核数据测量与评价研究

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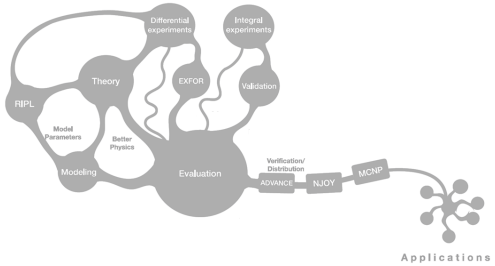
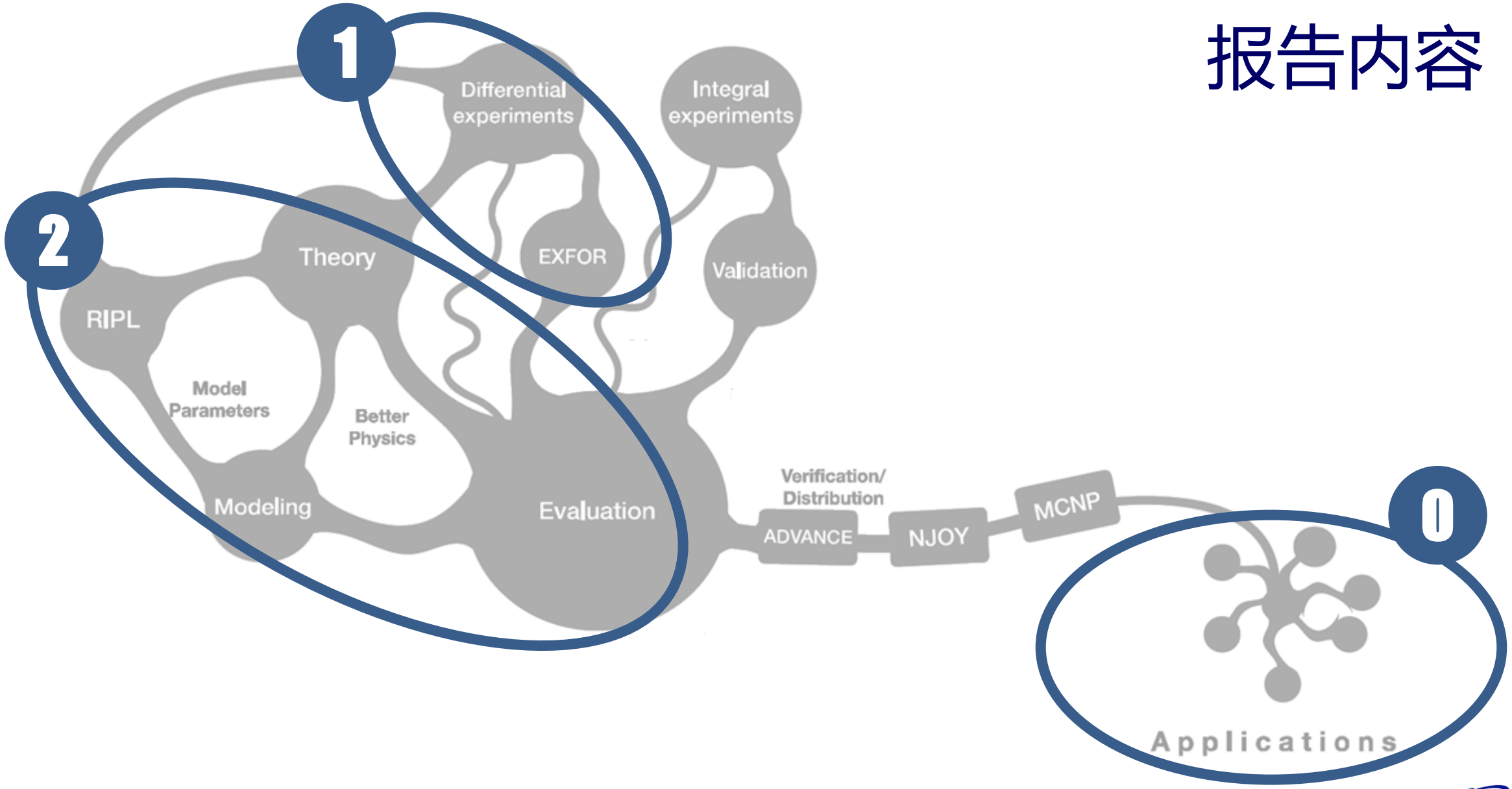
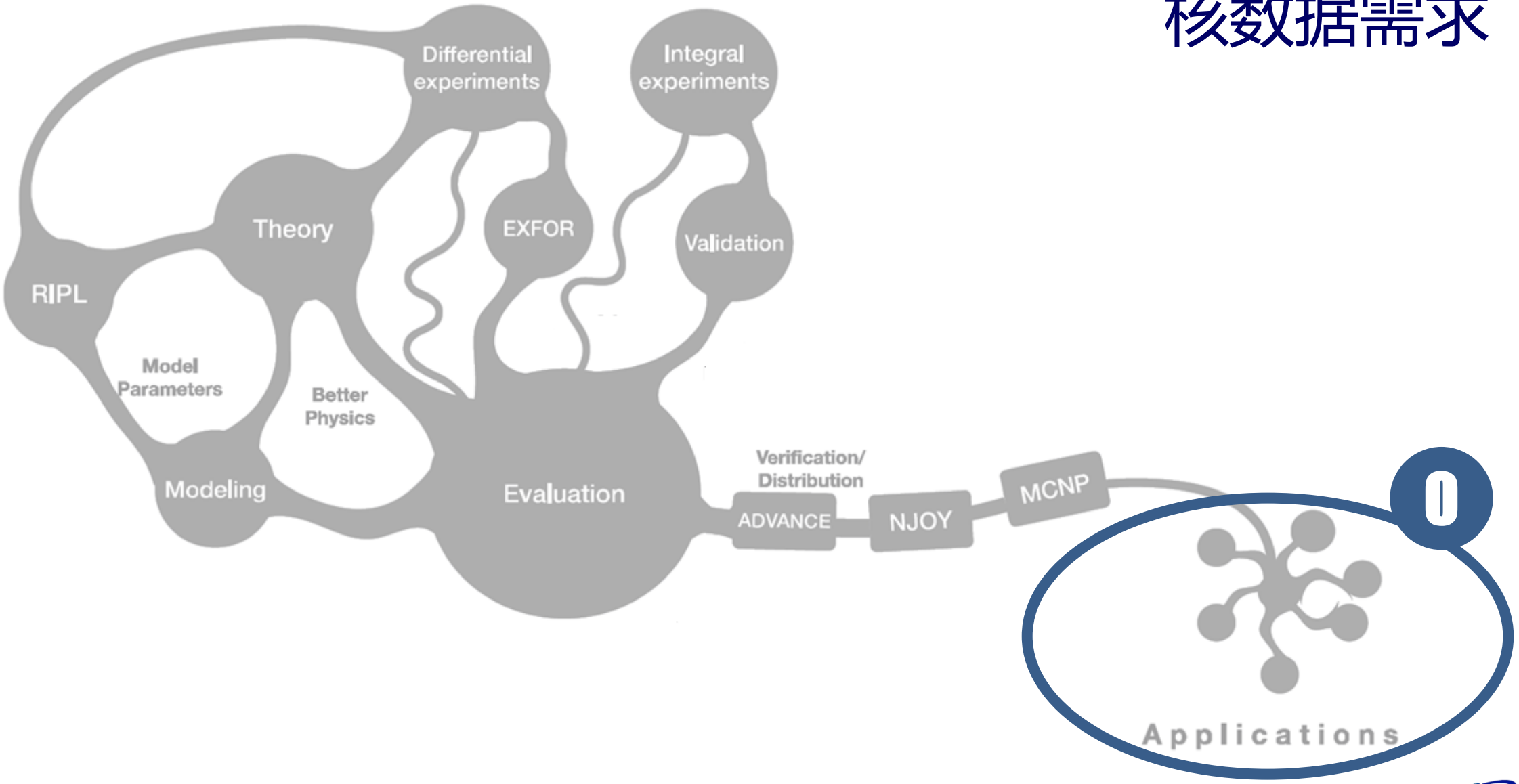
中国原子能科学研究院
2021.08.13



报告内容


1
2
0
Differential experiments
Integral experiments
Theory
EXFOR
Validation
RIPL
Model Parameters
Better Physics
Modeling
Evaluation
Verification/ Distribution
ADVANCE
NJOY
MCNP
Applications

核数据需求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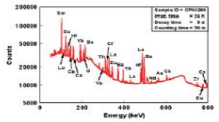
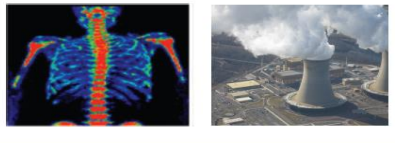
核数据研究过程与目标

The Nuclear Data Pipeline

Our goal is to get the highest quality data and uncertainties to users

security science isotopes energy

Experiment → Theory & Evaluation → Data Processing → Transport Codes → Benchmarking → User

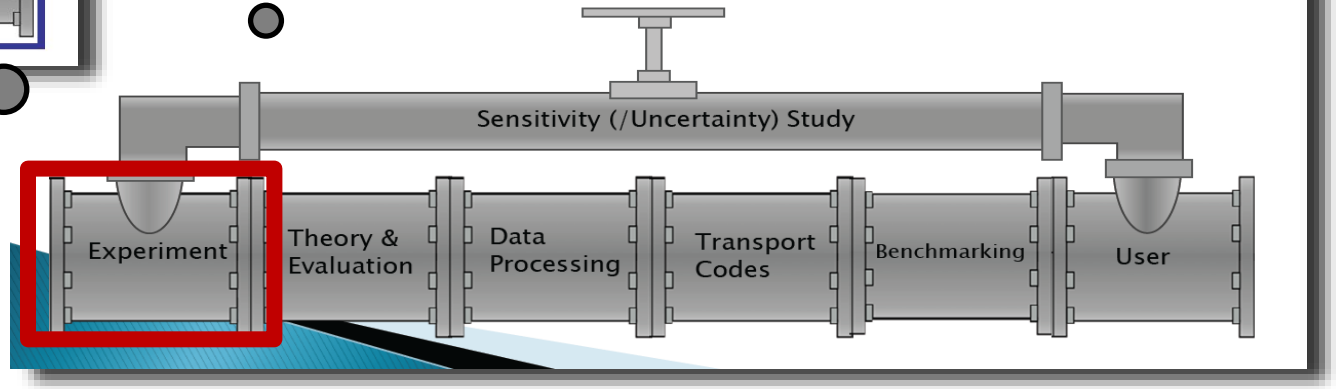
用户根据灵敏度研究确定优先度

目的是为用户提供高质量数据和高可靠不确定度

The Nuclear Data Pipeline

Our users use sensitivity studies to set priorities

When possible, these studies are informed with underlying uncertainties



Ref: Nuclear Data Pipeline Getting Data To The User David Brown (BNL/NNDC), Jeremy Conlin, Michael Zerkle, Patrick Talou, Robert Casperson (LLNL), Teresa Bailey, Yaron Danon (RPI), Workshop for Applied Nuclear Data Activities (WANDA), 3-5 Mar 2020

