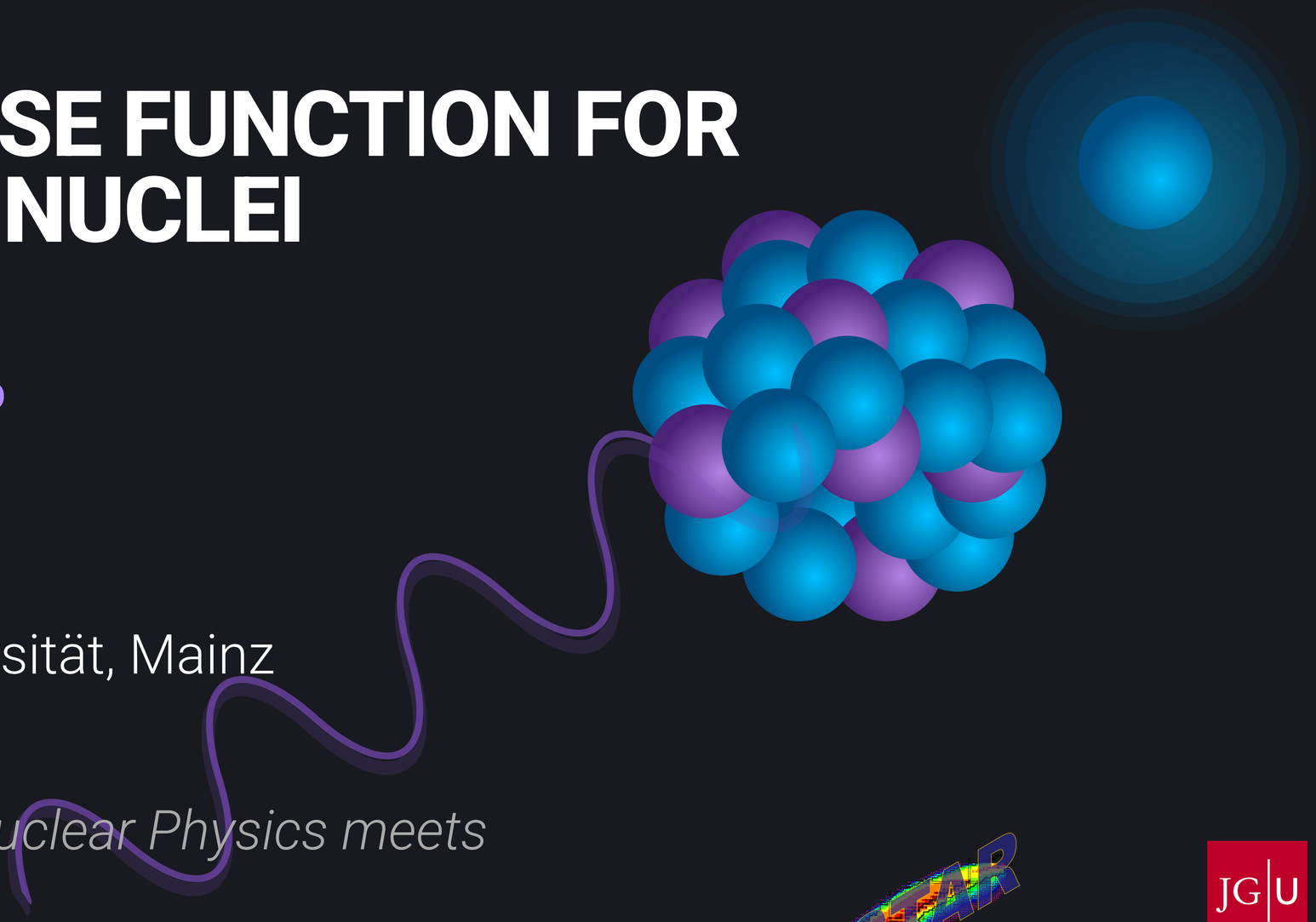
DIPOLE RESPONSE FUNCTION FOR NEUTRON-RICH NUCLEI



From ab initio calculations to neutron rich matter

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Johannes Gutenberg-Universität, Mainz

MITP | Many-Body Theory: Nuclear Physics meets Quantum Chemistry

Mainz - 1 September 2026

NUSTAR

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

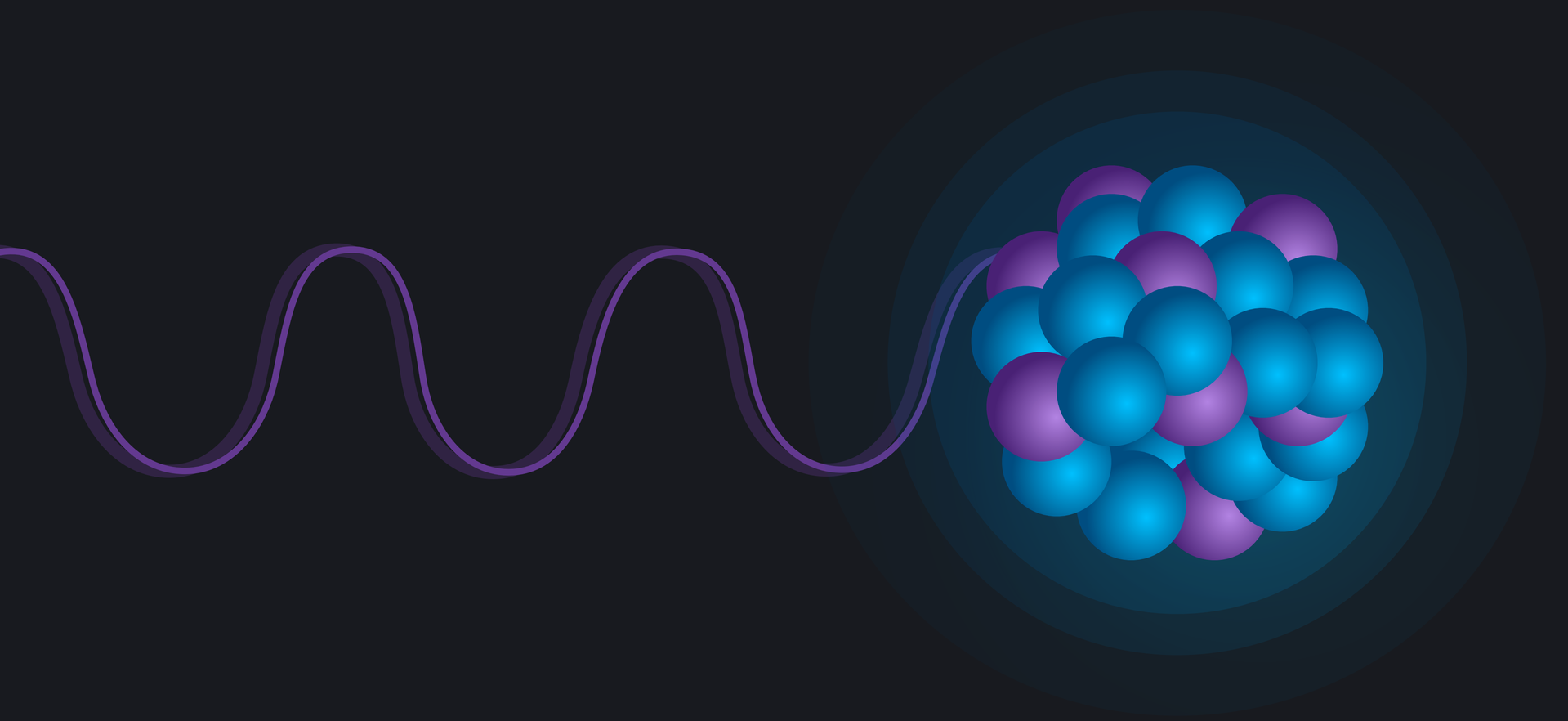
ACT I: The physics

Why focusing on neutron-rich nuclei?

- Test *ab initio* methods in asymmetric systems
- Explore the evolution of collective excitations
- Constrain neutron-matter equation of states (EoS)

ACT I: The physics

How to study internal dynamics?



$R(\omega)$

Response function

ACT I: The physics

Cross section ⟷ Dipole Response Function

$$\sigma_\gamma(\omega) = 4\pi^2 \alpha \omega R_\mathrm{d}(\omega)$$

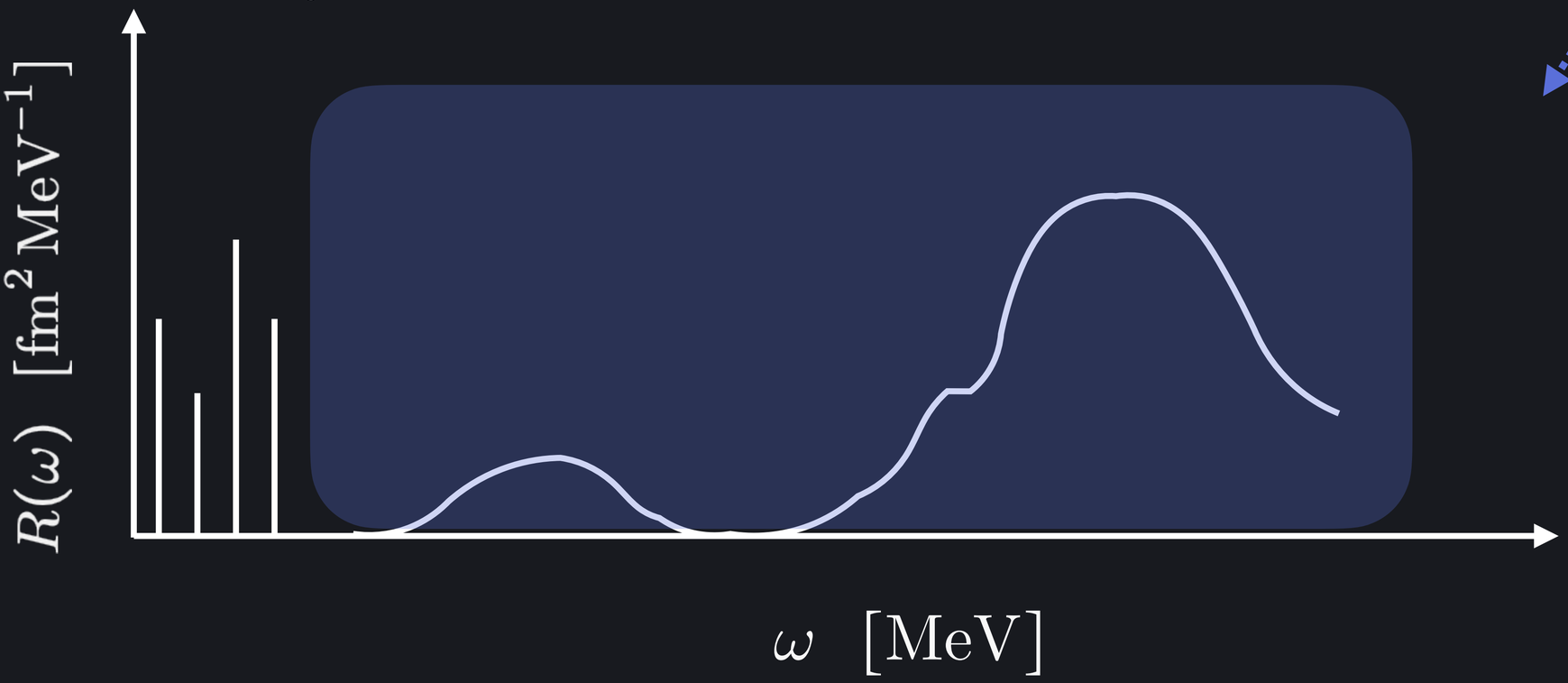
Measured in experiments

Calculated ab initio

ACT II: The challenge

How to deal with the continuum?

