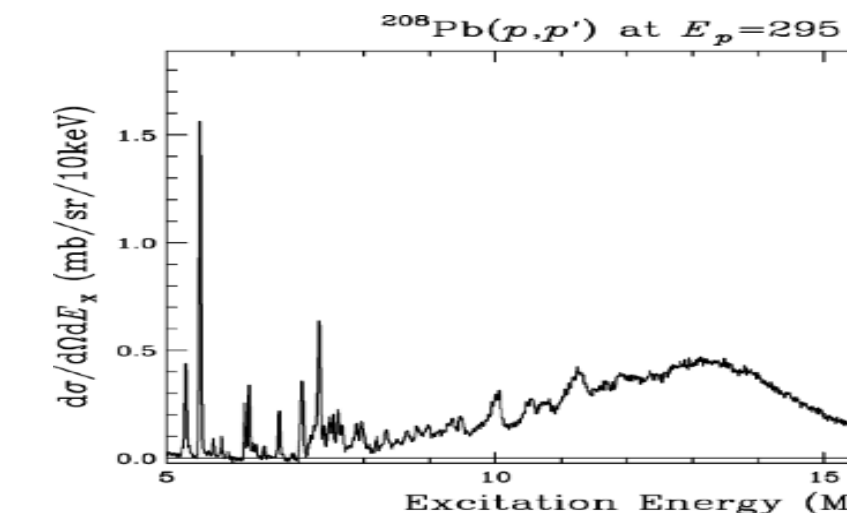
Probing Photo-Nuclear Response of Nuclei (Electric Dipole)

Virtual photo excitation by proton scattering @RCNP

- Missing mass method
with proton Coulomb excitation

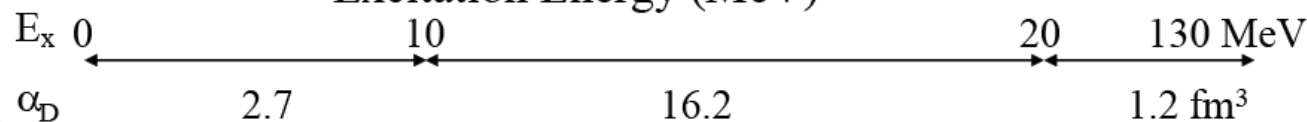


Electric Dipole Polarizability: ^{208}Pb



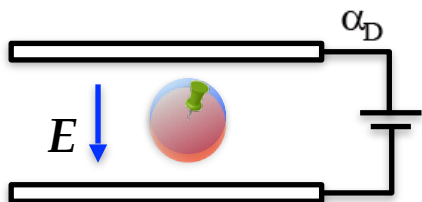
I. Gheorghe et al.
PRC2024

NewSUBARU
RCNP



total $20.1 \pm 0.6 \text{ fm}^3$

AT et al., PRL107, 062502(2011)



Electric Dipole Polarizability

Clear definition

Unambiguous in the integration range

↔ Pygmy Dipole Strength

Inversely energy weighted sum-rule

More sensitive to the low-energy strength

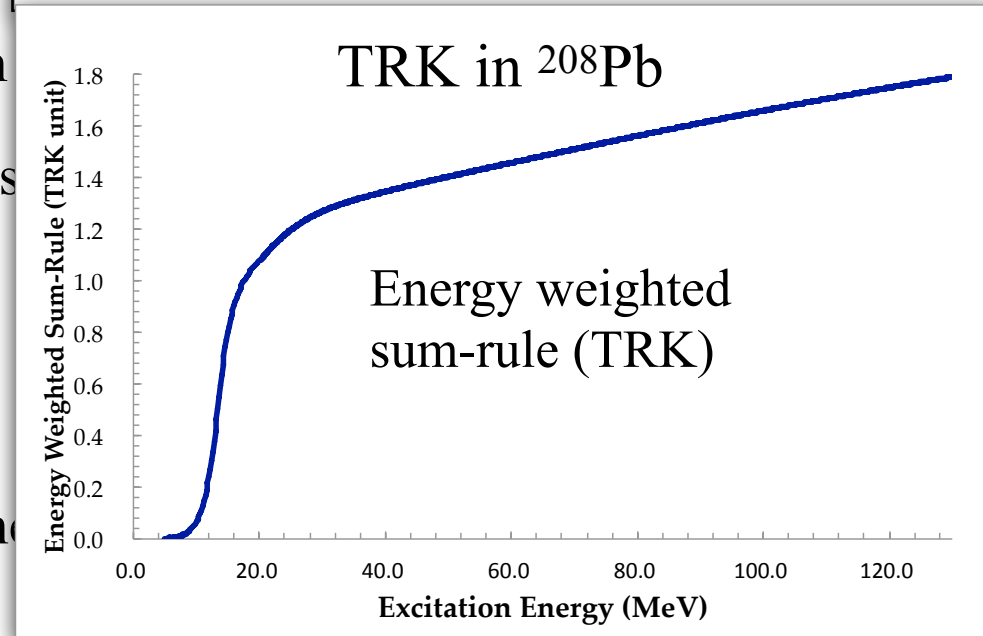
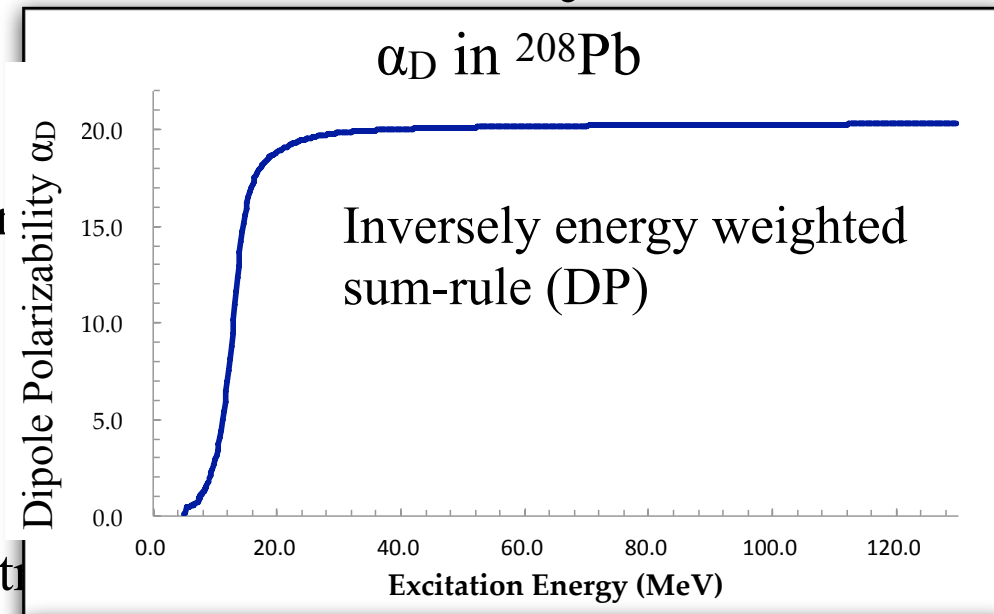
Good convergence in the excitation energy range

↔ energy-weighted (TRK) sum-rule

Sum-rule for all the transitions

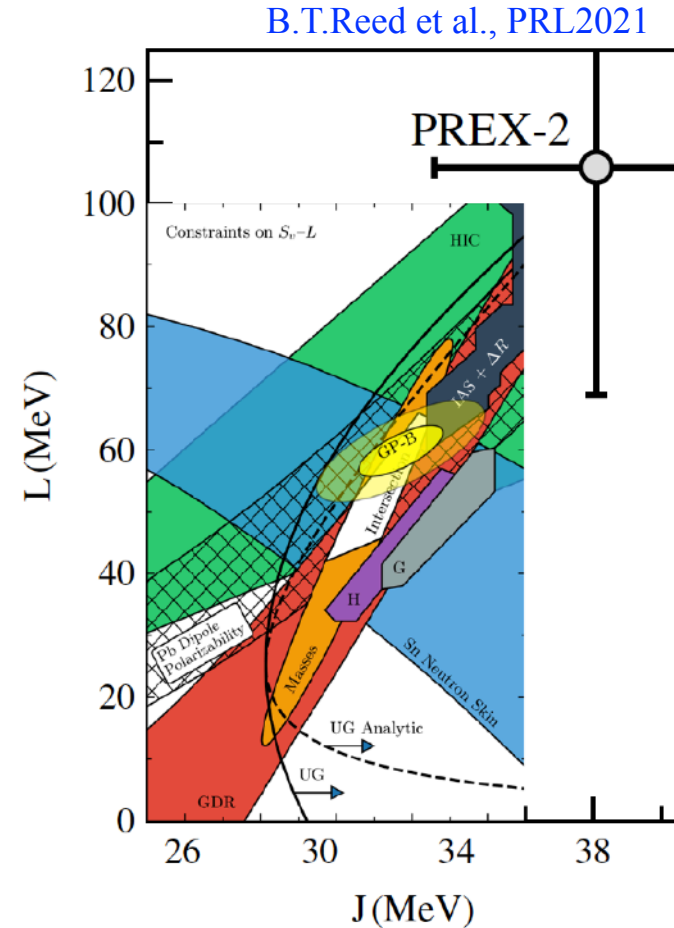
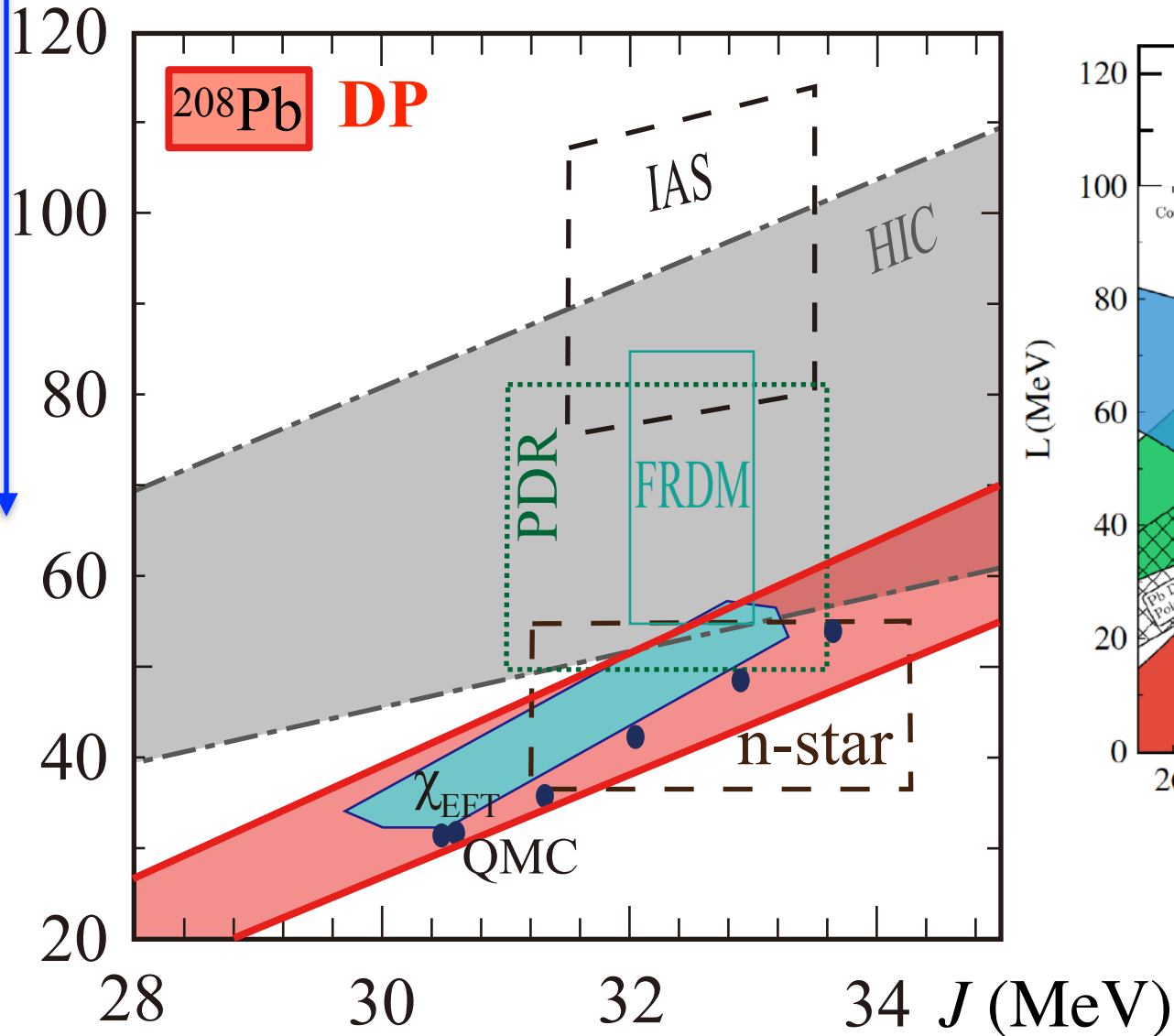
= Ground state property

↔ easier comparison with theoretical calculations



Constraints on Symmetry Energy (J and L)

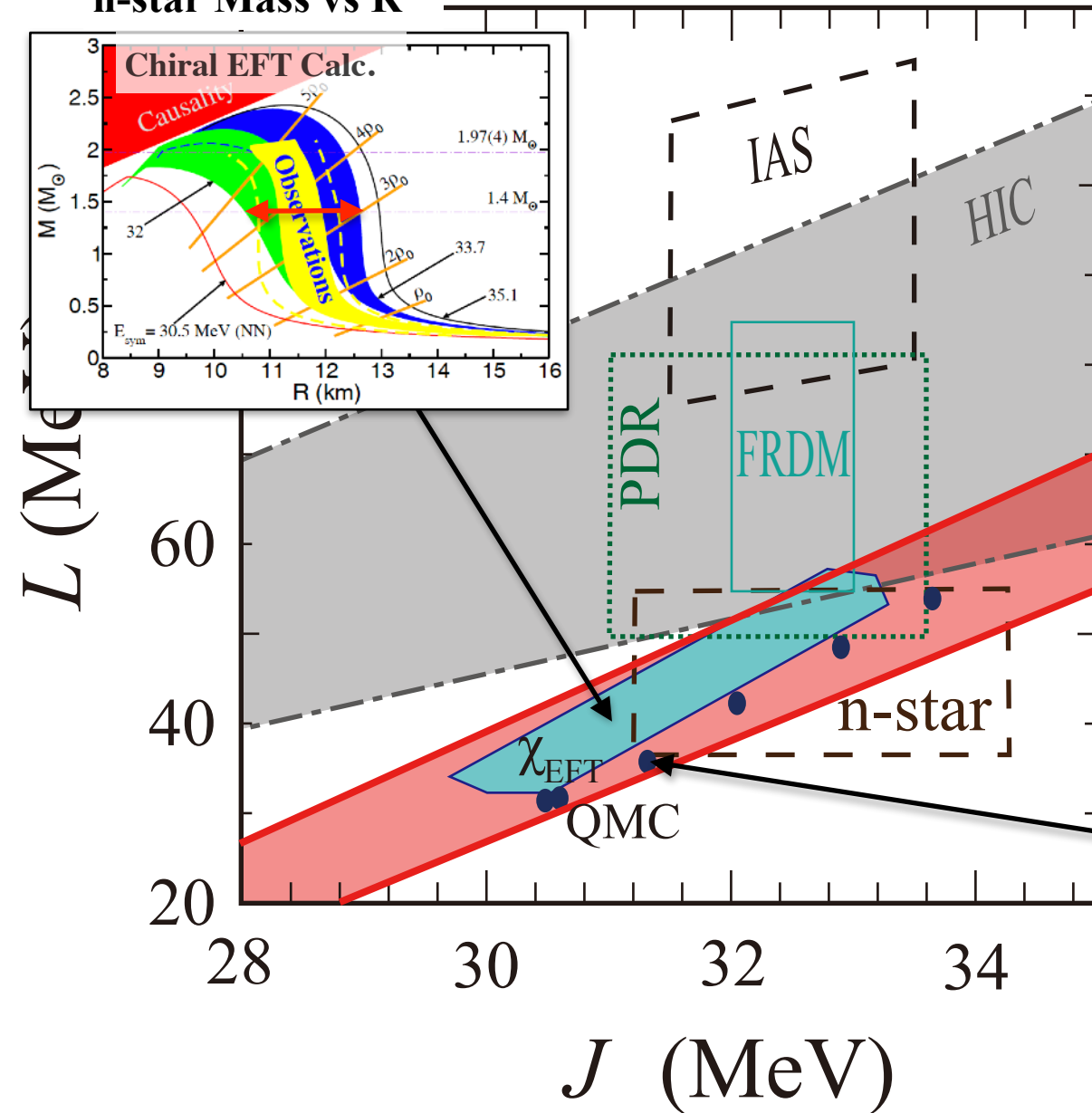
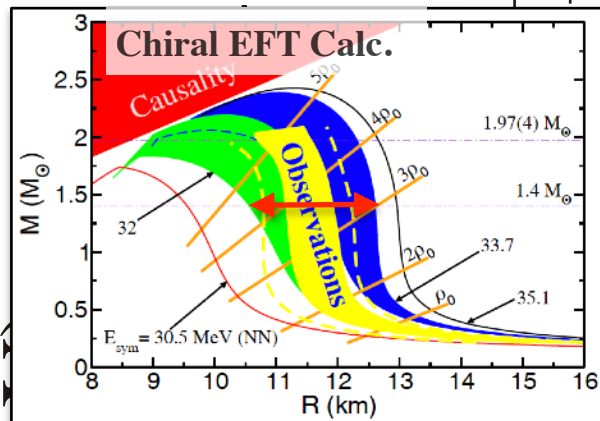
$R_{\text{skin}} = R_n - R_p = (0.283 \pm 0.071) \text{ fm}$
 $\text{PREX-2 } 106 \pm 37 \text{ MeV}$
 B.T.Reed et al., PRL2021



DP: Dipole Polarizability
 208Pb AT PRL2011 11

Constraints on Symmetry Energy (J and L)

n-star Mass vs R



Tsang PRC2012

HIC: Heavy Ion Collision Analysis
Tsang PRL2009

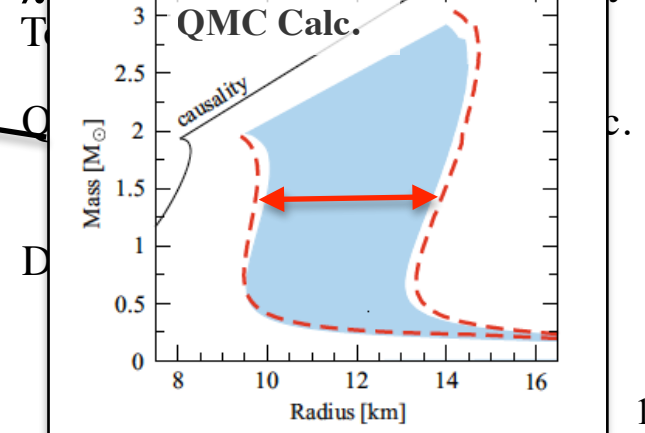
IAS: Isobaric Analog State Energy
Danielewicz&Lee NPA2009

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

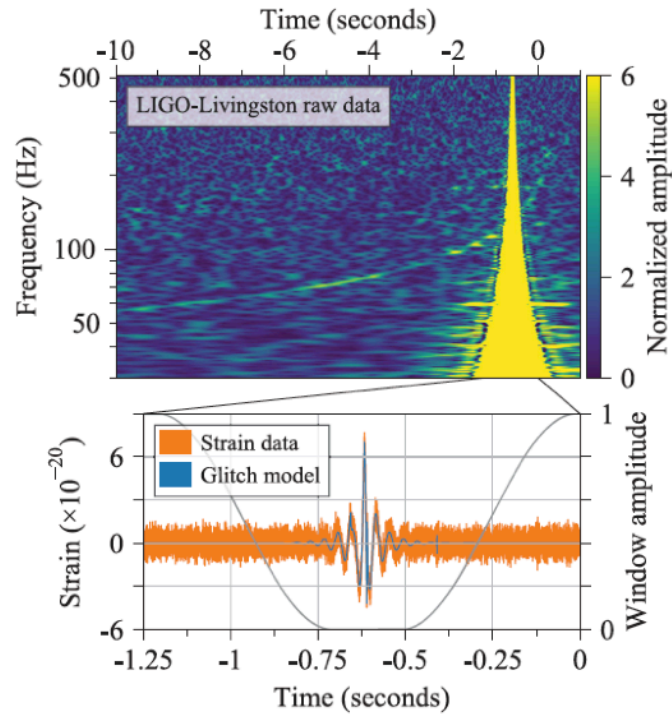
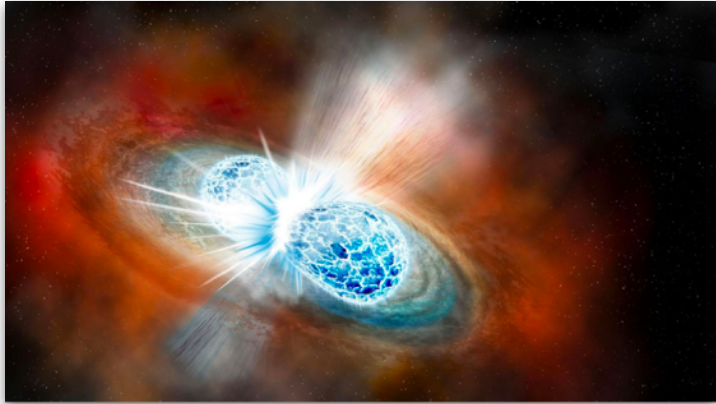
FRDM: Finite Range Droplet Model
Moller PRL2012

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

χ_{EFT} : Chiral Effective Field Theory,



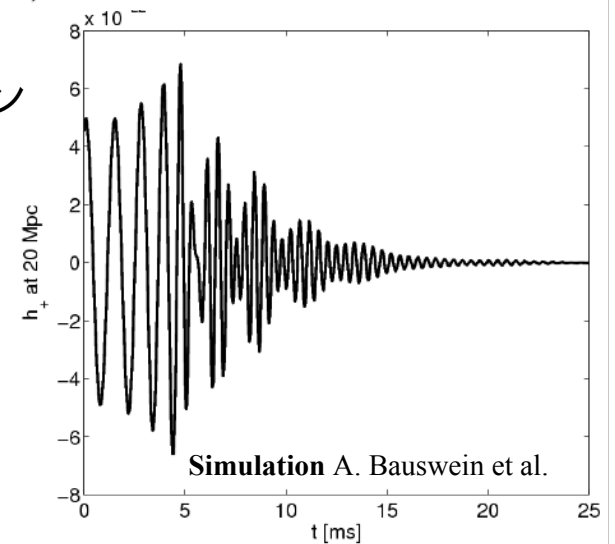
Neutron Star Merger GW



GW
PRL119, 161101(2017)

観測

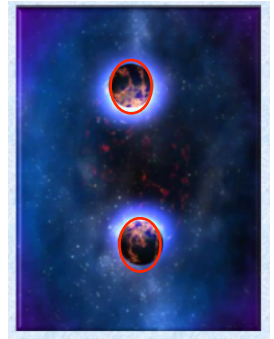
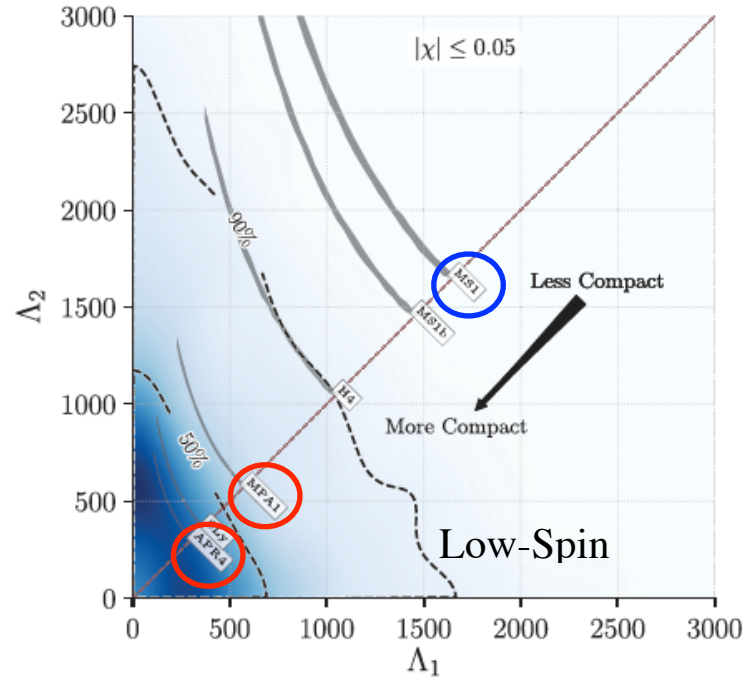
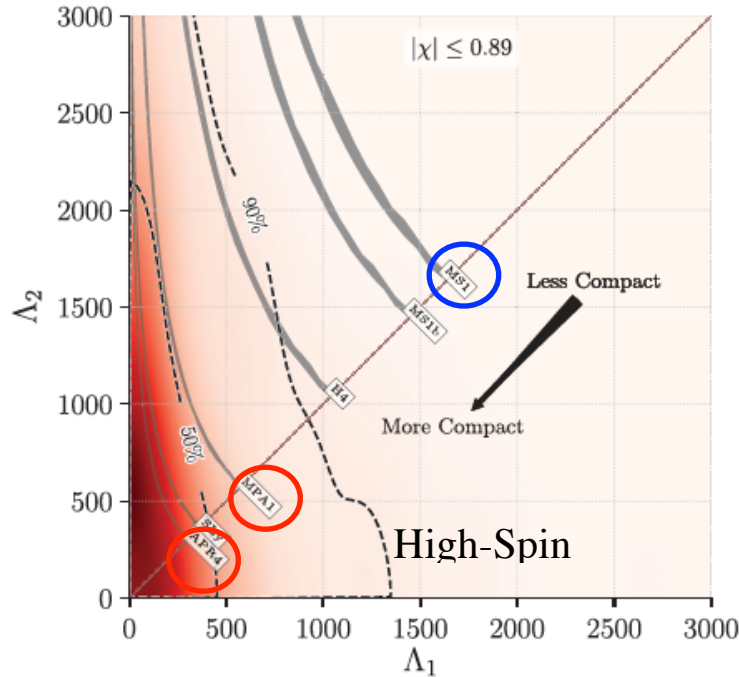
シミュレーション



Advanced LIGO

Constraints from the N-Star Merger GW

PRL119, 161101(2017)



Tidal Deformation

潮汐力

Tidal Deformation Parameters

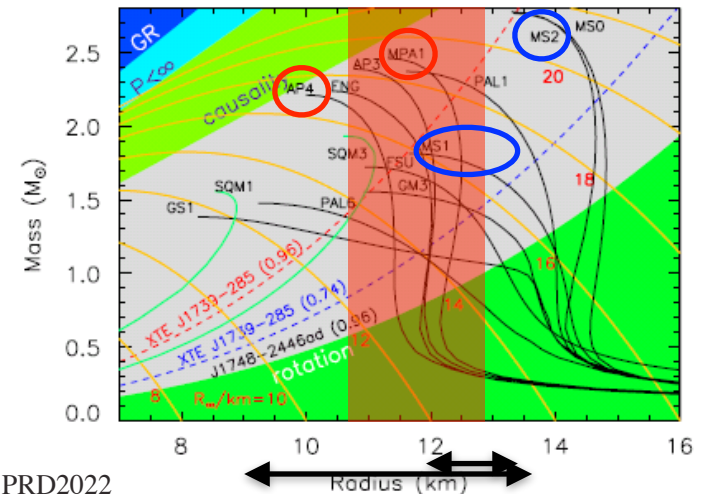
N-Star Radius ($1.4M_\odot$)

$R^{1.4} < 13.76 \text{ km}$ F.J. Fattoyev et al., PRL120, 172702(2018)

$12.00 < R^{1.4} < 13.45 \text{ km}$ E.R. Most et al., PRL120, 261103(2018)

$9.0 < R^{1.4} < 13.6 \text{ km}$ I. Tews et al.,

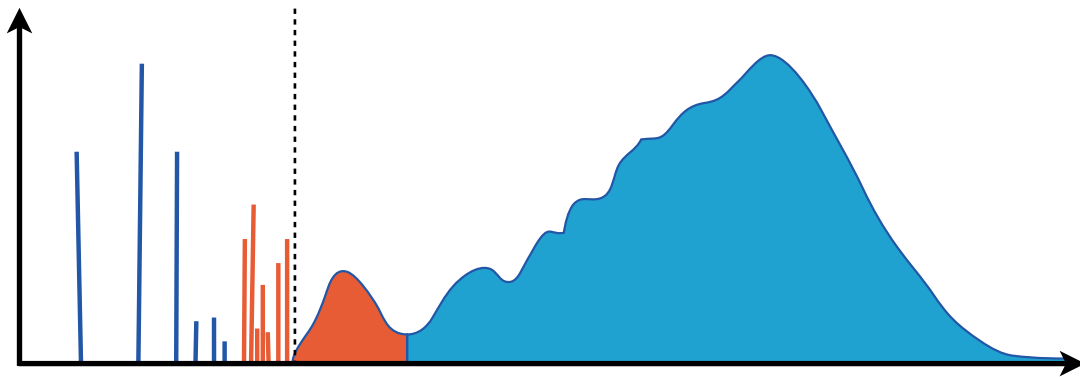
N-star merger GW analysis is giving constraints on the nuclear EOS that are consistent with the study of atomic nuclei.