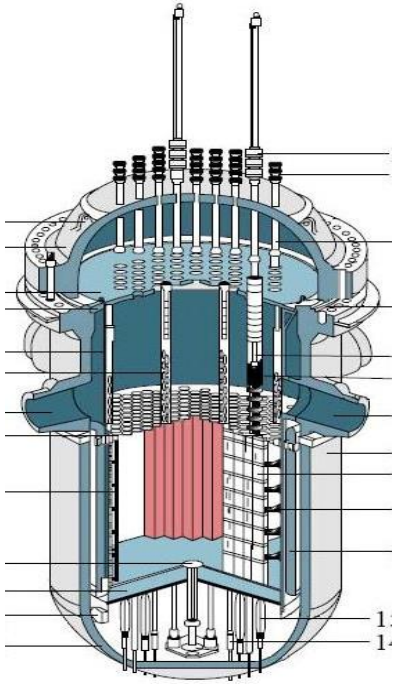
核数据主要需求来源

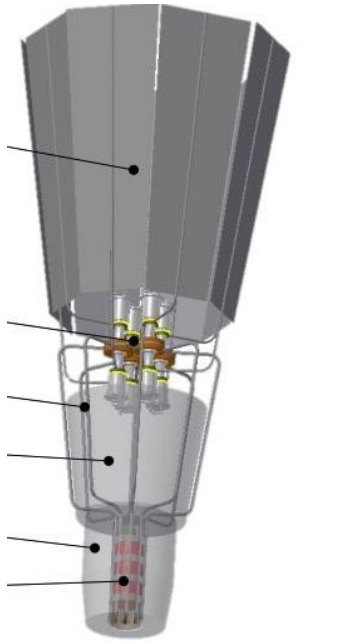
★ 核动力（陆地、海洋、空间等）

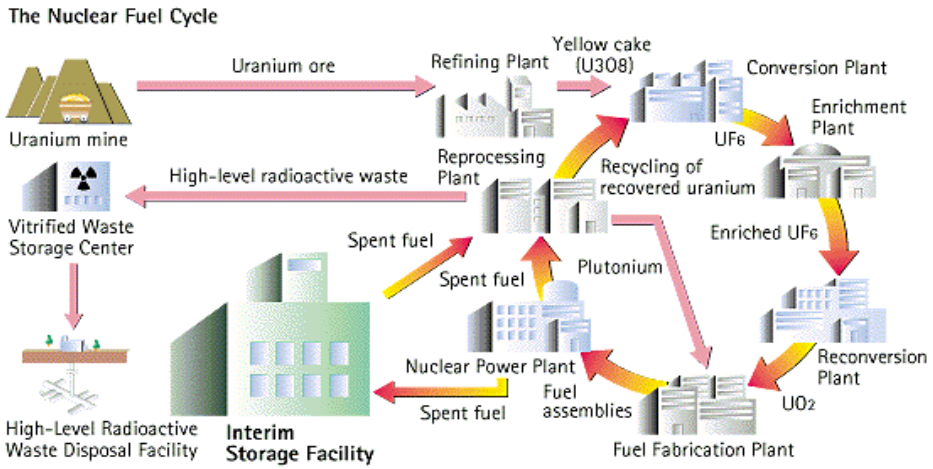
- 全套中子反应数据
- 燃料核、结构材料核、屏蔽材料核、裂变产物核等（规模最大）
- 阈-20 MeV，共振区重要
- 所有反应道、包括协方差

★ 其它用途

- 激发函数、裂变产额、衰变数据
- 燃料核、自发裂变核等
- 阈-20 MeV
- 反应截面、累积产额、独立产额、半衰期及衰变分支比等





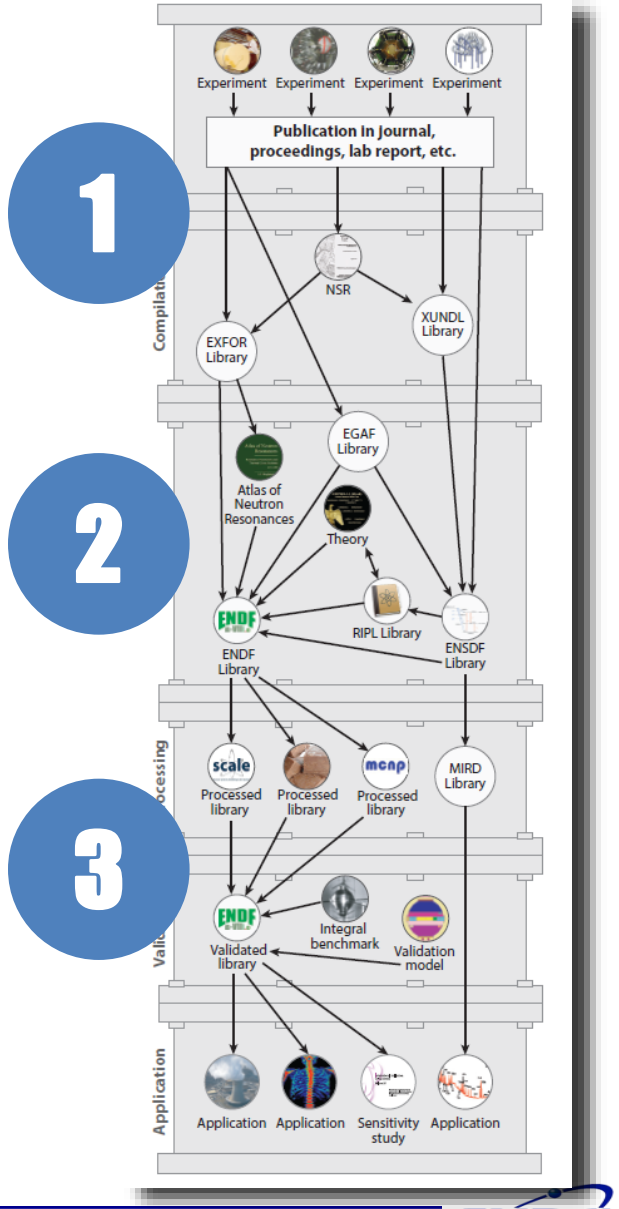


核数据研究内容

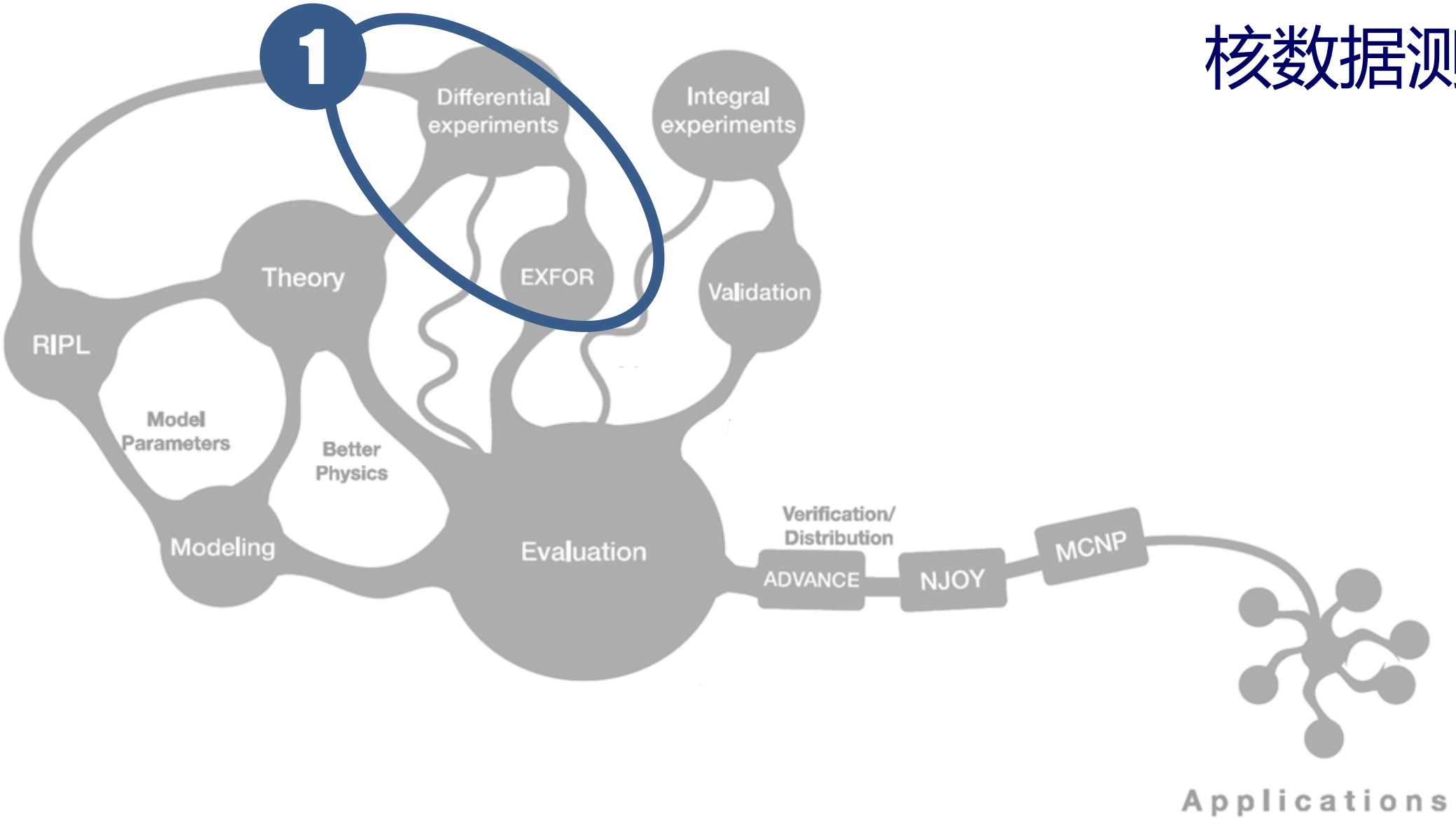
核数据研究

1. 核数据实验测量
2. 核数据理论计算与评价
3. 核数据可靠性与应用

- 核数据测量平台
- 测量样品制备
- 核数据测量方法
- 核数据精确测量
- 核反应理论模型
- 核结构理论模型
- 实验数据评价
- 核数据库建库
- 群常数制作
- 核数据宏观检验
- 核数据协方差
- 核数据S/U分析
- 核数据调整



核数据测量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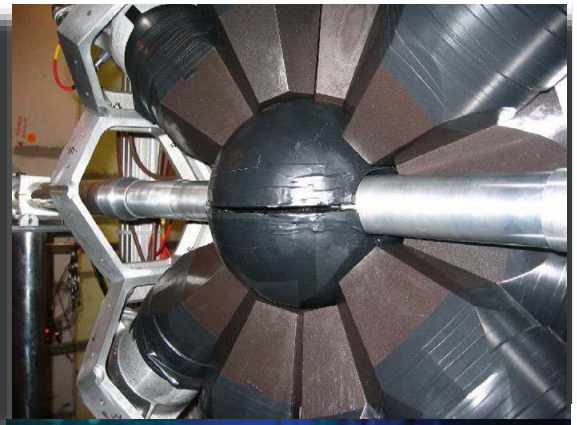
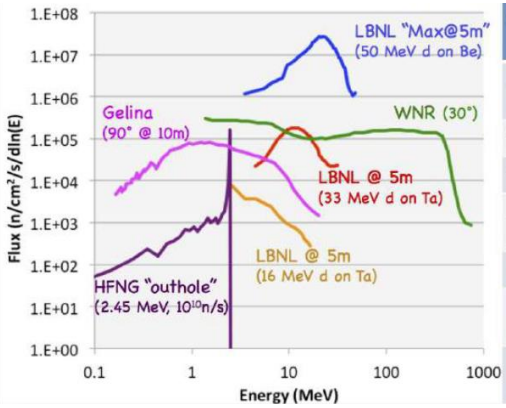
核数据测量