$$R(\omega) = \sum\!\!\!\!\!\!\int_f |\langle \Psi_f | \Theta | \Psi_0 \rangle|^2 \delta(E_f - E_0 - \omega)$$



ACT II: The challenge

The Lorentz Integral Transform (LIT)

Convolve the response with a Lorentzian kernel

$$L(\sigma) = \frac{\sigma_I}{\pi} \int \frac{R(\omega)}{(\omega - \sigma_R)^2 + \sigma_I^2} = \frac{\sigma_I}{\pi} \langle \tilde{\Psi} | \tilde{\Psi} \rangle$$

$$\sigma = \sigma_R + i\sigma_I$$

Solve a **bound-state-like** equation with standard many-body methods

$$(H - E_0 + \sigma)|\tilde{\Psi}(\sigma)\rangle = \Theta|\Psi_0\rangle$$

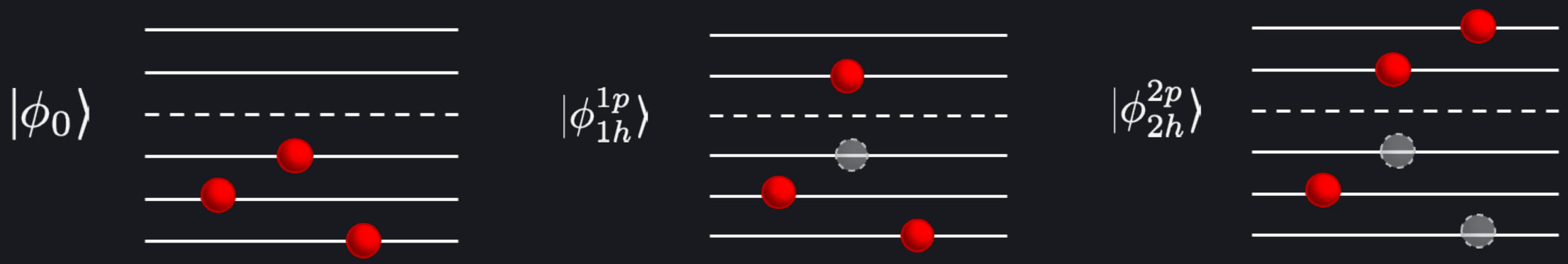
V. D. Efros, et al, J. Phys. G: Nucl. Part. Phys., vol. 34, no. 12 (2007)
S. Bacca, et al., Phys. Rev. Lett., vol. 111, no. 12, (2013,)

ACT III: The method

Many-body framework: Coupled Cluster

Ground-state **correlations** via an exponential ansatz

$$|\Psi_0\rangle = e^{\hat{T}}|\phi_0\rangle \qquad \hat{T} = \hat{T}_1 + \hat{T}_2 + \dots$$



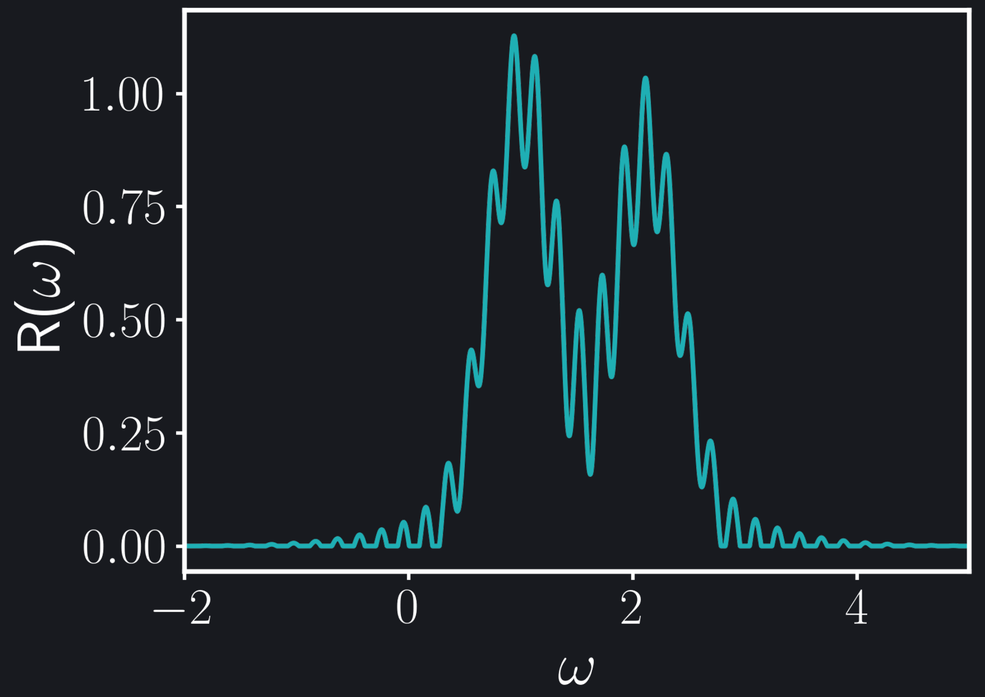
Coupled Cluster enables **realistic** calculations of neutron-rich medium-mass nuclei.

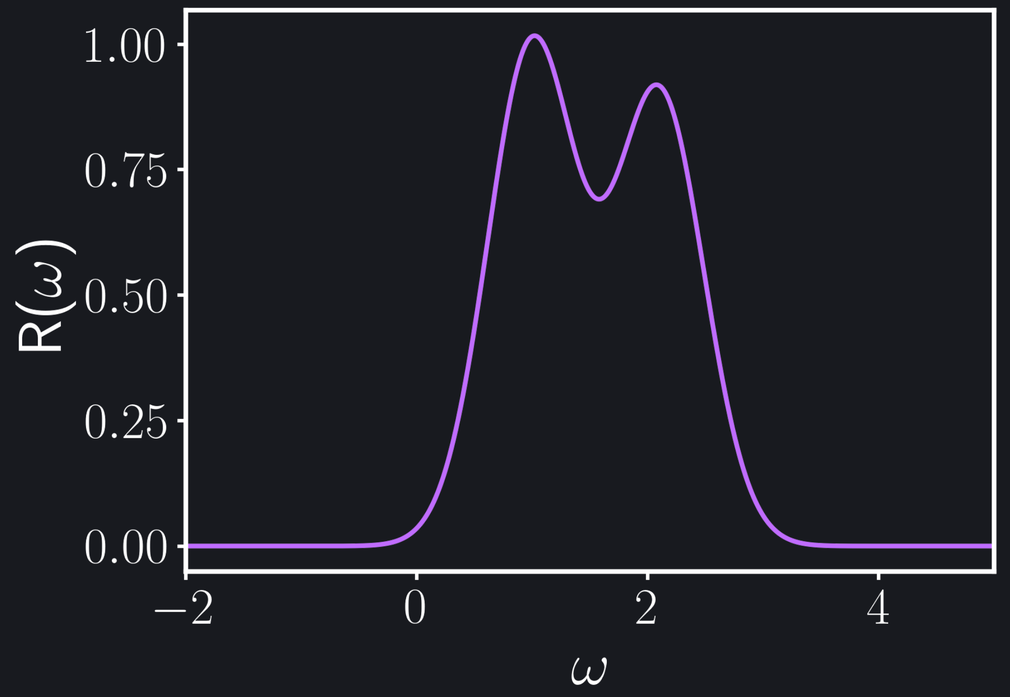
G. Hagen et al., Rep. Prog. Phys., vol. 77, no. 9 (2014)

