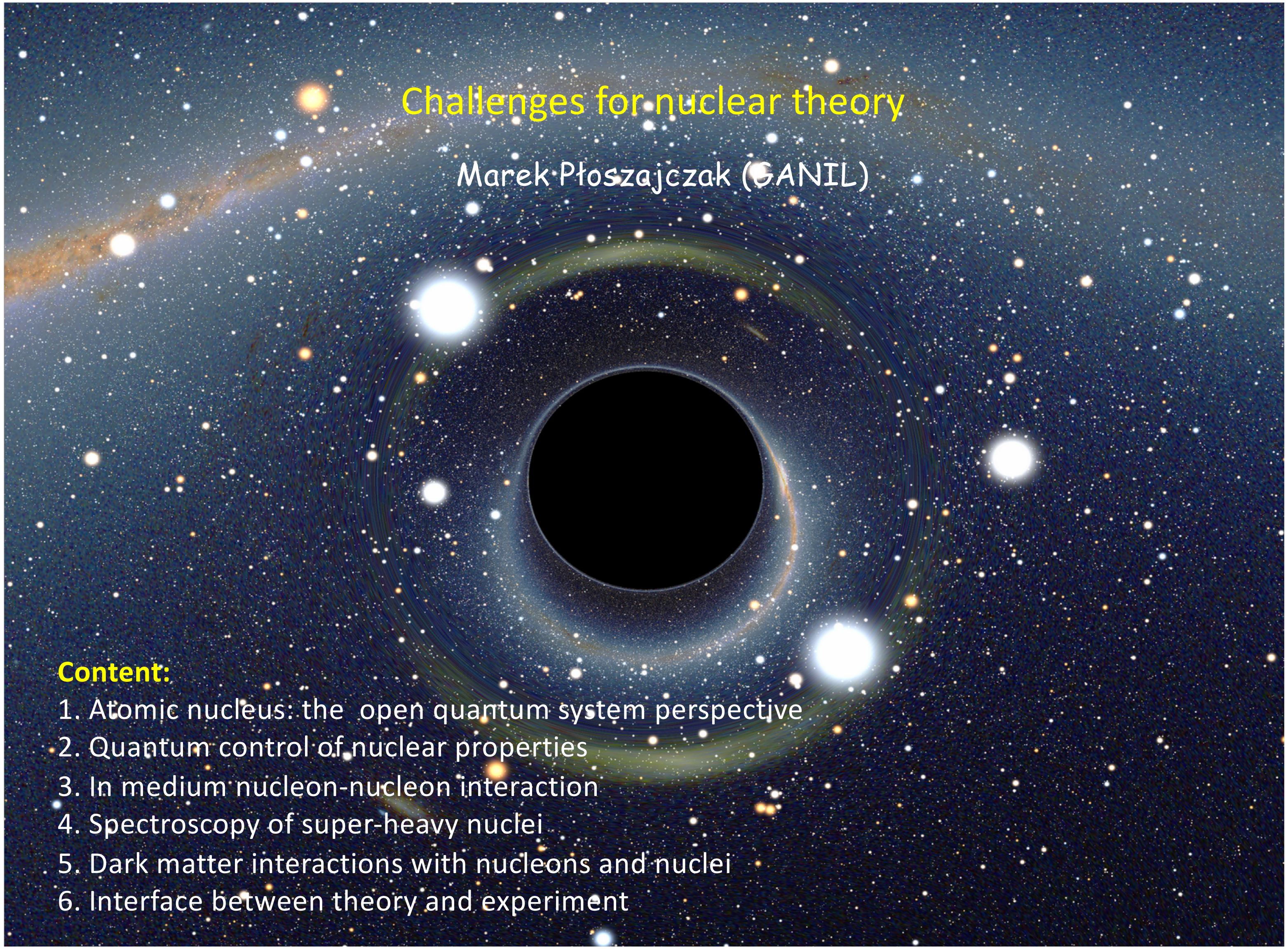
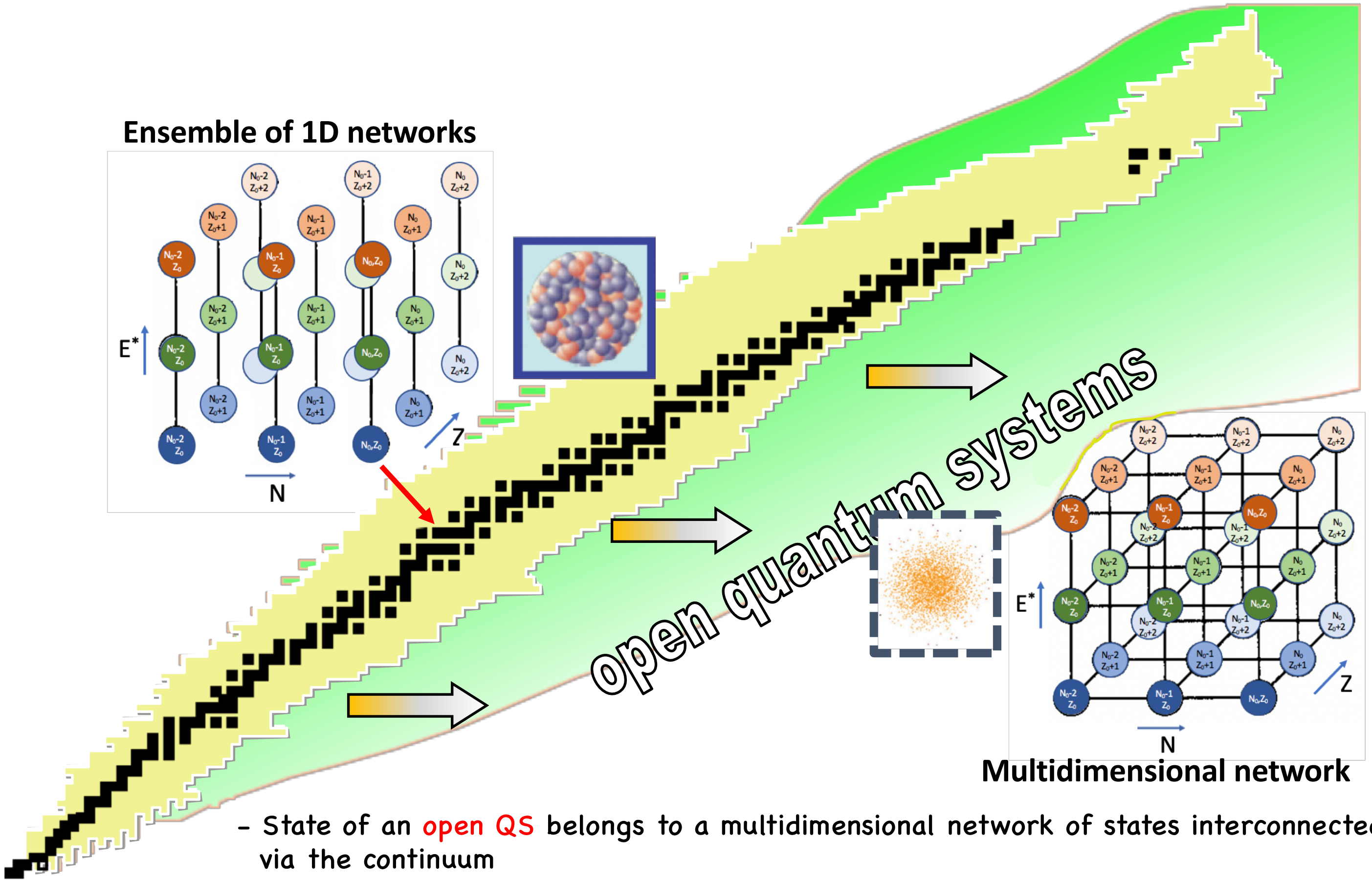