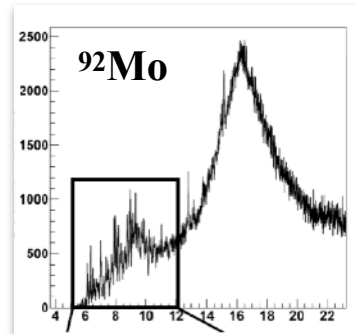
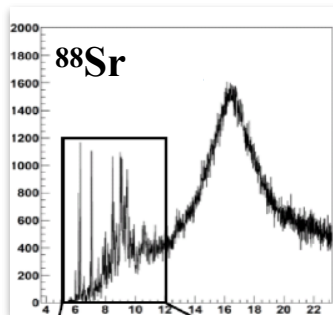
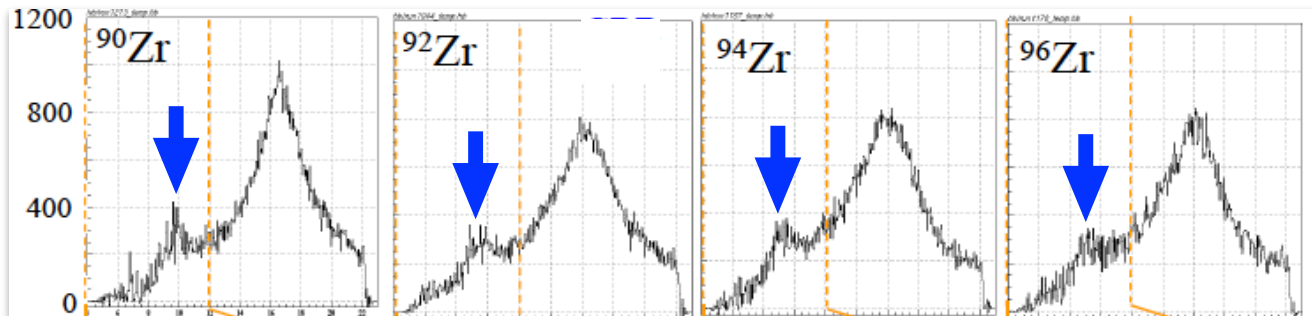
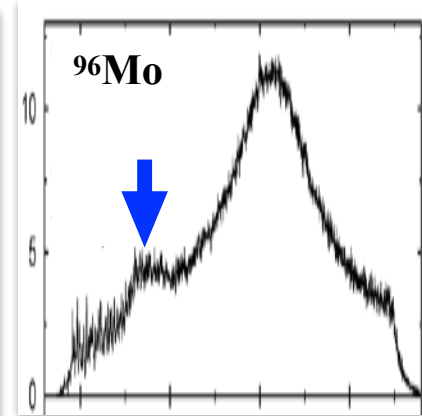
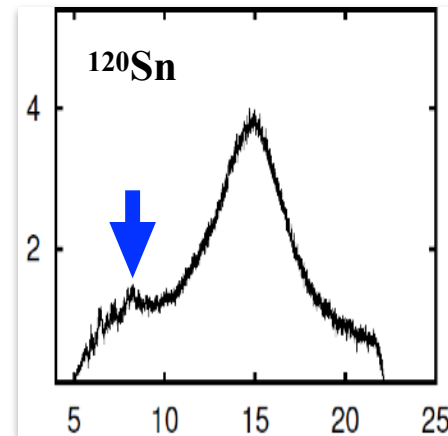
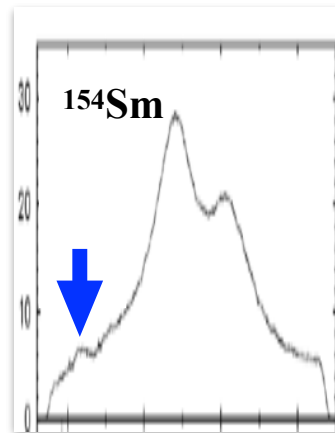
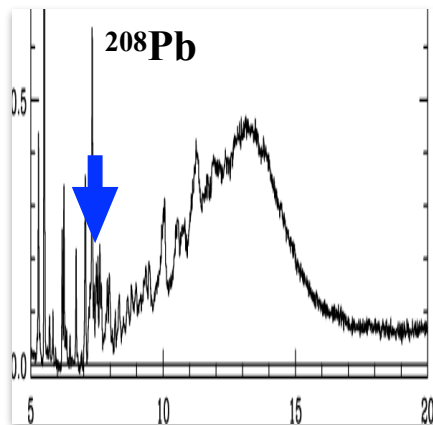
高感度化された重力波検出器の今後の観測で2000個の

重力波観測で 5-200m の精度で中性子半径がわかる(!) K. Chatziioannou, PRD2022

Pygmy Dipole Resonance



Universal Existence of PDR in Nuclei with $A > \sim 90$?

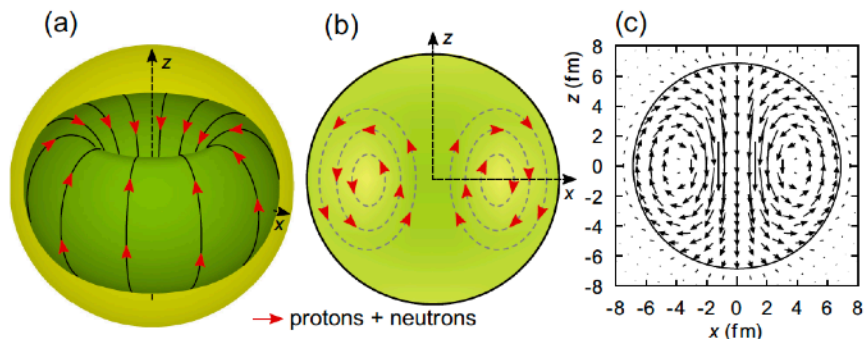


There must be a common reason of the existence.

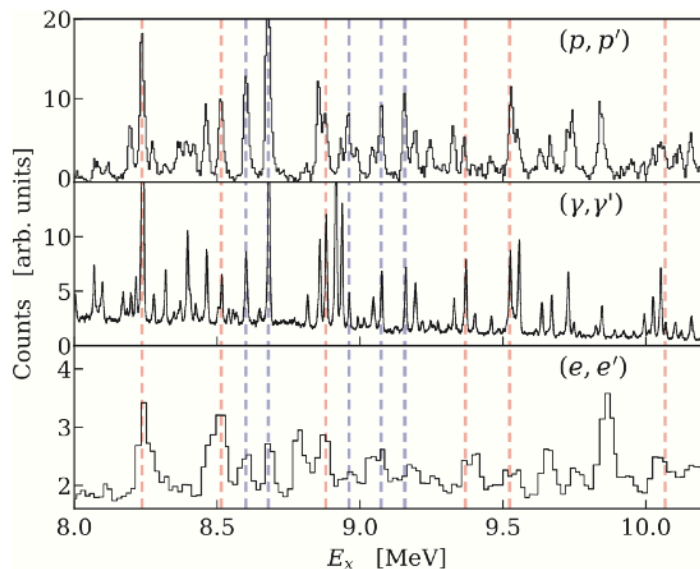
Candidate Toroidal Electric Dipole Mode in ^{58}Ni

P. von Neumann-Cosel et al., PRL**133**, 232502 (2024)

I. Brandherm et al., PRC**110**, 034319 (2024)



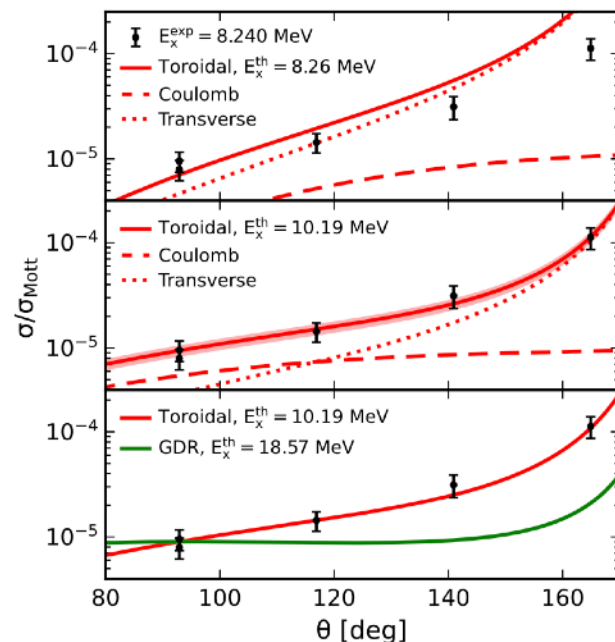
Toroidal Electric Dipole Mode



Several excited states assigned to $M1$ by (e, e')

→ found to be $E1$ by high-resolution (p, p') at RCNP

→ confirmed by (γ, γ') data



(e, e') angular distributions

→ consistent with toroidal dipole characterized by strong transverse current at backward angles

8 candidates of toroidal dipole states were found.

Smallest quantum vortex mode ever observed!

→ requires re-study of the Pygmy Dipole Resonance states found in many nuclei.

Photo-nuclear Reaction in heavy Nuclei

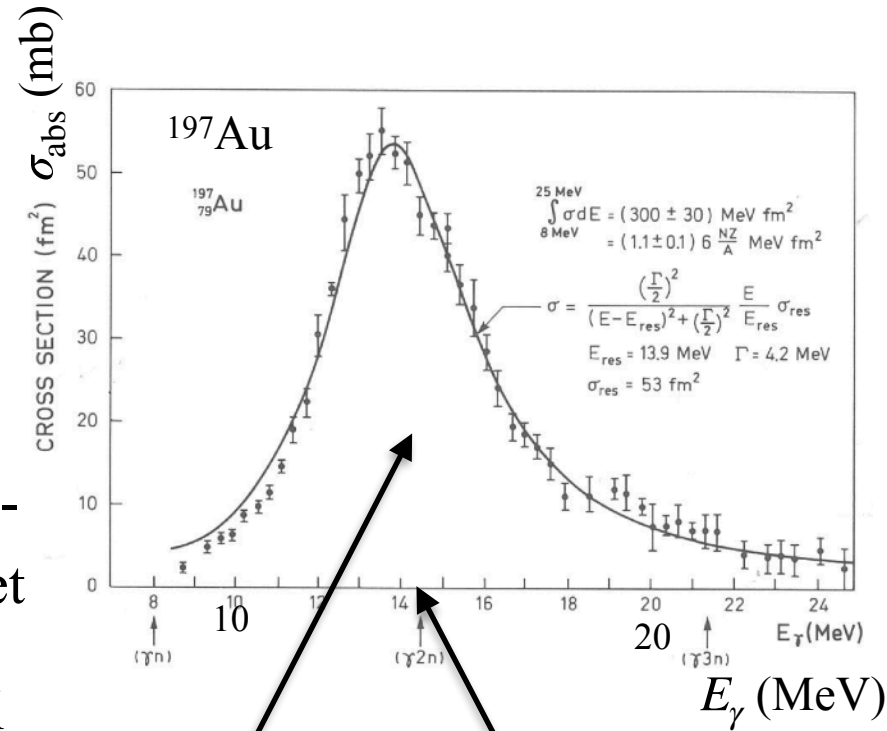
is relatively well-studied.

- Smooth mass dependences
- $\sigma_{\text{abs}} \simeq (\gamma, xn)$ cross sections

Only neutron detection is required

Measurement was feasible with a low-intensity gamma beam and thick target

- Single Lorentzian for spherical nuclei
(double for deformed nuclei)
- Statistical decay model is applicable



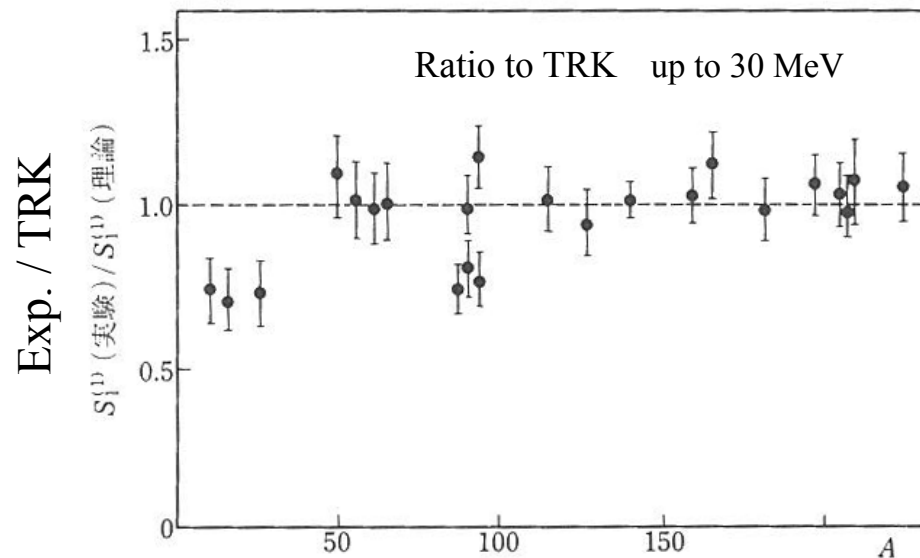
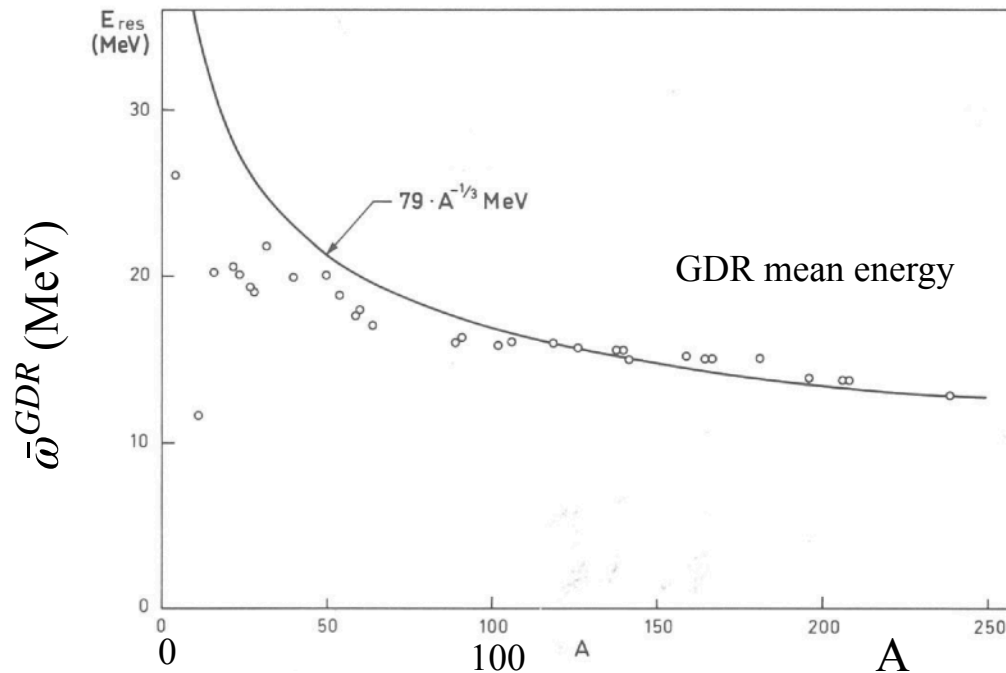
Integrated c.s.: TRK Sum-Rule

$$\int \sigma_{\text{abs}}^{E1}(\omega) d\omega \simeq 60 \frac{NA}{A} \text{ MeV mb}$$

Mean energy

$$\bar{\omega}^{E1} \simeq 85 A^{-1/3} \text{ MeV}$$

Photo-absorption cross section: heavy nuclei



How is the case of light nuclei?

Photo-nuclear Reaction in Light Nuclei

- $\sigma_{\text{abs}} \neq (\gamma, xn)$

p, α emissions are comparable or larger

Thin target & high beam intensity
is required for the decay measurement.

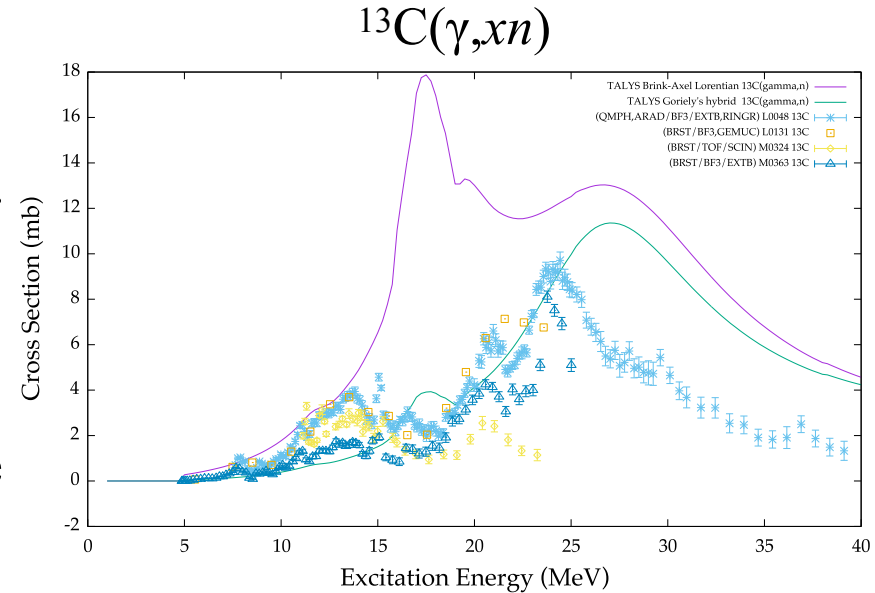
- Fine structures in the resonance shape

The feature depends on each nuclei

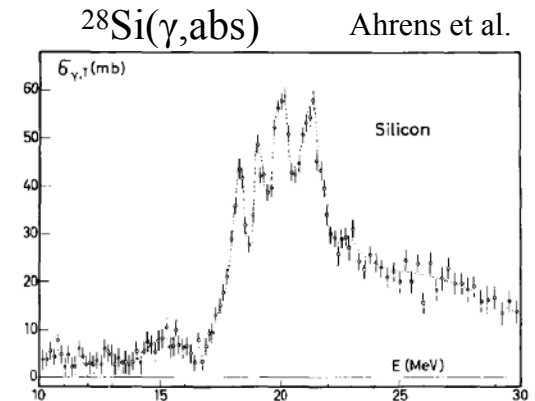
- Statistical decay is not dominant.
(requires direct and pre-equilibrium decays)

- Properties off the systematics

- Theoretical challenges



Example: $^{13}\text{C}(\gamma, xn)$ reaction data and predictions (TALYS)



- Large inconsistency among experimental data
- Unsatisfactory theoretical predications

Photo-nuclear Reaction in Light Nuclei

- $\sigma_{\text{abs}} \neq (\gamma, xn)$

p , α emissions are comparable or larger

Thin target & high beam intensity
is required for the decay measurement.

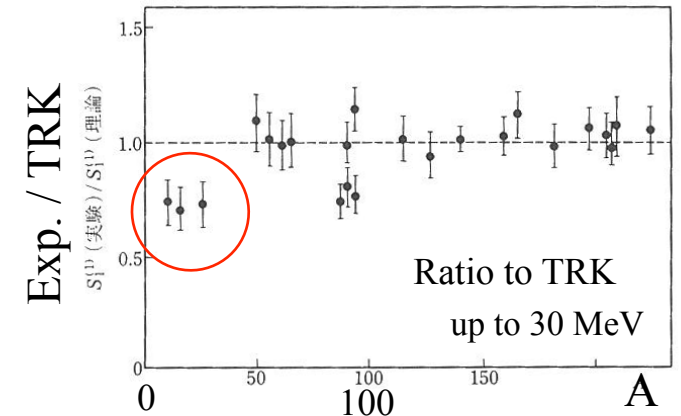
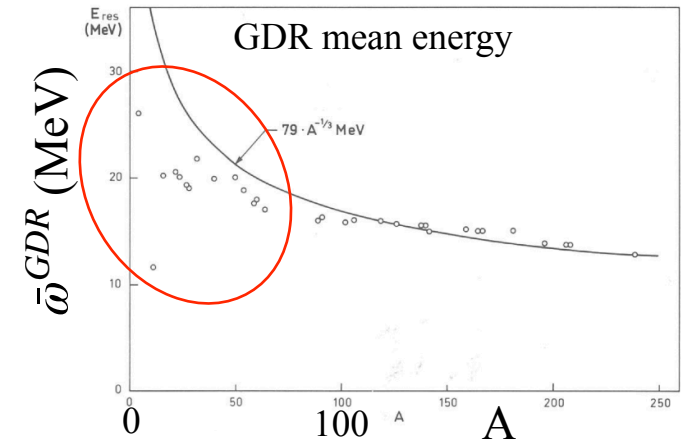
- Fine structures in the resonance shape

The feature depends on each nuclei

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- Properties off the systematics

- Theoretical challenges (next page)

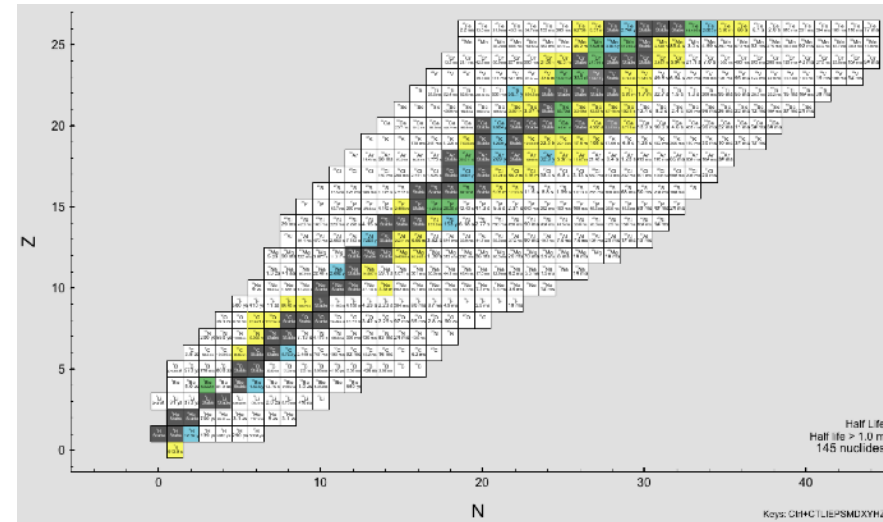


Theoretical Challenges

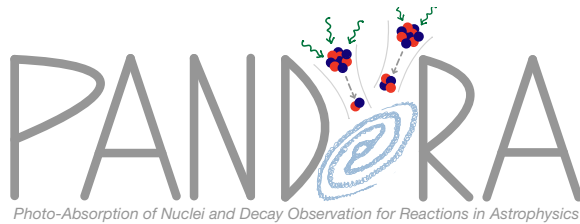
- (genuine) ab-initio calculations:
only applicable to $A \leq 12$ for g.s. and Low-lying excited states
- Shell model
was not applicable for collective IVGDR excitation.
Recent large scale shell-models are now covering IVGDR.
- Mean field models (RPA families)
Less applicable to light nuclei. Parameters are optimized for heavy nuclei
- Anti-symmetrized molecular dynamics (AMD)
Good for this mass regions and for collective excitation.
Interactions are less realistic due to computational power.

Systematic Measurement on Photo-Absorption Cross Section and decays for light stable nuclei for

- E1 excitation strength distribution
- n, p, α , γ decay branching ratios
- 10-20 light stable nuclei: $A < 60$

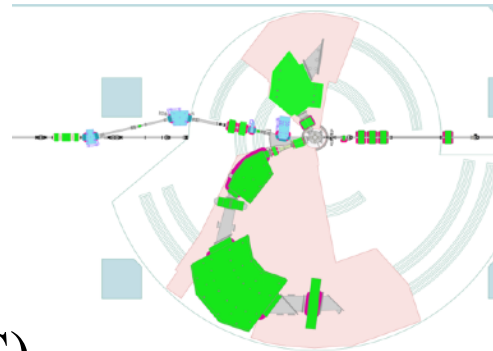


PANDORA Project:



- Systematic measurement
- Reference target: ^{27}Al (and ^{12}C)
- Consistency check and complementary information by using virtual and real photon measurements

RCNP



iThemba LABS



ELI-NP

Photo-Nuclear Reaction

is important as one of fundamental reactions for studying

- Nuclear structures/reactions
- 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

Data and theoretical predications are used in simulations of various fields.