ACT III: The method

Back to our main goal: the inversion

Ill-posed problem → the solution is not unique





ACT III: The method

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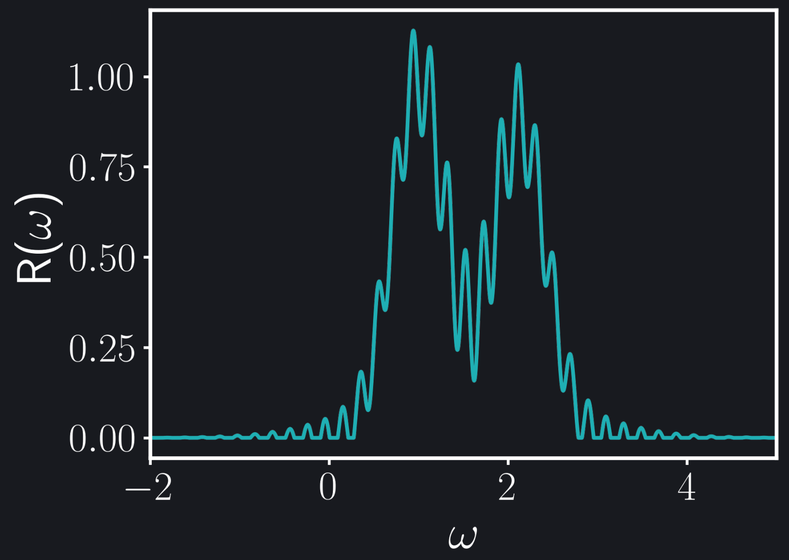
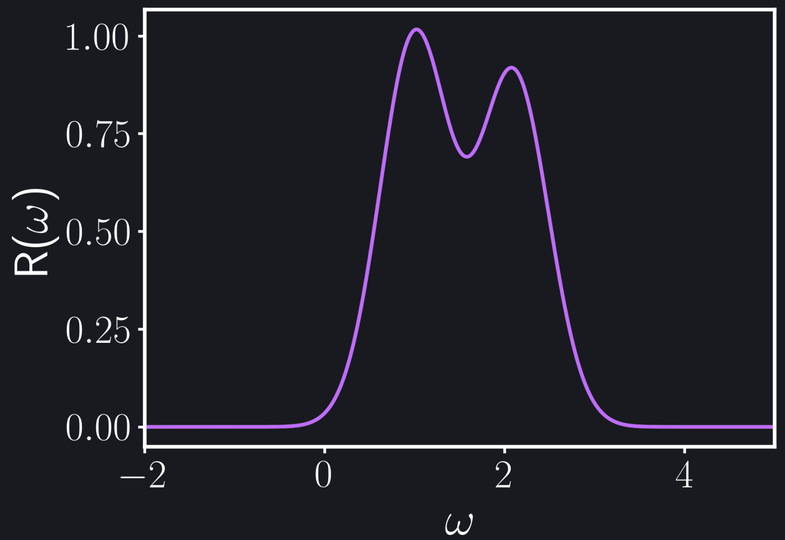
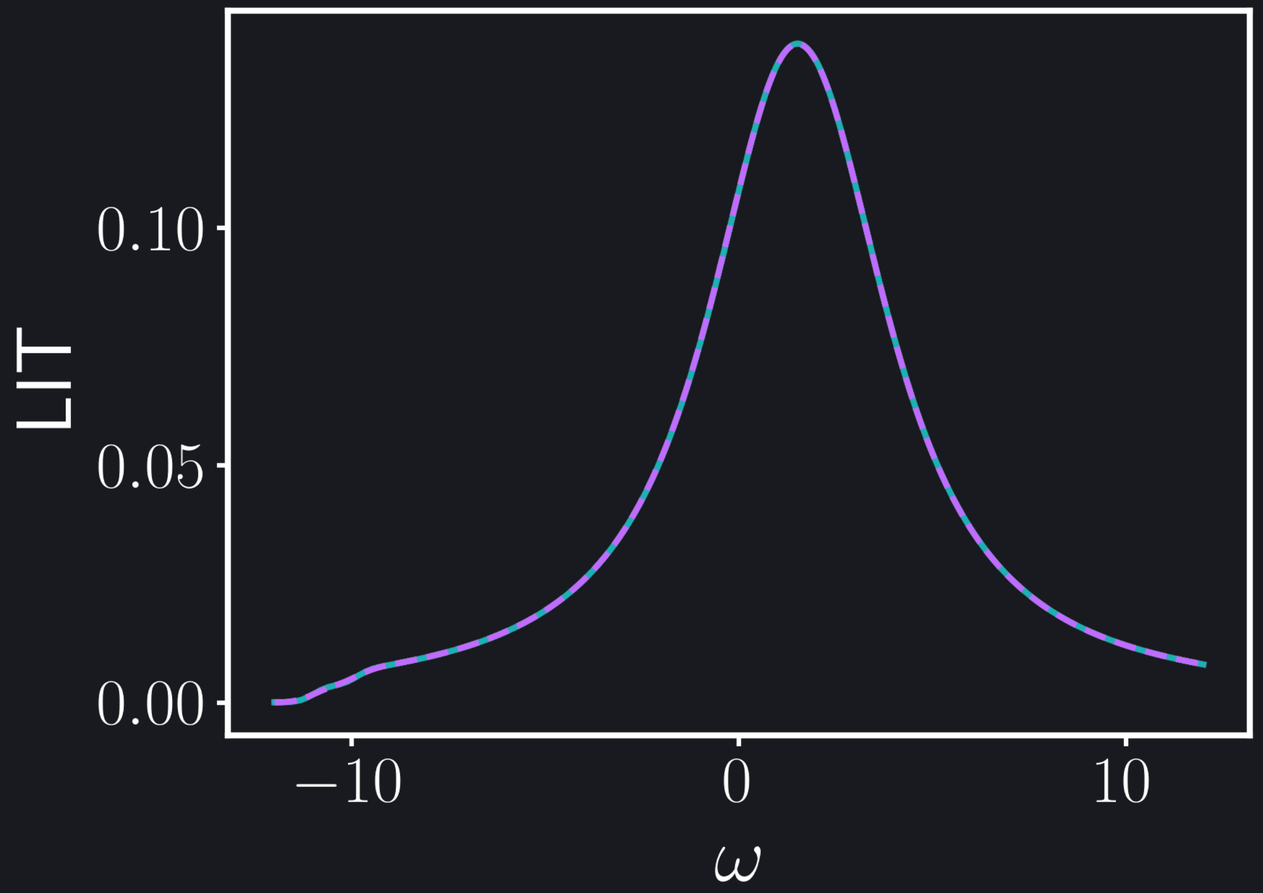
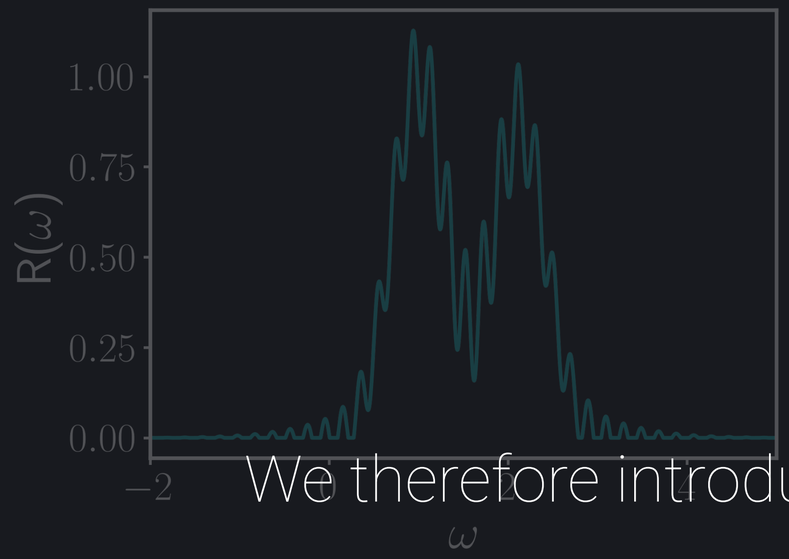


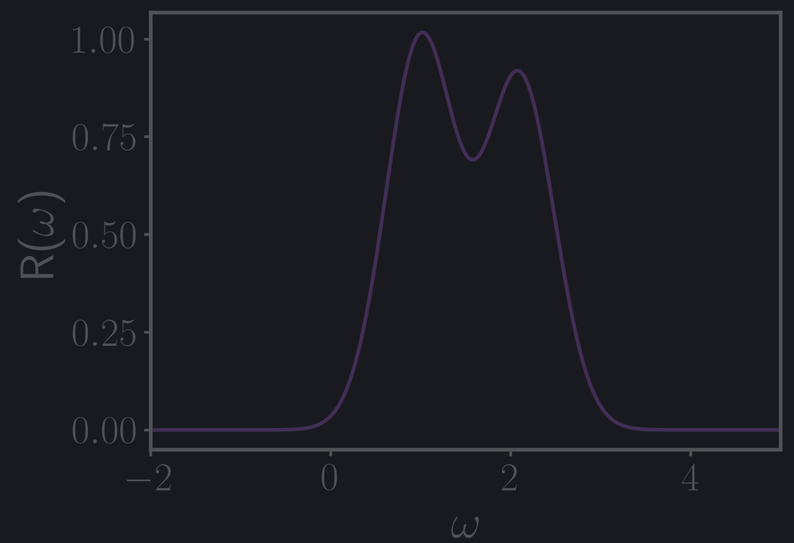




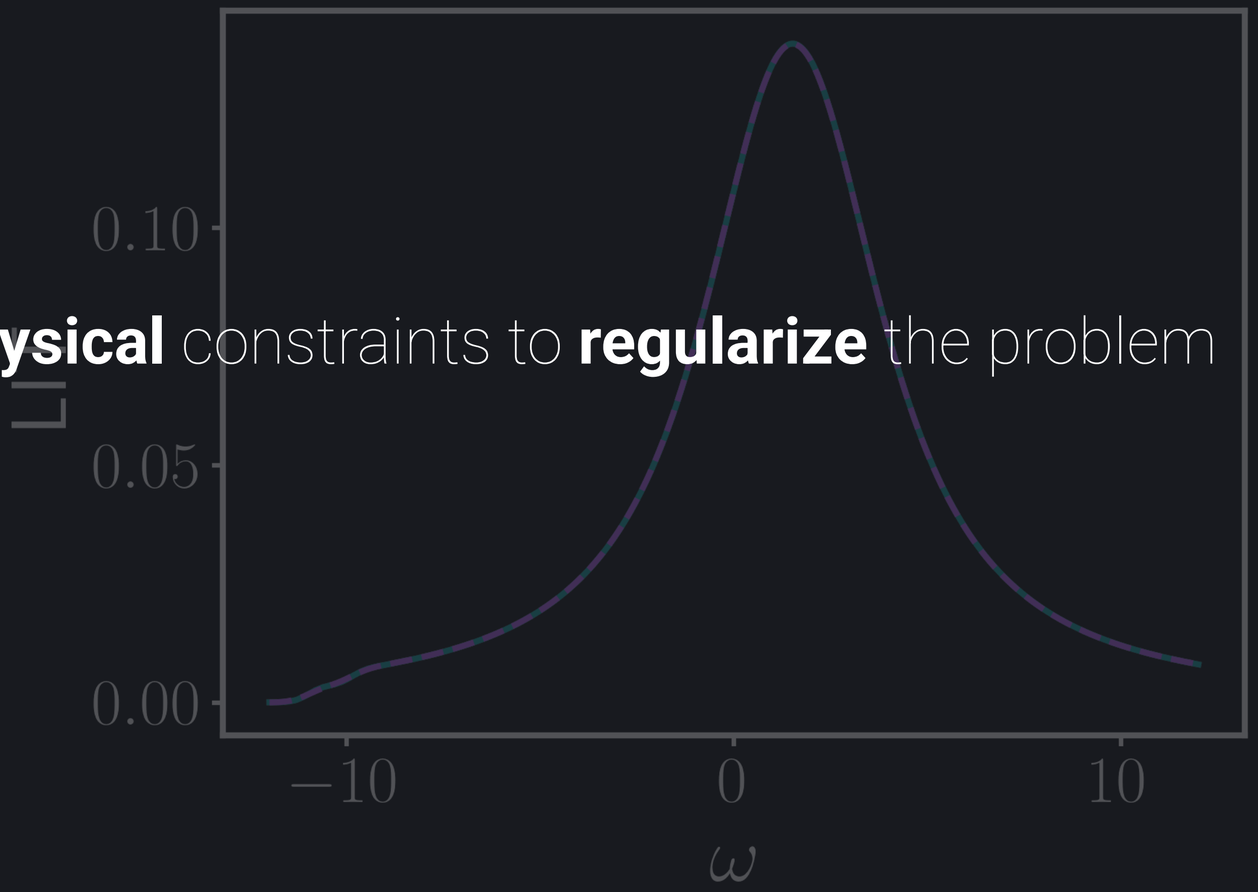
ACT III: The method

Back to our main goal: the inversion





We therefore introduce **physical** constraints to **regularize** the problem



ACT III: The method

Back to our main goal: the inversion

Express the response function in a suitable basis:

$$\tilde{R}(\omega) = \sum_{n=1}^{\nu} c_n \, f_n(\omega; \alpha, \beta)$$

- Fit **coefficients** and ensure positivity
- Estimate **uncertainties**: basis size, threshold