Challenges for nuclear theory
Marek Płoszajczak (GANIL)
Content:
1. Atomic nucleus: the open quantum system perspective
2. Quantum control of nuclear properties
3. In medium nucleon-nucleon interaction
4. Spectroscopy of super-heavy nuclei
5. Dark matter interactions with nucleons and nuclei
6. Interface between theory and experiment

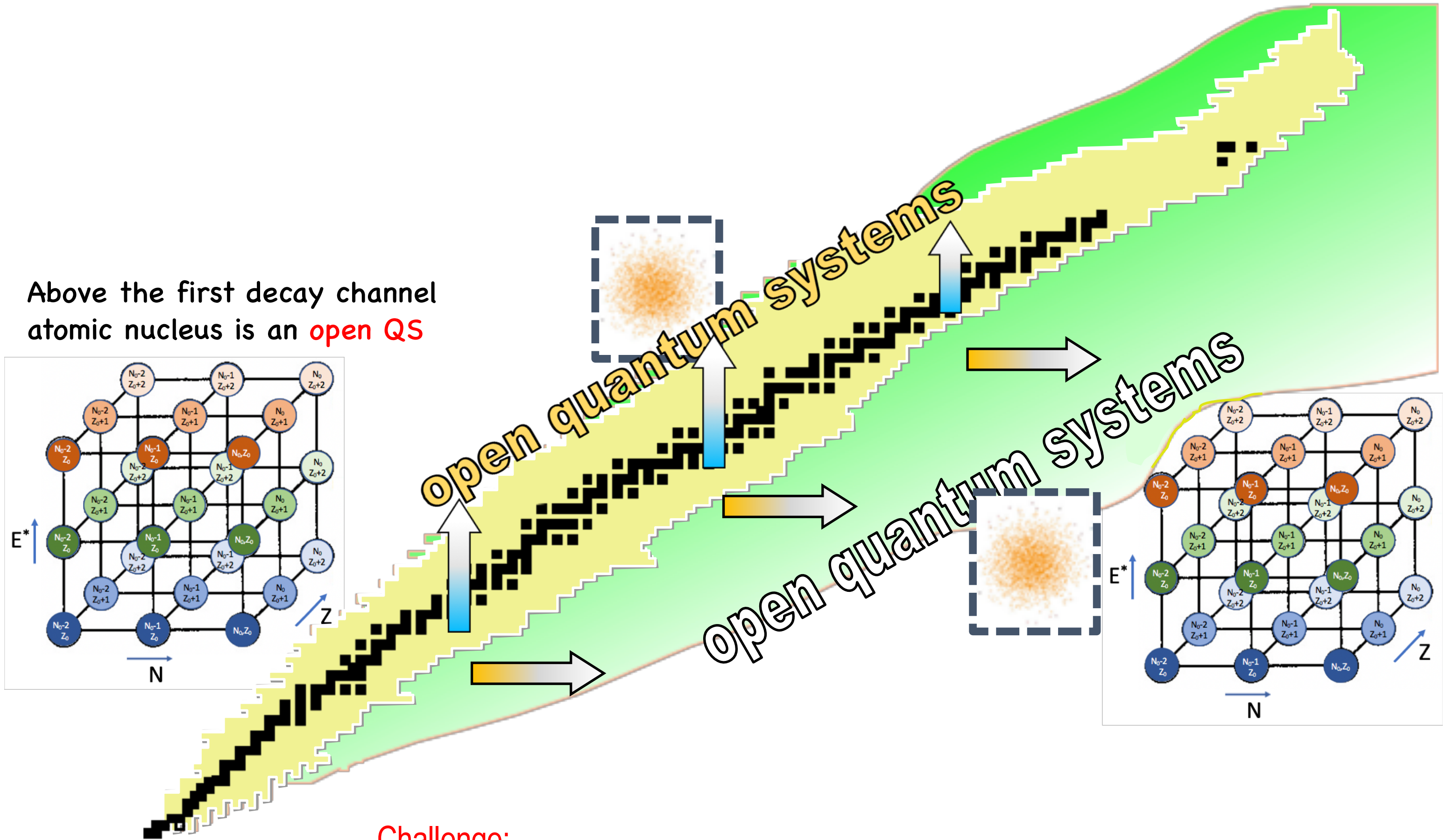
Atomic nucleus: the open quantum system perspective



- State of an open QS belongs to a multidimensional network of states interconnected via the continuum

- New phenomena: coalescence of eigenfunctions/eigenvalues, segregation of time scales, near-threshold collectivity and clustering, multichannel effects in reaction cross-section and shell occupancies, etc. ...