99.99999% of the elements in the universe consists of nuclei below $A=60$

^{12}C and ^{16}O are still important to measure

Oxygen (^{16}O) forms 65% (30%) of the human body (Earth)
and Carbon (^{12}C) 8% (0.02%)

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



^{16}O	65%	30%
^{12}C	8%	0.02%

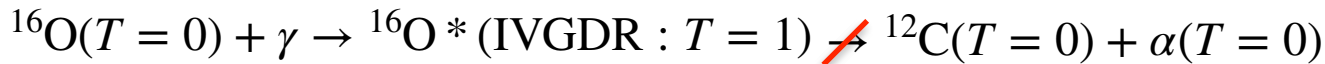
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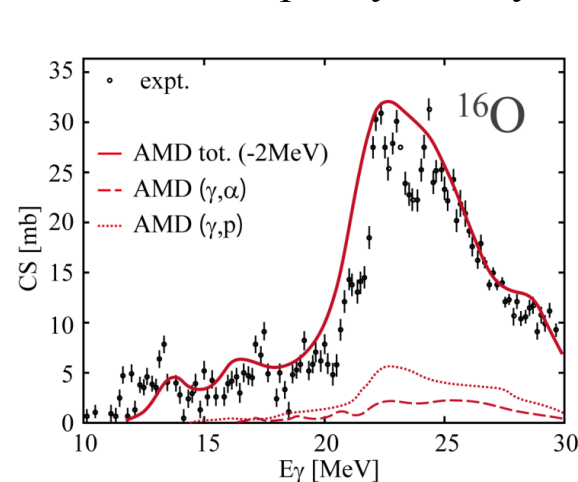
α -decay of IVGDR in ^{12}C or ^{16}O are not known well.

 α -decay to low-lying ($T = 0$) states is isospin-forbidden.

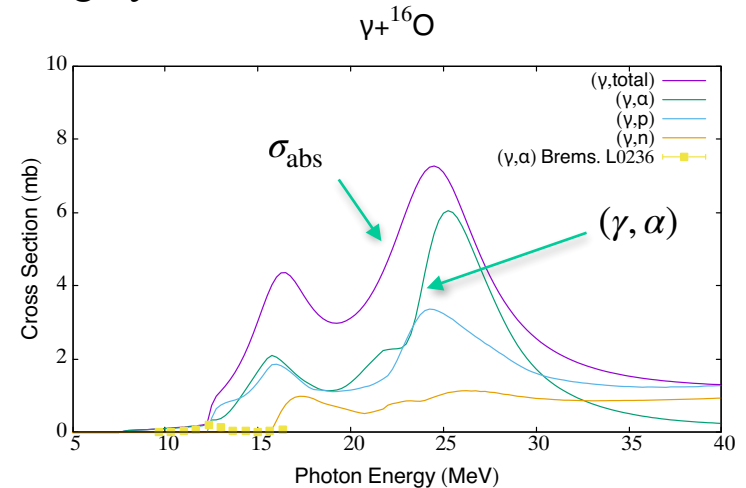


isospin forbidden decay

requires implementation of isospin-symmetry breaking by Coulomb interaction



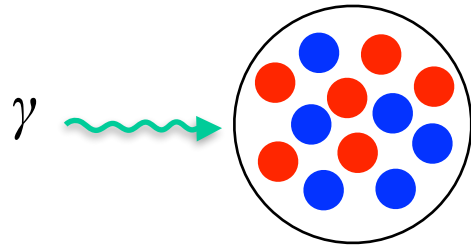
prediction by AMD
M. Kimura et al.,



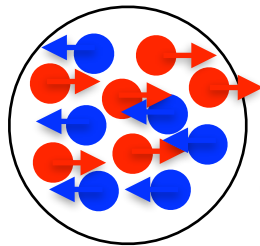
calculation with TALYS
(default parameters)

Decay of IVGDR

time dependent description of the decay of a collective excitation
an ordered motion to a random motion



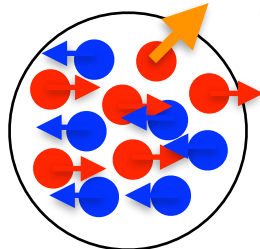
IVGDR
collective motion



direct decay
(n,p,α,γ,...)

spreading

pre-equilibrium



pre-equilibrium decay

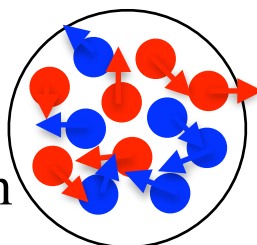
spreading

...

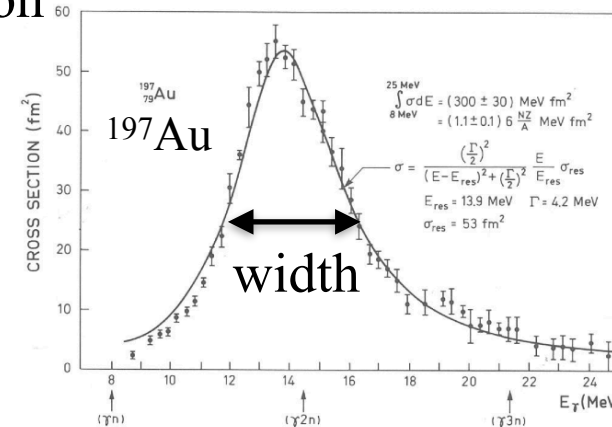
pre-equilibrium decay

spreading

compound nucleus
thermal equilibrium



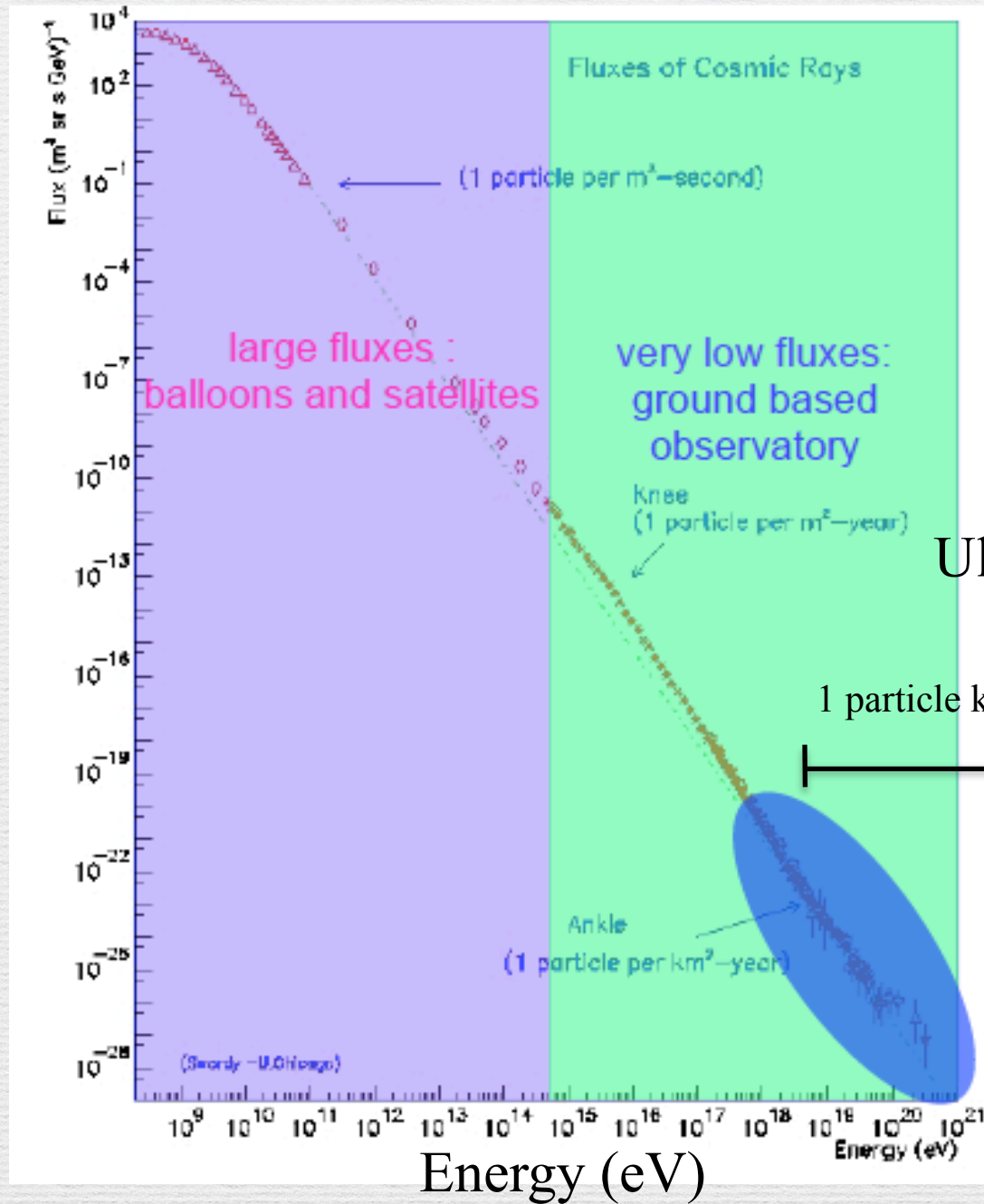
compound (statistical) decay



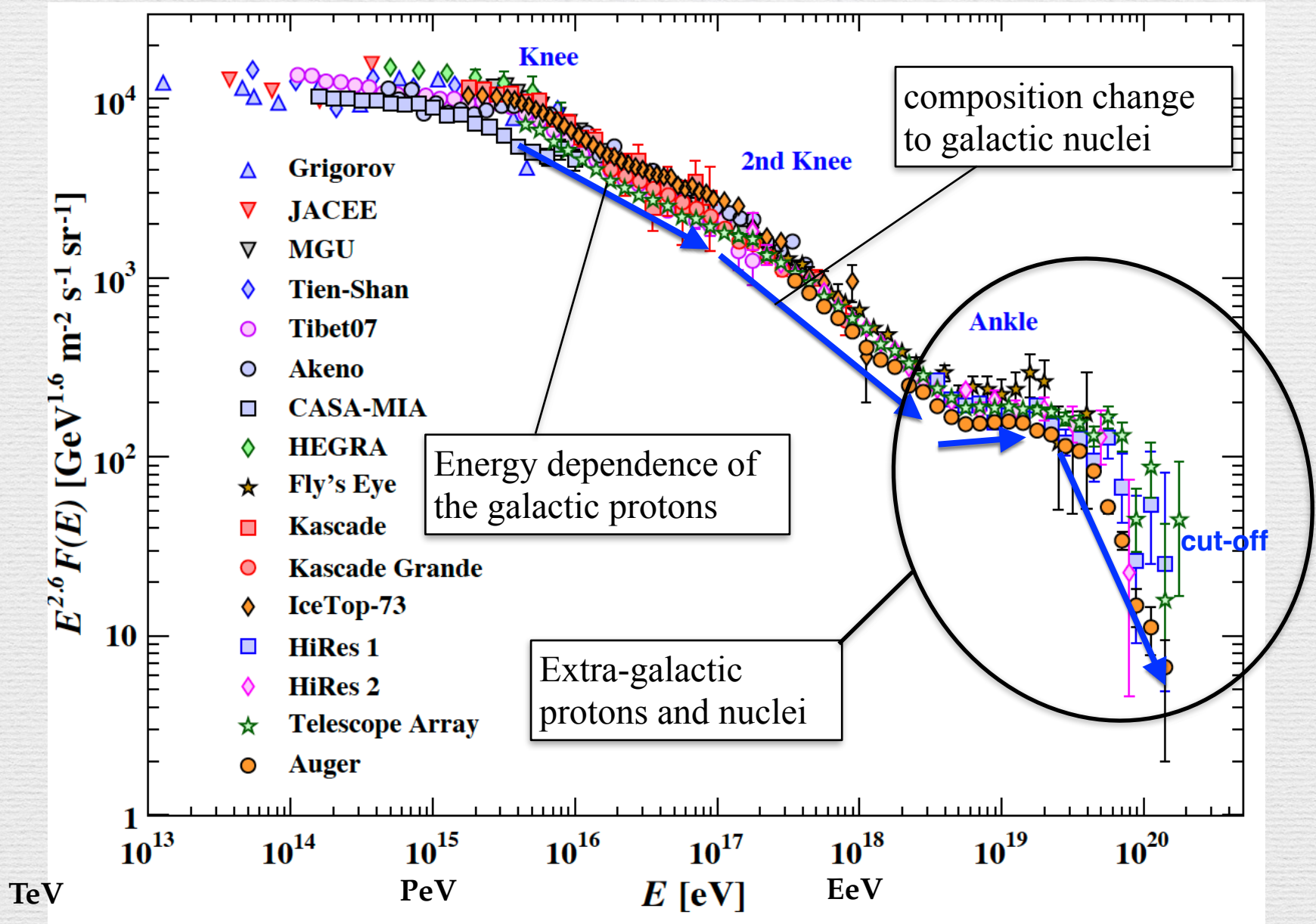
Intergalactic Propagation of Ultra-High-Energy Cosmic Rays

Cosmic Rays

Flux ($\text{m}^{-2} \text{sr}^{-1} \text{s}^{-1} \text{GeV}^{-1}$)

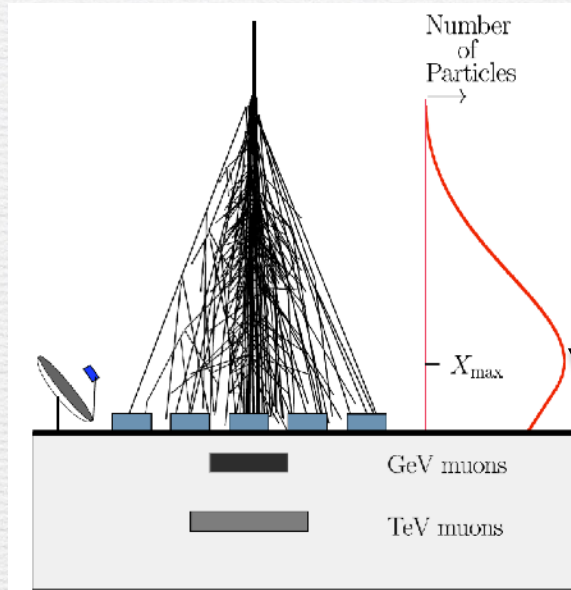
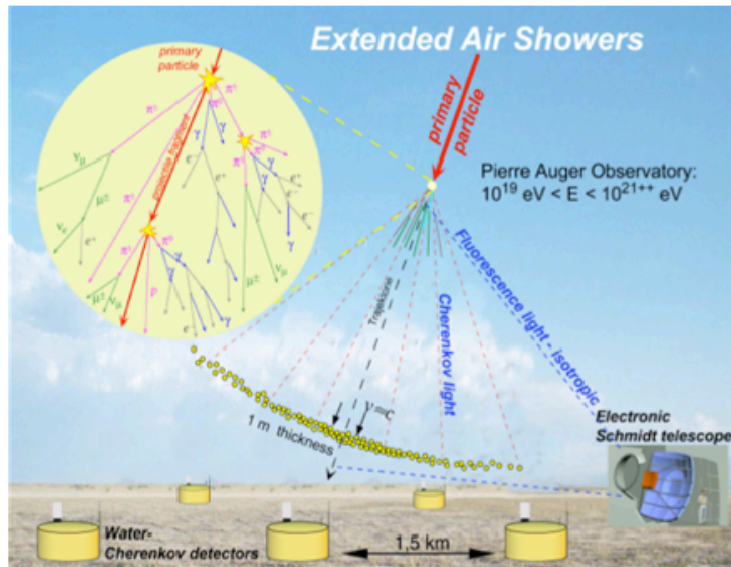


Ultra-High-Energy Cosmic Rays (UHECRs) [PDG2018]

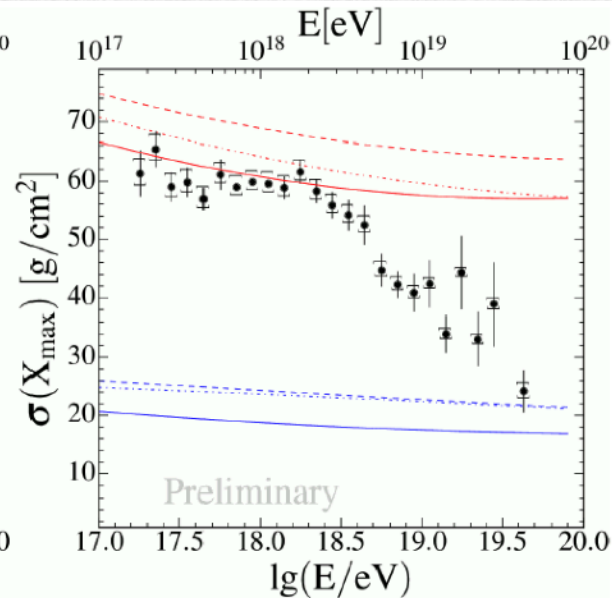
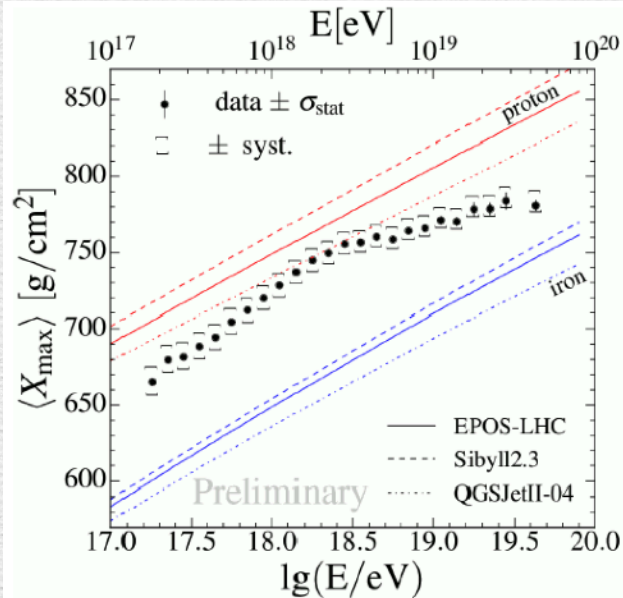


Observation of UHECRs

Extended Air Shower (EAS)



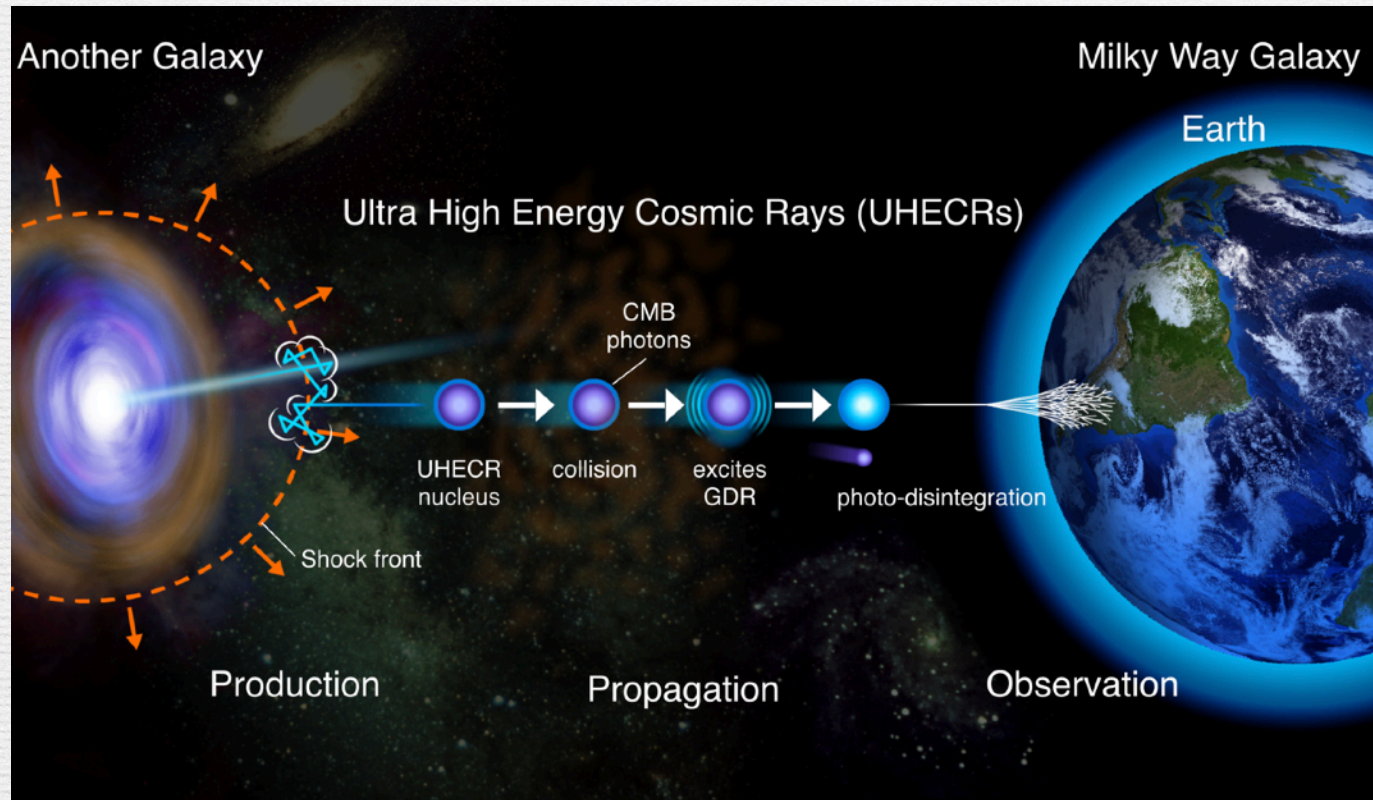
X_{max} :
atmospheric depth at the
maximum number of
particles of the air shower



[mol18]
[gor18]

The observed mass tends to become heavier as the energy increase at the highest energy.

Intergalactic Propagation of UHECR Nuclei



Cosmic Microwave Background (CMB)

WMAP

$T=2.73\text{ K}$

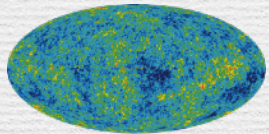
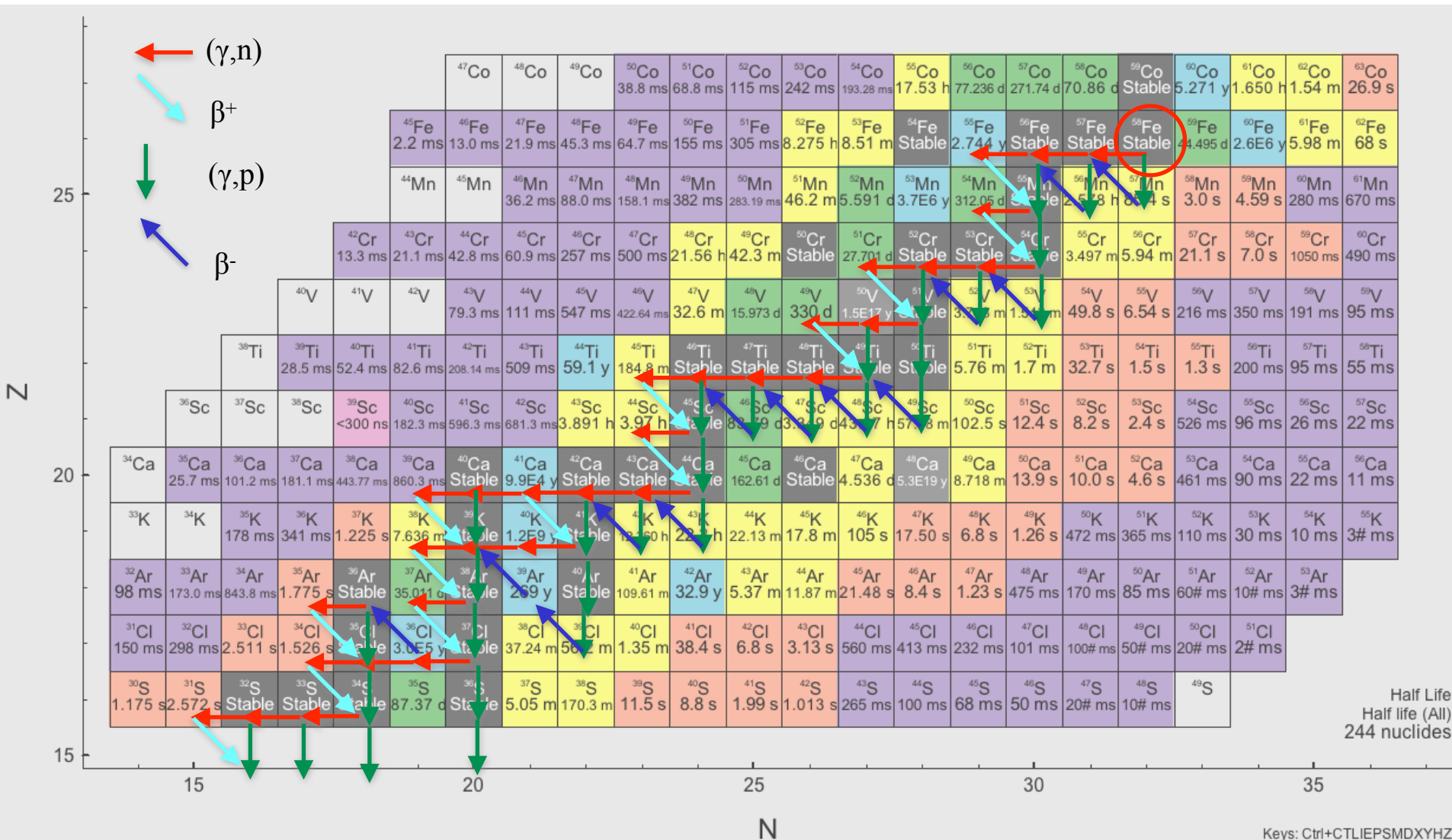


Photo-nuclear reactions govern the maximum travel distance of UHECR nuclei and their composition/energy evolution in the inter-galactic propagation.



GZK cut-off

Photo-disintegration Pass of ^{56}Fe



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

Unstable nuclei ($T_{1/2} > 1 \text{ min}$) also contribute.