V. D. Efros, et al, J. Phys. G: Nucl. Part. Phys., vol. 34, no. 12 (2007)

ACT III: The method

The workflow

Coupled Cluster

To solve the bound-state-like problem

1

2

Obtain the LIT

From which we can obtain directly integrated quantities

Invert the LIT

To reconstruct the response function

3

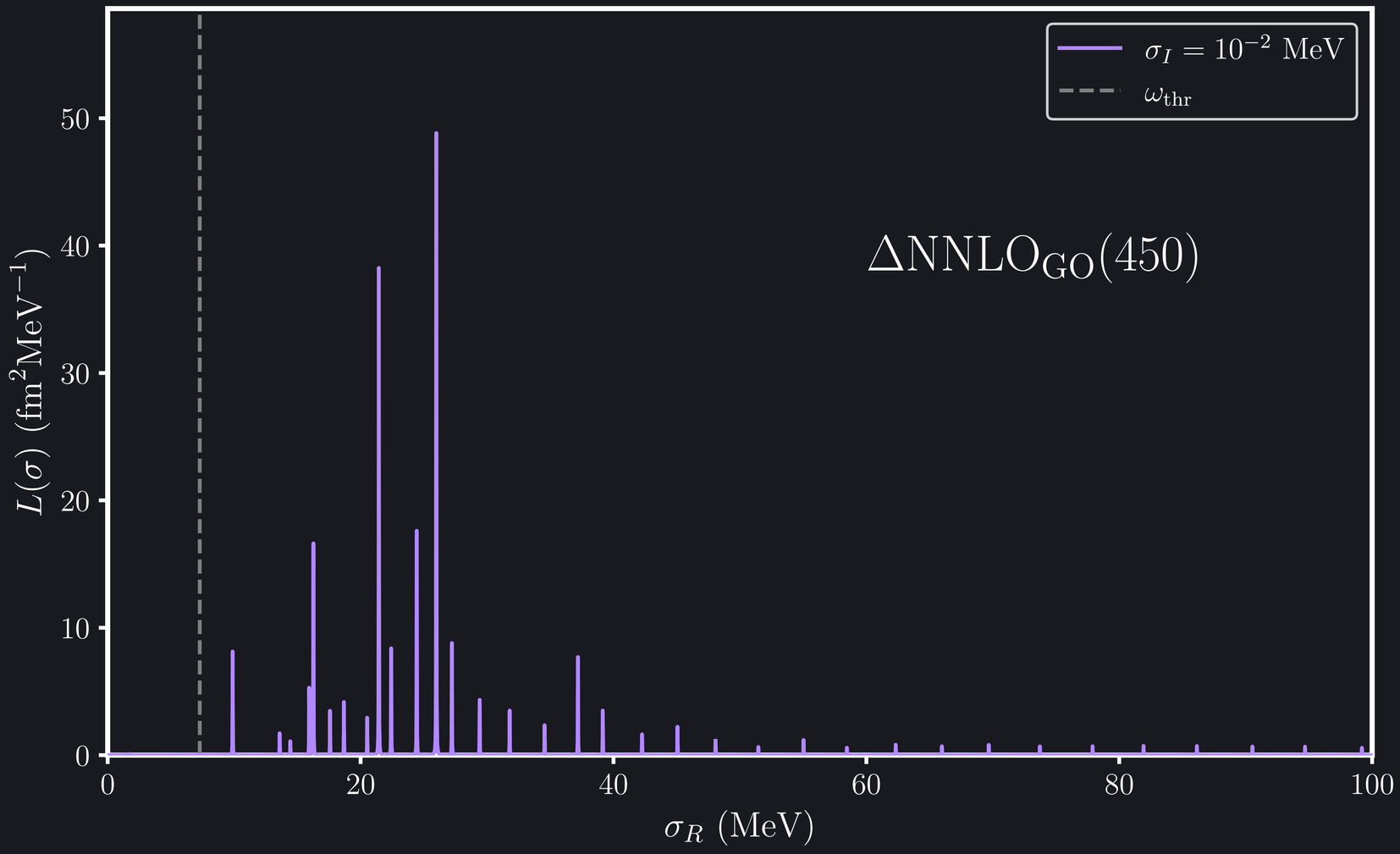
4

Observable cross-section

Compare with available data

ACT IV: Results

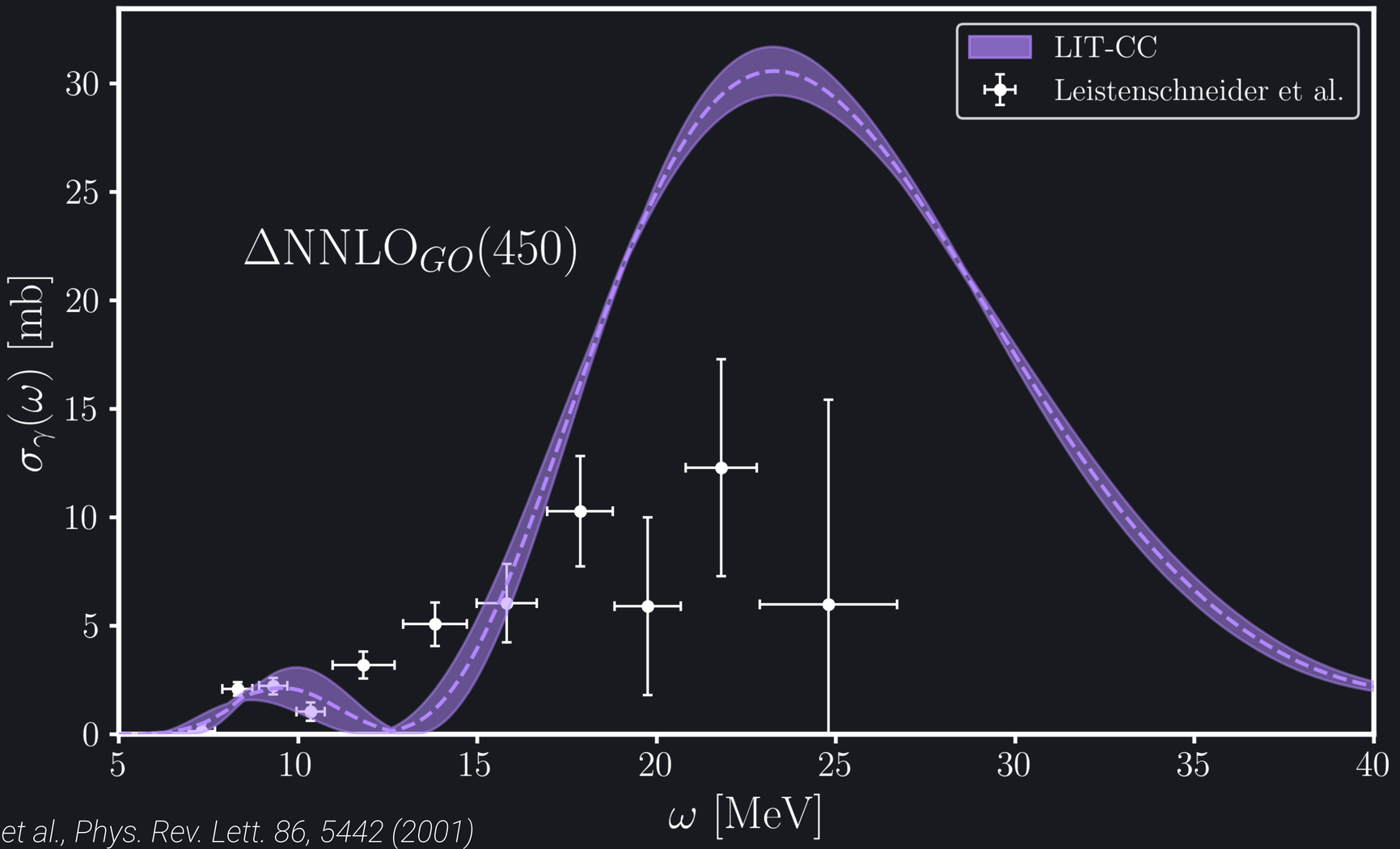
Discretized LIT of ^{22}O



*F. Marino, **M. El Batchy**, and S. Bacca, EPJ Web of Conferences 342, 01019 (2025)*