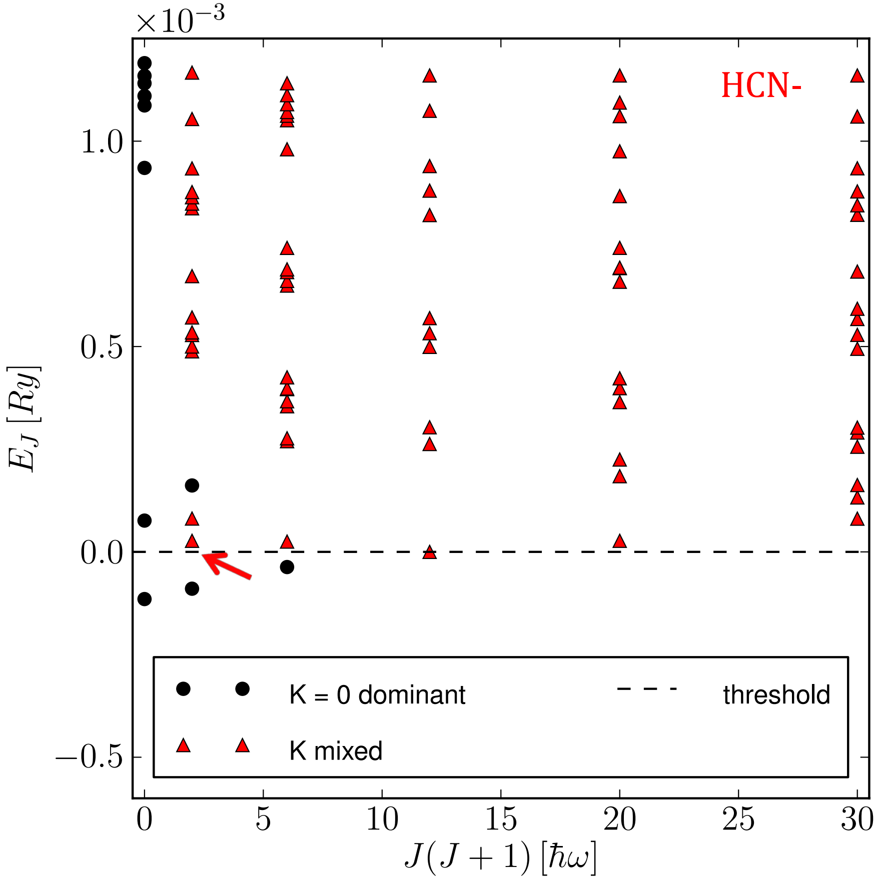
Above the first decay channel
atomic nucleus is an open QS



Challenge:

Properties of clusters of correlated states in the multidimensional network in different domains of E*, N, Z?

Bands of resonant states in the dipolar anion



Resonances in rotational bands of dipolar anions are strongly K mixed

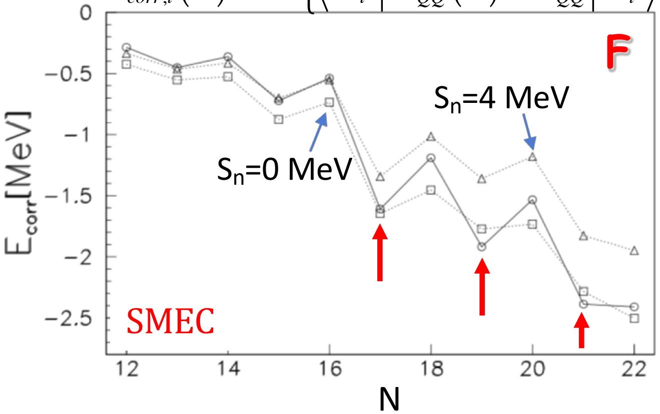
Challenge:

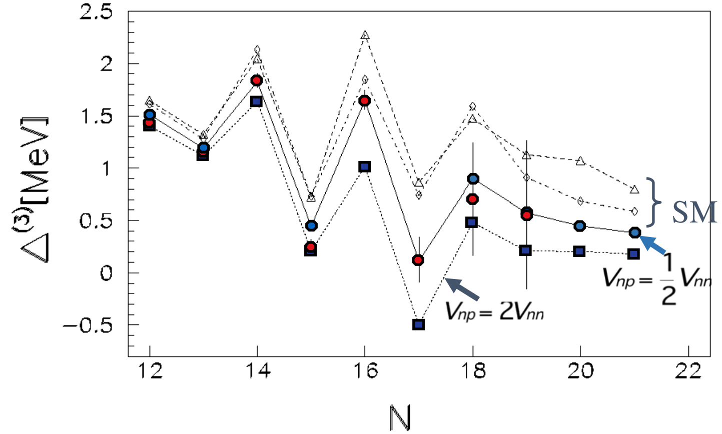
Are the γ-selection rules for in- and out- band **nuclear** transitions in the resonance bands unchanged?

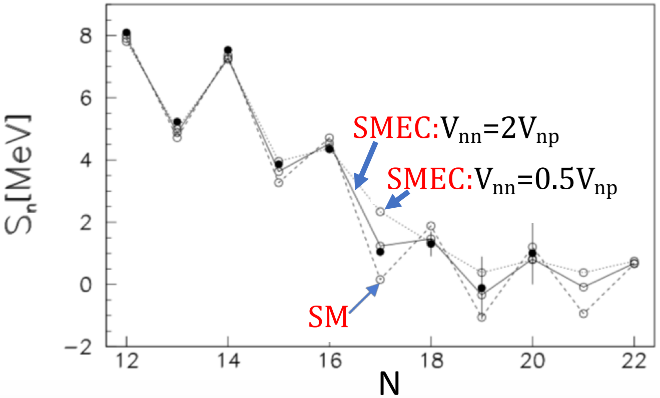
What is the nature of near-threshold γ decays?

Continuum coupling correction to binding

$$E_{corr;i}(E) = \mathrm{Re}\left\{\left\langle \Psi_i^A \middle| \mathcal{H}_{QQ}^{eff}(E) - H_{QQ} \middle| \Psi_i^A \right\rangle\right\}$$







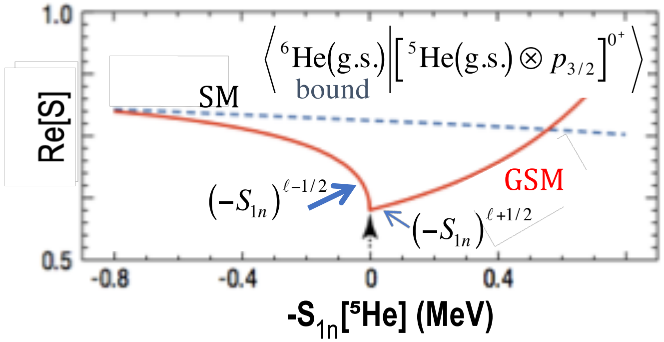
- Anti-odd-even staggering of continuum coupling energy correction E_{corr}
- Blocking mechanism gradually disappears → gapless superconductivity?
- Reduction of the continuum coupling strength V_{np} if $S_n \gg S_p$ ($S_n \ll S_p$)
- Continuum coupling induces effective A-particle correlations

Yan-an Luo et al.. (2009)

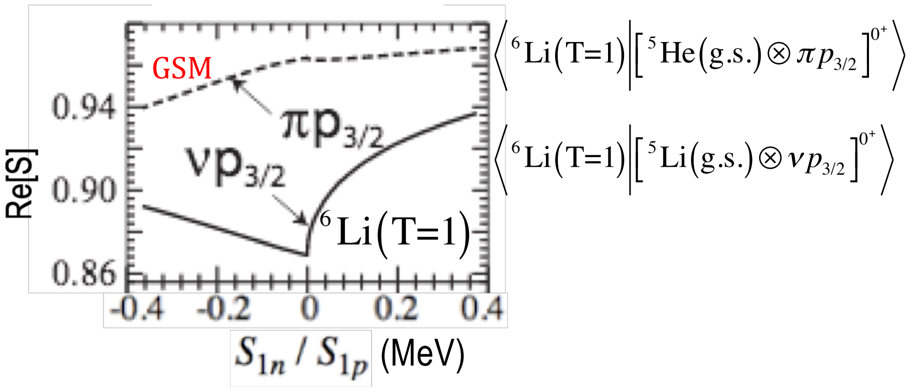
Challenge:

What is the nature of pairing correlations in open QS?