UHECR: Intergalactic Propagation

$$1 \text{ Mpc} = 3.26 \times 10^6 \text{ light year}$$

the Milky Way Galaxy



0.03 Mpc



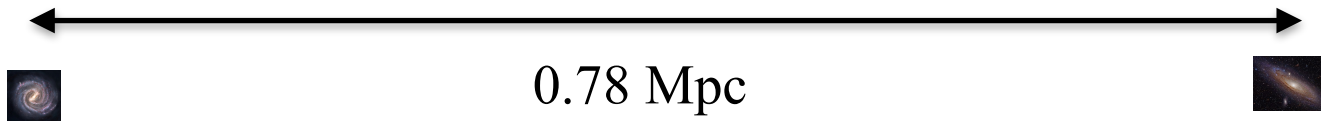
0.03 Mpc for $T_{1/2} = 5 \text{ min}$ at $\gamma = 10^{10}$

UHECR: Intergalactic Propagation

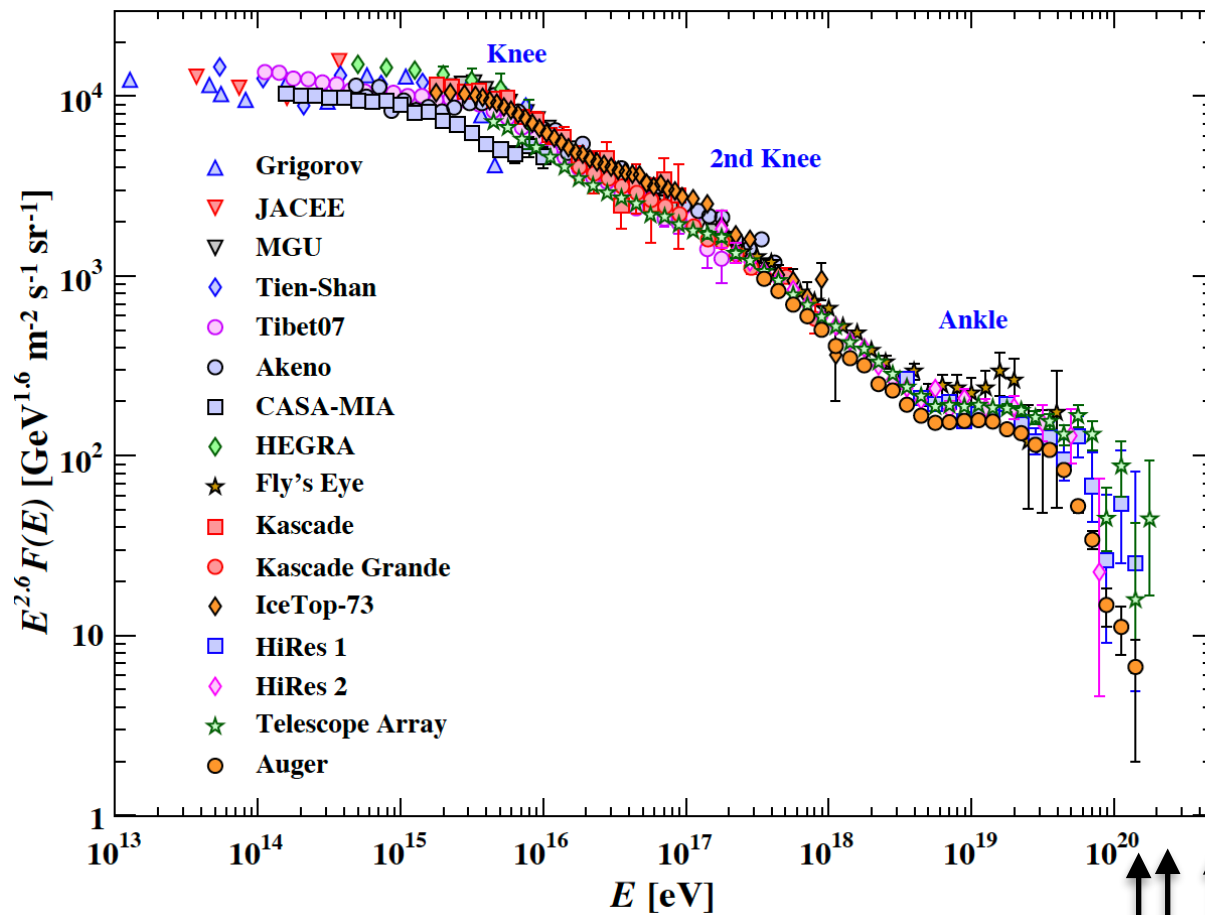
the Milky Way Galaxy



Andromeda Galaxy



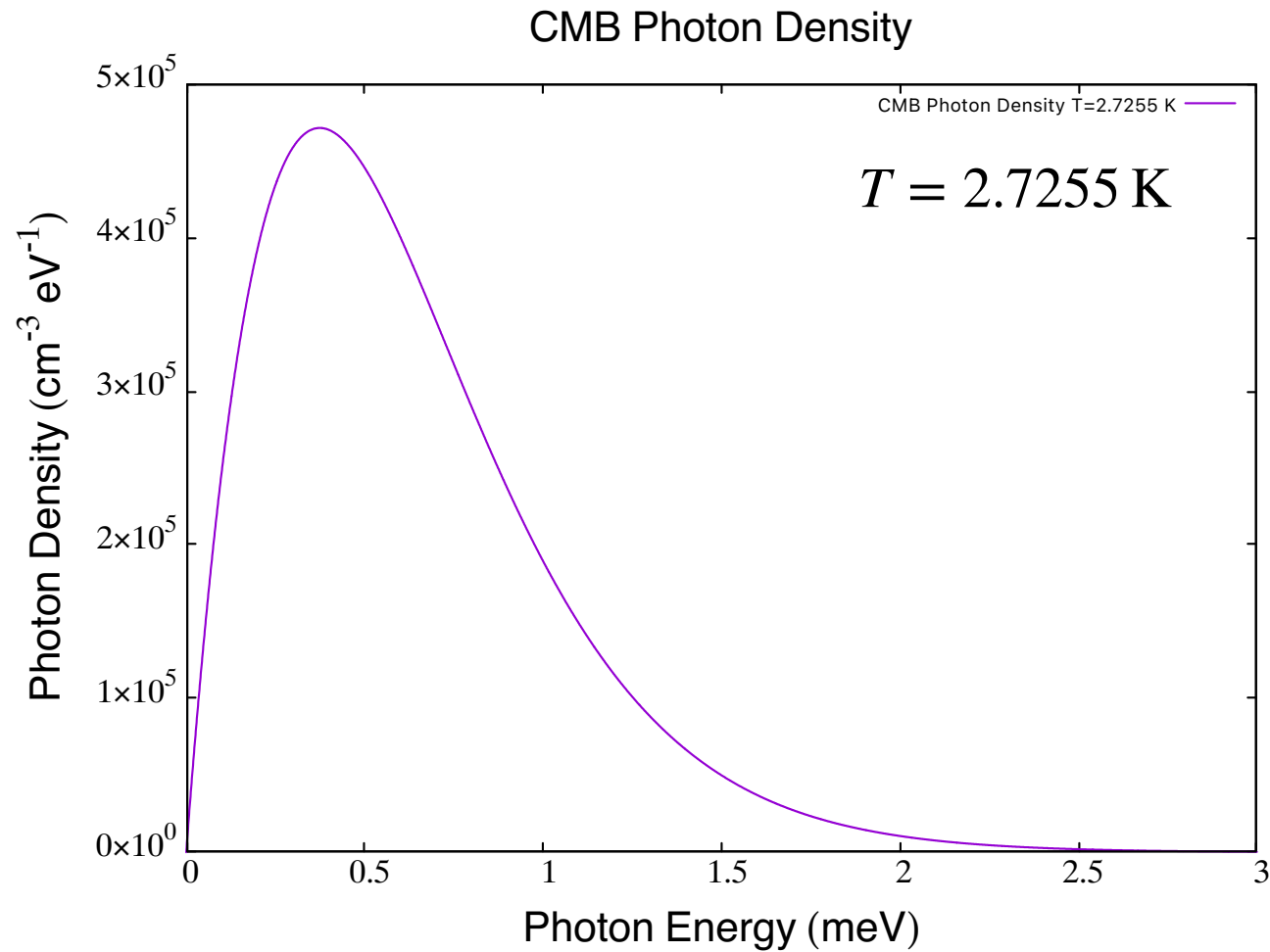
UHECR: Intergalactic Propagation



$$\gamma = \frac{E}{M} = 10^{10}$$

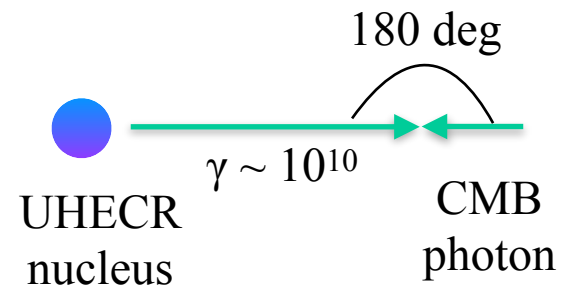
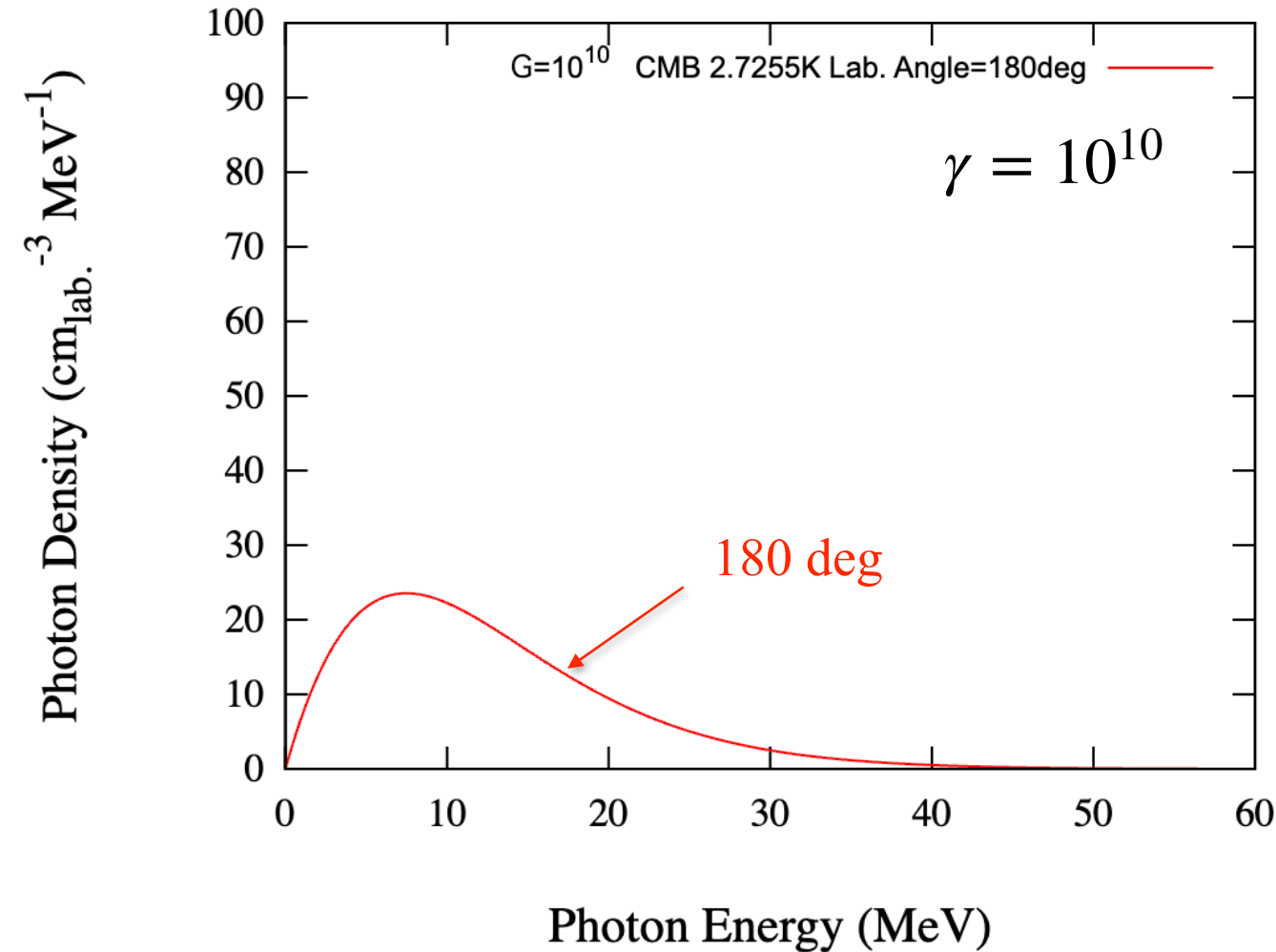
	mass
^{16}O	14.9 GeV/c ²
^{27}Al	25.1 GeV/c ²
^{56}Fe	52.1 GeV/c ²

UHECR: Intergalactic Propagation



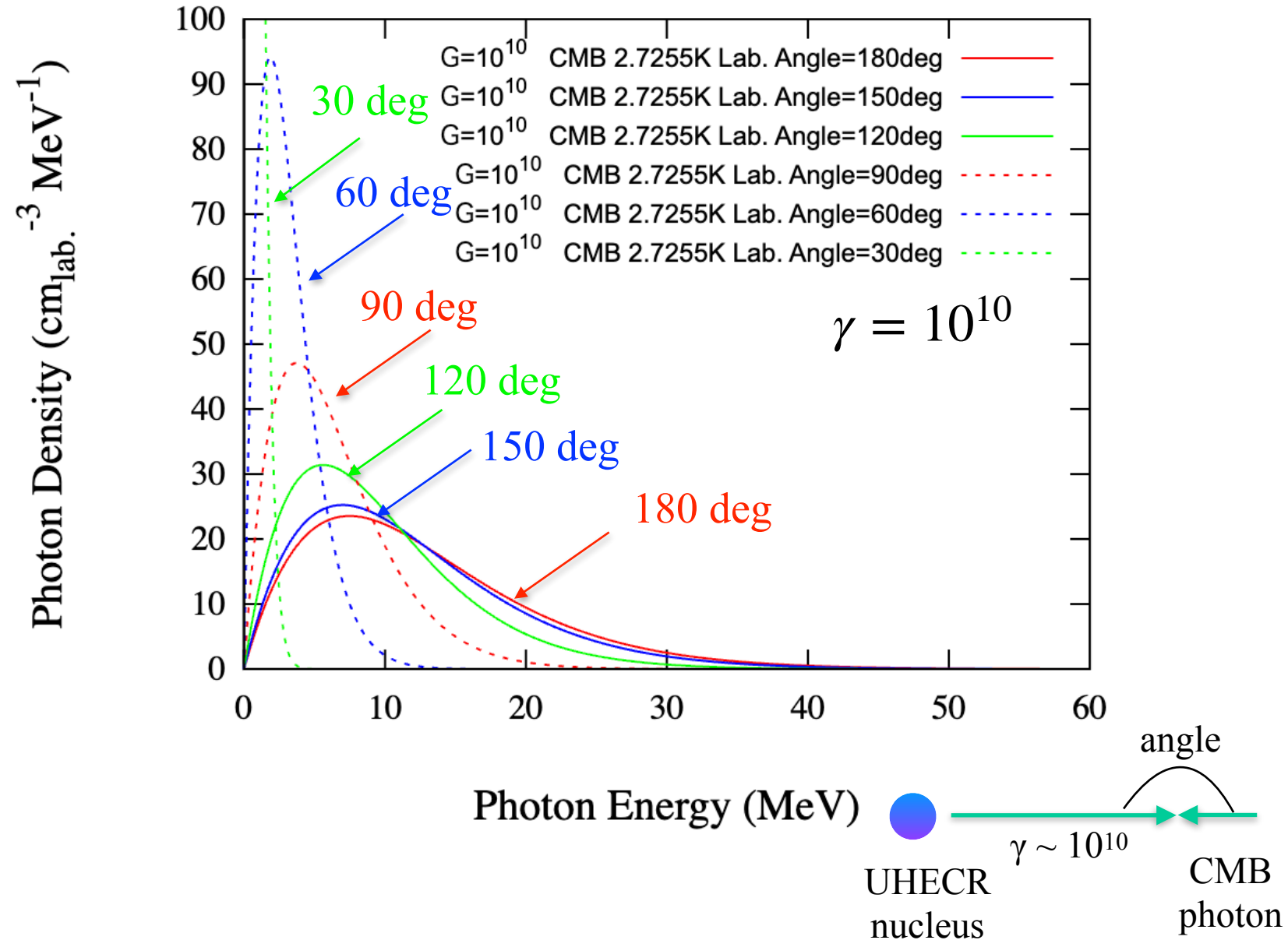
UHECR: Intergalactic Propagation

CMB Photon Energy in the CR Rest Frame



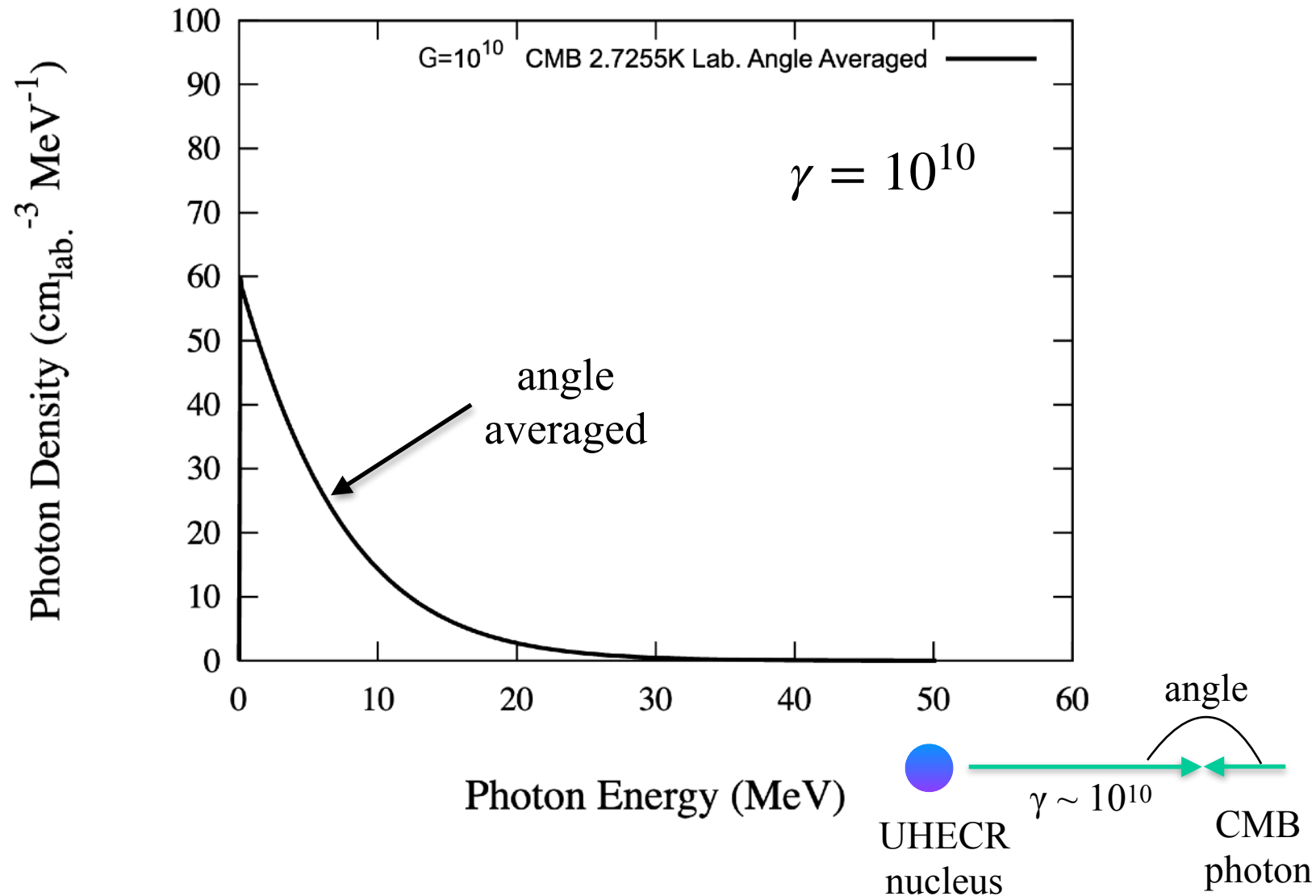
UHECR: Intergalactic Propagation

CMB Photon Energy in the CR Rest Frame



UHECR: Intergalactic Propagation

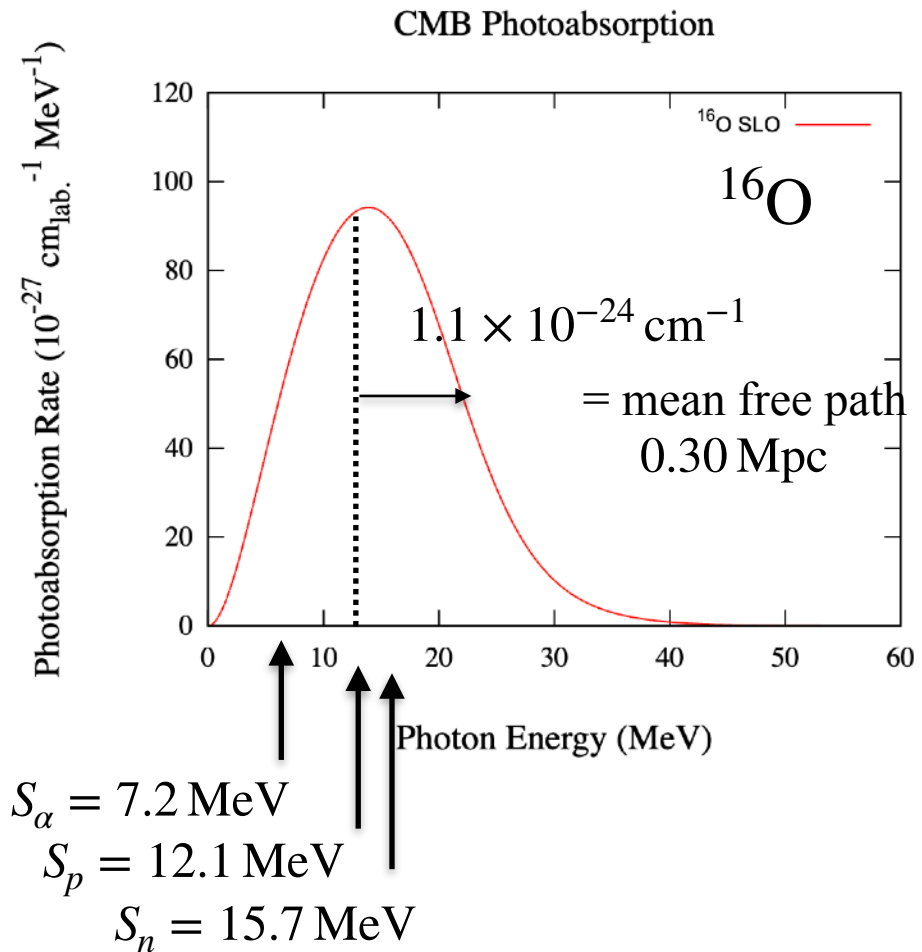
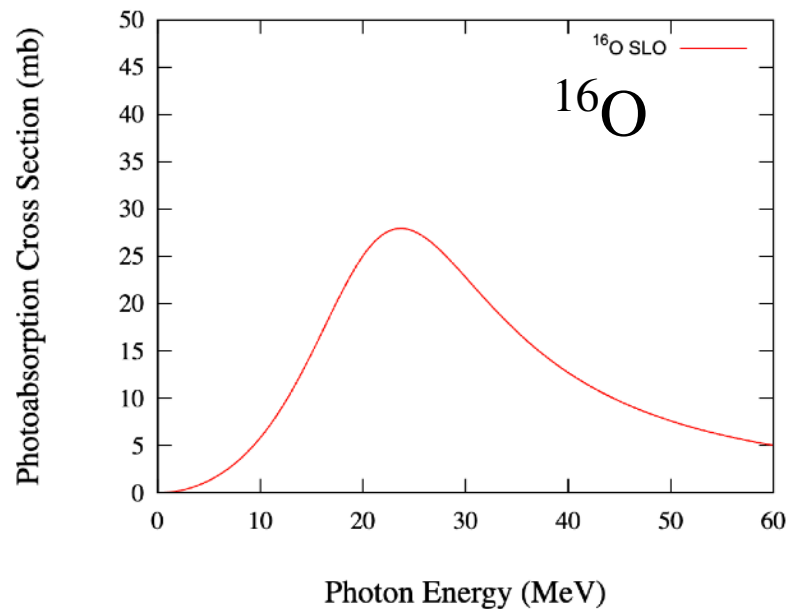
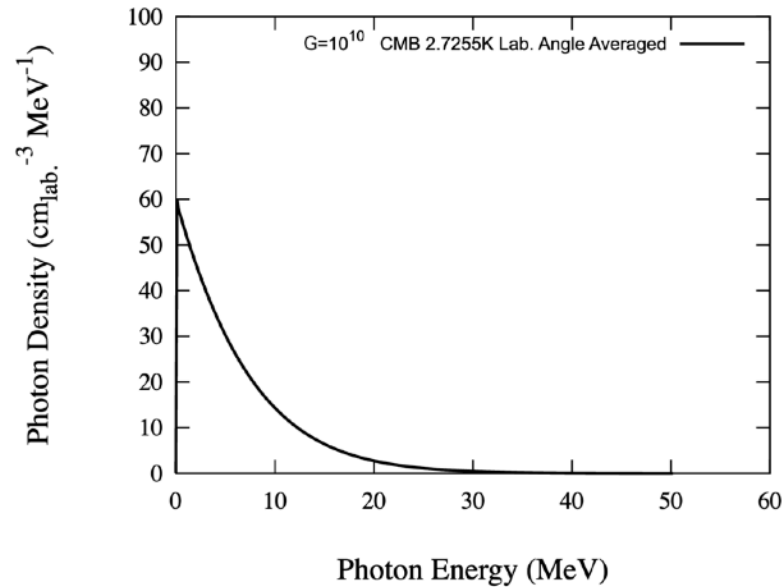
CMB Photon Energy in the CR Rest Frame