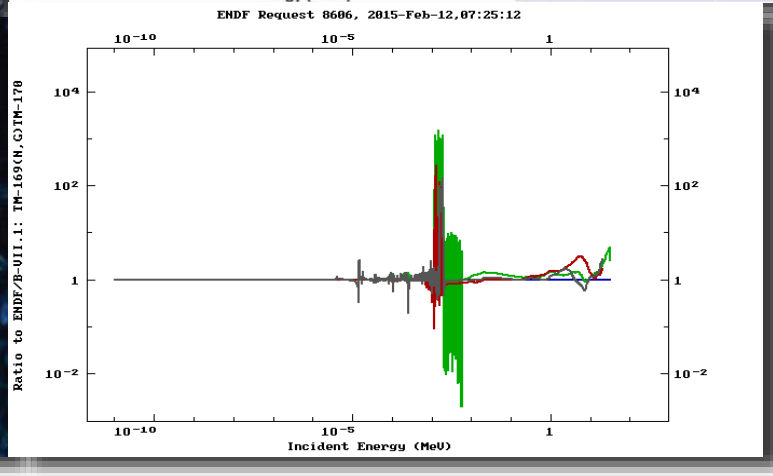
核数据实验：微观实验、宏观实验

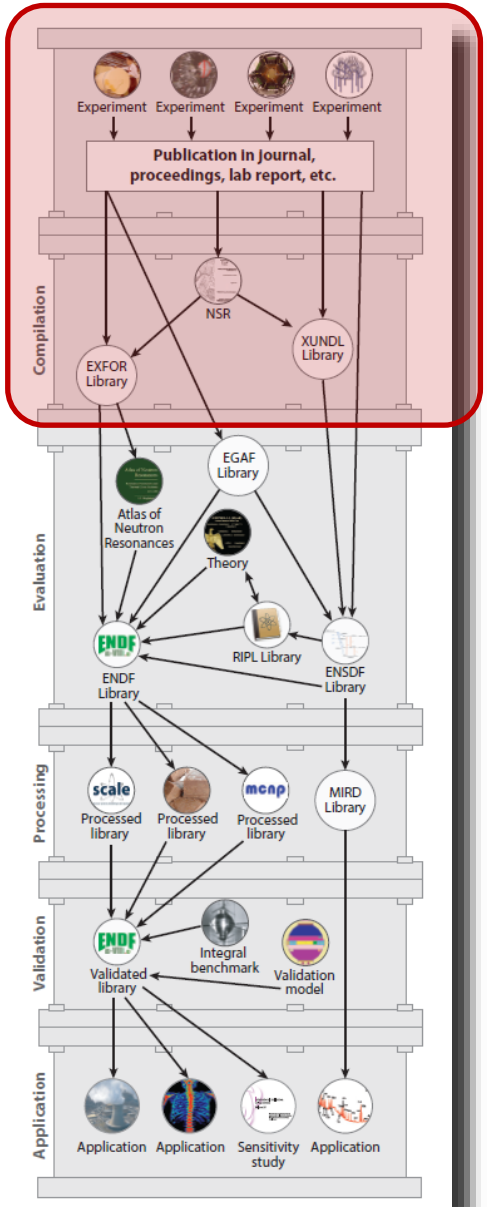
中子核数据测量四要素：中子源、探测器、实验方法与同位素样品制备技术





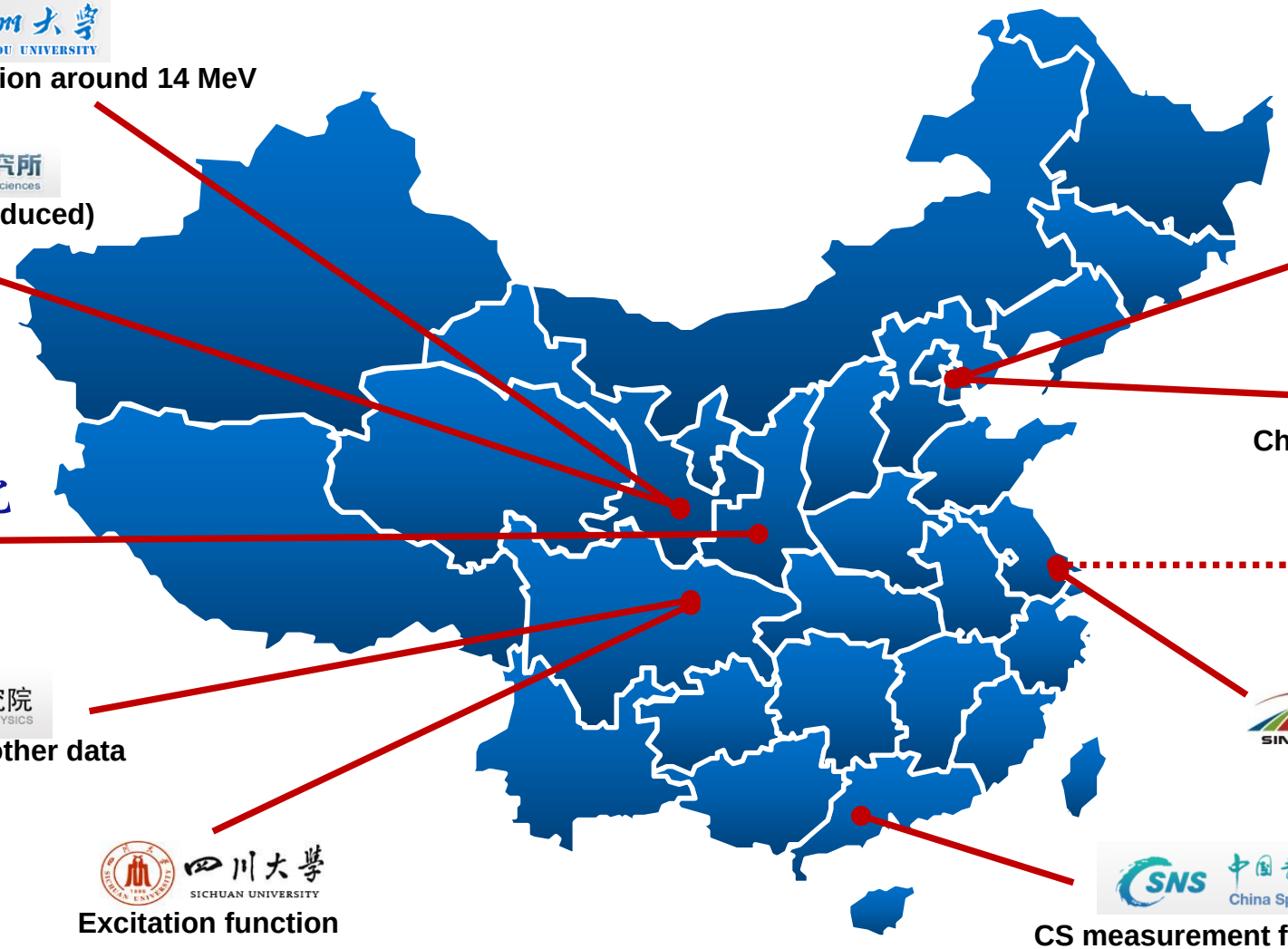
Source	Tot. Flux (n/cm2/s)
50 MeV d on Be (10μA, 5m)	$2x10^7$
WNR (30°)	10^6
Gelina (90° @ 10m)	$2x10^5$
33 MeV d on Ta (2μA @ 5m)	$2x10^5$
HFNG (2.27m)	10^4
16 MeV d on Ta (2μA @ 5m)	$5x10^3$
Kentucky T(p,n) (@ 2m)	$2x10^3$





新大型科学平台建成，更多单位参与核数据测量研究

Nuclear Data Measurement Activities in China



兰州大学 LANZHOU UNIVERSITY
Excitation function around 14 MeV

中国科学院近代物理研究所 Institute of Modern Physics, Chinese Academy of Sciences
ADS related data (proton induced)

中国原子能科学研究院 CHINA INSTITUTE OF ATOMIC ENERGY
Excitation function, FY, γ production yields, DX and DDX, benchmark experiments, etc

北京大学 PEKING UNIVERSITY
Charged reaction measurement (n,LCP)

西北核技术研究院
Decay data

SLEGS 上海激光电子伽马源
Photonuclear data measurement ?

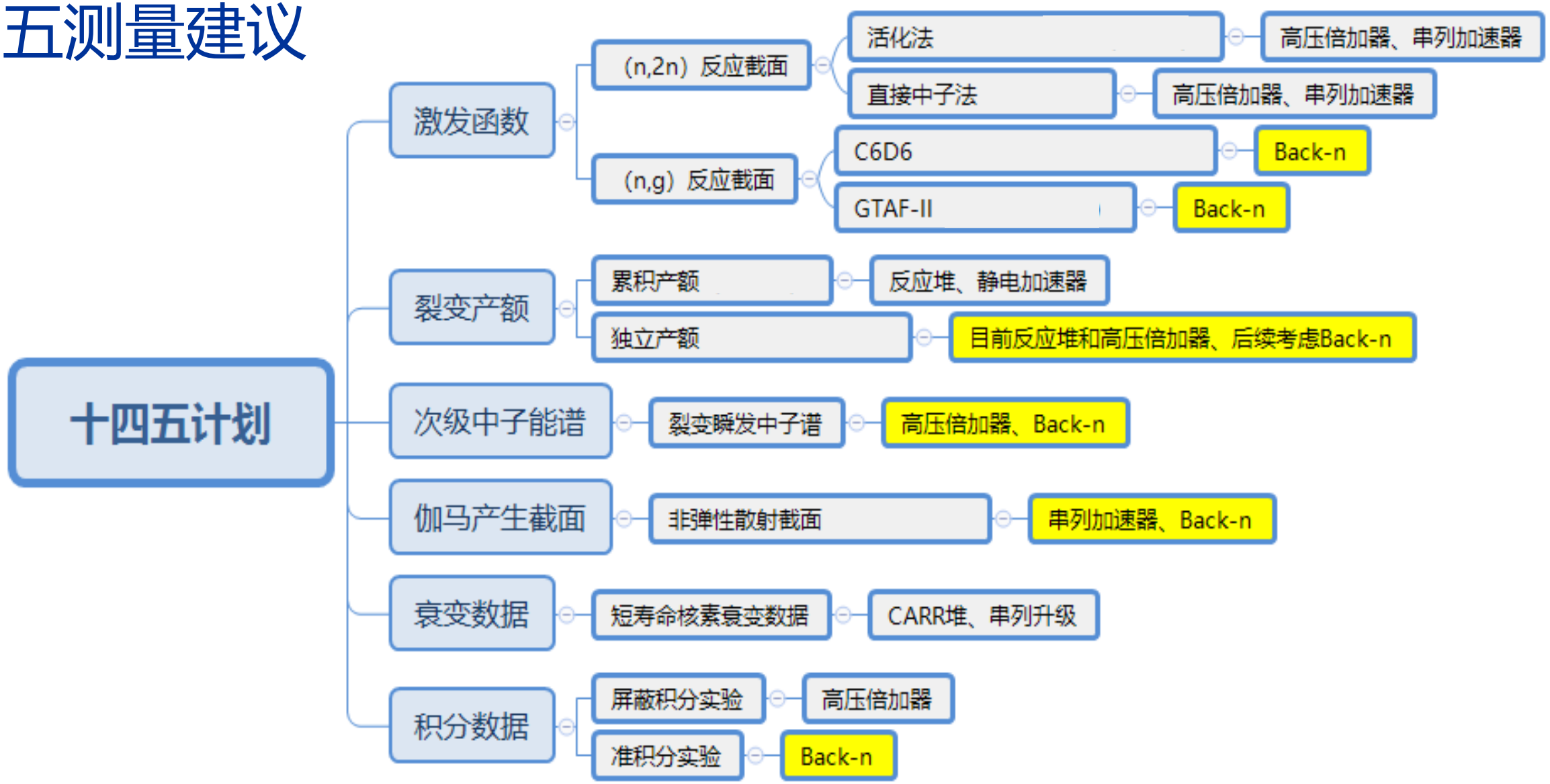
中国工程物理研究院 CHINA ACADEMY OF ENGINEERING PHYSICS
Integral experiments, other data measurement

SINAP 中国科学院上海应用物理研究所 Shanghai Institute of Applied Physics, Chinese Academy of Sciences
Th-U cycle related data