Occupation of s.p. shells in near-threshold states



- The interference phenomenon between resonant states and non-resonant continuum in the vicinity of the particle emission threshold
- Analogy with the Wigner threshold phenomenon for reaction cross-sections



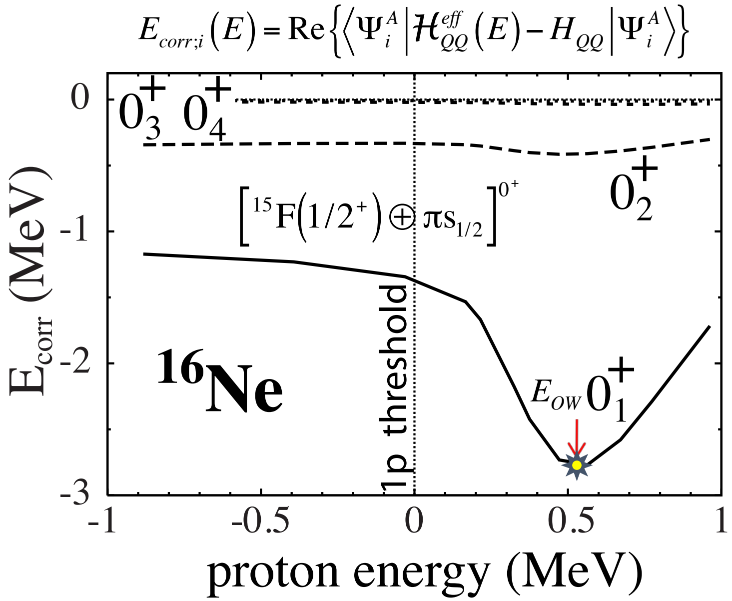
→ Near-threshold configuration mixing acts differently at the proton and neutron drip lines

N. Michel et al. (2010)

Challenge:

Violation of the mirror symmetry by the coupling to the continuum

Mechanism of the near-threshold collectivization



Okolowicz et al., Prog. Theor. Phys. Suppl. 196 (2012) 230
Fortschr. Phys. 61 (2013) 66

- Interaction through the continuum leads to the formation of the collective eigenstate ('aligned state') which couples to the decay channel and carries many of its characteristics
- Point of the strongest collectivity (centroid of the 'opportunity energy window') is determined by an interplay between the competing forces of repulsion (Coulomb and centrifugal int.) and attraction (continuum coupling)
- Emergence of new energy scales related to the configuration mixing via decay channel(s)
- This generic mechanism explains why so many states both on and off the nucleosynthesis path, exist 'fortuitously' close to open channels

Challenge:

What is the nature of multi-nucleon correlations and clustering in the vicinity of particle emission thresholds?

Quantum control of nuclear properties

- Nuclei, atoms:
  - well defined state
  - limited tunability

⟷

- Artificial quantum systems: (quantum dots, atomic clusters, …)
  - no "identical" systems
  - wide tunability

- Excitation of highly stripped nuclei in channeling along the crystal axis:

  Example: Inverse internal conversion of 73 eV isomeric state ($T_{1/2}$=26 min) of ^{235}U in a laser generated plasma environment — Goldanski, Namiot (1976); Cue, Poizat, Remilleux (1989); Zhu-Shu Yuan, Kimball (1993)

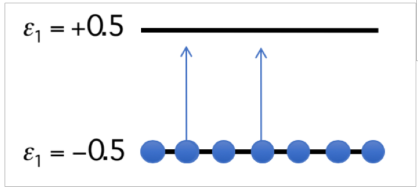
- Application of laser radiation to low-energy nuclear physics: — Matinyan (2018)
  - * Laser-induced nuclear anti-Stokes transitions, laser-induced and laser-assisted internal conversion
  - * Electron Bridge mechanism: — Krutov, Fomenko (1968); Crasemann (1973)

    Example: Nuclear isomer excitation in ^{229}Th by intense laser fields — Andreev et al (2018)

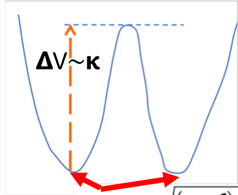
↓

Nucleus becomes a distinguished part of a larger system, i.e. nucleus is the open quantum system which is found in interaction with an external quantum system, the environment

Quantum tunneling in the driven many-body system



$$|\psi_{SD}(z)\rangle \equiv |z\rangle = \exp(z^* G_{21})|0\rangle \Rightarrow \lim_{N\to\infty} \Psi_{g.s}^{(SU(2))} \equiv \Psi_{HF}^{(SU(2))}$$



$$\pm q_{eq} = \pm\sqrt{(\kappa-1)/\kappa}$$

$$\hat{H} = \sum_{k=1}^{2} \varepsilon_k \left(\sum_{n=1}^{N} a^+_{nk} a_{nk}\right) - \frac{1}{2}\sum_{k,l=1}^{2} V_{kl} \left(\sum_{n=1}^{N} a^+_{nk} a_{nl}\right)^2$$

$$V_{kl} = V(1-\delta_{kl}) \qquad V \geq 0$$

$$\Longleftrightarrow$$

$$H_{cl} = \frac{\langle \psi_{SD}|\hat{H}|\psi_{SD}\rangle}{N\varepsilon} = -\frac{1}{2} + \frac{1}{2}(1-\kappa)q^2 + \frac{1}{2}(1+\kappa)p^2 + \frac{1}{4}\kappa(q^4 - p^4)$$

$$\kappa = \frac{V(N-1)}{\varepsilon}$$

$$G_{kl} = \sum_{n=1}^{N} a^+_{nk} a_{nl} \Rightarrow \begin{cases} K_0 = \frac{1}{2}(G_{22} - G_{11}) \\ K_+ = G_{21} \\ K_- = G_{12} \end{cases}$$

$$\hat{H} = \varepsilon K_0 - \frac{1}{2}V(K_+^2 + K_-^2) \qquad \varepsilon = \varepsilon_2 - \varepsilon_1$$

$$V(q) = H_{cl}(q, p=0) = \frac{1}{4}\kappa q^4 + \frac{1}{2}(1-\kappa)q^2 - \frac{1}{2}$$