UHECR: Intergalactic Propagation

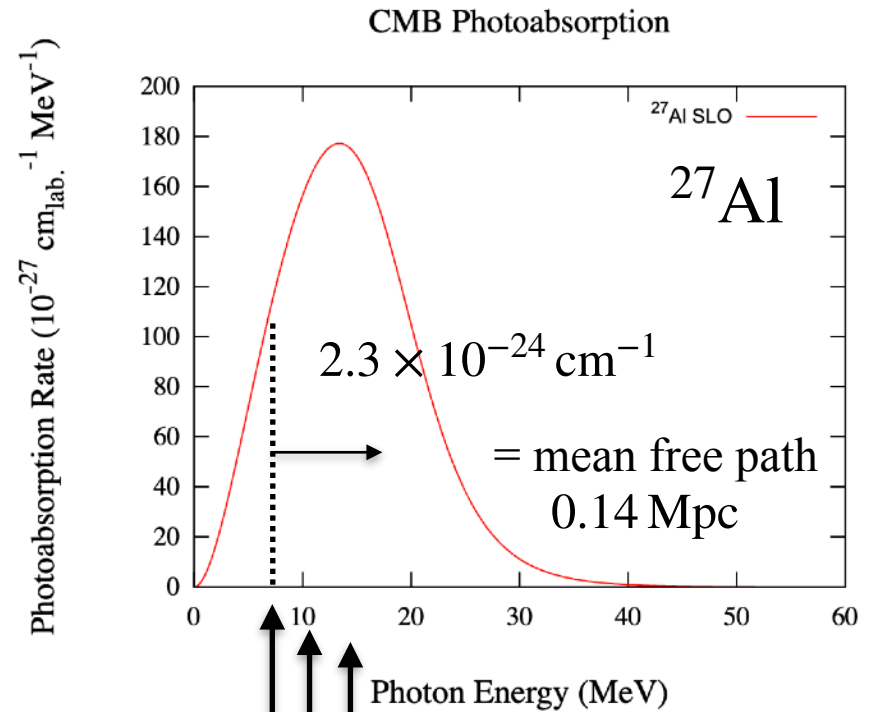
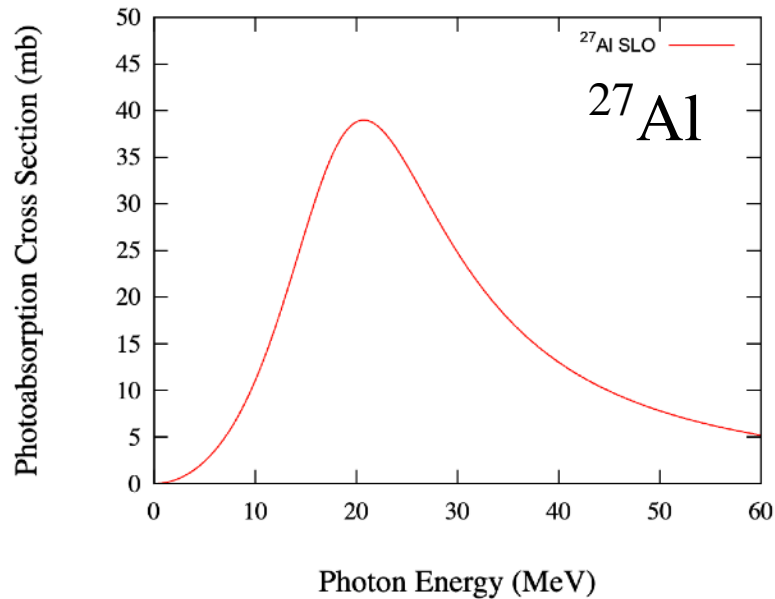
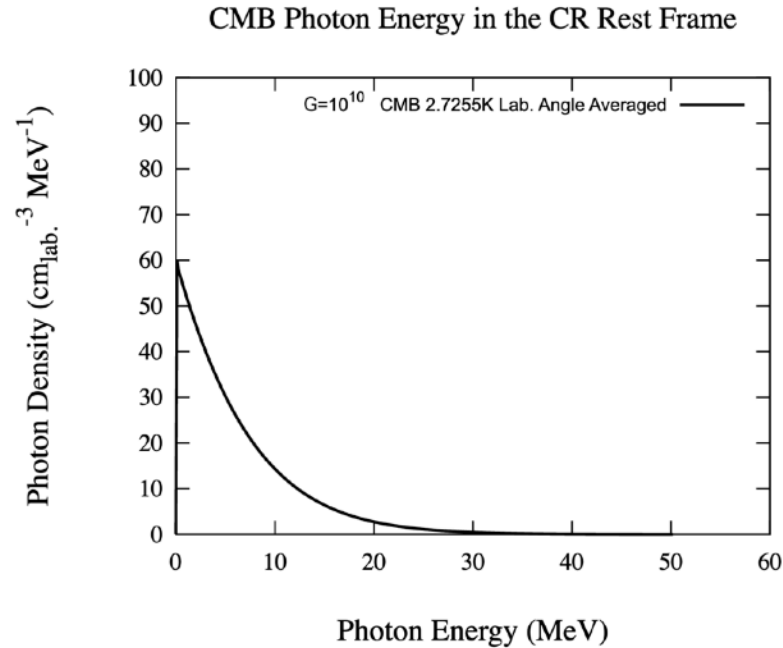
$$^{16}\text{O} \quad \gamma = 10^{10}$$

CMB Photon Energy in the CR Rest Frame



UHECR: Intergalactic Propagation

$$^{27}\text{Al} \quad \gamma = 10^{10}$$



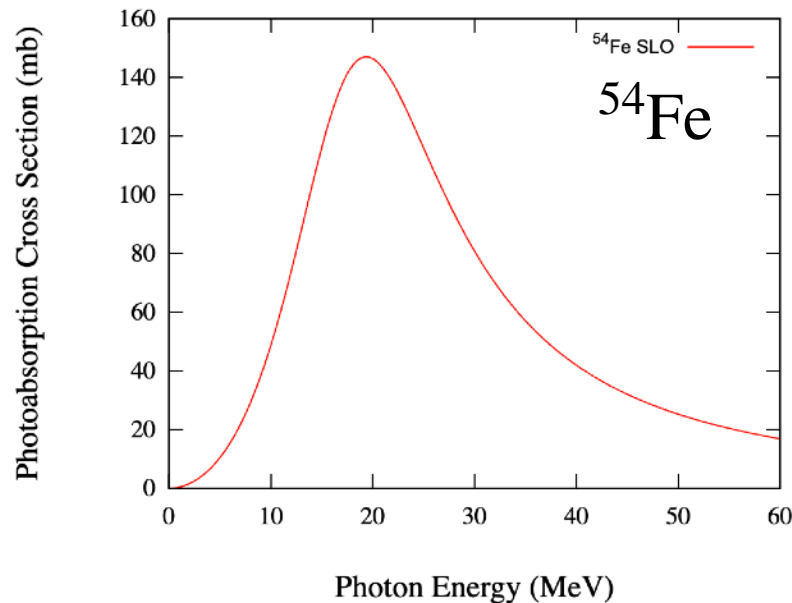
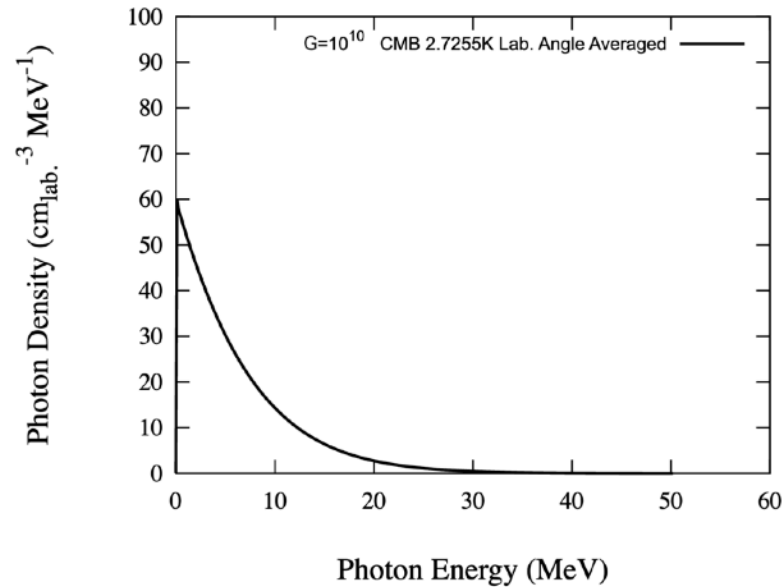
$$S_p = 8.3 \text{ MeV}$$

$$S_\alpha = 10.1 \text{ MeV}$$

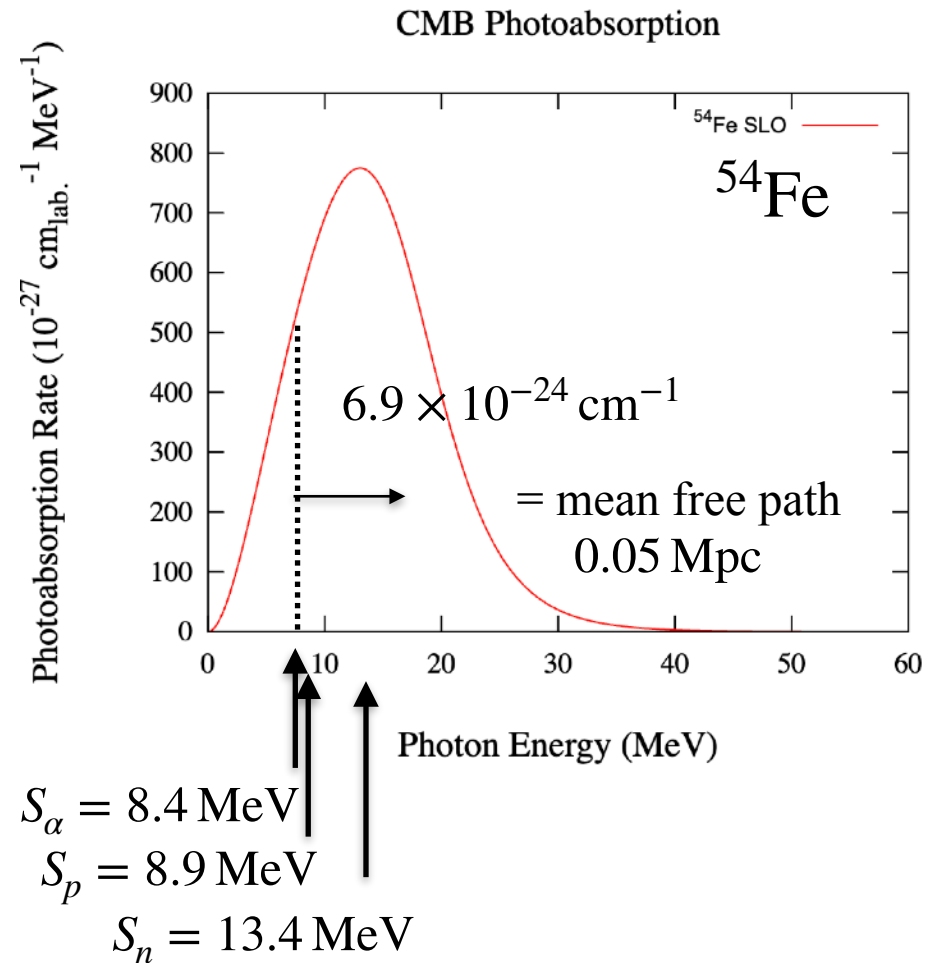
$$S_n = 13.1 \text{ MeV}$$

UHECR: Intergalactic Propagation

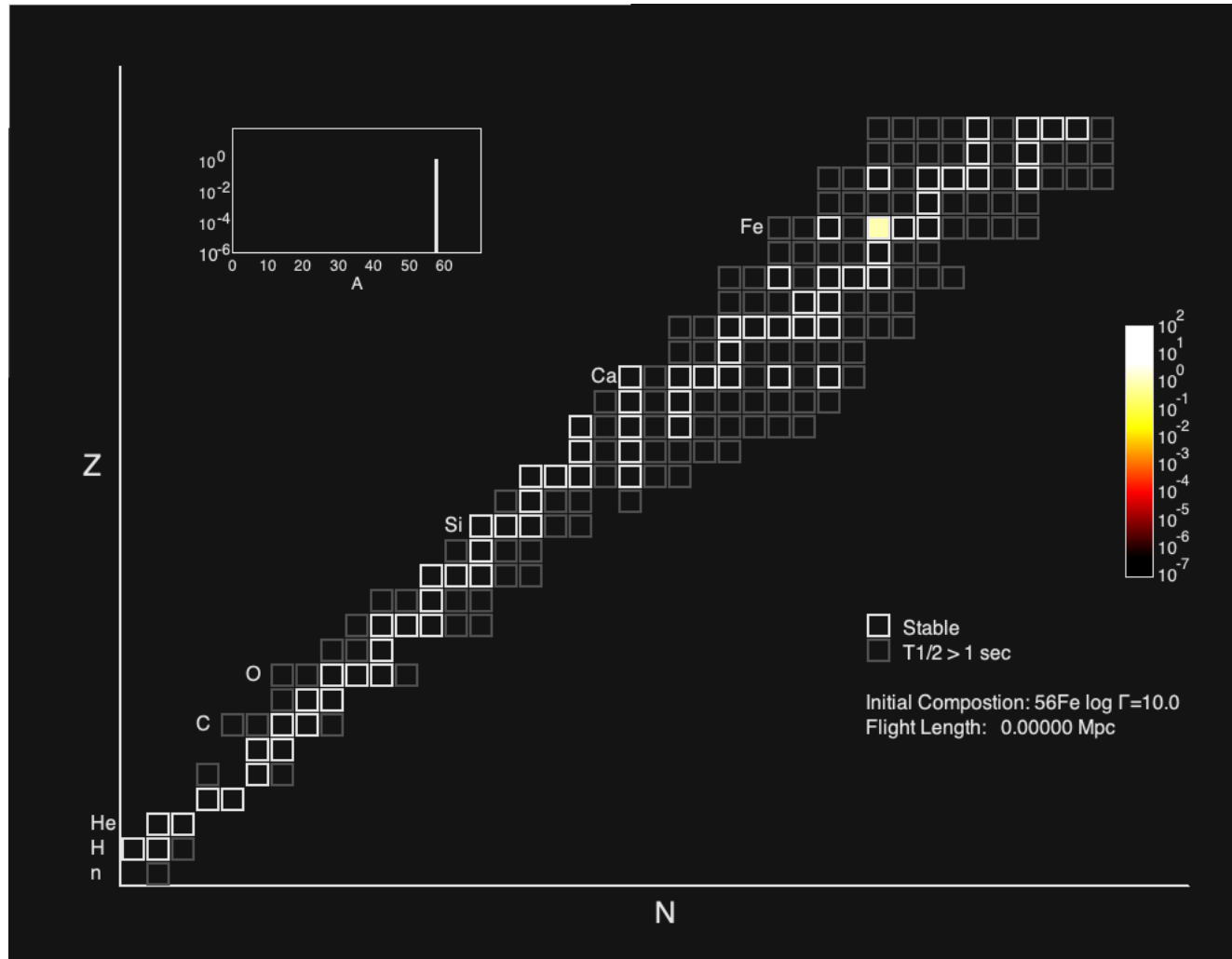
CMB Photon Energy in the CR Rest Frame



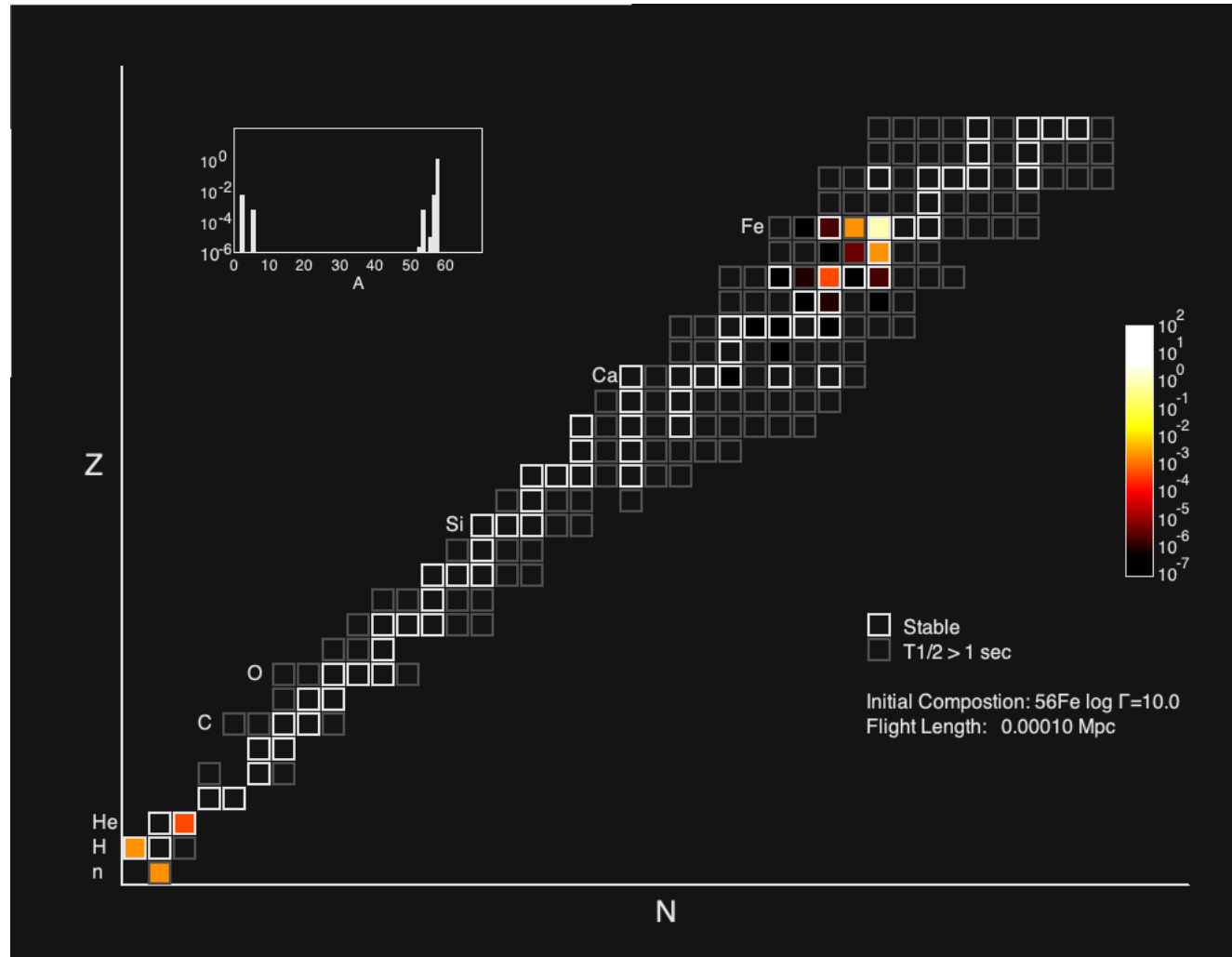
$$^{54}\text{Fe} \quad \gamma = 10^{10}$$



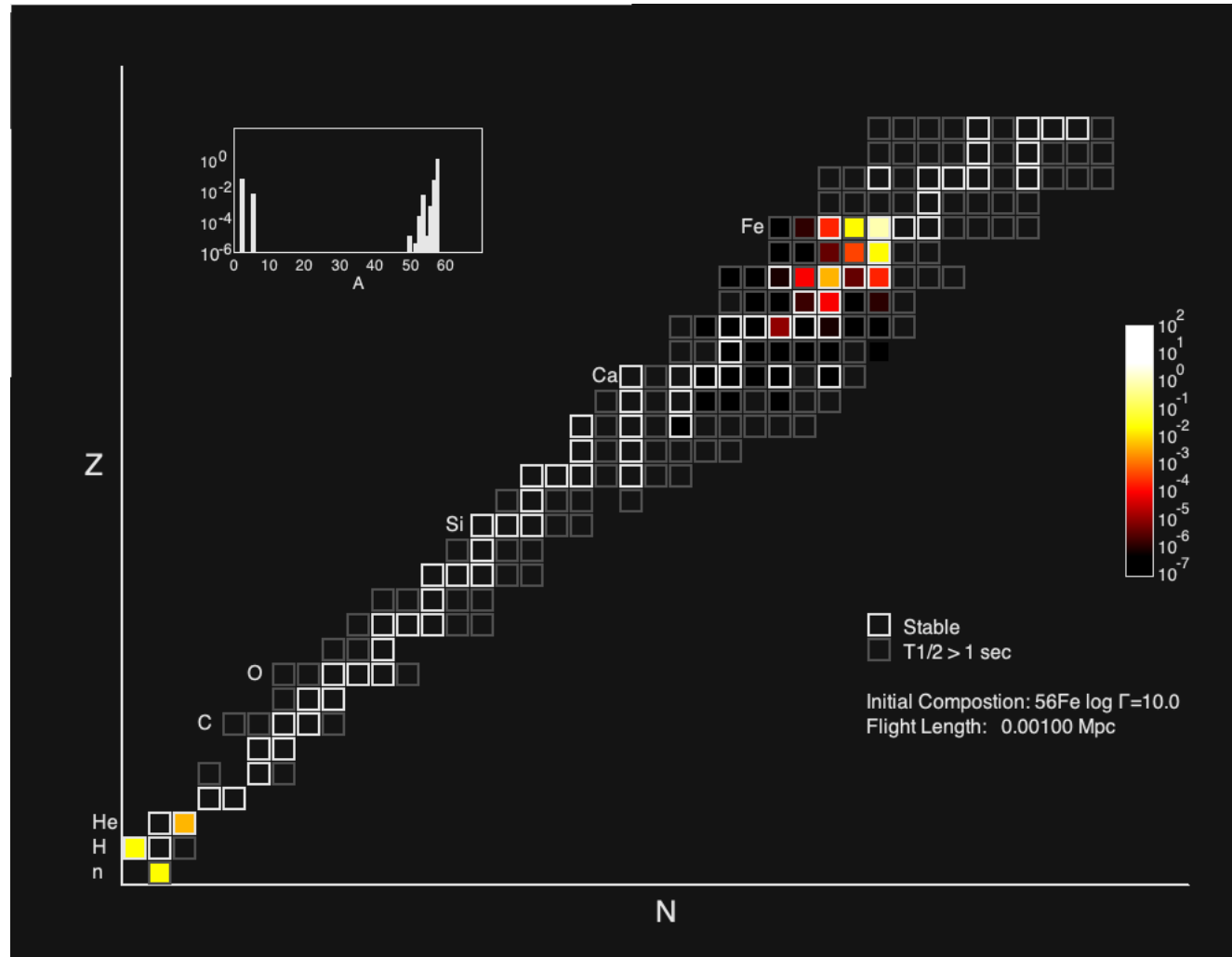
UHECR: Intergalactic Propagation by a Toy-Model Simulation



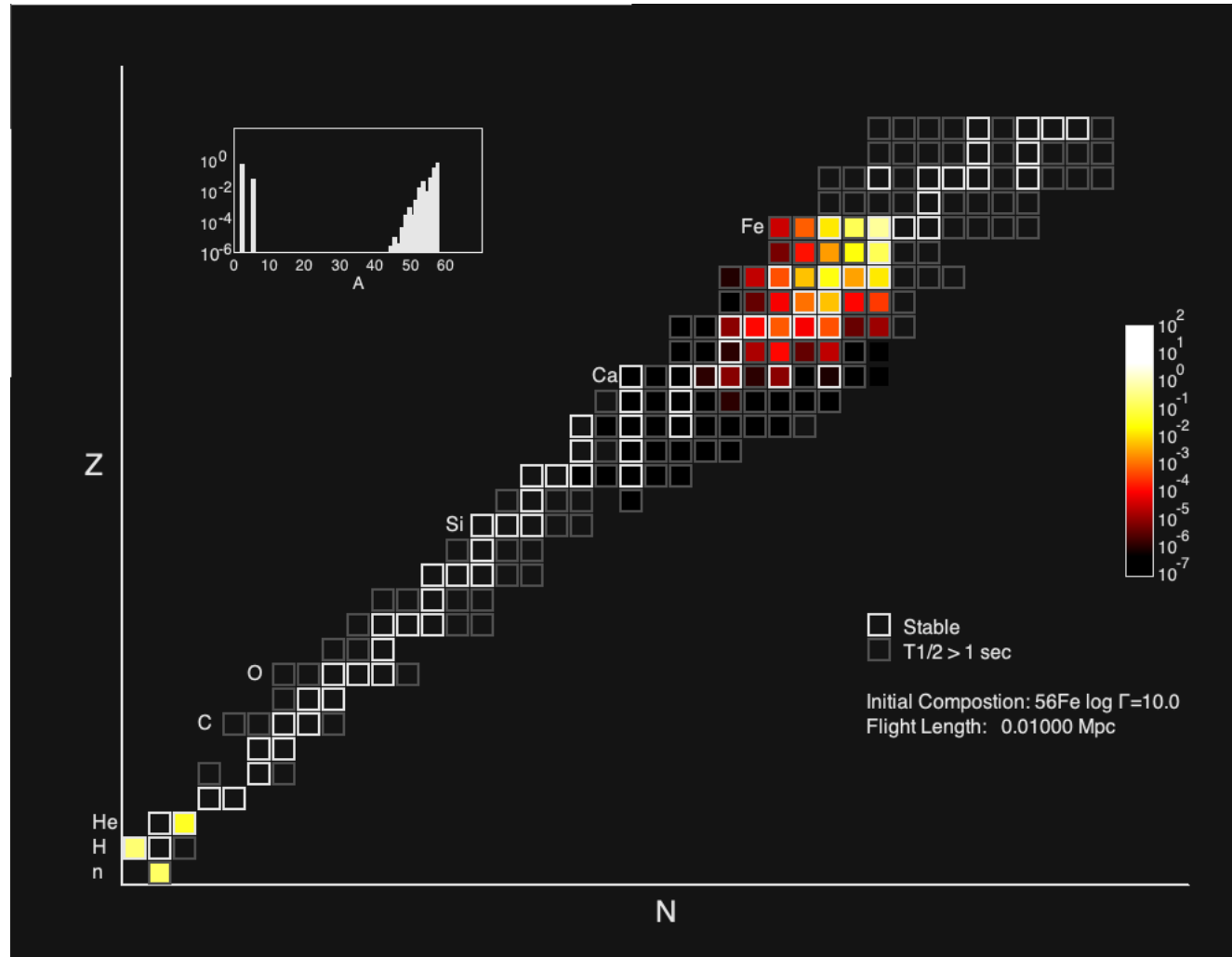
UHECR: Intergalactic Propagation by a Toy-Model Simulation