ACT IV: Results

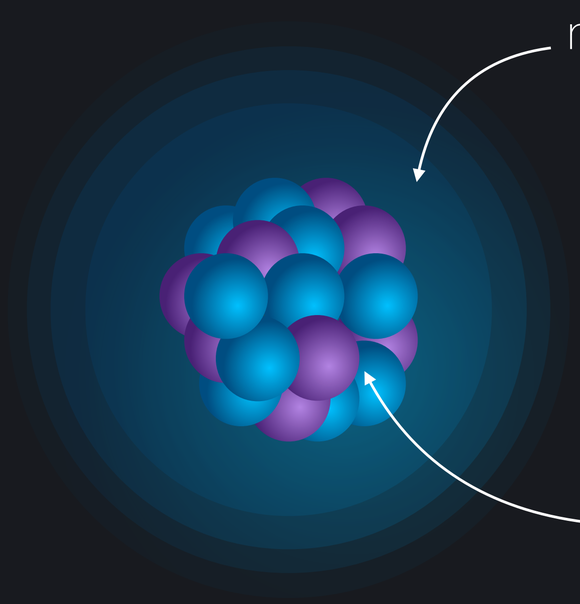
Reconstructed ^{22}O cross section



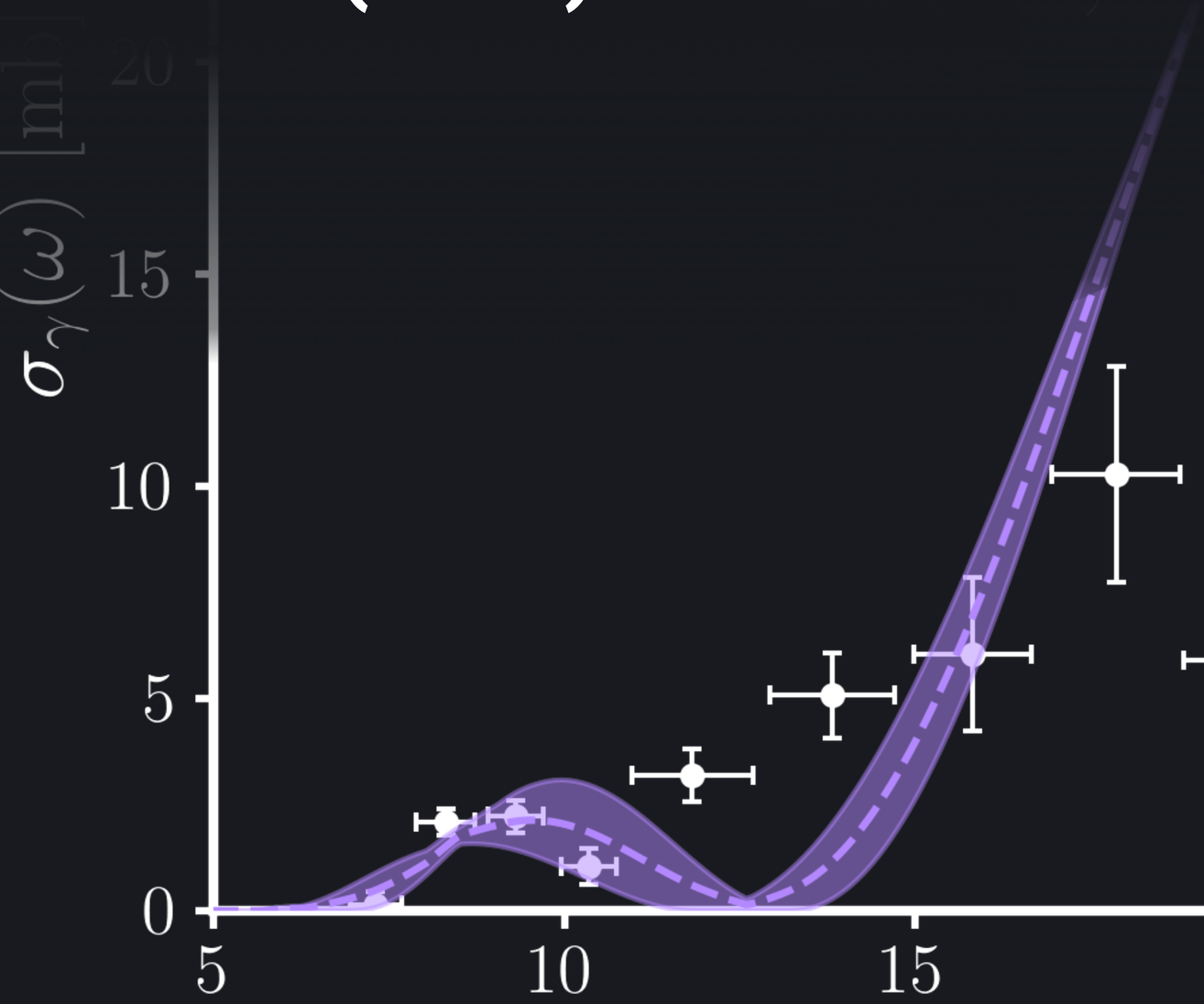
A. Leistenschneider et al., Phys. Rev. Lett. 86, 5442 (2001)

ACT IV: Results

The Pygmy Dipole Resonance (PDR)



neutron skin oscillation against the core



A. Bracco, et al., Prog.Part.Nucl.Phys. 106 (2019) 360-433
F. Bonaiti, et al, arXiv:2510.19940.

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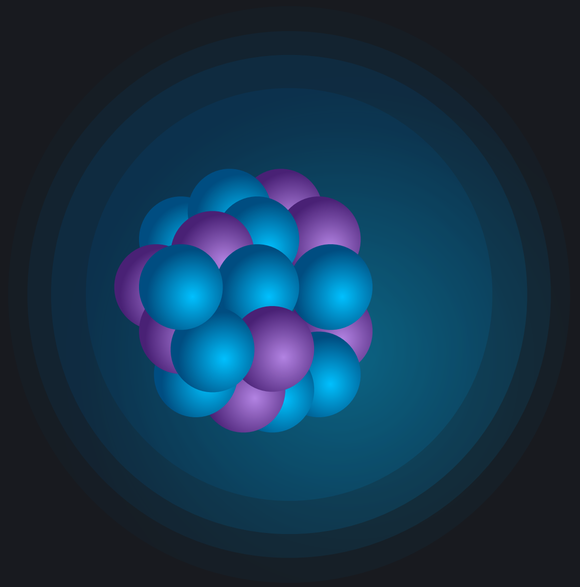

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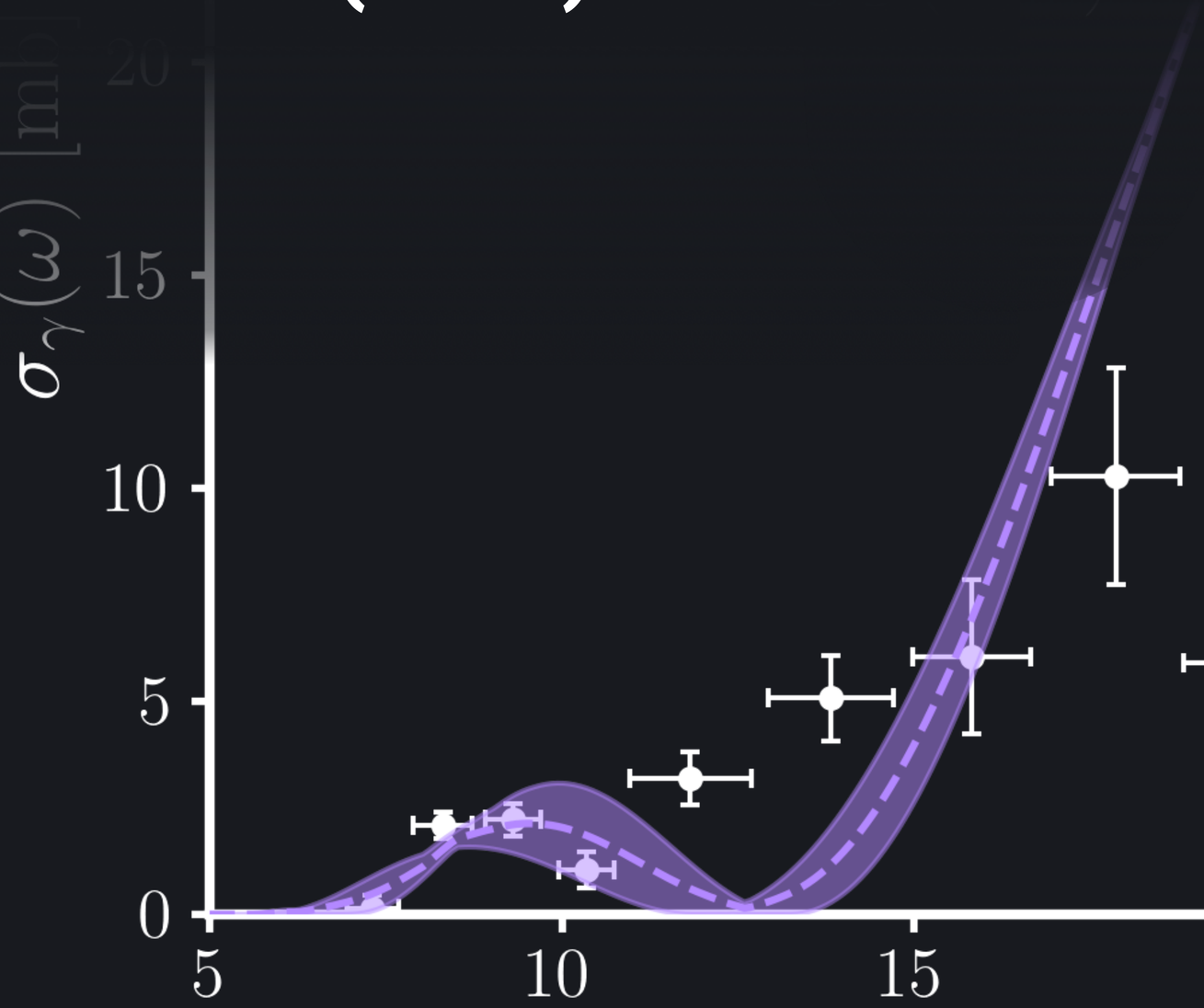

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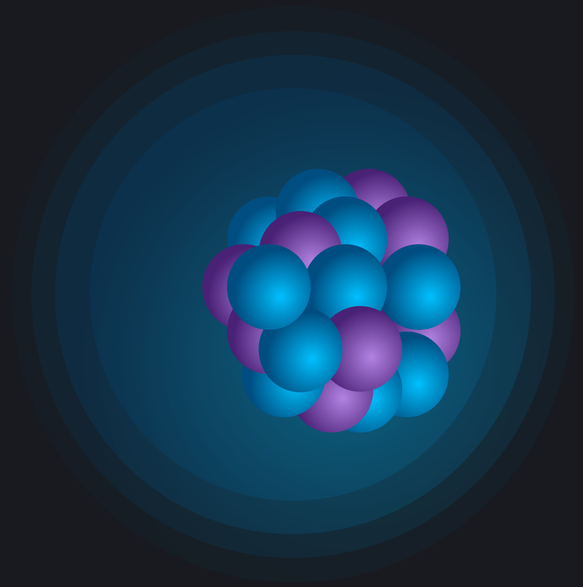