四川大学 SICHUAN UNIVERSITY
Excitation function

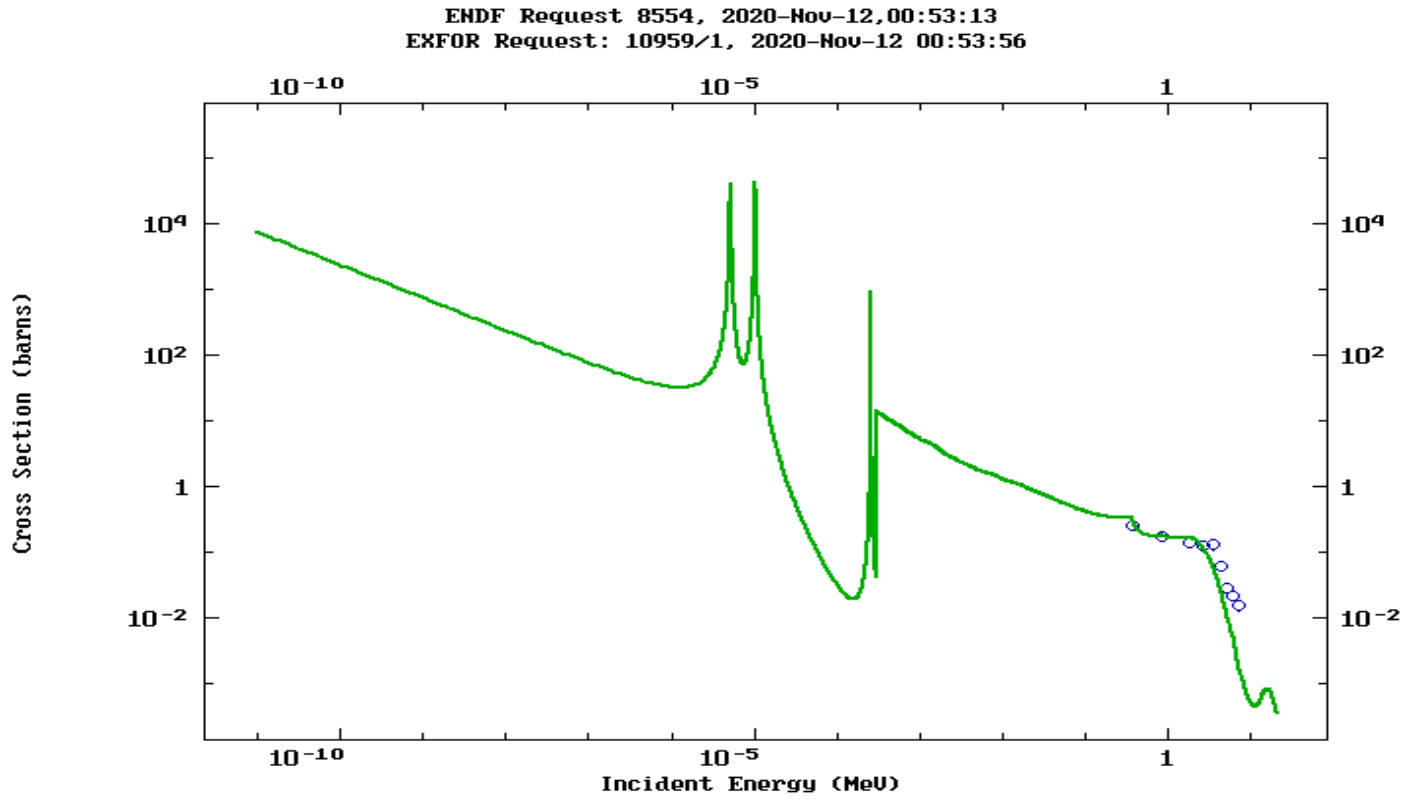
CSNS 中国散裂中子源 China Spallation Neutron Source
CS measurement for wide energy

十四五测量建议


十四五计划
激发函数
(n,2n) 反应截面
活化法
高压倍加器、串列加速器
直接中子法
高压倍加器、串列加速器
(n,g) 反应截面
C6D6
Back-n
GTAF-II
Back-n
裂变产额
累积产额
反应堆、静电加速器
独立产额
目前反应堆和高压倍加器、后续考虑Back-n
次级中子能谱
裂变瞬发中子谱
高压倍加器、Back-n
伽马产生截面
非弹性散射截面
串列加速器、Back-n
衰变数据
短寿命核素衰变数据
CARR堆、串列升级
积分数据
屏蔽积分实验
高压倍加器
准积分实验
Back-n

研究重点：中重核素 (n,γ)和(n,x)反应截面测量

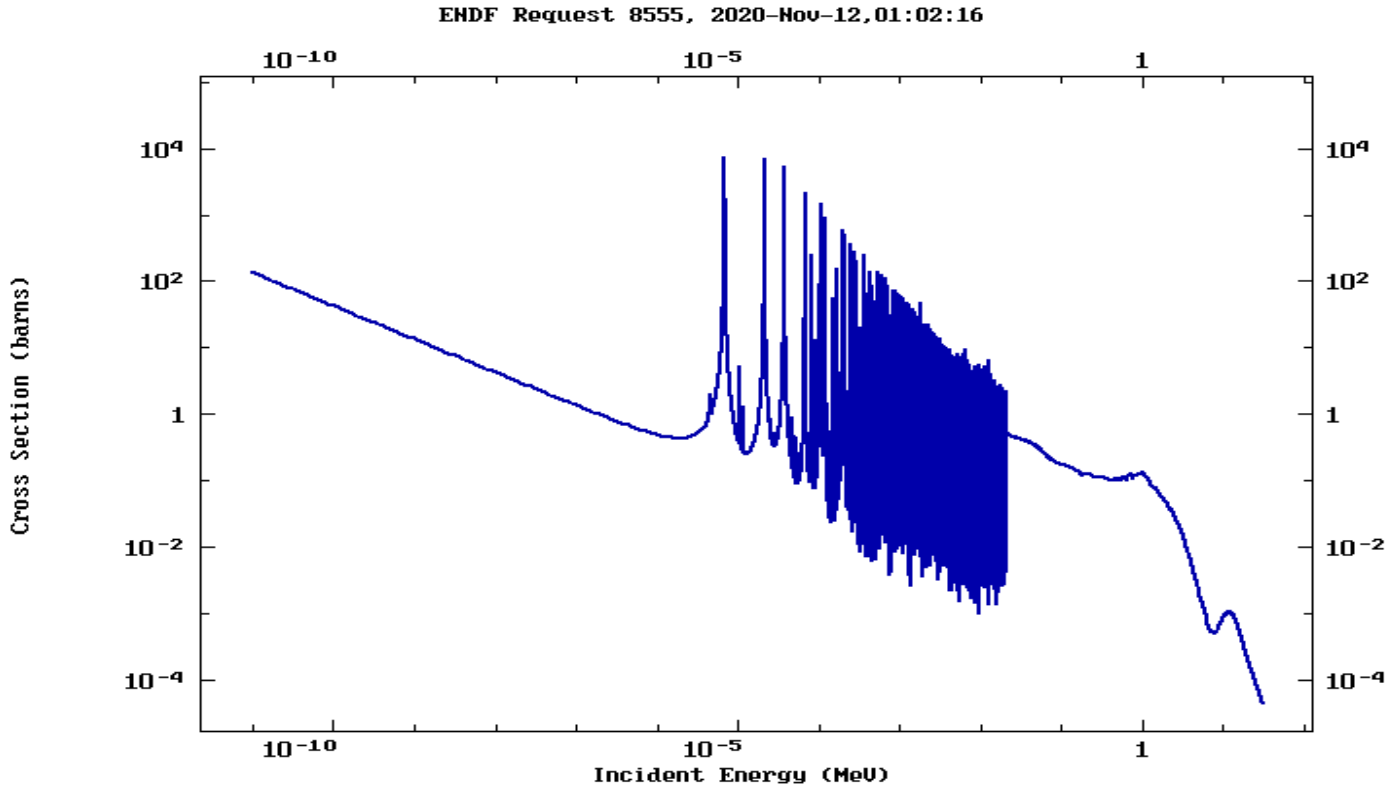
中重核(n,γ)、(n,x)反应截面，高精度实验数据。



研究重点：共振区截面数据测量

开展^{238}U、Zr同位素等的共振区（1eV-100keV）高精度点截面测量，消除多普勒展宽、能量分辨以及多次散射的测量数据的影响，共振能量的测量精度好于1.5%，全截面不确定度<2%，俘获截面不确定度<5%。并在此基础上评价给出共振参数。