UHECR: Intergalactic Propagation by a Toy-Model Simulation

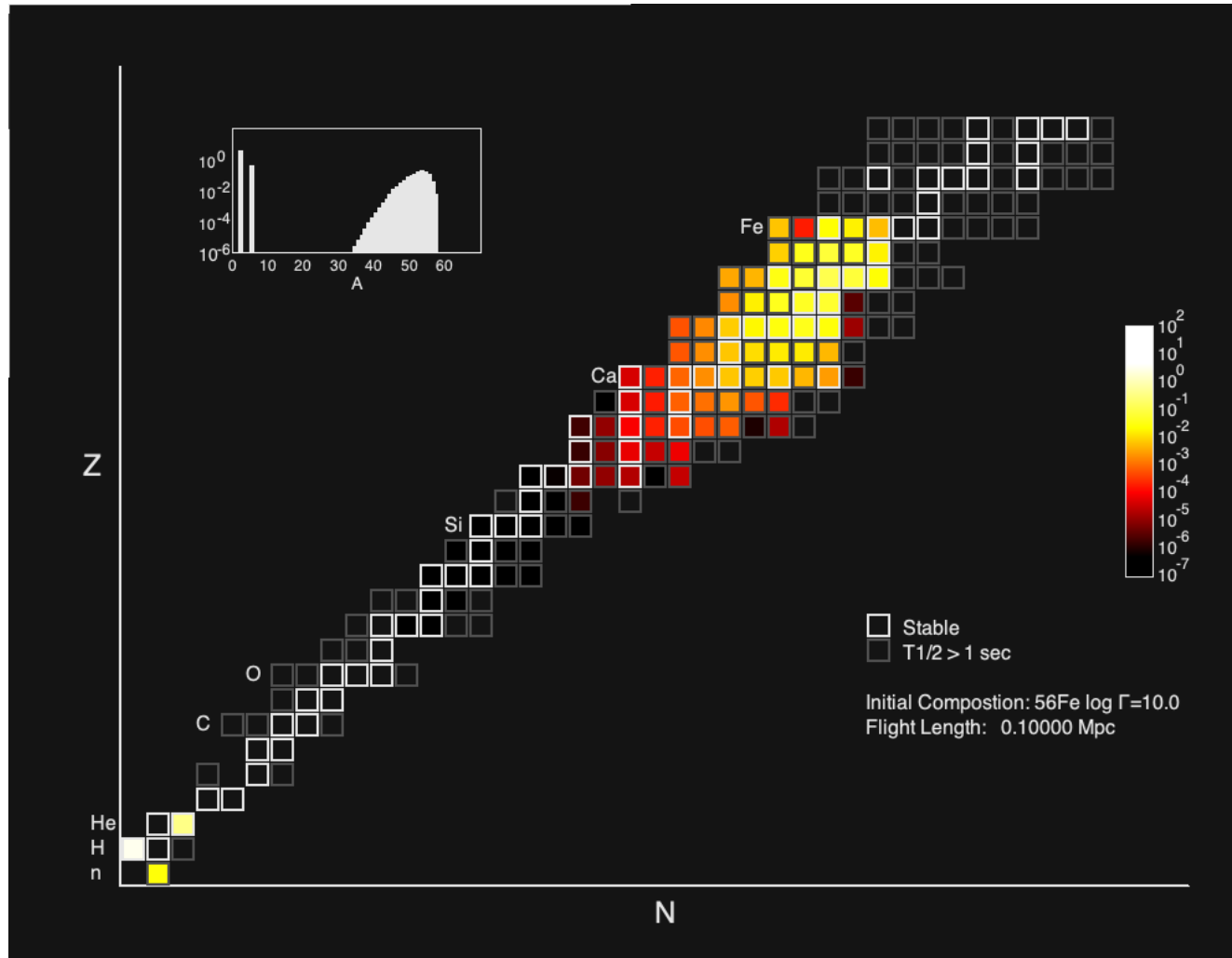


UHECR: Intergalactic Propagation by a Toy-Model Simulation

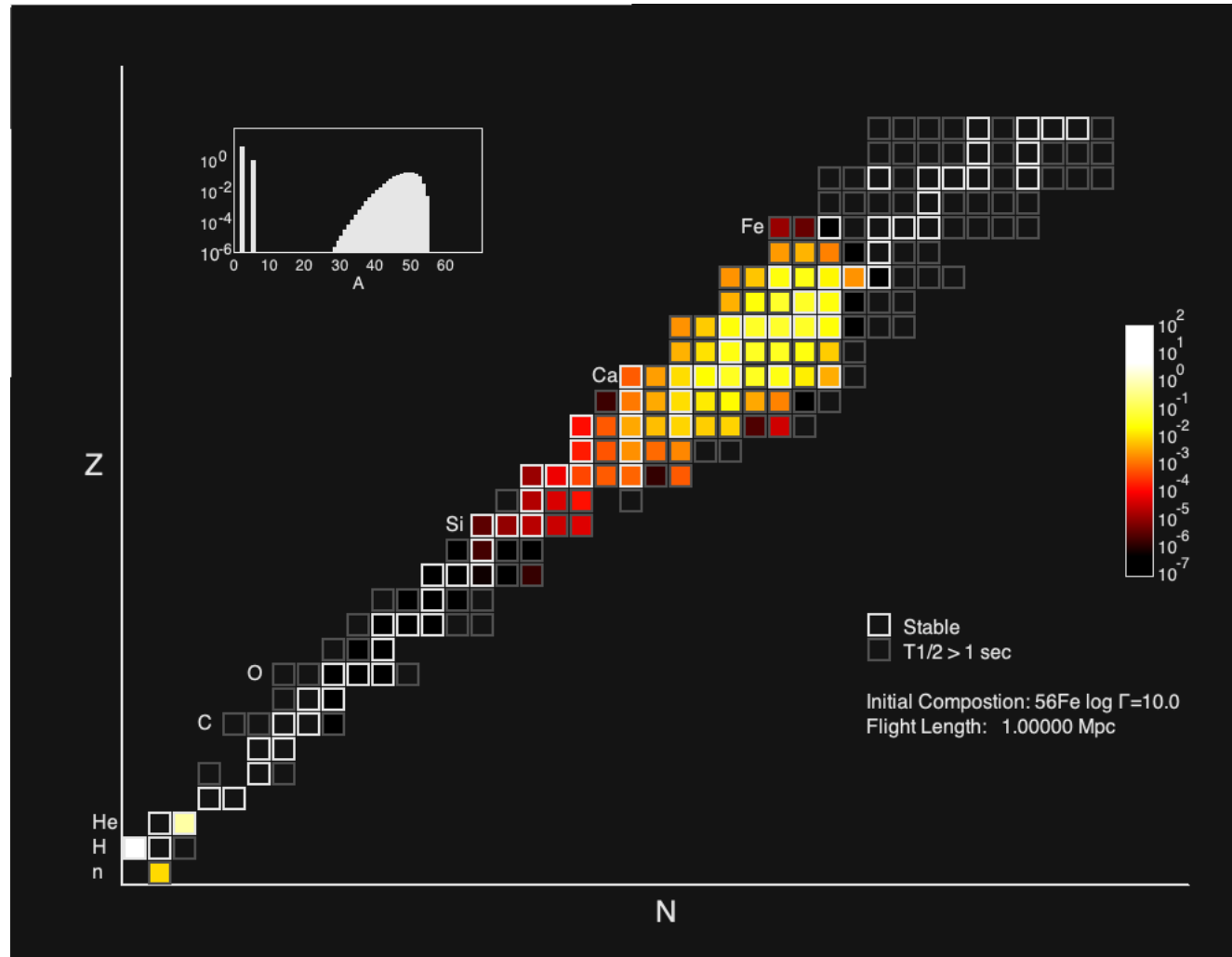


UHECR: Intergalactic Propagation by a Toy-Model Simulation

0.1 Mpc

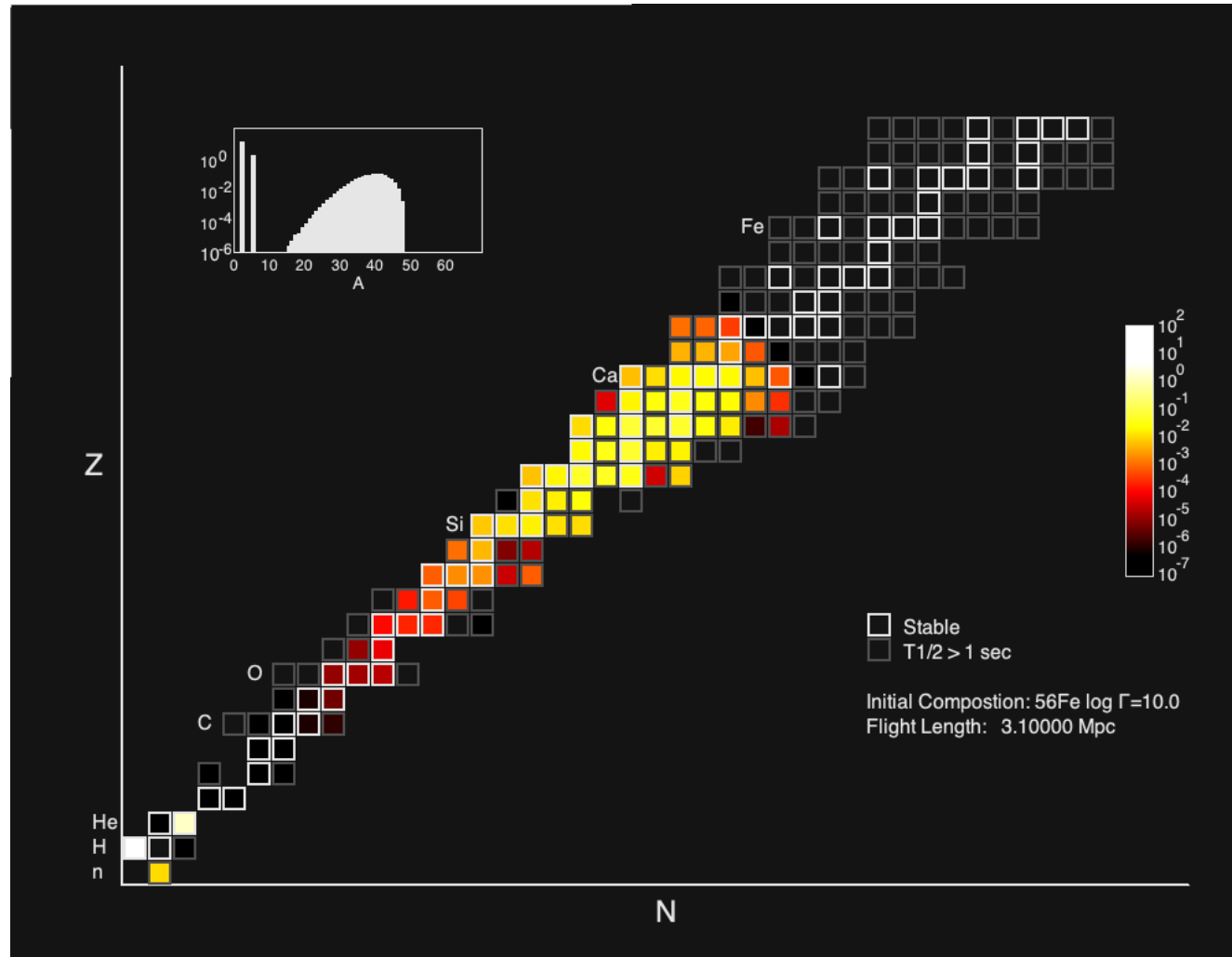


UHECR: Intergalactic Propagation by a Toy-Model Simulation



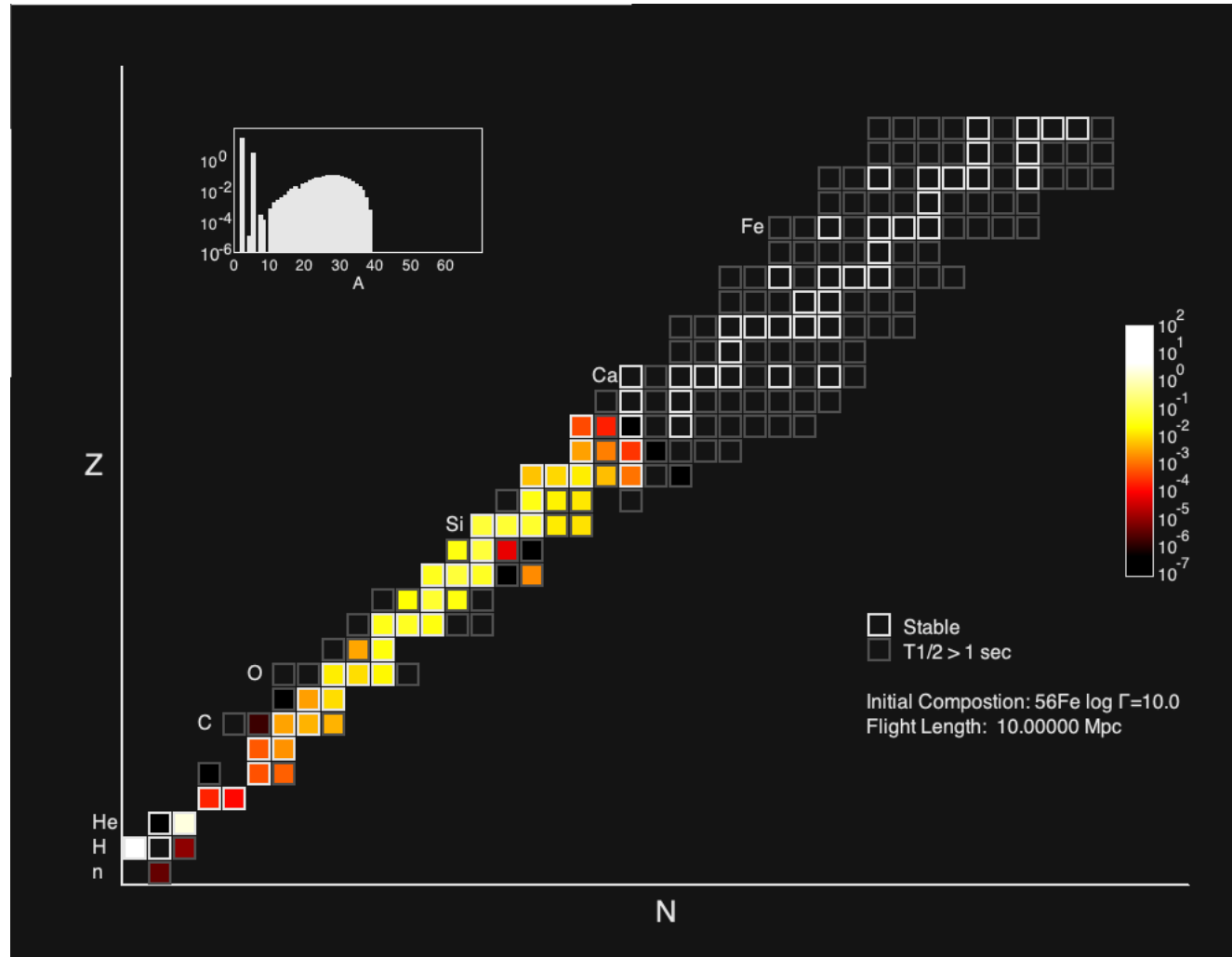
1 Mpc

UHECR: Intergalactic Propagation by a Toy-Model Simulation



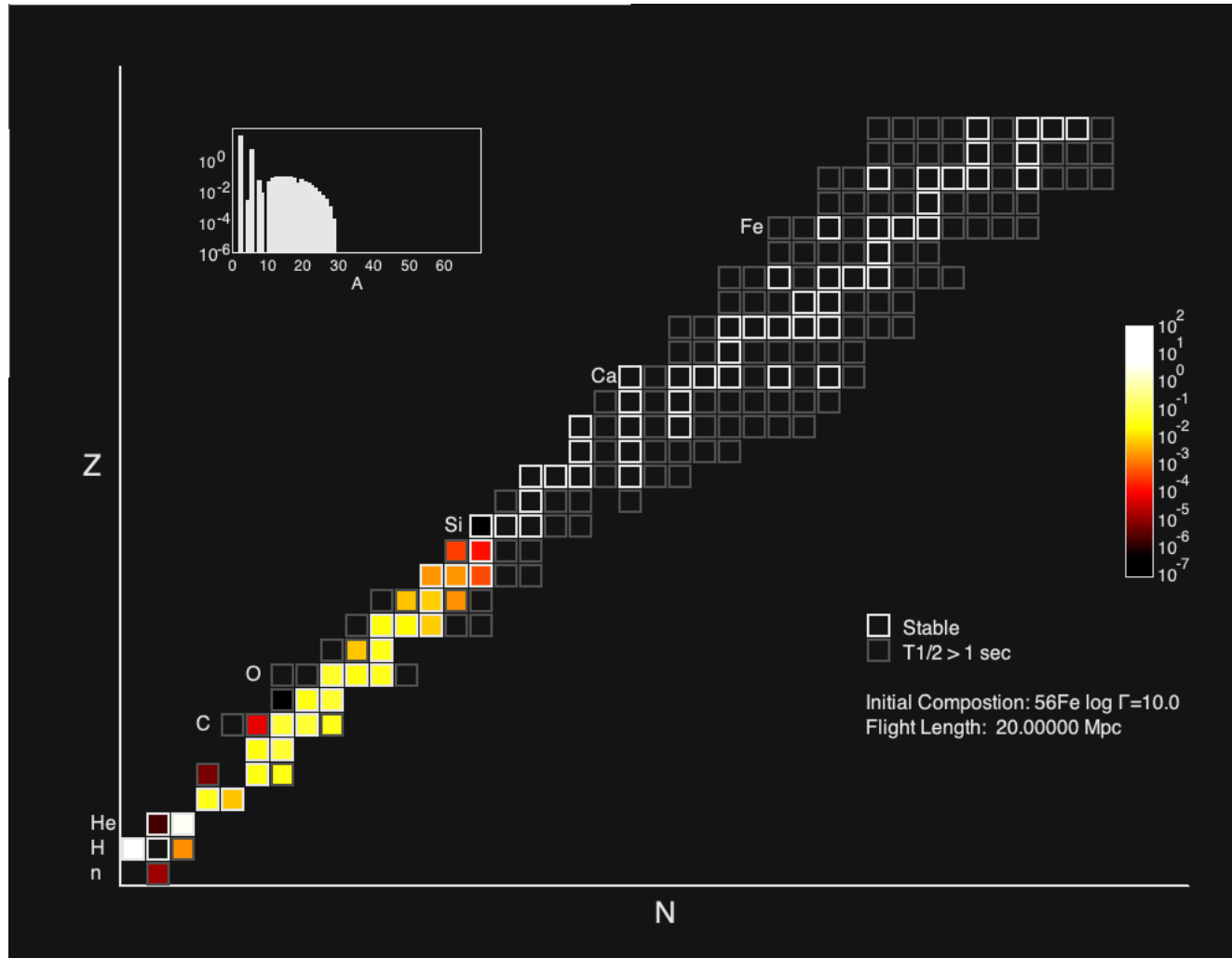
UHECR: Intergalactic Propagation by a Toy-Model Simulation

10 Mpc



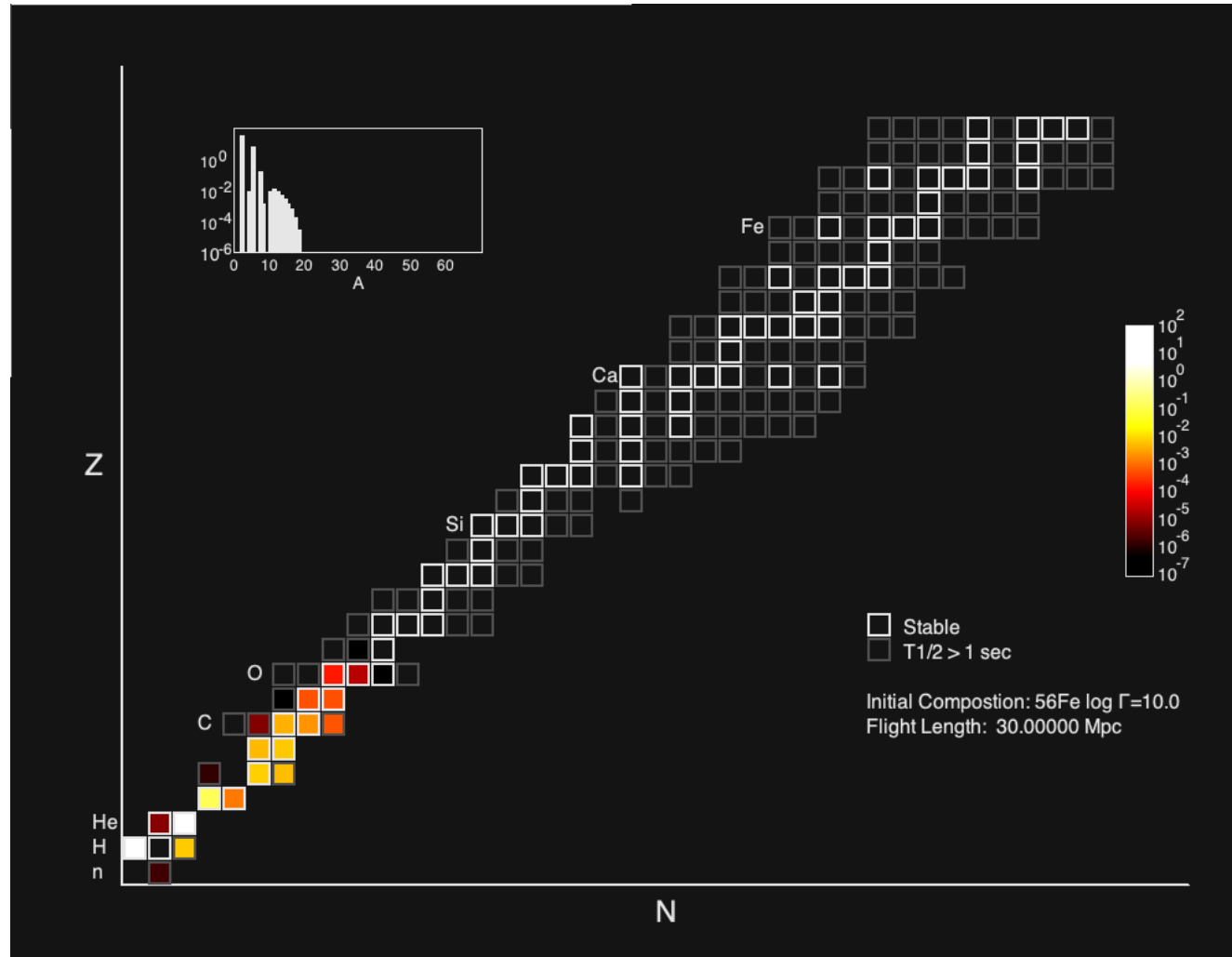
UHECR: Intergalactic Propagation by a Toy-Model Simulation

20 Mpc

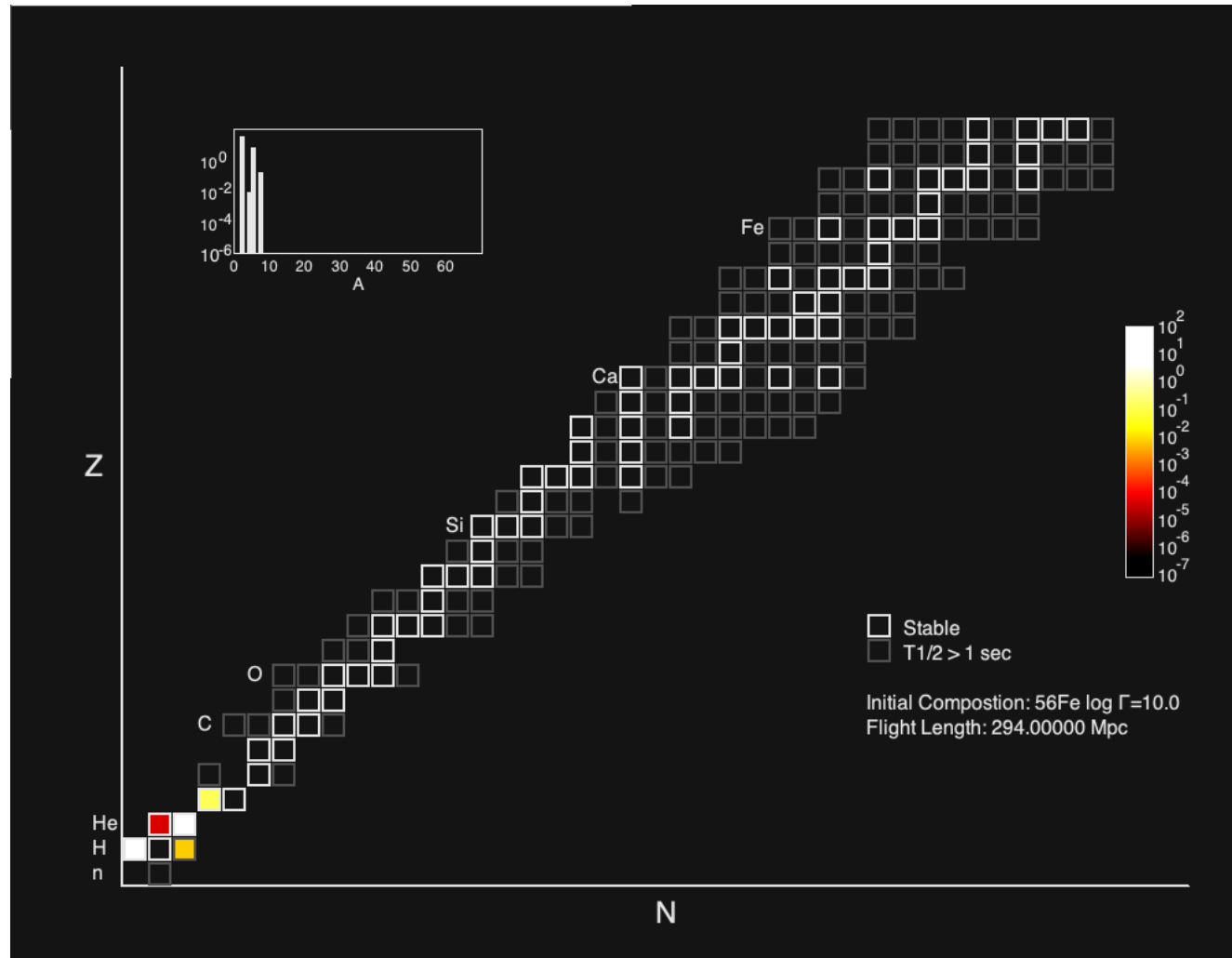


UHECR: Intergalactic Propagation by a Toy-Model Simulation

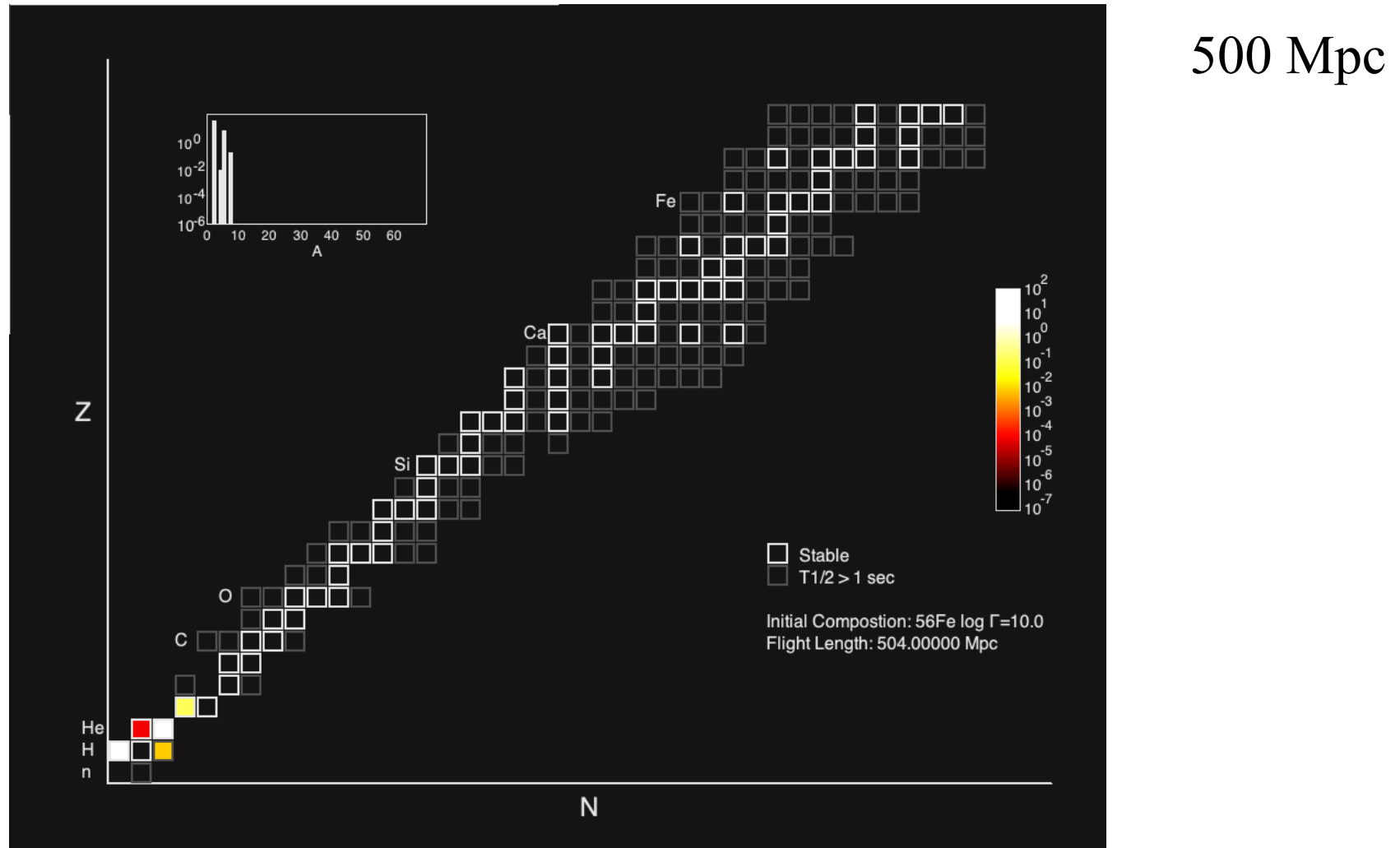
30 Mpc



UHECR: Intergalactic Propagation by a Toy-Model Simulation



UHECR: Intergalactic Propagation by a Toy-Model Simulation

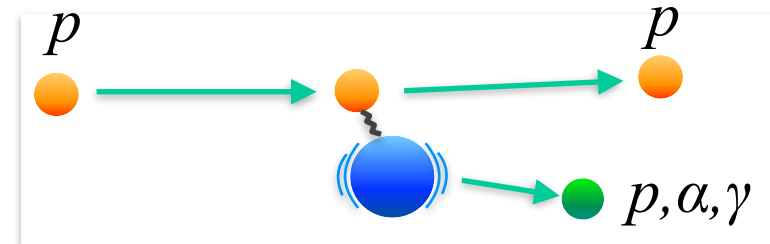
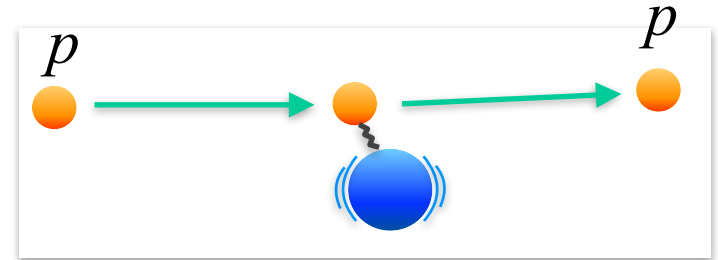