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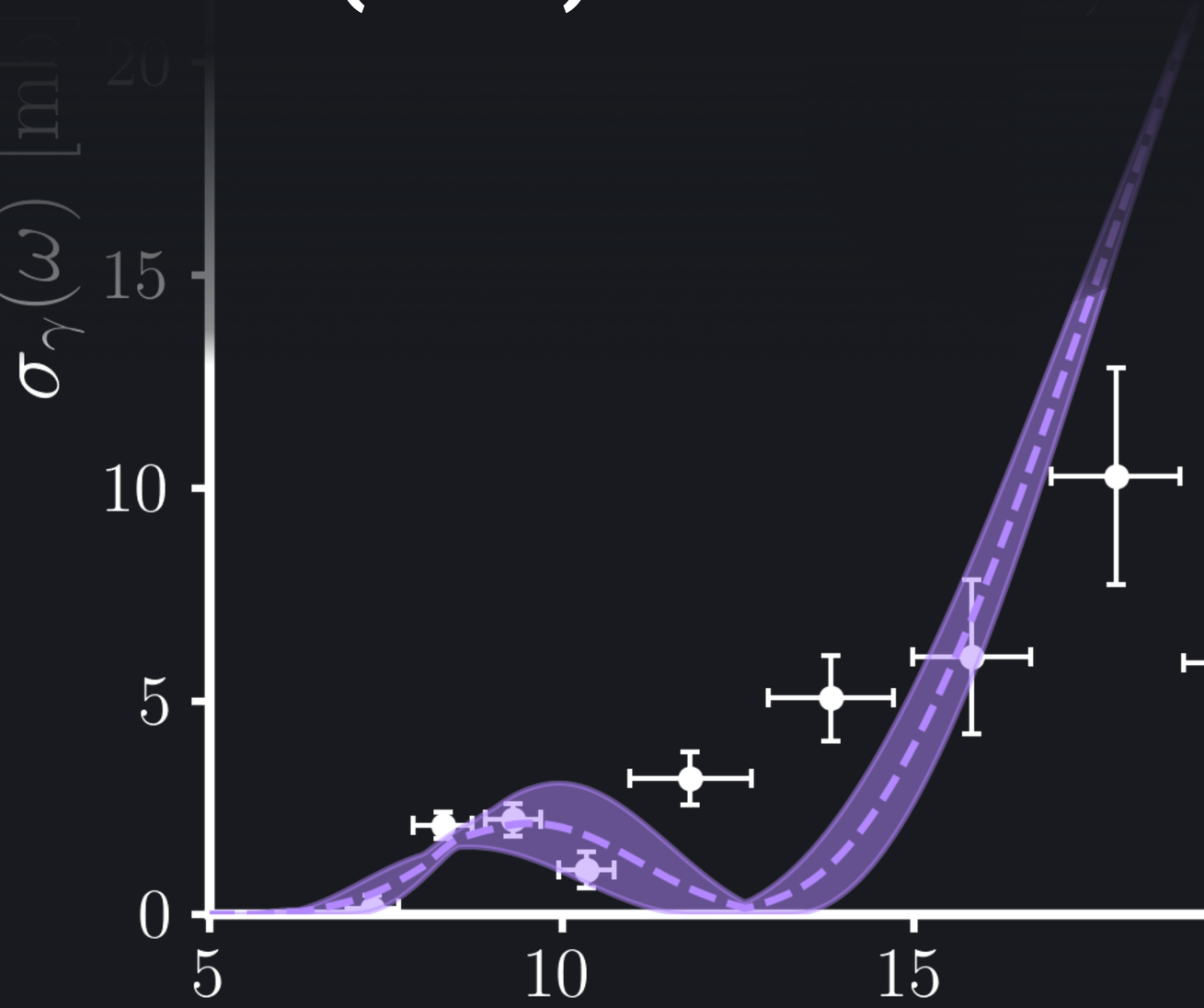

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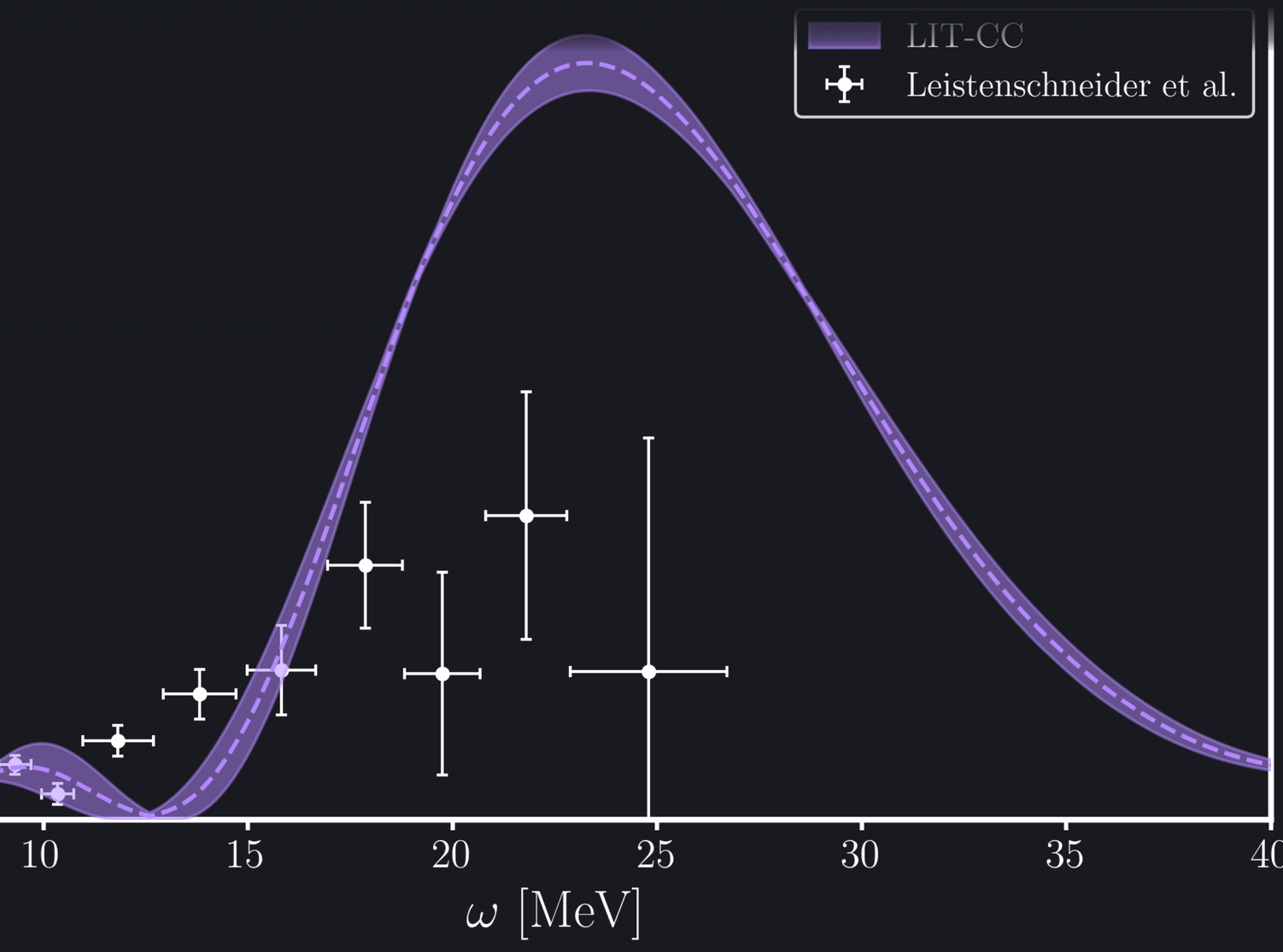
ACT IV: Results

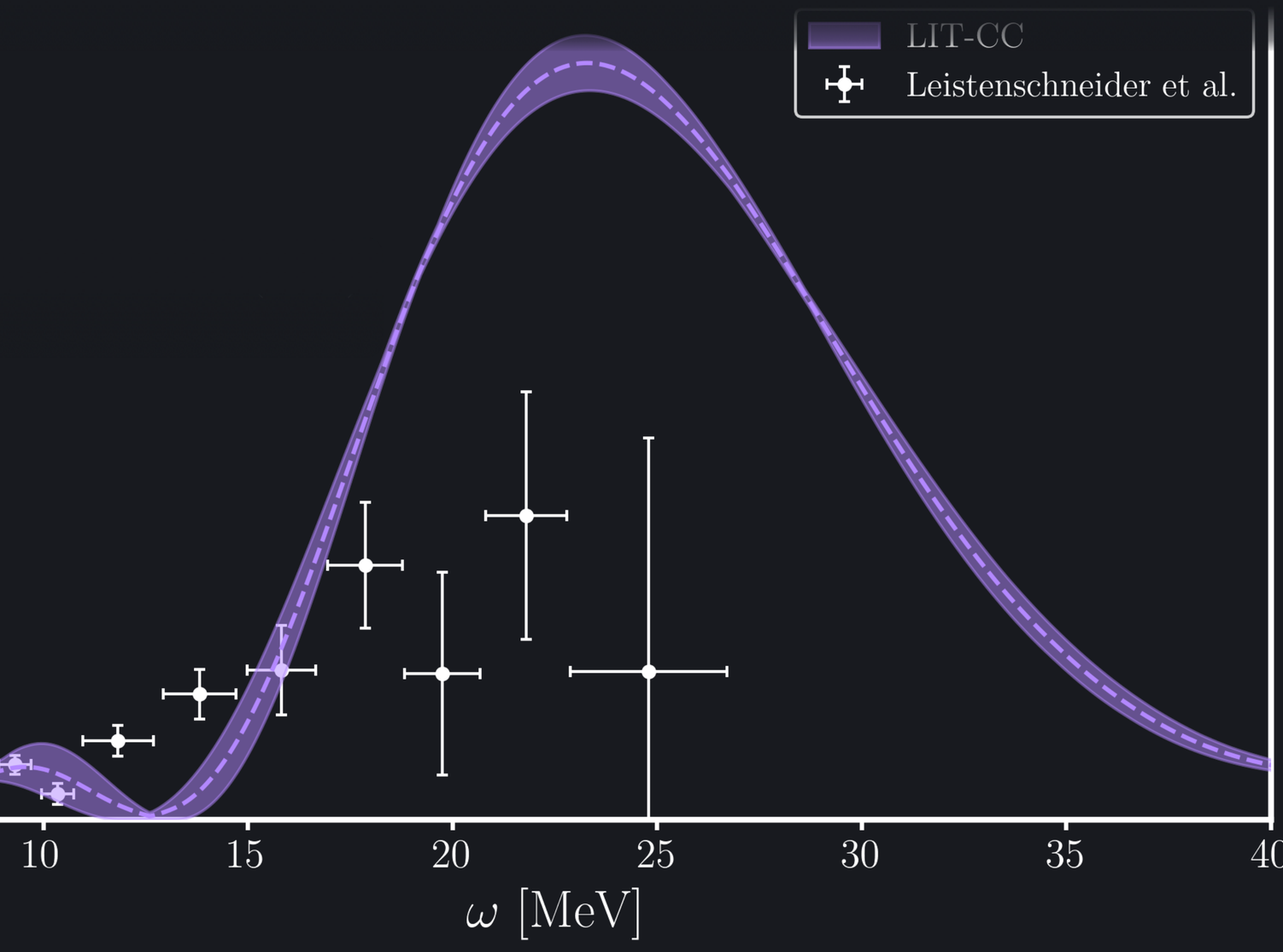
The Giant Dipole Resonances (GDR)



collective oscillation of protons against neutrons

ACT IV: Results

The Giant Dipole Resonances (GDR)