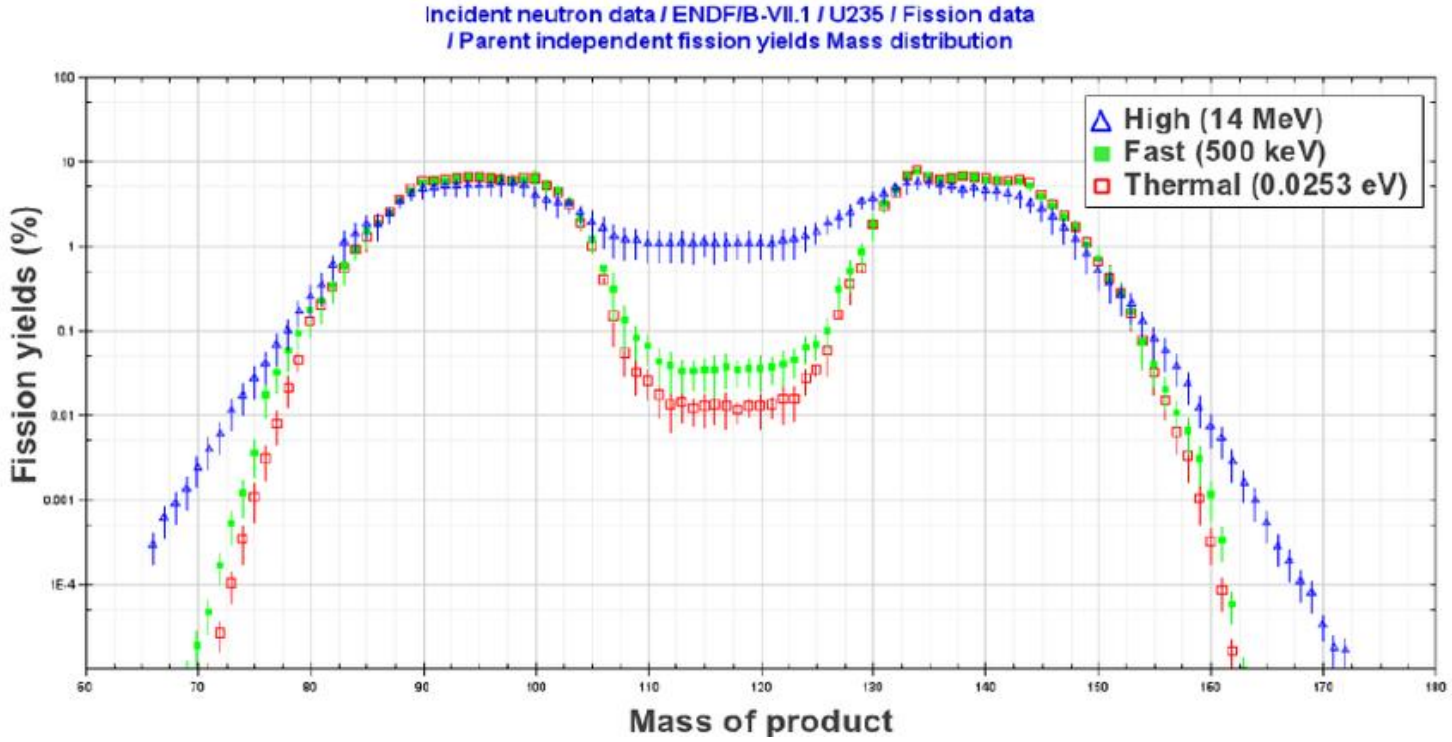
主要包括全截面和(n,γ)反应截面。



研究重点：裂变产额及产额-能量关系研究

裂变产额及产额-能量关系是极其重要的数据。

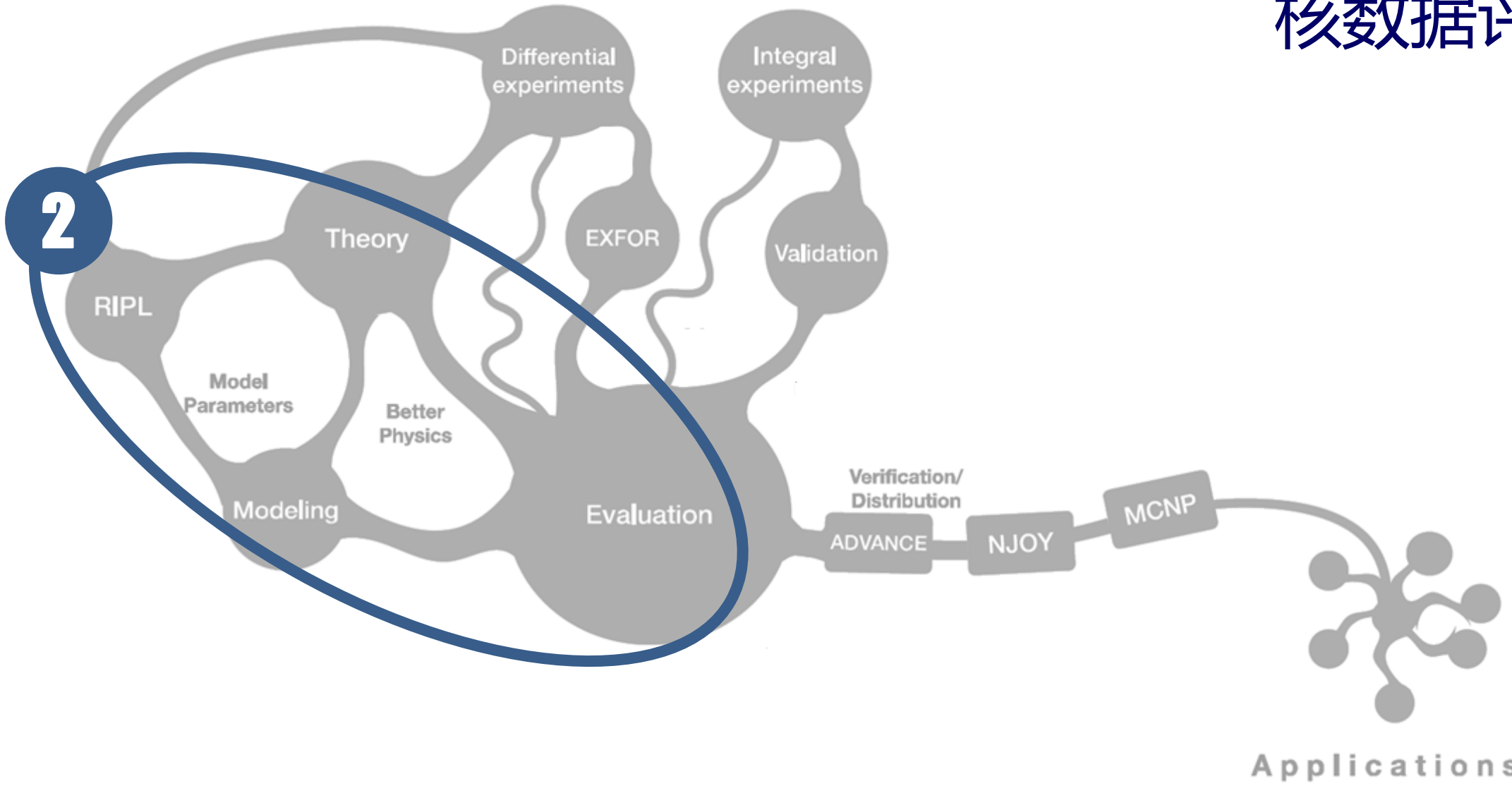
独立产额-技术成熟后，利用Back-n开展U裂变系统重点产物核在线测量。



研究重点：裂变核U、Pu和Am等全能区面数据测量

1. 共振能区截面测量、$^{233,235,238}U$、^{239}Pu、^{232}Th、Am、Fe、Al、Si、Ca、Pb、Zr、V、W、Au等全截面与俘获截面测量，共振能量的测量精度好于1.5%，全截面不确定度<2%，俘获截面不确定度<5%。
2. 中重核的俘获截面测量，不确定度<5%
3. 建立（n,x）反应截面测量技术，开展相关中重核（n,x）反应截面测量。
4. 建立eV-30MeV宽能区裂变截面测量技术
5. 建立裂变产额及产额-能量关系研究

核数据评价


2
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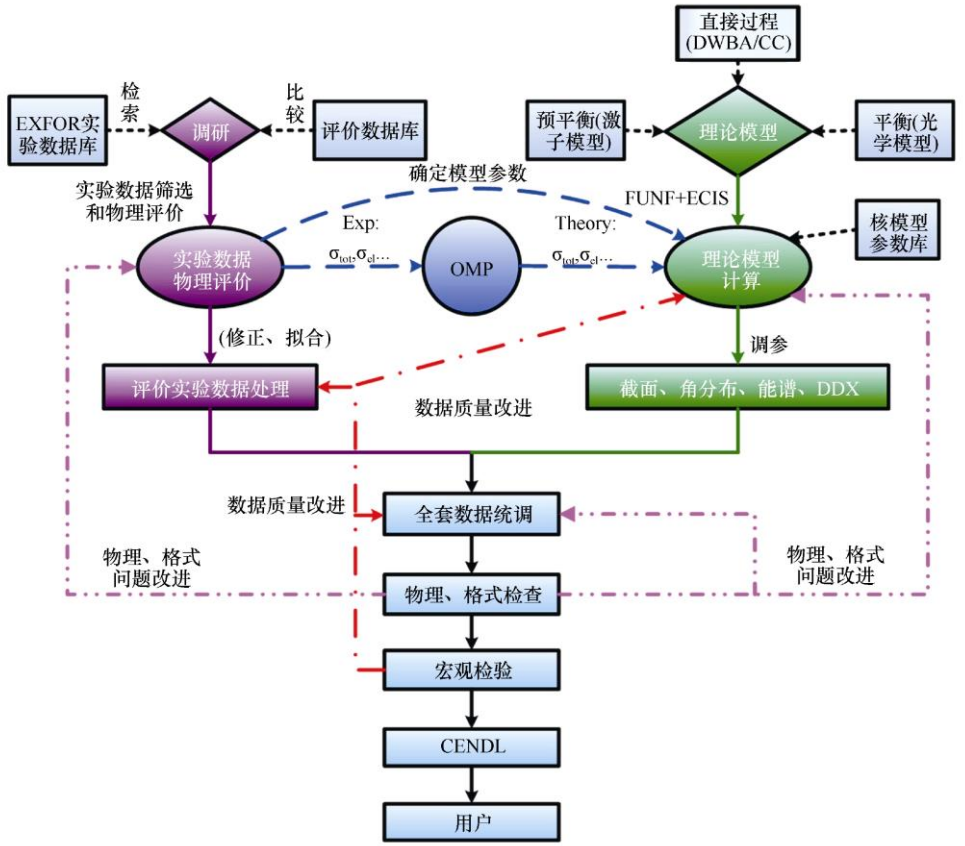
核数据模型计算与评价

核反应理论

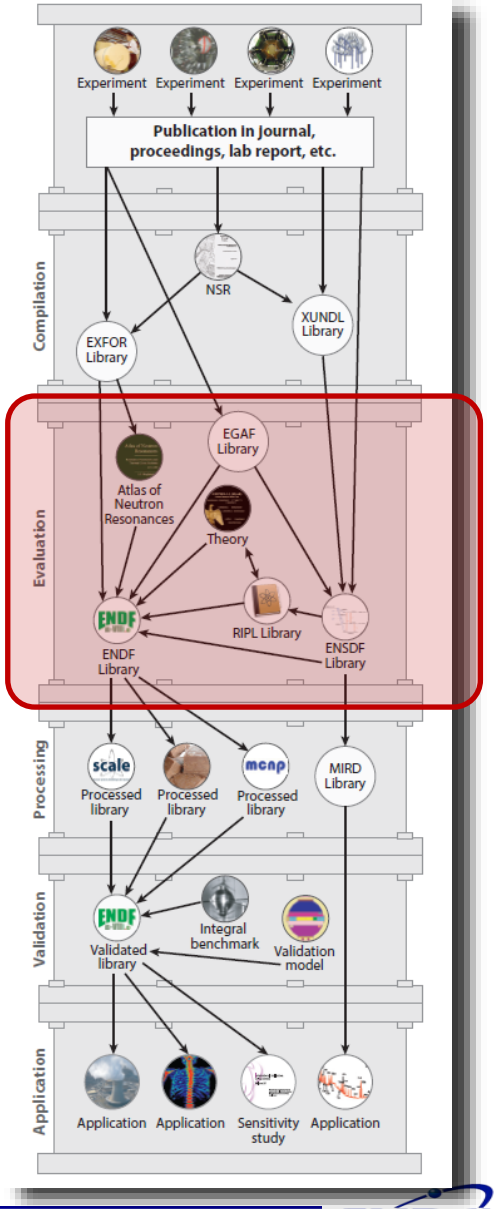
- Optical Model (OM)
- Coupled Channels (CC)
- Distorted Wave Born Approximation (DWBA)
- Multi-step Direct (TUL)
- Multi-step Compound with gamma emission (NVWY)
- Exciton Model with cluster emission in terms of Iwamoto-Harada model (PCROSS)
- Hauser-Feshbach model with multiparticle emission, full gamma-cascade and dynamical deformation effects
- .....

核数据模型计算程序

- **轻核：** EDA、RAC、AMUR、LUNF
- **中重核及裂变核：** UNF, FUNF, MEND, TALYS, EMPIRE, COCNN, OPTMAN,GNASH
- **裂变过程：** GEF



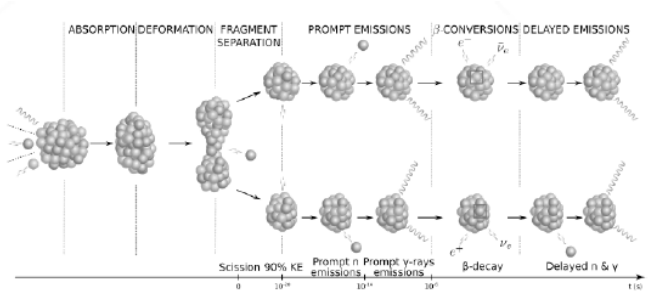
全套中子数据评价基本流程



核数据模型与程序发展

核反应模型研究新结果

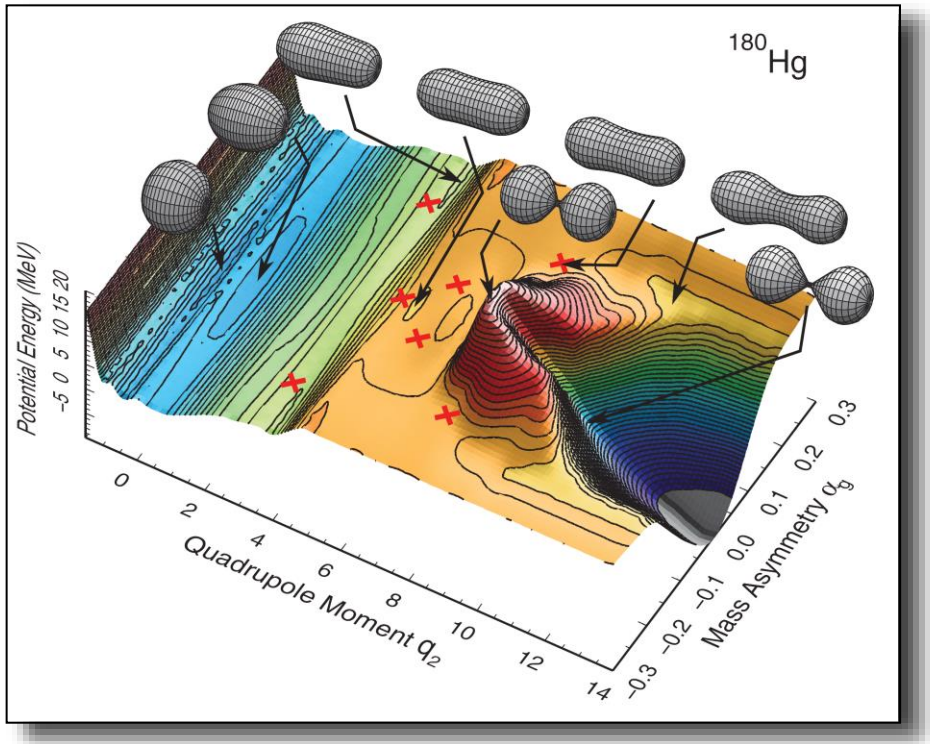
Nuclear Theory



- Advances in fundamental nuclear theories
  - Predictions based on more fundamental microscopic theories
  - Ab initio calculations for light nuclei
- Grand Challenges (a selection)
  - Comprehensive, quantitative & predictive theory of **nuclear fission**
  - **Nuclear structure** (level densities, isomeric states, branching ratios), especially for nuclei away from stability
  - Consistent theories/models of **nuclear reaction & nuclear structure**
  - Integration of fundamental nuclear physics codes (microscopic, quantum mechanical, event-by-event) directly into **transport simulations**
  - Development of **machine learning-trained emulators** on fundamental physics codes