Experimental Methods

Probing Photo-Nuclear Response of Nuclei

Virtual photo excitation by proton scattering (RCNP, iThemba LABS)

- Missing mass method with proton Coulomb excitation
- better for total strength and strength distribution
higher cross sections
also applicable for p, α, γ decays

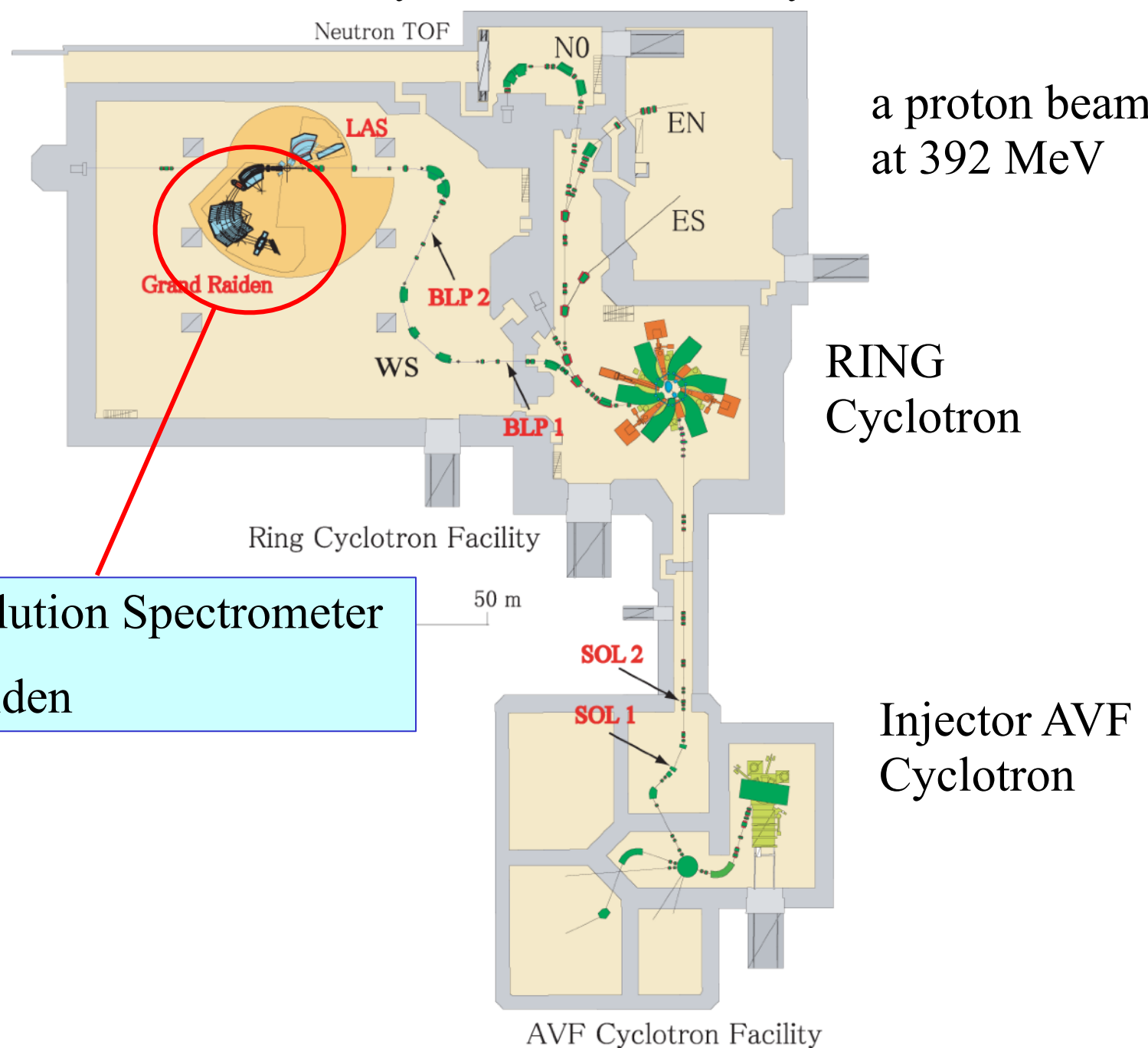


Real photo excitation (ELI-NP etc.)

- Gamma-beam by laser-Compton scattering with an electron beam
- individual decay channels
better for absolute normalization
applicable also for n and xn decays in addition to p, α, γ



Research Center for Nuclear Physics, The University of Osaka

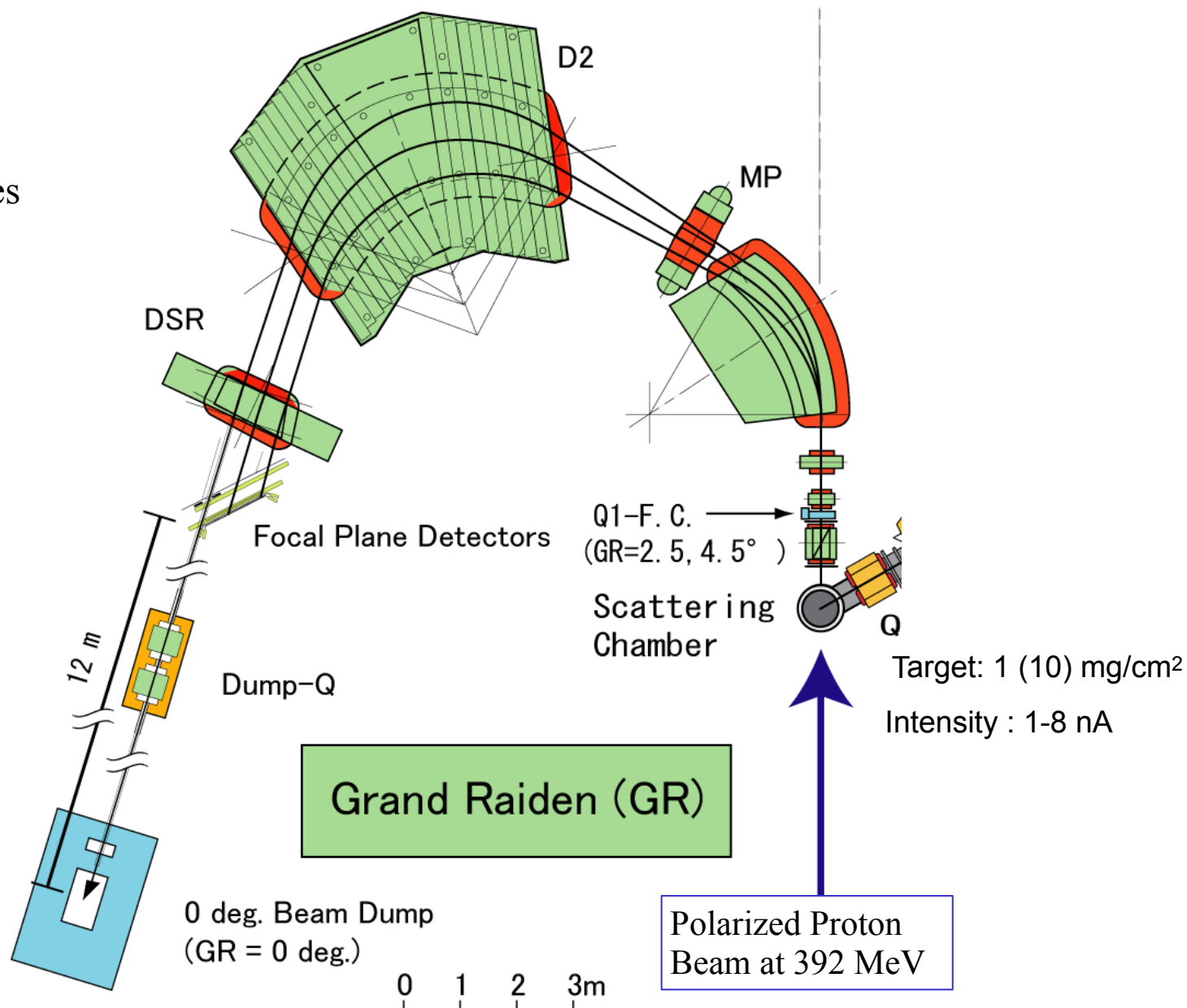


a proton beam
at 392 MeV

High-resolution Spectrometer
Grand Raiden

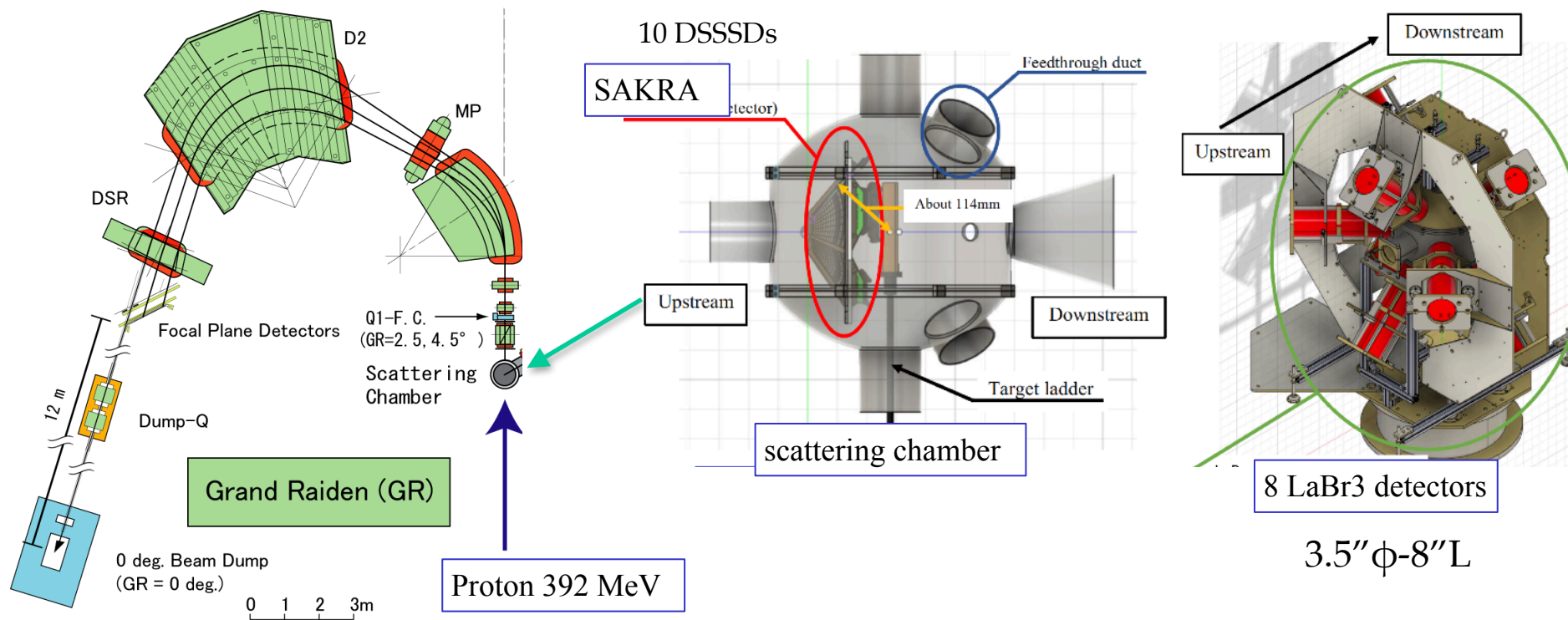
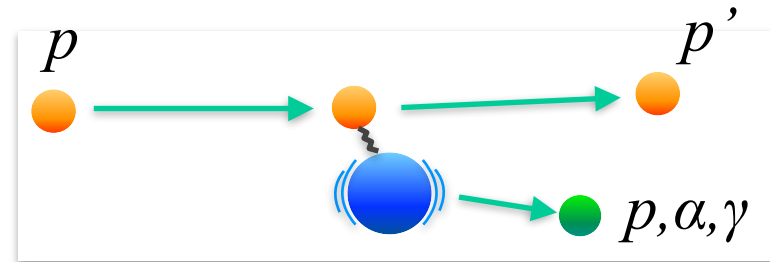
High-Resolution Spectrometer “Grand Raiden”

Proton scattering
at very forward angles

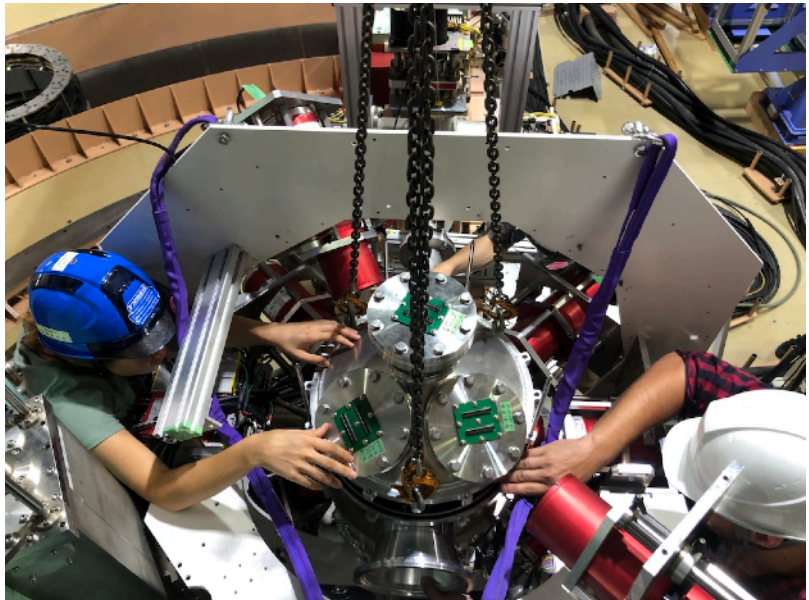
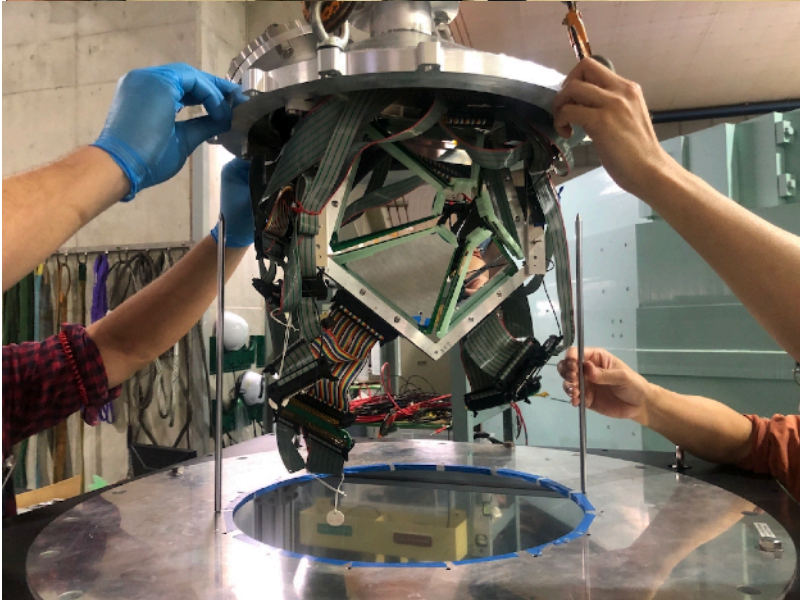


Virtual photo excitation by proton scattering

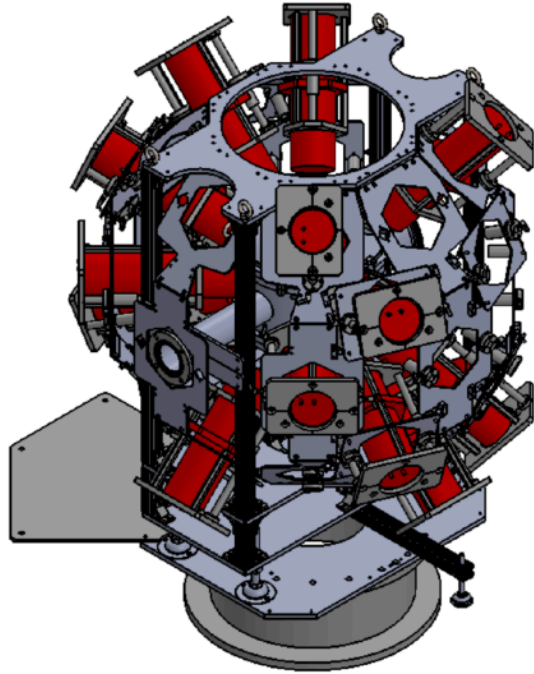
- Missing mass measurement with Coulomb excitation
- coincidence for p, α, γ branching ratio



E536: 1st PANDORA experiment at RCNP, Oct. 2023



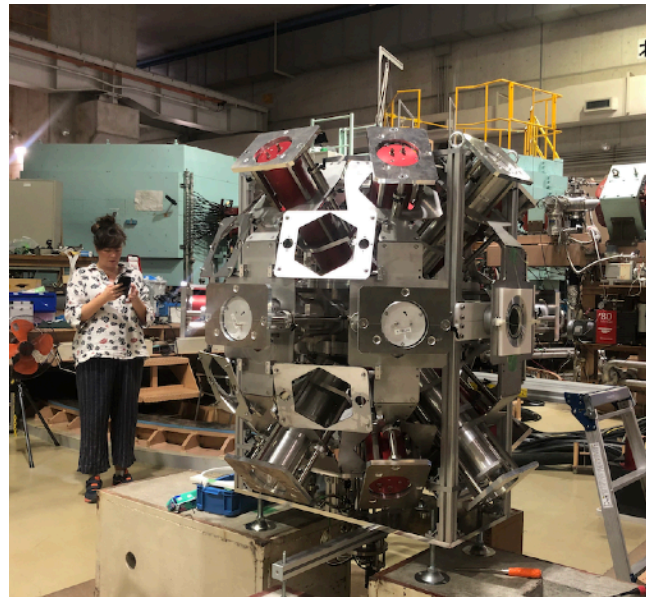
E589: 2nd PANDORA experiment at RCNP, Oct. 2025



LPIS: 16 large volume LaBr₃ detectors
8 from Milano
8 from iThemba LABS



LaBr₃ detectors from iThemba LABS



red: Milano

紅

white: iThemba LABS

白

LPIS: LaBr₃ detectors mounted

Targets

Measurements on 10-20 nuclei
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

• ^6Li , ^7Li , ^9Be , ^{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 thin box & 2025 thick box

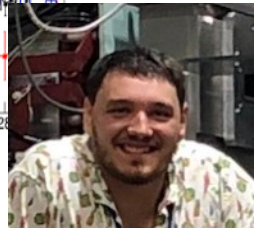
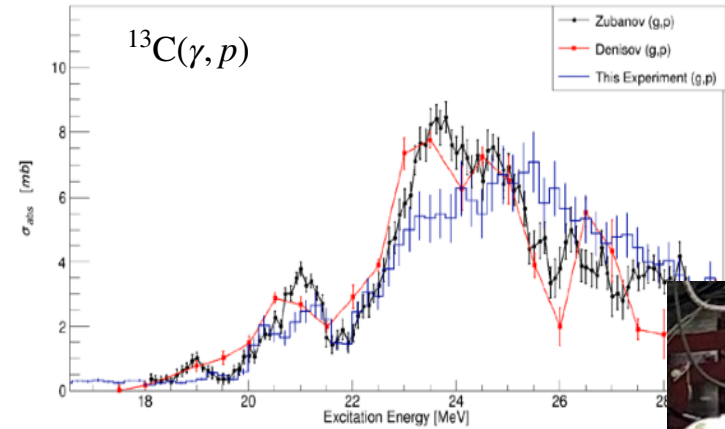
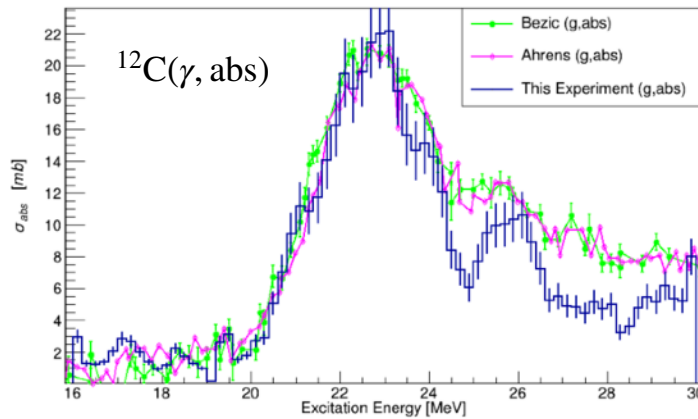


photo-abs. c.s. + charged particle decay
+ gamma



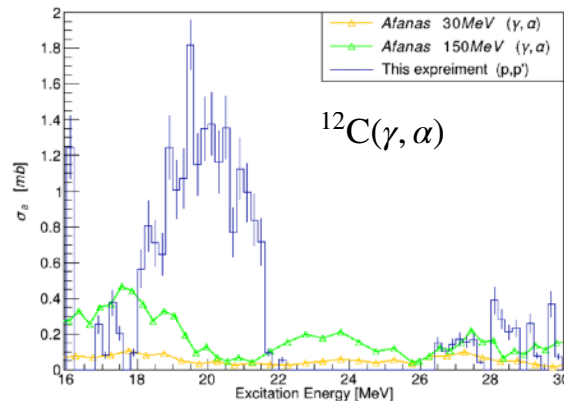
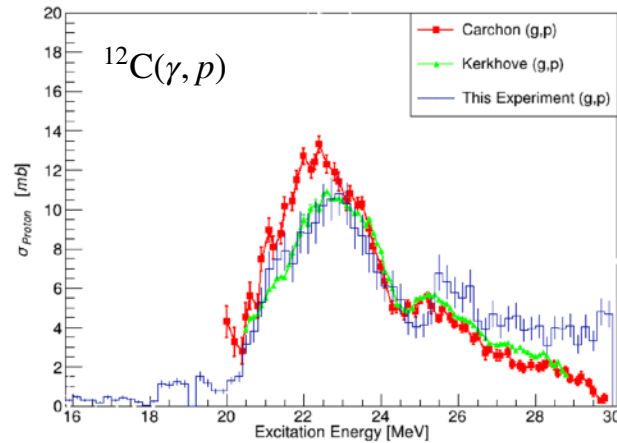
photo-abs. c.s. + gamma

Preliminary Results

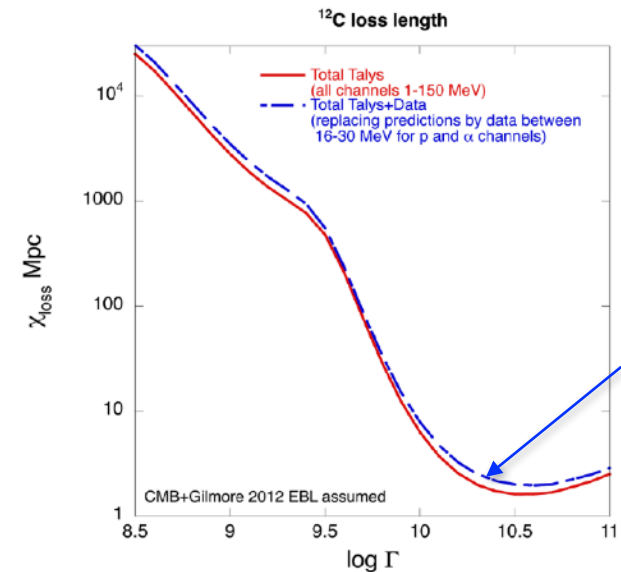


J.A.C. Bekker (SA)

— This experiment



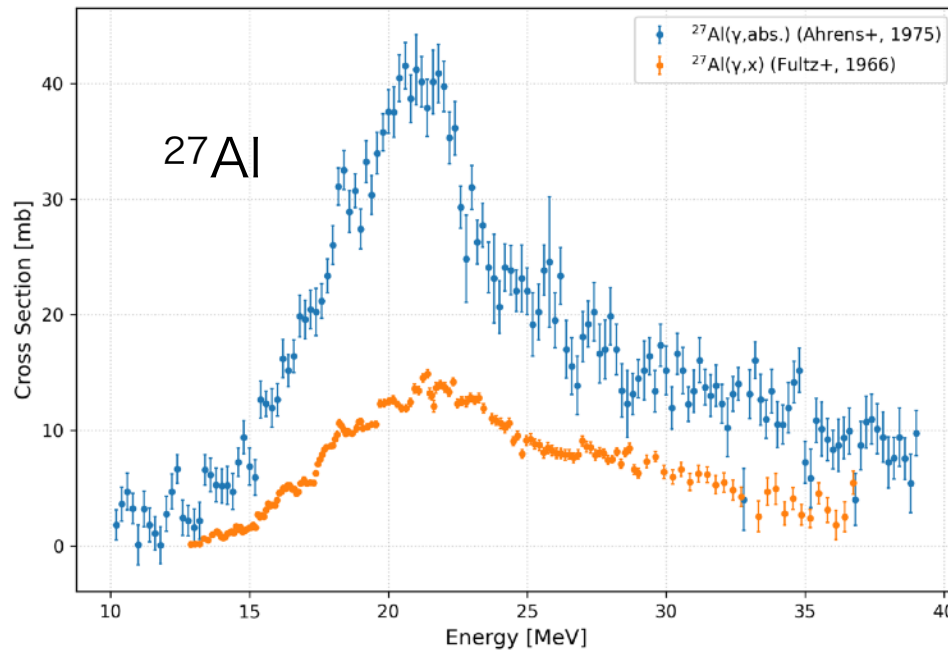
UHECR Energy loss length simulation



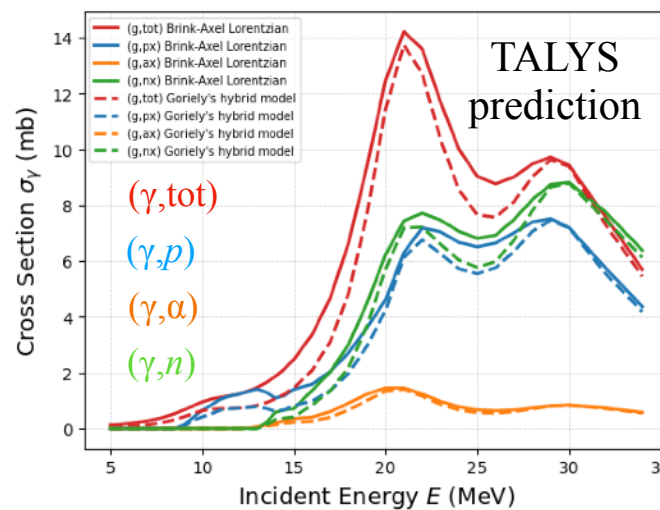
with data
of this exp.