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ACT IV: Results

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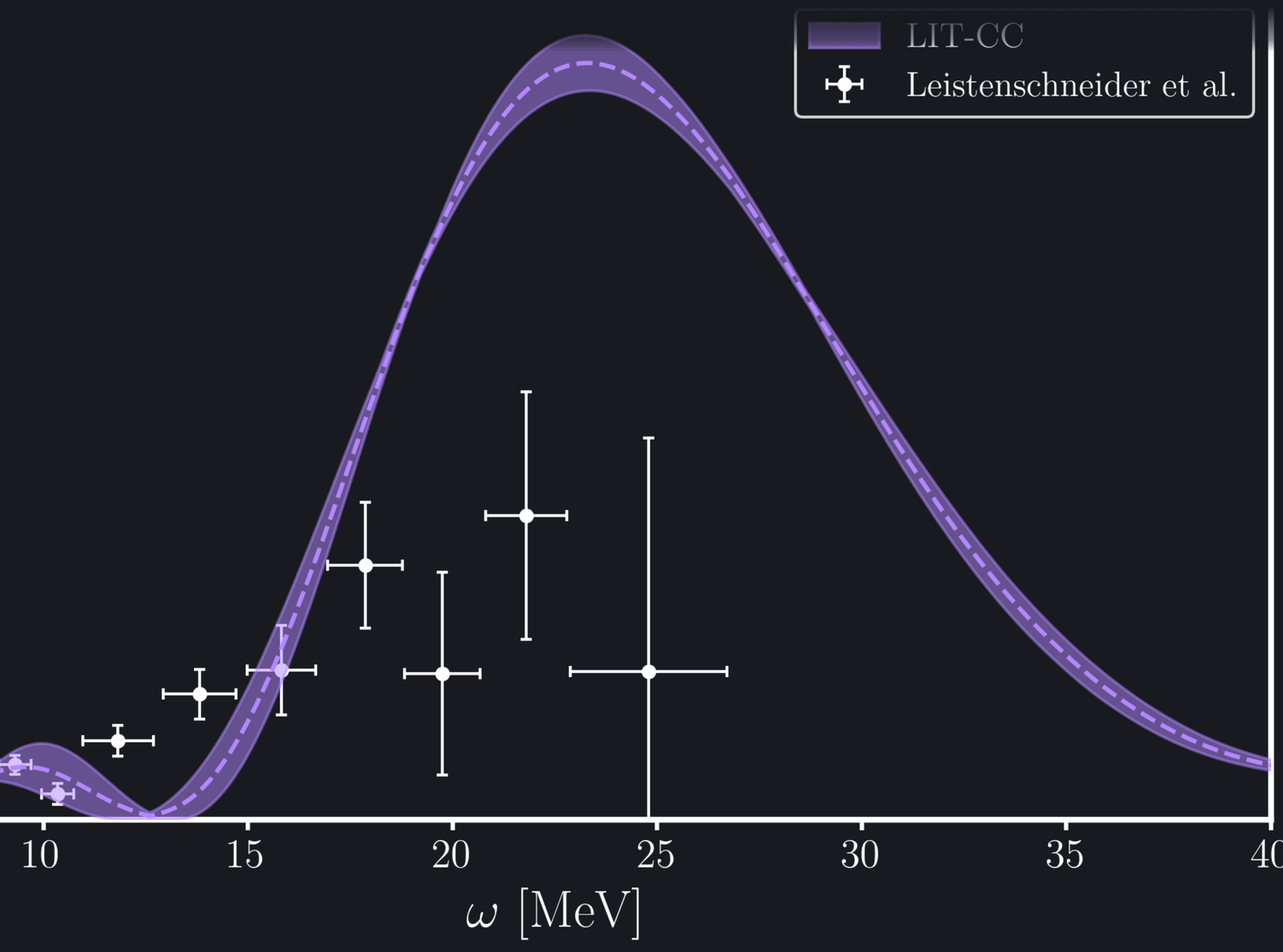
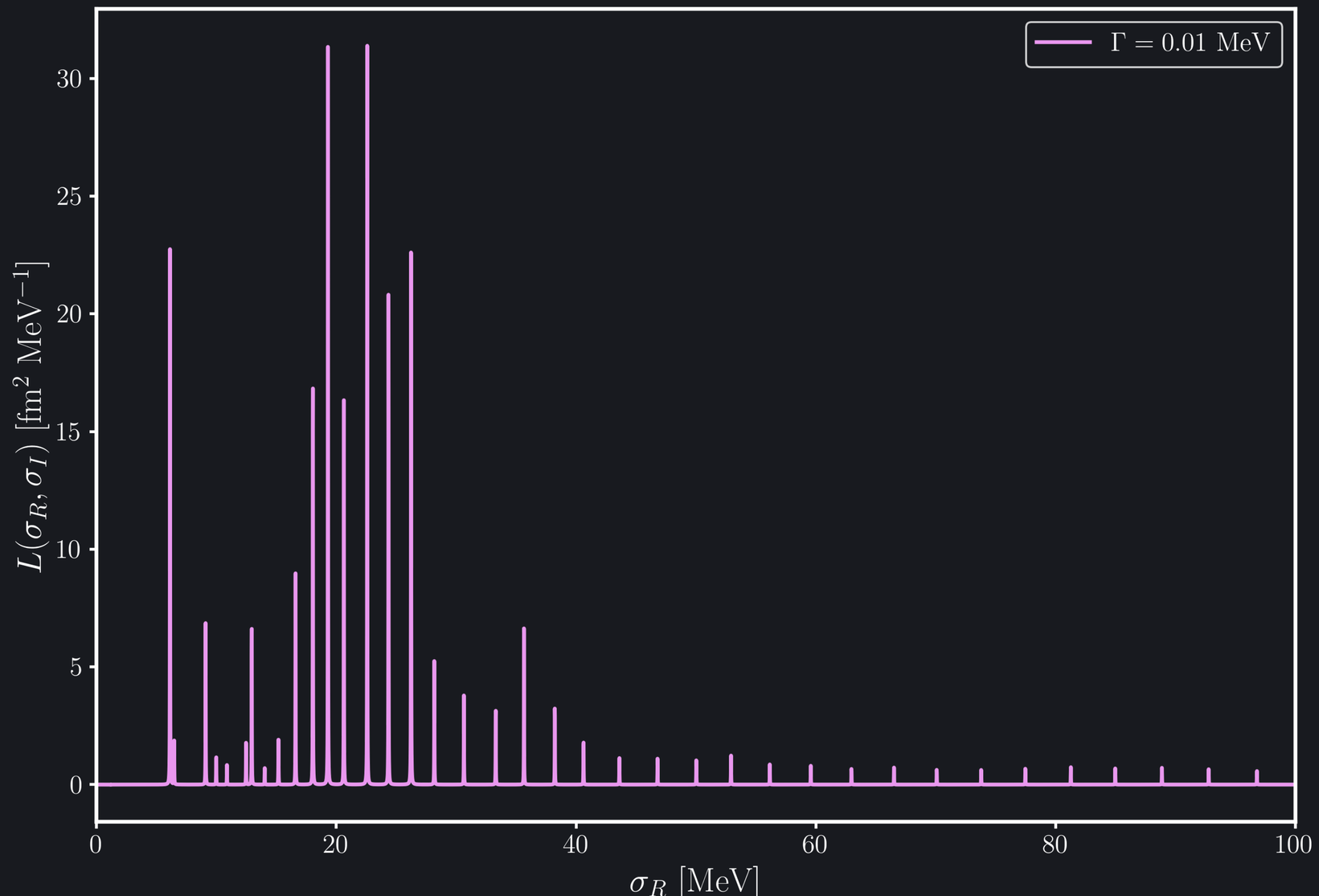