Ref: Patrick Talou Los Alamos National Laboratory

裂变理论研究

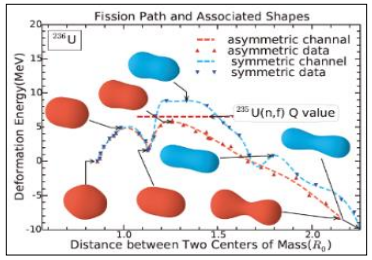


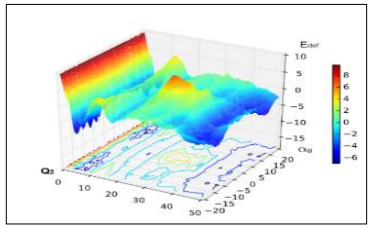
宏观和微观方法：实现了五维集体变形坐标下的位能曲面的精确计算，成功解释了许多原来不理解的裂变现象，定性解释了^{180}Hg质量不对称分布。

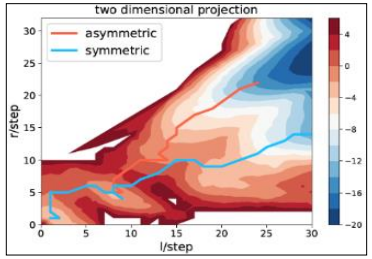
Ref:P. Moller etal, Nature 409,785(2001)