^{27}Al photo-reaction: available data

65



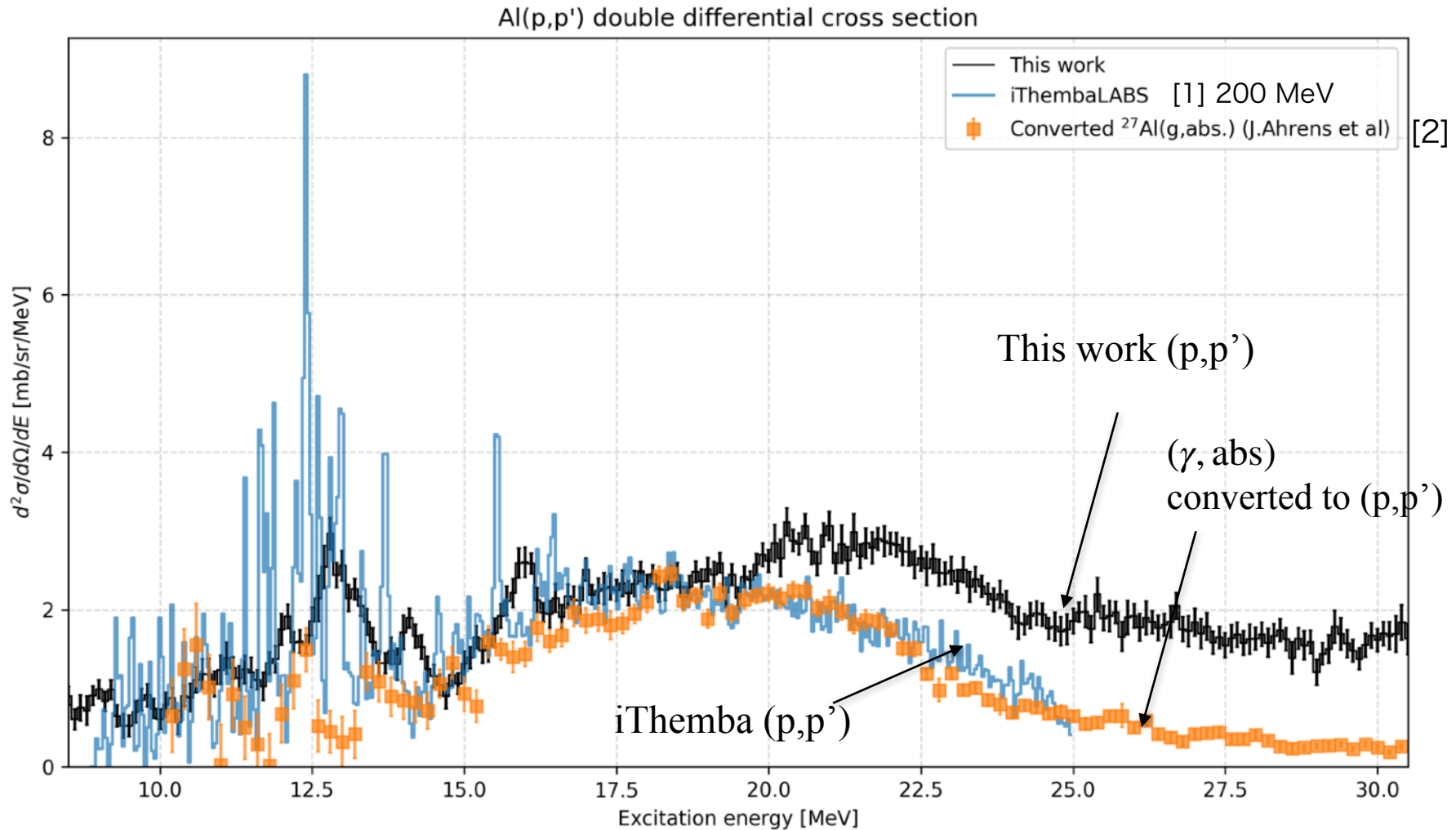
← (γ, abs)
← $(\gamma, n) + (\gamma, 2n)$ Fultz et al., L0039



The peak photo-absorption cross section is significantly underestimated
.(~ 1/3)

$^{27}\text{Al}(p, p')$ Differential Cross Section

66

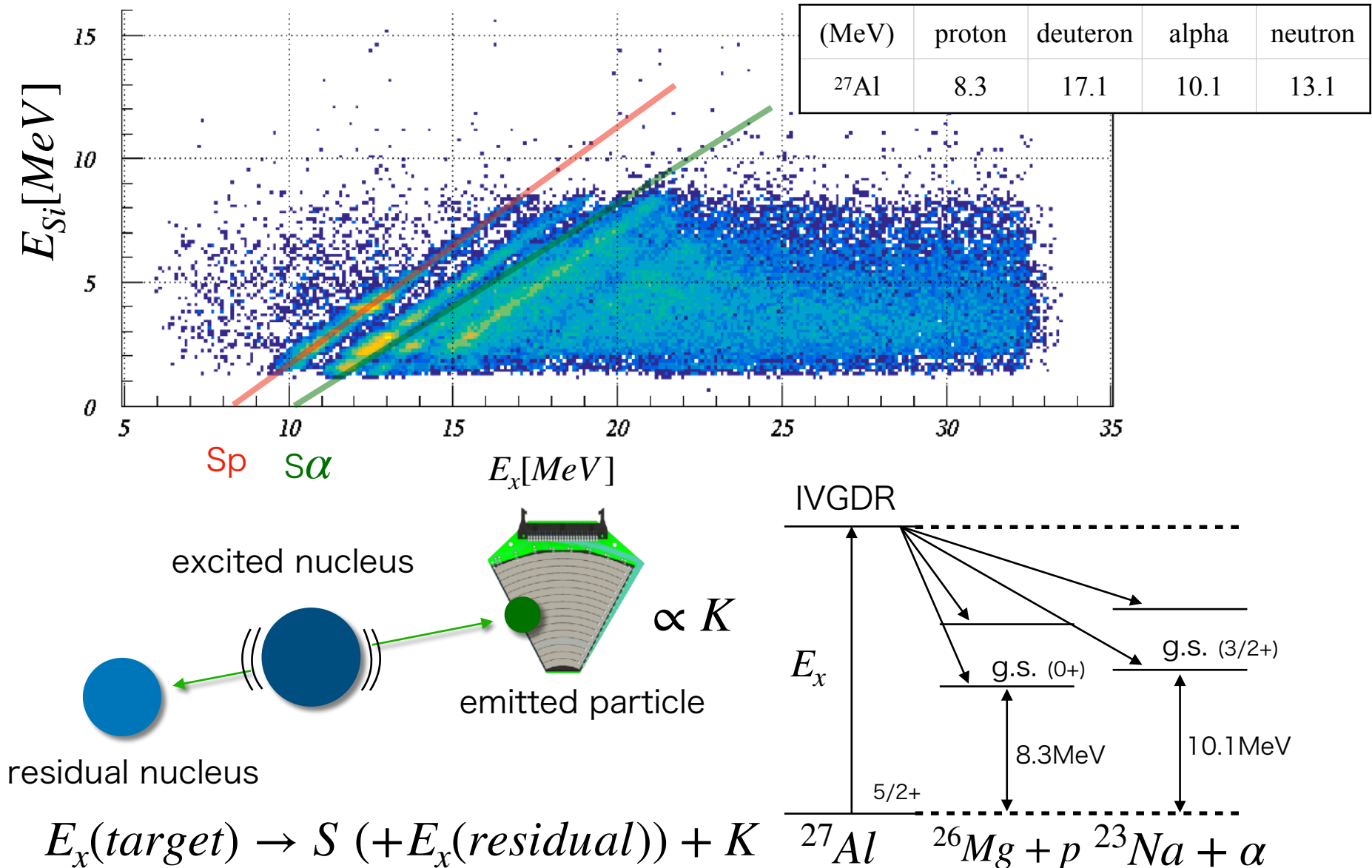


[1] M. Jingo *et al.*, Eur. Phys. J. A 54, 224 (2018).

[2] J. Ahrens *et al.*, Nucl. Phys. A 251, 479(1975).

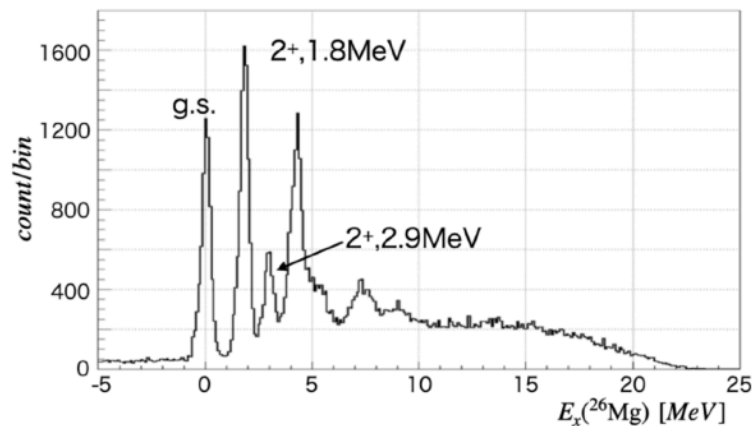
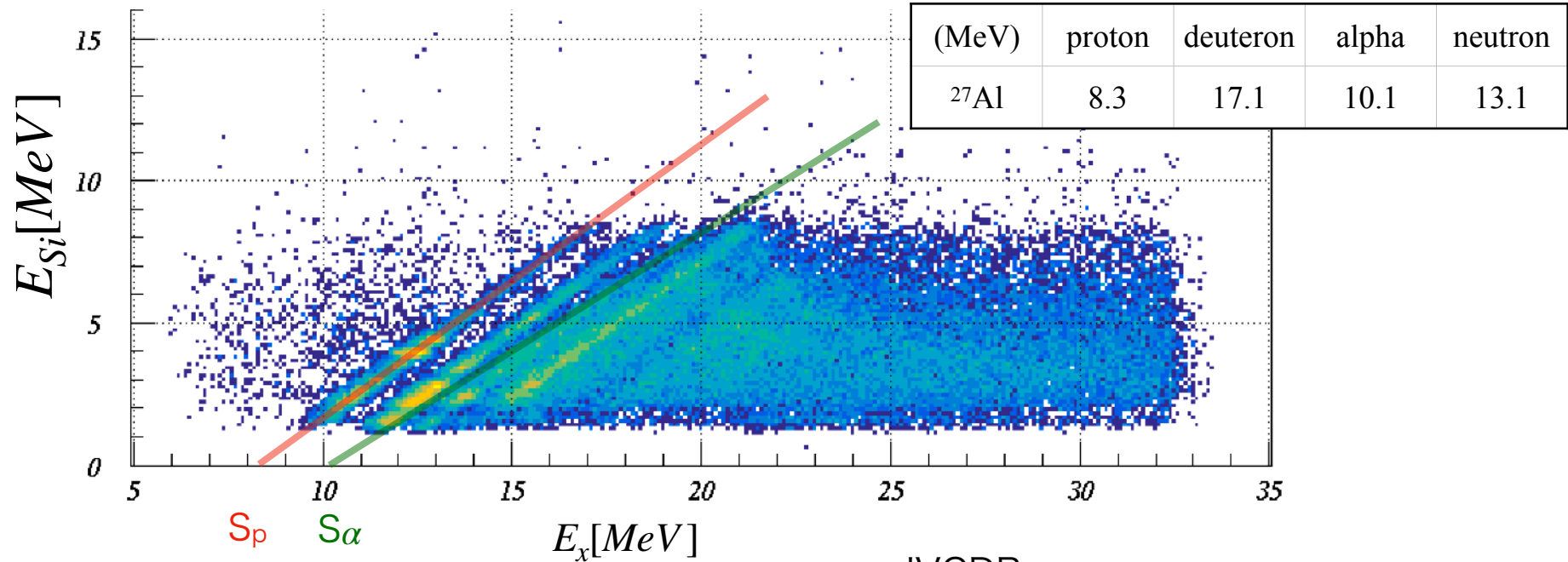
Charged Particle Decay Coincidence

67

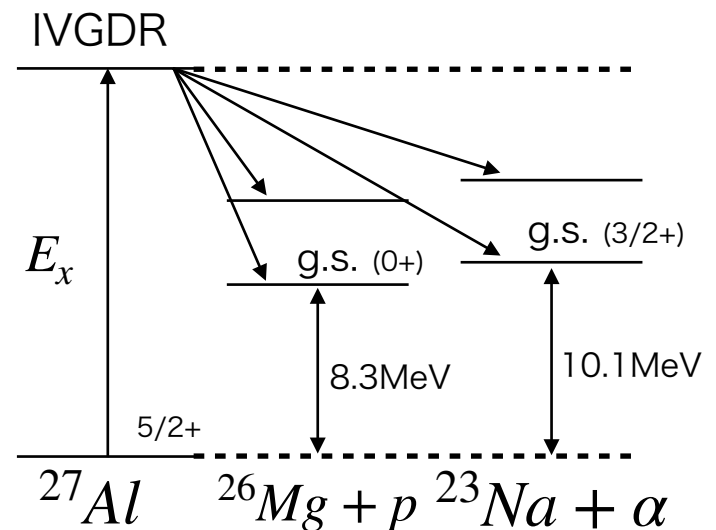


Charged Particle Decay Coincidence

68



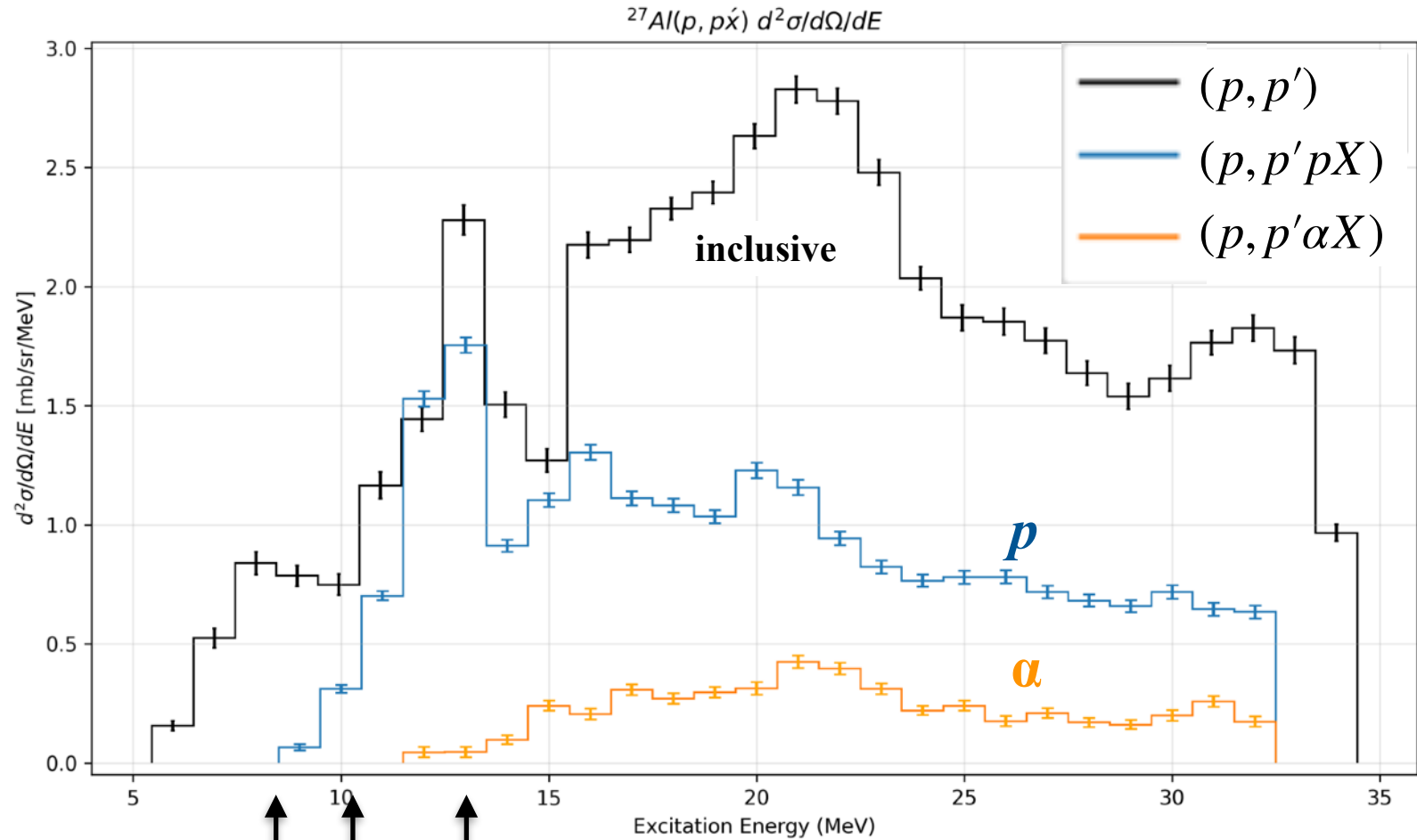
daughter states assuming proton-decay



Preliminary Results

69

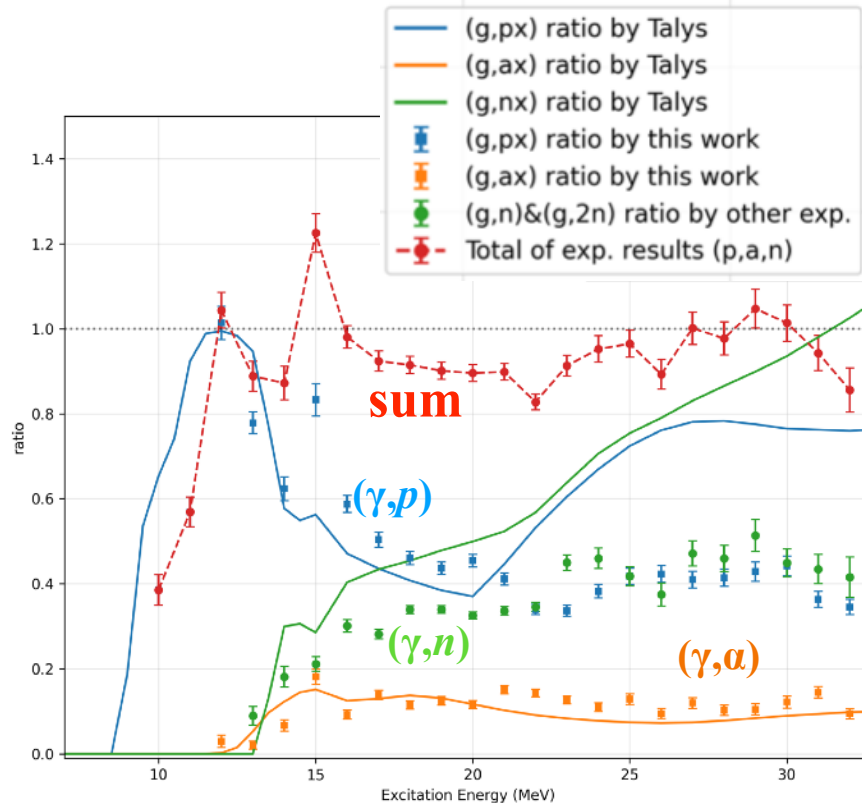
Differential Cross Section at 0 degrees



$S_p = 8.3 \text{ MeV}$

$S_\alpha = 10.1 \text{ MeV}$

$S_n = 13.1 \text{ MeV}$



TALYS prediction

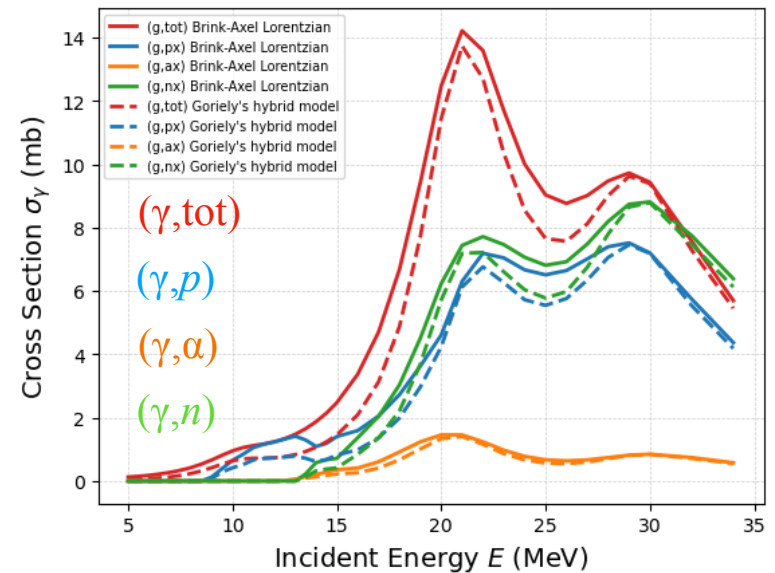


photo-reaction cross sections

Statistical Errors are shown for this work

separation energies

	α	p	n	d	αp	αn	pp	nn	pn
^{27}Al	10.1	8.3	13.1	17.1	18.9	22.5	22.4	24.4	19.4

Multi-particle decays are not treated properly yet.

n and p branching ratios:

comparable above 20 MeV

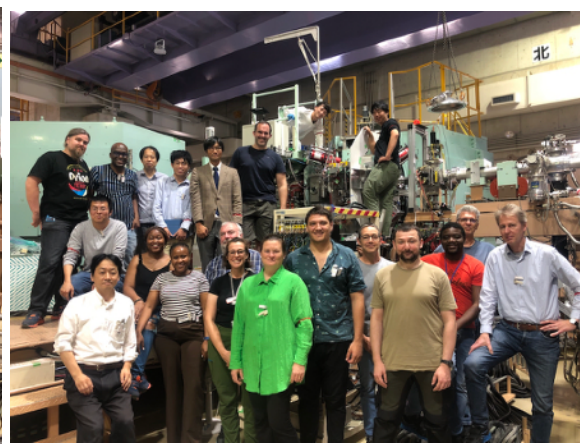
α decay: $\sim 10\%$ above 15 MeV

Well predicted by TALY

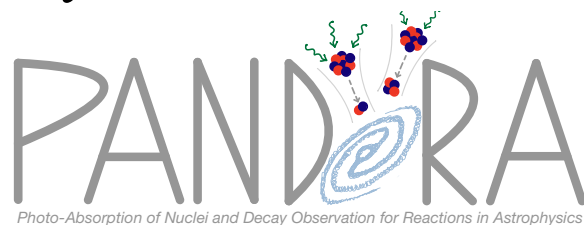
Summary

- Electric dipole response of nuclei, that describes the photo-nuclear reaction, is a fundamental property of nuclei that is relevant to nuclear collective excitations, nuclear equation of state, astrophysical nuclear reactions, and applications.
- Photo-absorption cross sections and decay branching ratios of light stable nuclei are systematically studied up to $A \sim 60$ in the PANDORA project.
- The photo-nuclear reaction data are important for developing nuclear structure/decay models and for simulating the inter-galactic propagation of UHECRs.
- Virtual photon excitation by proton scattering has been applied at RCNP. Preliminary data on $^{12,13}\text{C}$ and ^{27}Al have been shown.

Thank you for your attention



Thank you for all the collaborators!



※ Not all the collaborators are shown in the pictures.