Time-dependent driving

$$\hat{H}(t) = H\left(t + \frac{2\pi n}{\beta}\right) \qquad n = 0, \pm 1, \pm 2, \ldots$$

$$H_{cl}(t) = H_{cl}\left(t + \frac{2\pi n}{\beta}\right)$$

$$V(t) = V_0 + \frac{\alpha\varepsilon}{N-1}\sin^9(\beta t) \Leftrightarrow \kappa(t) = \kappa_0 + \alpha \sin^9(\beta t)$$

$$\Psi(t) = \sum_k c_k \Omega_k(t) = \sum_k c_k \exp(-ie_k t)\Phi_k(t)$$

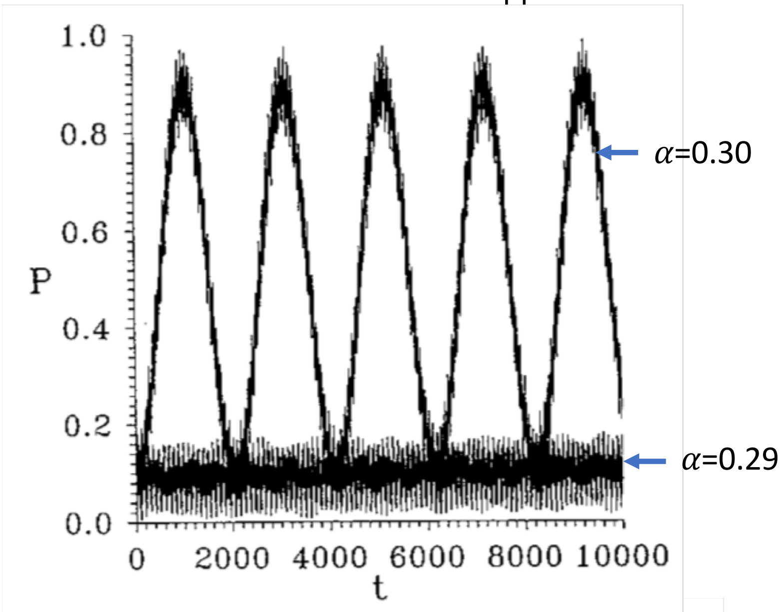
quasi-energies

$$\Phi_k(t) = \Phi_k\left(t + \frac{2\pi n}{\beta}\right) \qquad n = 0, \pm 1, \pm 2, \ldots$$

quasi-energy eigenstates

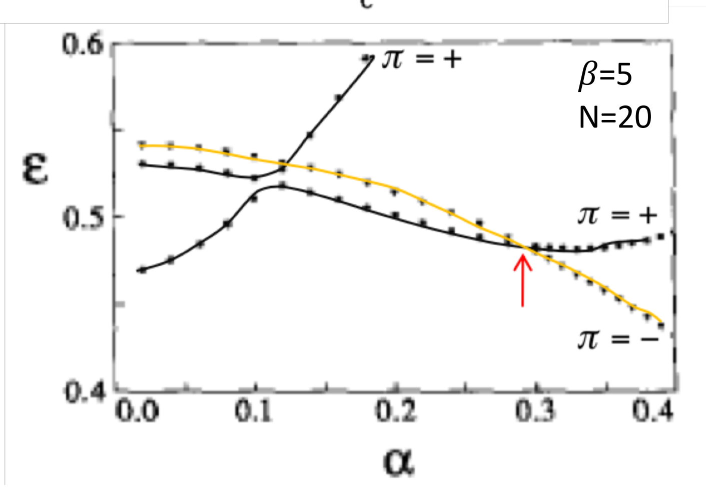
Evolution of the wave packet depends on the energy spectrum of Floquet states which depends on the external environment and can be tuned

Coherent suppression of tunneling



By a suitable choice of the driving amplitude one can extinguish the dominant oscillation frequency

Kaminski, MP, Arvieu (1994)



Challenge:

How to engineer the environment of an atomic nucleus in order to control its lifetime?, i.e. can one design an **artificial** atomic nucleus?

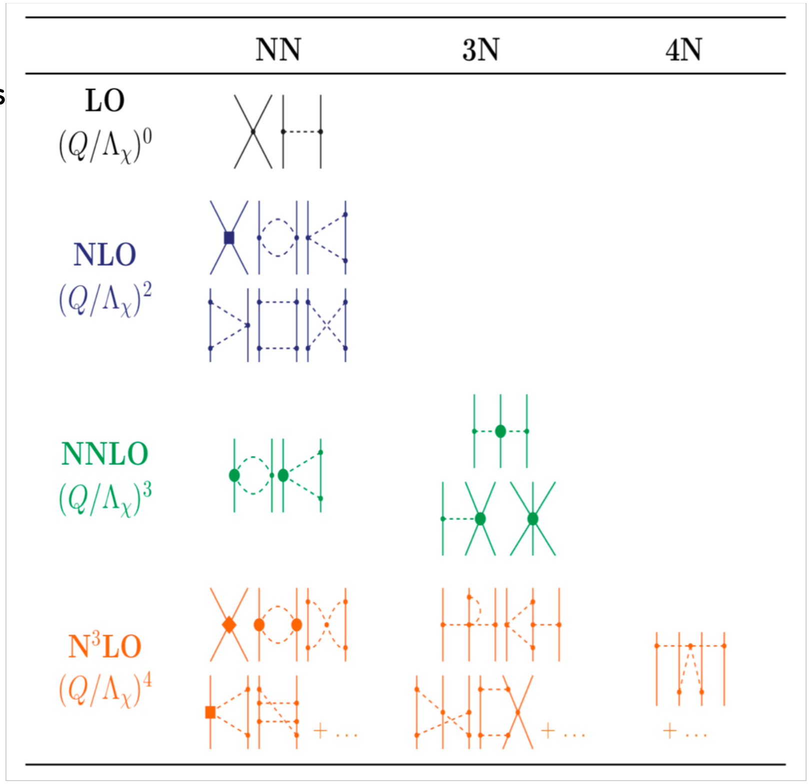
In medium nucleon-nucleon interaction

- First principles for nuclear physics: QCD
  - non-perturbative at low energies
  - lattice QCD in the future; first applications to spectrum, magnetic moments, polarizabilities (A<5) and np→dγ, β-decay of ^{3}H, … for unphysical quark masses: m_π~450 MeV, m_N~1200 MeV