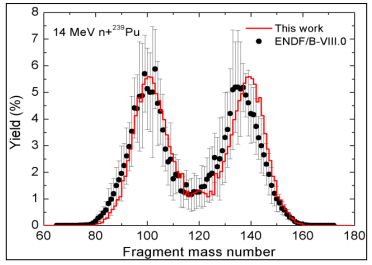
裂变理论模型研究

建立基于宏观-微观方法多维势能曲面计算和动力学研究体系









- 广义洛伦兹形状（5维）
- 双中心壳模型和有限程液滴模型(4、3维)
- 傅里叶展开核形状描述（4、3）

裂变系统位能曲面

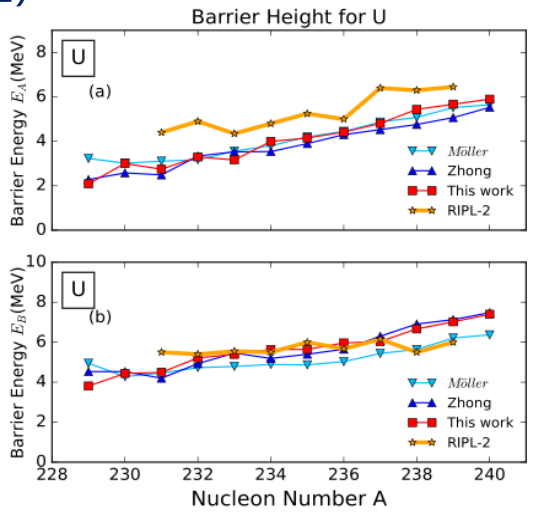
裂变过程动力学

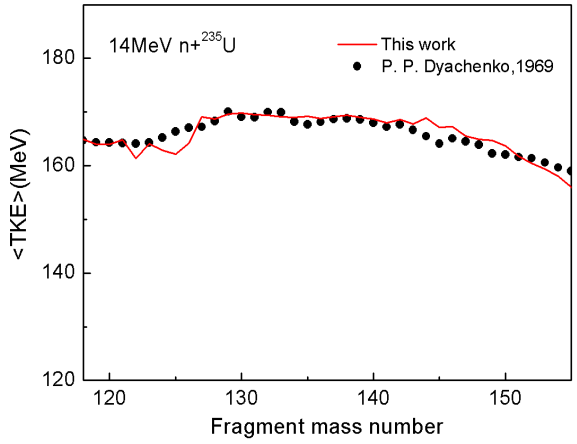
- 多维位能曲面随机游走
- 朗之万方法

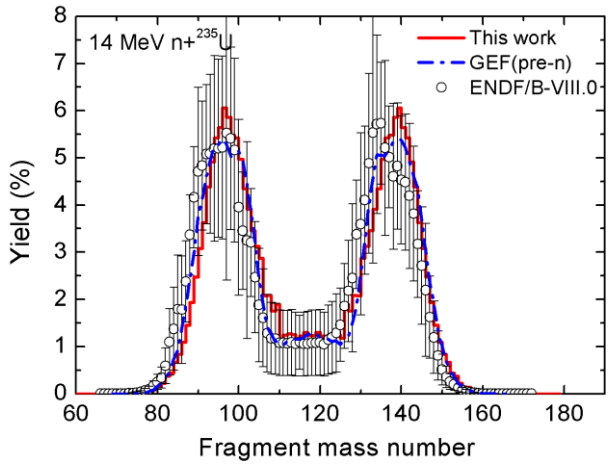
裂变物理量

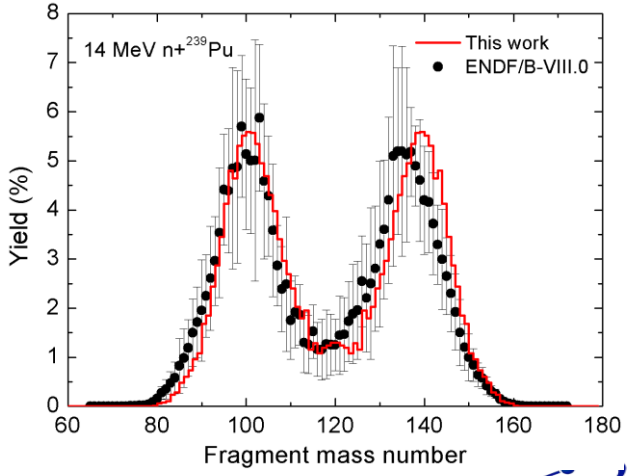
- 裂变模式
- 裂变产额、总动能分布
- 等等裂变物理量

LSD模型 Folded-Yukawa势



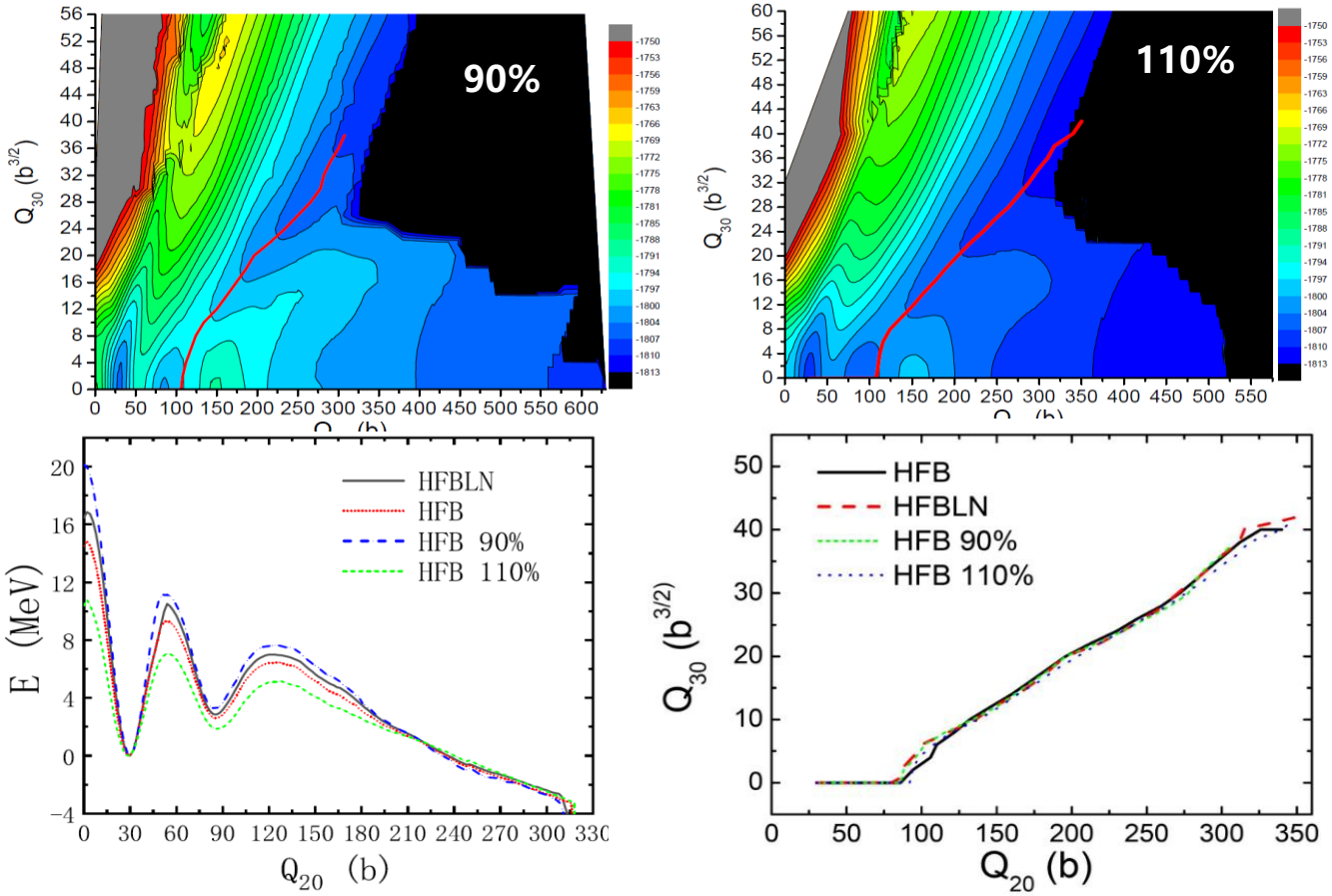




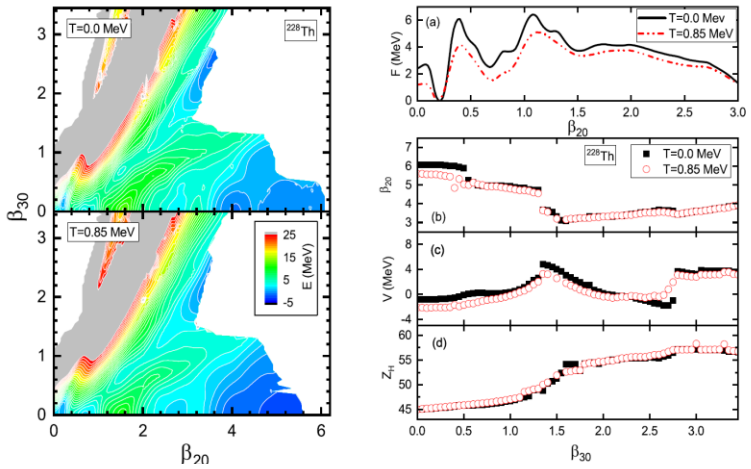


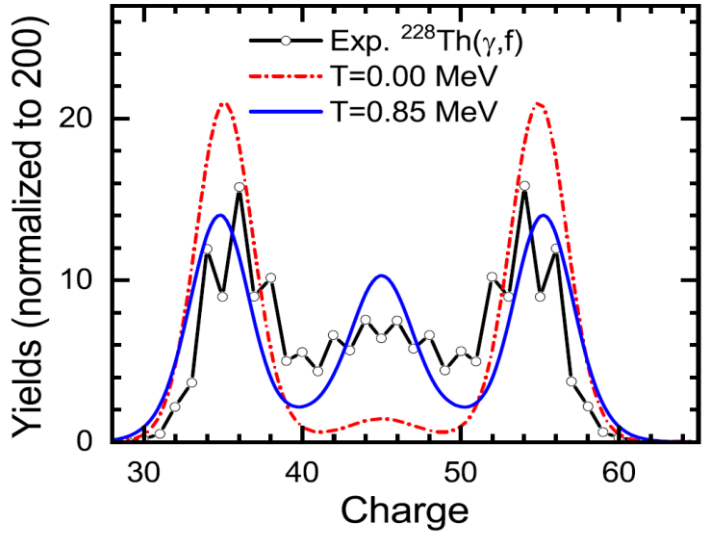
建立基于密度泛函裂变动力学研究方法

- 基于密度泛函->位能曲面+动力学+物理量
- 基于密度泛函->裂变机制研究



对力强度对垒高度(左）与最优裂变路径（右）影响。

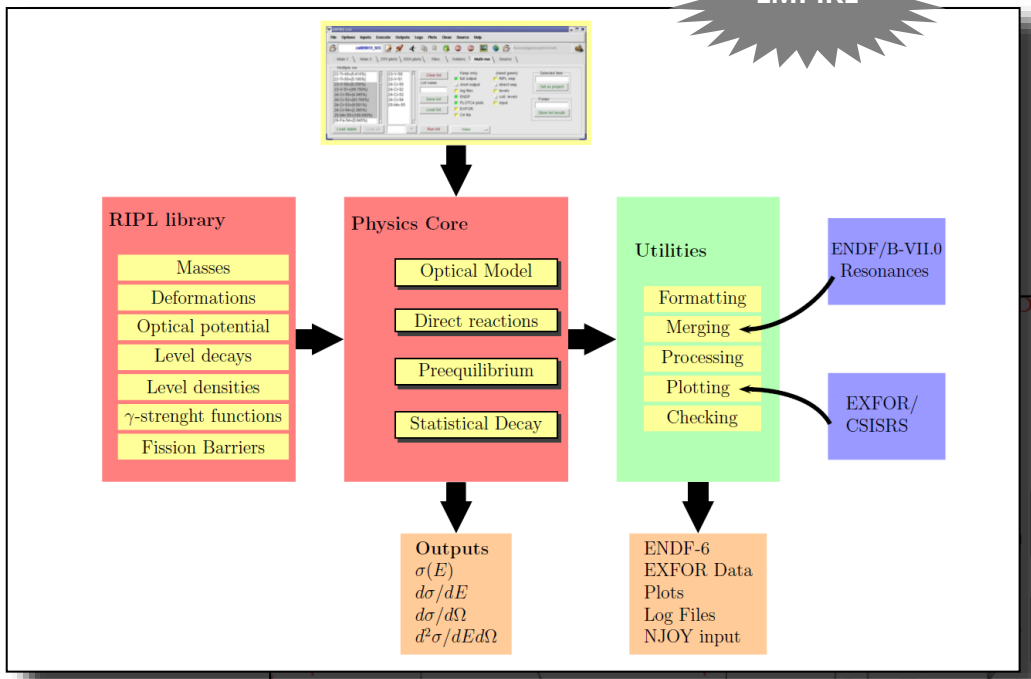




温度使位垒降低，对称裂变谷与不对称裂变谷之间的脊降低，对称裂变谷加深。温度对断点位置、断点处碎片质量、电荷影响不大(上）温度增加，对称裂变产额增加，不对称裂变产额降低。定性结果与现有实验结果一致（下）*PHYSICAL REVIEW C 99, 054613 (2019)*

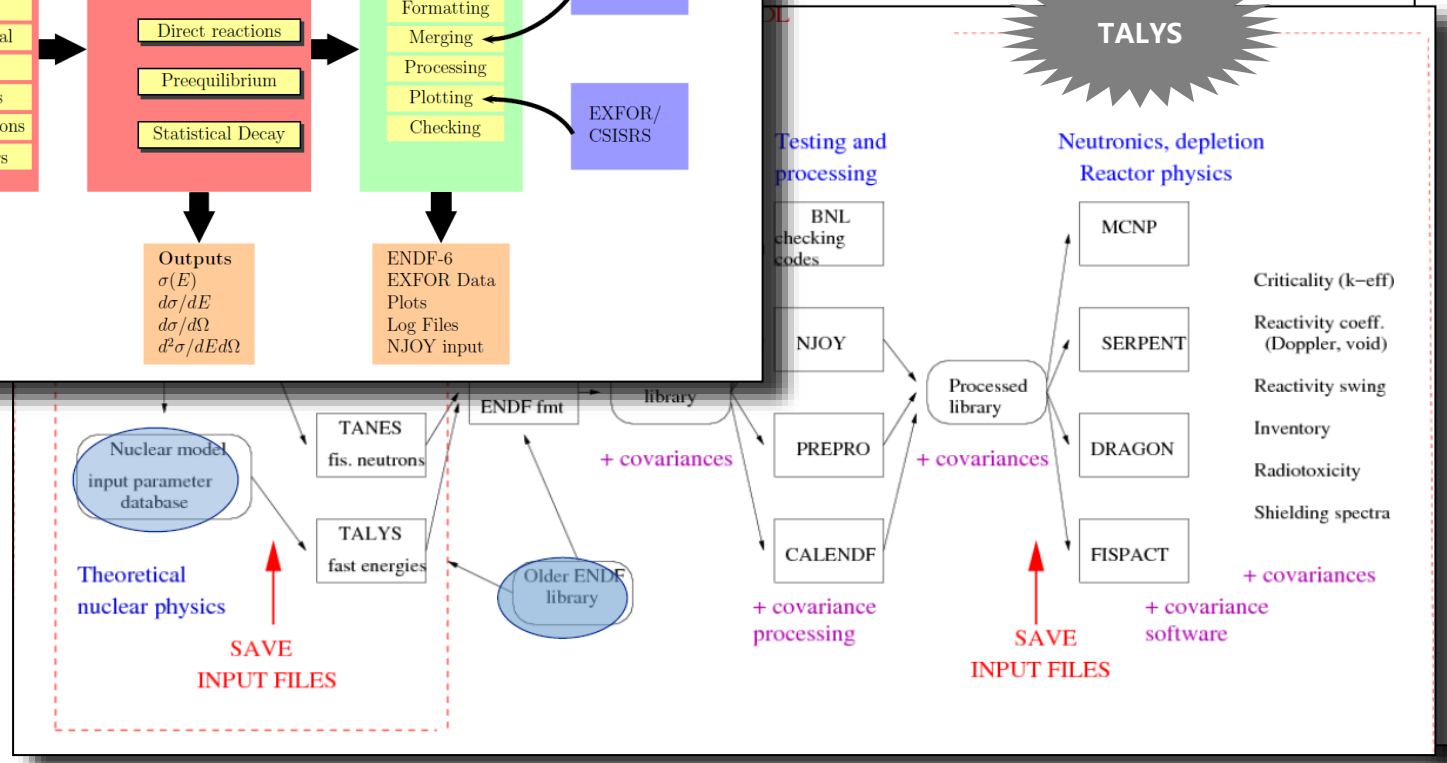
核数据模型程序进展

EMPIRE



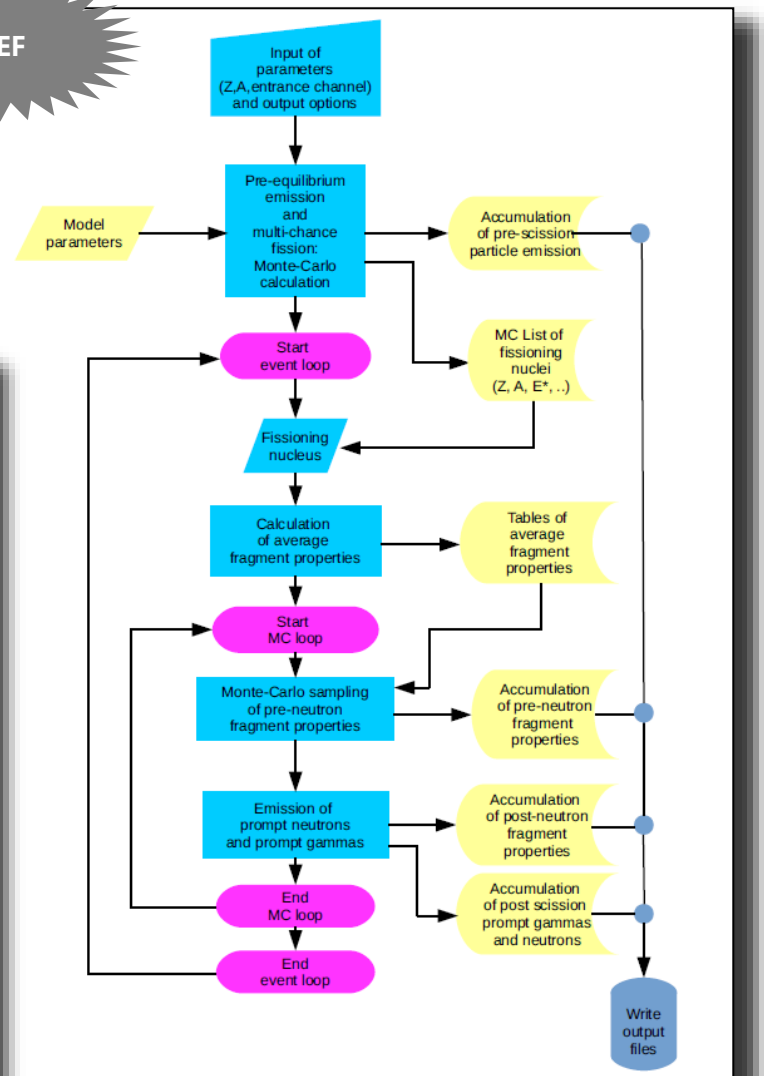
Ref: M. Herman, R. Capote, B.V. Carlson, P. Oblo˘zinsk´y, M. Sin, A. Trkov, H. Wienke, and V. Zerkin, EMPIRE: Nuclear Reaction Model Code System for Data Evaluation, Nuclear Data Sheets 108 (2007) 2655–2715

TALYS



Ref: A.J. Koning and D. Rochman ,"Modern nuclear data evaluation with the TALYS code system ", Nuclear Data Sheets 113, 2841 (2012).