collective oscillation of protons against neutrons

ACT V: First prediction

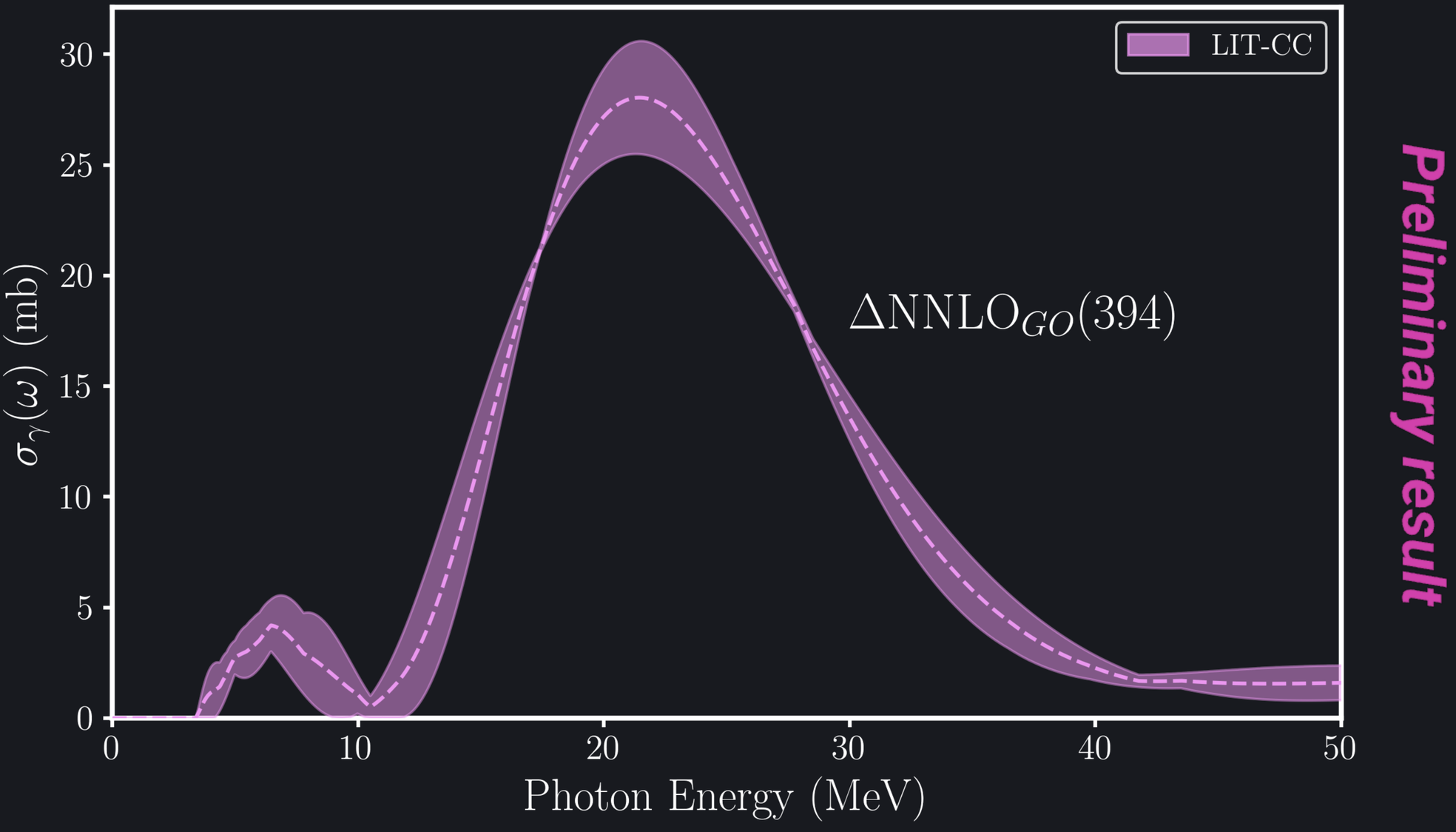
Discretized LIT of ^{24}O



Preliminary result

ACT V: First prediction

Reconstructed ^{24}O cross section



ACT VI: The future

Future directions

He-6
Extending the analysis to halo nucleus > 2PA/2PR CC approach

Isotopic Chain Expansion
To explore trends near the dripline

Methodology Refinement
Better explore the capabilities and limitations across various nuclei

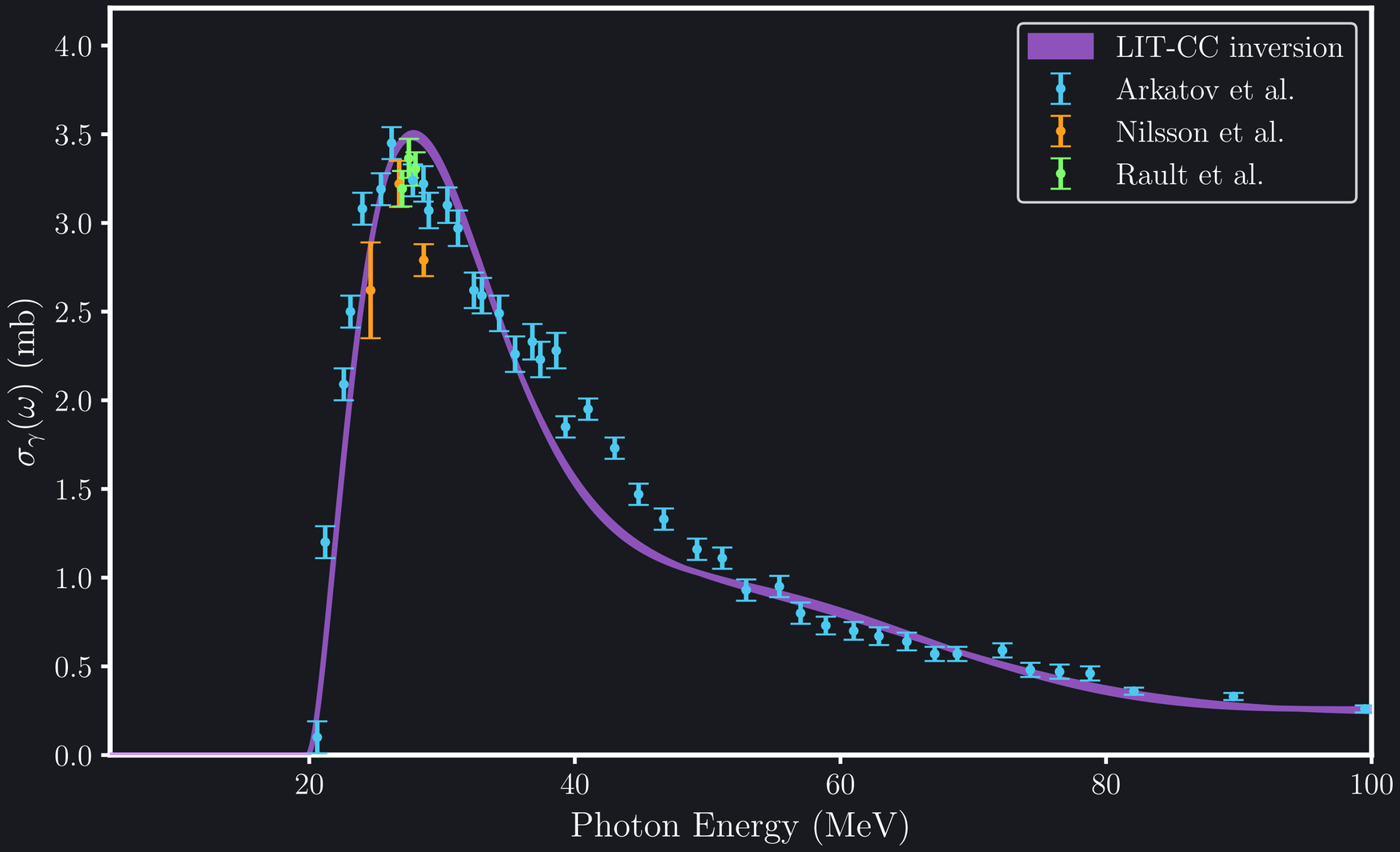
ENCORE

THANK YOU!

Questions?

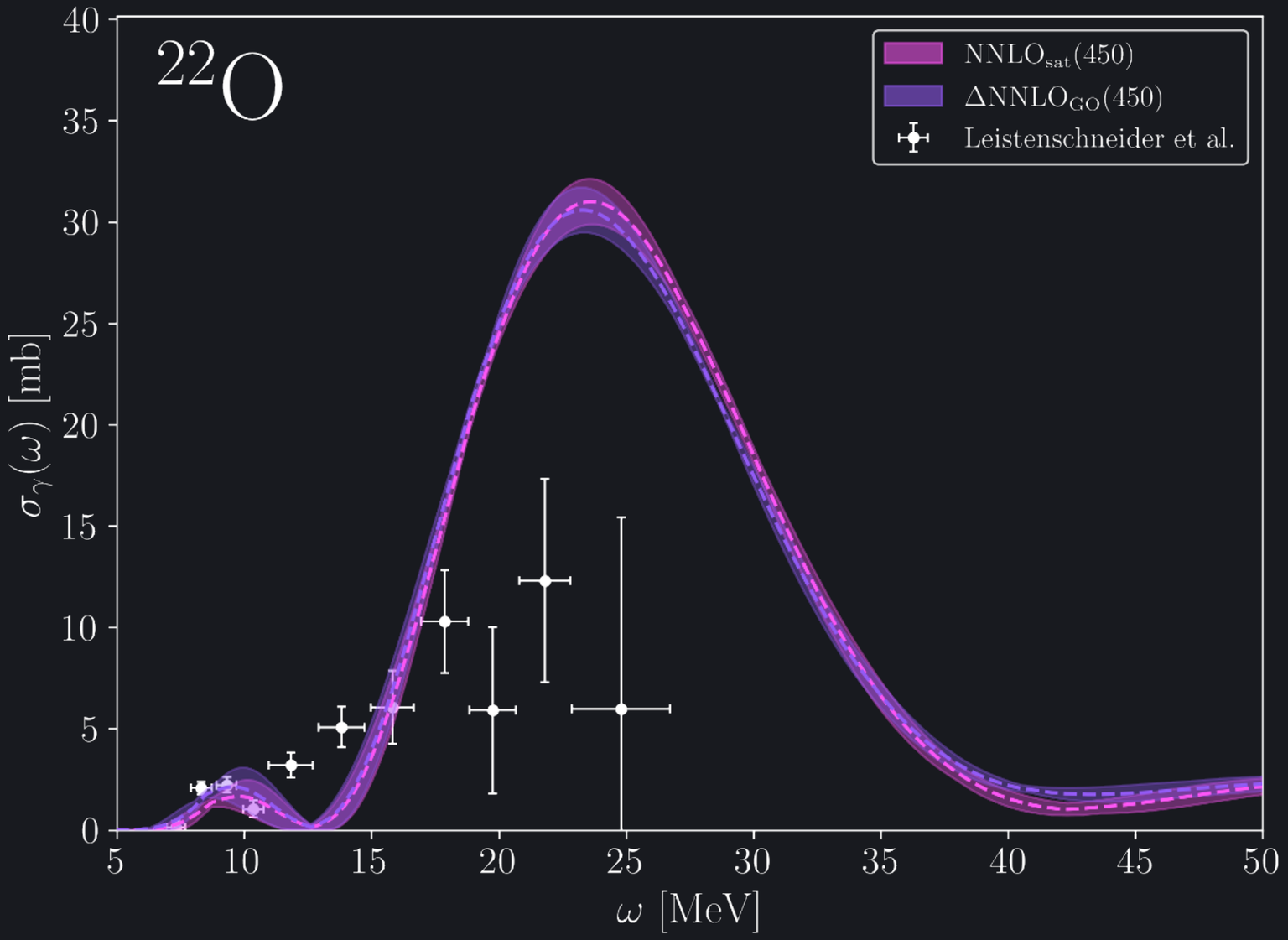
OUTRO: Validation

Test on the ^{4}He



OUTRO: Validation

^{22}O cross section: interaction dependence



The PDR is robust against interaction choice

↓

physical feature

OUTRO: Validation

Sum rules for Oxygen-chains

^{22}O	m_0 [fm^2] Lanczos	m_0 [fm^2] inversion	Δ%	α_D [fm^3] Lanczos	α_D [fm^3] inversion	Δ%
$NNLO_{sat}(450)$	7.1111	7.0533 (18)	0.81%	0.8587	0.8475 (23)	1.31%
$\Delta NNLO_{GO}(450)$	7.2063	7.1542 (112)	0.72%	0.8900	0.8773 (20)	1.42%

^{24}O	m_0 [fm^2] Lanczos	m_0 [fm^2] inversion	Δ%	α_D [fm^3] Lanczos	α_D [fm^3] inversion	Δ%
$NNLO_{sat}(394)$	8.3143	8.3012 (95)	0.16%	1.3753	1.3596 (112)	1.14%