- For now inter-nucleon forces from chiral effective field theory (χEFT)
  - based on the symmetries of QCD; χ-symmetry of QCD ($m_u \approx m_d \approx 0$) broken with pion as a Goldstone boson
  - degrees of freedom: nucleons and pions

but

- χEFT is not regularizable; dependence on cutoffs
- Systematic low-momentum expansion to a given order (Q/Λ_χ) is still debated
  ➡ the hierarchy of many-body interactions and consistency of the χEFT framework is not yet proven



Challenge:

The determination of EFT scheme which allows for a reliable and systematic low-momentum expansion and defines the hierarchy of many-body interactions

Dispersive optical model perspective on in-medium NN interaction

How neutron (proton) interact in nuclear medium? → (N-Z)-dependence of the optical potential

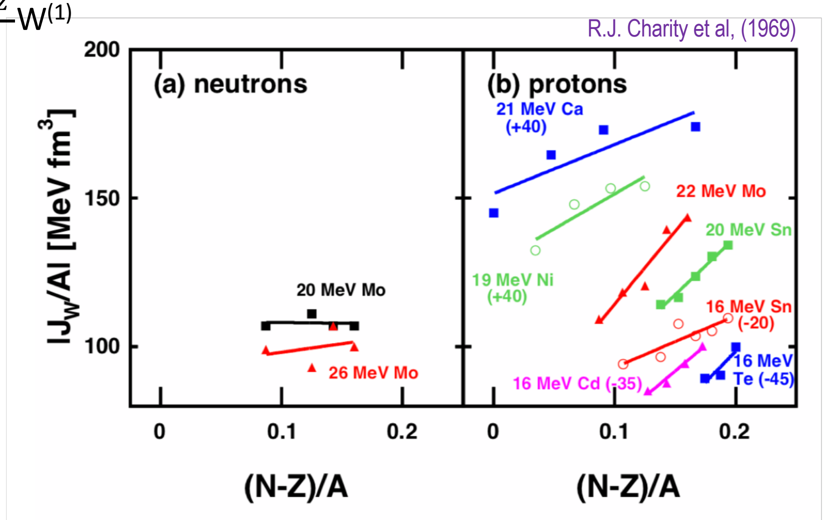
$$W^{(p)} = \frac{\hbar v \rho_N}{2}\left(\frac{N}{A}\langle\sigma_{np}\rangle + \frac{Z}{A}\langle\sigma_{pp}\rangle\right) = \frac{\hbar v \rho_N}{4}[(\langle\sigma_{np}\rangle + \langle\sigma_{pp}\rangle)] + \frac{N-Z}{A}(\langle\sigma_{np}\rangle - \langle\sigma_{pp}\rangle) = W^{(0)} + \frac{N-Z}{A}W^{(1)}$$

G.R. Satchler (1969)

$$W^{(n)} = \frac{\hbar v \rho_N}{2}\left(\frac{N}{A}\langle\sigma_{nn}\rangle + \frac{Z}{A}\langle\sigma_{np}\rangle\right) = \frac{\hbar v \rho_N}{4}[(\langle\sigma_{np}\rangle + \langle\sigma_{nn}\rangle)] + \frac{N-Z}{A}(\langle\sigma_{np}\rangle - \langle\sigma_{nn}\rangle) = W^{(0)} - \frac{N-Z}{A}W^{(1)}$$

Average int. of projectile nucleon with individual target nucleons : $W \simeq W^{(0)} \pm \frac{N-Z}{A}W^{(1)}$

R.J. Charity et al, (1969)



Most global optical potentials do not include the asymmetry dependence of the central potential

	^{40}Ca	^{48}Ca
π nℓj		
$1s_{1/2}$	0.73	0.63
$0d_{3/2}$	0.76	0.69
$0f_{7/2}$	0.73	0.63
ν nℓj		
$1s_{1/2}$	0.76	0.80
$0d_{3/2}$	0.78	0.77
$0f_{7/2}$	0.71	0.80

Protons (neutrons) experience stronger (weaker) correlations in neutron-rich matter

R.J. Charity, W. Dickhoffl,(1969)

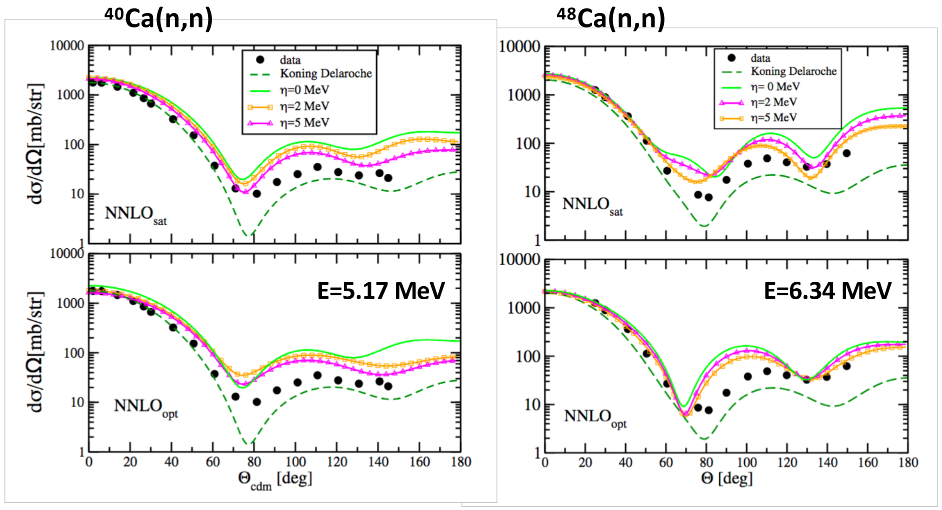
Challenge:

Simultaneous study of neutron/proton elastic cross section, spectral functions and charge distributions in long isotopic chains

Optical model from first principles

- New Hamiltonian approaches for nuclear structure and reactions: NCGSM, NCSMC, CC, IM-SRG, ...
  - → unification of nuclear structure and reactions in low-energy continuum

Optical potential from CCSD approach



J. Rotureau et al. (2018)

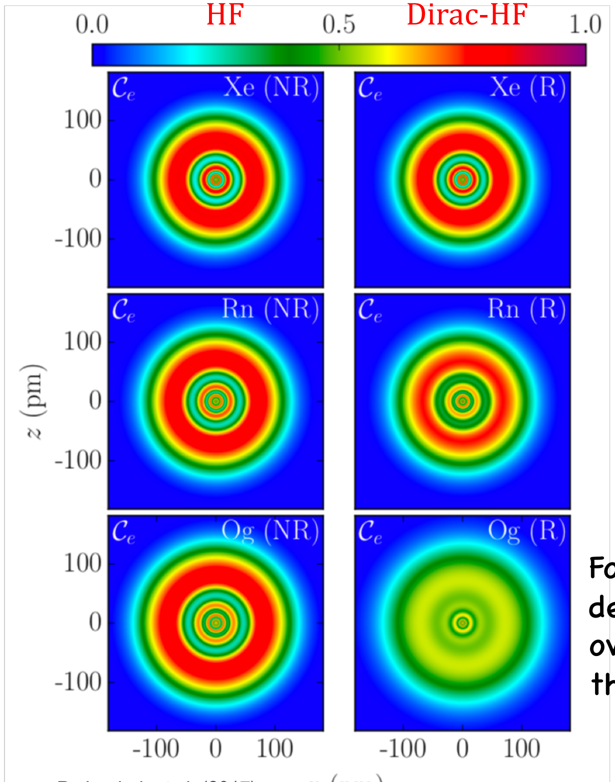
Challenge:

Construction of the microscopic optical potential with the correct absorption properties

Spectroscopy of superheavy nuclei

- Relativistic effects in super-heavy atoms may change the electronic structure
  - transition from the LS-coupling to jj-coupling of the Dirac equation at large Z
  - large spin-orbit splitting smears out the single-particle density

Electronic localization function



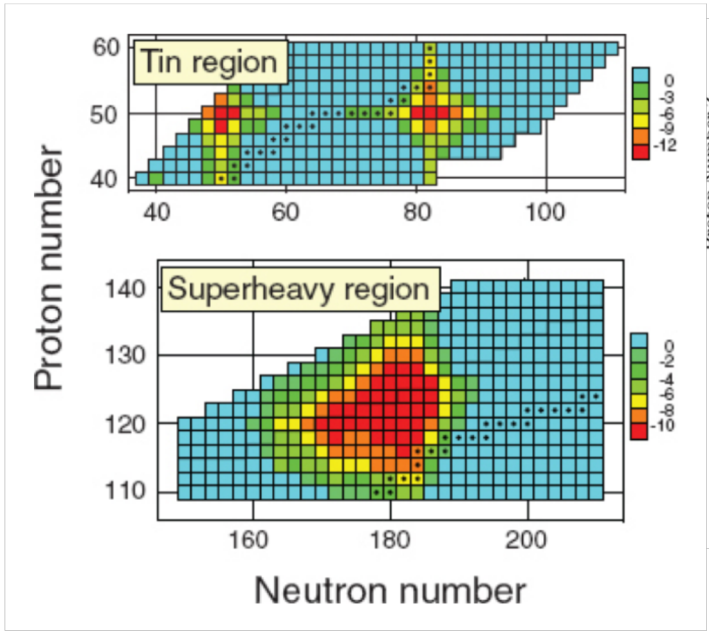
P. Jerabek et al, (2017)

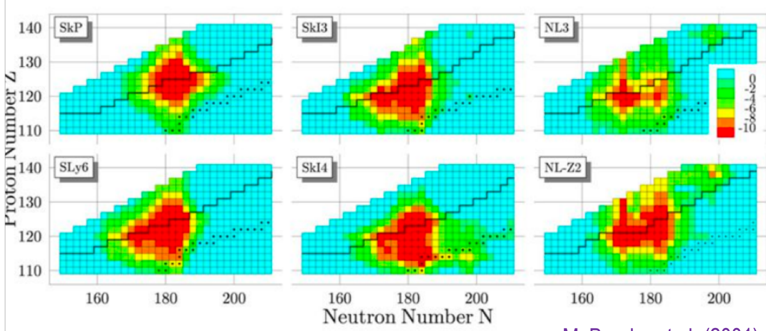
For the element Og the electron density is more uniformly distributed over the entire atom approaching the electron-gas regime

Is it the end of Mendeleev periodicity law as we know it?

- Single-particle level density grows faster than $A^{1/3}$
  - great sensitivity to the interplay between short-range (attractive) nuclear interaction and long-range (repulsive) Coulomb interaction

- Disappearance of spin-orbit gaps (magic numbers)
  - great sensitivity to the details of in-medium NN interaction and continuum coupling
  - gradual transition to the uniform-gas regime for nucleonic localization
    → familiar pattern of shells separated by magic gaps is gone!





M. Bender et al, (2001)

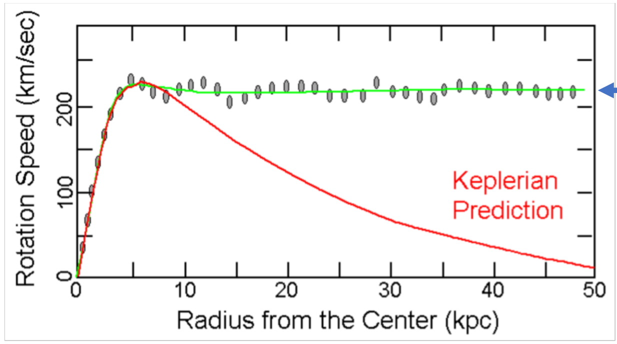
	Z	N
W.S	114	184
HFB	126	184
RMF	120	172

Challenge:

What should be the theoretical approach to analyze and systematize the spectroscopic data in super-heavy mass region?

Dark matter interaction with nucleons and nuclei

- Perhaps the most-likely-to-be resolved new-physics problem
- Closely linked to laboratory-based accelerator and underground experiments
- Existence of dark matter deduced from its dynamical effects in astrophysics:
  - flat velocity rotation curves in galaxies



$V \propto$ const
$m(r) \propto r$
$\rho(r) \propto 1/r^2$

W. Haxton (2014)

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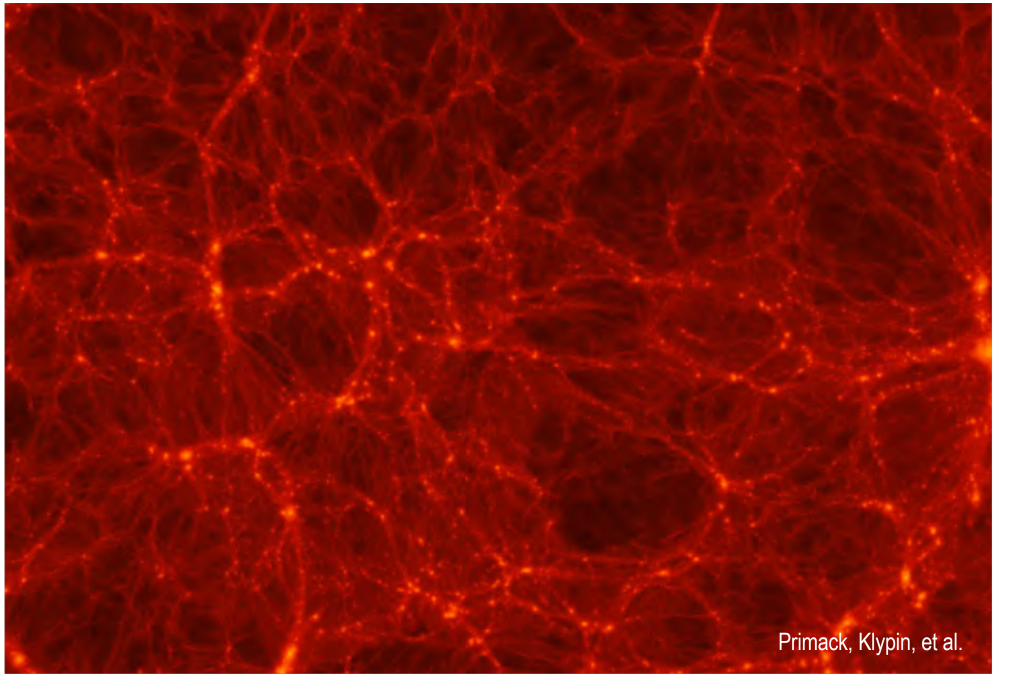
  - required to explain the observed pattern of cluster-cluster correlations



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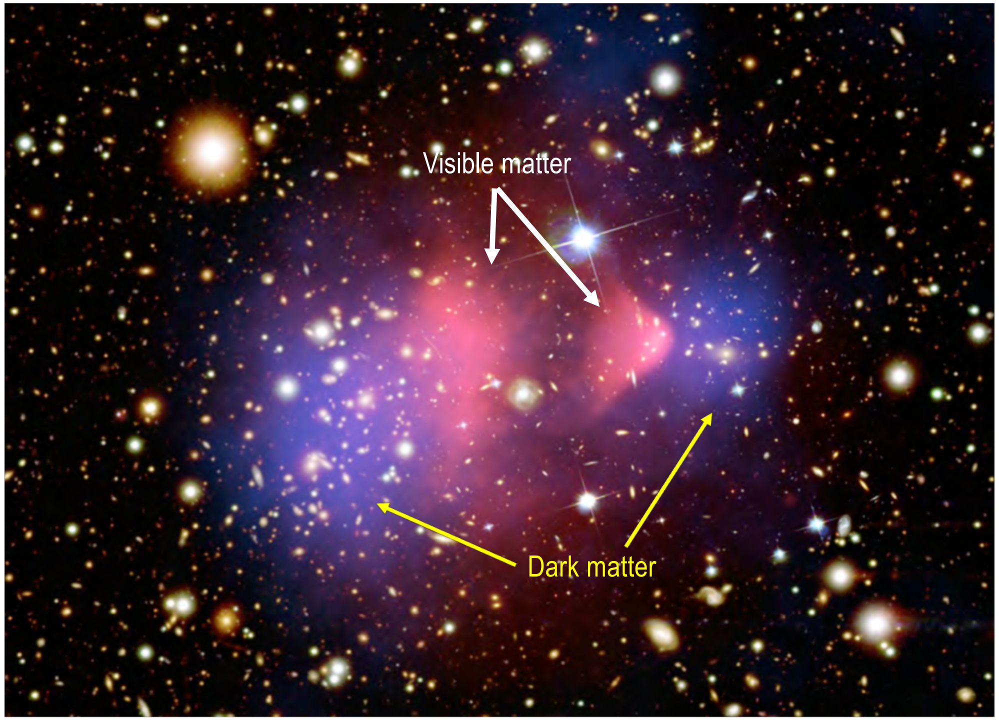

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- Bulk of the dark matter must reside beyond the standard model (SM)
- Properties:
  - long-lived or stable
  - cold or warm (slow enough to seed the structure formation)
  - gravitationally active
  - lacks strong couplings to itself or to baryons
  - leading candidates: weakly interacting massive particles (WIMPs) and axions
- Detection:
  - collider searches : SM particles → WIMPs
  - astrophysical signals (indirect) : WIMPs → SM particles
    - ⁎ claims of a dark matter annihilation signal at the galactic center, consistent with a ~30-40 GeV WIMP annihilating to b quarks, producing ~5 GeV photons
  - nuclear searches : WIMPs + Nucleus(m_A,J,T) → WIMPS + Nucleus(recoil) (direct)
    - ⁎ world-wide effort to search for WIMPs in elastic scattering on nuclei with different spins, isospins, masses

Challenge:

The determination of WIMP-nucleus interaction

Interface between theory and experiment

- In many cases, nuclear input MUST involve massive extrapolations based on predicted quantities … and extrapolations are ~~impossible~~ tough.
- Naïve approach to a model error estimate:
  - Take a set of reasonable models M_i
  - Make a prediction $E(y;M_i)$
  - Compute average and variation within this set
  - Compute rms deviation from existing experimental data. If the number of fit-observables is large, statistical error is small and the error is predominantly systematic.
- Bayesian Model Averaging (BMA): what is required?
  - Common dataset (as large as possible) needs to be defined
  - Make a statistical analysis for individual models
  - Make individual model predictions, including statistical uncertainties
  - Decision should be made on the prior model probability (**model selection**)
  - **Model averaging refers to the process of estimating some quantity under each model and then averaging the estimates according to how likely each model is**

  → There is no need to choose one model; it is possible to average the predictions from several models

BMA could be very useful to prepare experiments in unknown regions… but should not be used as an excuse for poor science

Challenge:

Bayesian neural networks are prone to instabilities and can be very time-consuming

Message to take

- Theory and experiment are intertwined

  → Theory gives the mathematical formulation of our understanding and predictive ability while experiment forces us to create new theories and provides verification to the existing ones

- Crucial advances in low-energy nuclear theory have been made in this century:
  - In medium nucleon-nucleon interaction from basic principles (EFT)
  - *Ab initio* structure and reactions (GFMC, NCSM(C), NCGSM, CCM,…)
  - Continuum Shell Model (GSM, SMEC); structure and reactions in the low-energy continuum
  - Many-body description of the large amplitude collective motion (e.g. fusion and fission)

  → Tremendous efforts are needed before before these conceptual advances will bring a real progress in the quantitative description of atomic nuclei

- Interaction with other fields of Physics and discoveries/technological progress in nuclear studies raise new challenges, change paradigms and methodology in nuclear studies

  → "No man is an island entire of itself; every man is a piece of the continent, a part of the main…"
  J. Donne (1572-1631), MEDITATION XVII, *Devotions upon Emergent Occasions*

- Costly nuclear-physics projects will compete with other large-scale projects in Science

  → Nuclear physics must demonstrate that it greatly contributes to the global progress of Science and advance societal applications

All of this requires excellent theory!