GEF



Ref: K.-H. Schmidt, B. Jurado, C. Amouroux, and C. Schmitt, General Description of Fission Observables: GEF Model Code, 131(2007)107-221

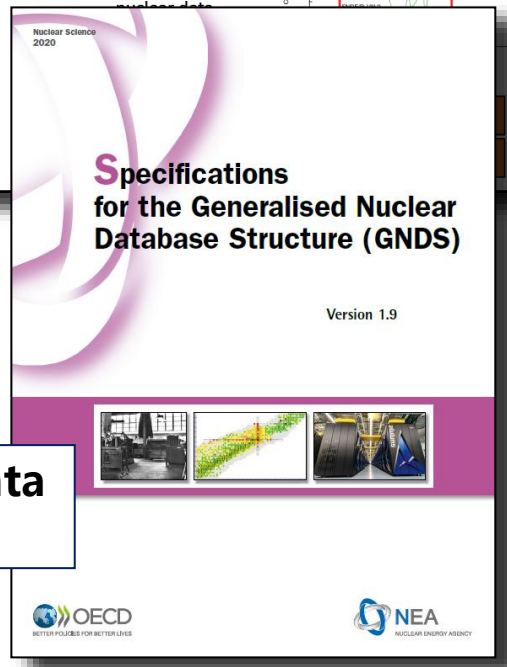
评价新手段与方法

Nuclear Data Evaluations

Combining the best of our knowledge (exp. & theoretical) about nuclear quantities into tabulated data files

- A (necessarily) compromising task
  - Uncertainties and limitations in experimental data
  - Approximations/assumptions of theoretical models
  - Discrepant observations/information
- Historical trend toward a more scientific and rigorous process
  - General use of theoretical models
  - More realistic account of experimental uncertainties
  - Use of rigorous mathematical and statistical tools (Bayes)
  - Better tools to ensure quality assurance and verification of data files

- Still lots of work to be done; some open questions:
  - How to account for model defects?
  - Realistic simulations of experimental setups, their biases and uncertainties
  - Quality control and improvements of the library itself, e.g., GNDS
  - Rigorous derivation of uncertainties and correlations (covariances)
  - "General purpose" and/or "adjusted" libraries

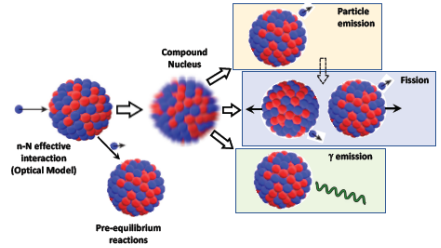


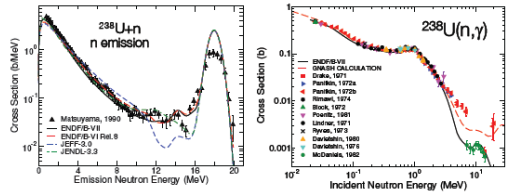
New Format of Nuclear Data GNDS

- ✓ 核数据模型计算程序系统的不断完善
- ✓ 实验测量数据的系统评价
- ✓ 核数据微观评价与宏观基准检验结果联合

Evaluated and predicted cross sections are critical to national security, energy and astrophysics applications

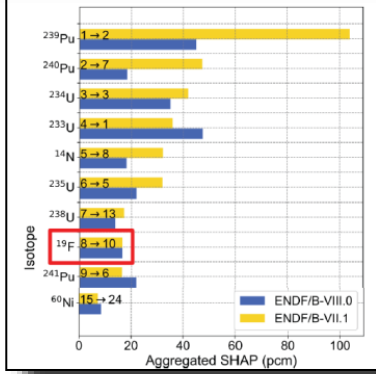
- Reaction data must be evaluated for use in applications
  - Central tool: Extended Hauser-Feshbach reaction framework
  - Uses diverse mix of structure & reaction models
- Challenges for reaction evaluations
  - Correlated reaction channels
  - Correlations across isotopes
  - No optimal combination of models
  - No model uncertainties
  - Need to sample models and large parameter spaces
  - Data do not give unique constraints to disentangle inputs
- Additional challenges for predictions
  - Lack of constraints
  - Extrapolation of models

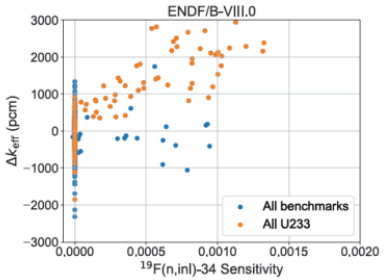


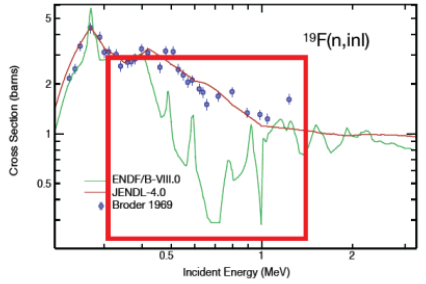


人工智能/机器学习等新技术应用

augment expert knowledge in pin-mark experiments leading to bias in simulating criticality benchmarks; E.g.: ML found ^{19}F(n,inl) issue missed by experts

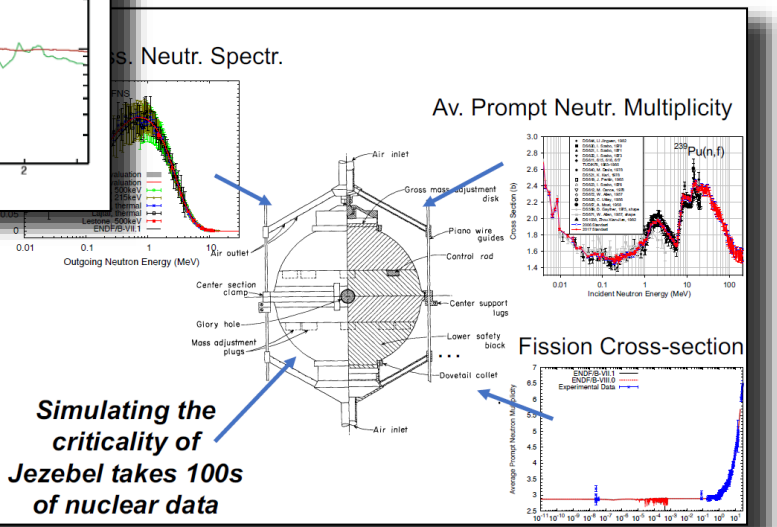






versus experimental values of validation measurements.

- **1000s of nuclear data are used to simulate 1(!) validation experimental value. A human brain cannot keep track of all these inter-dependencies.**

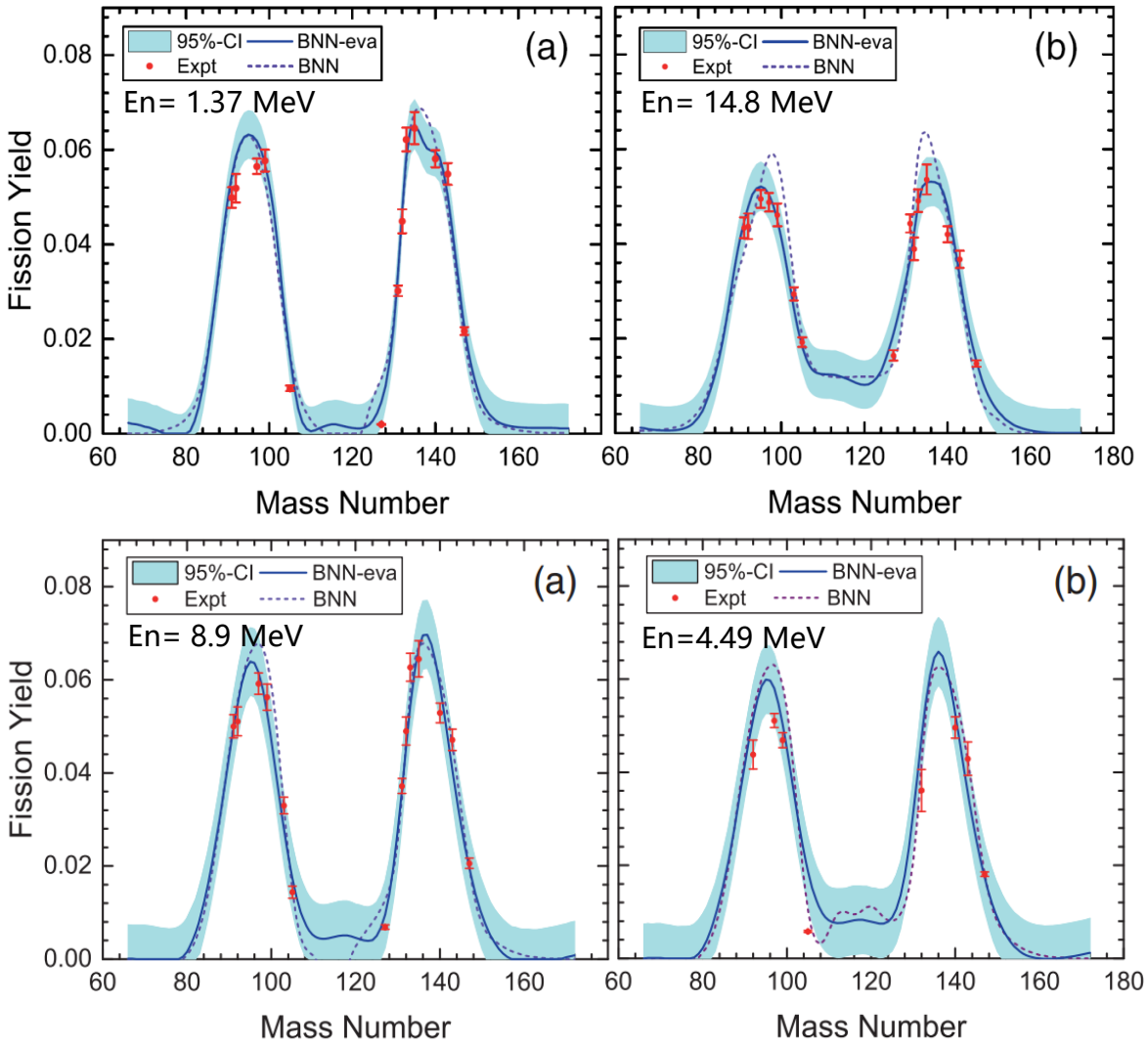


Simulating the criticality of Jezebel takes 100s of nuclear data

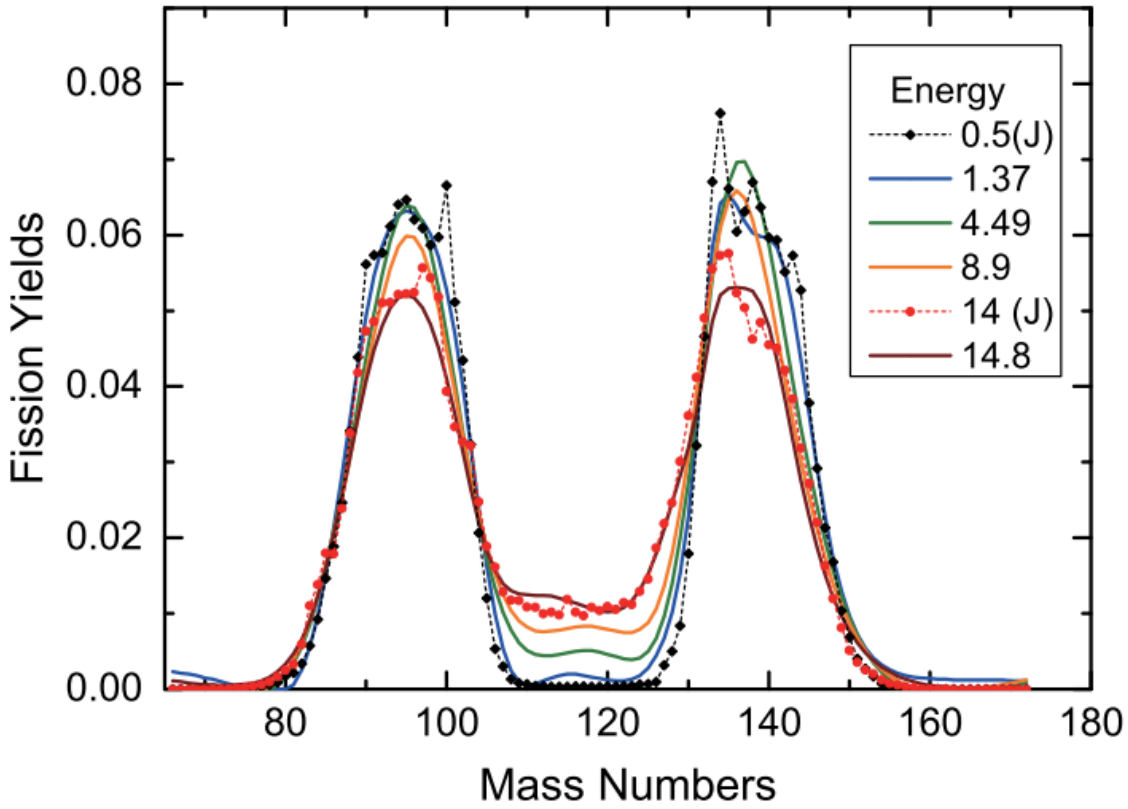
AI/ML for Nuclear Data

机器学习 贝叶斯神经网络方法评价裂变产额

$n + {}^{235}U$



Ref：Zi-Ao Wang, et al, Phys. Rev. Lett. 123, 122501 (2019)



神经网络能成功抓住部分物理图像。

贝叶斯神经网络对裂变产额的评价开辟了一个新的方向。

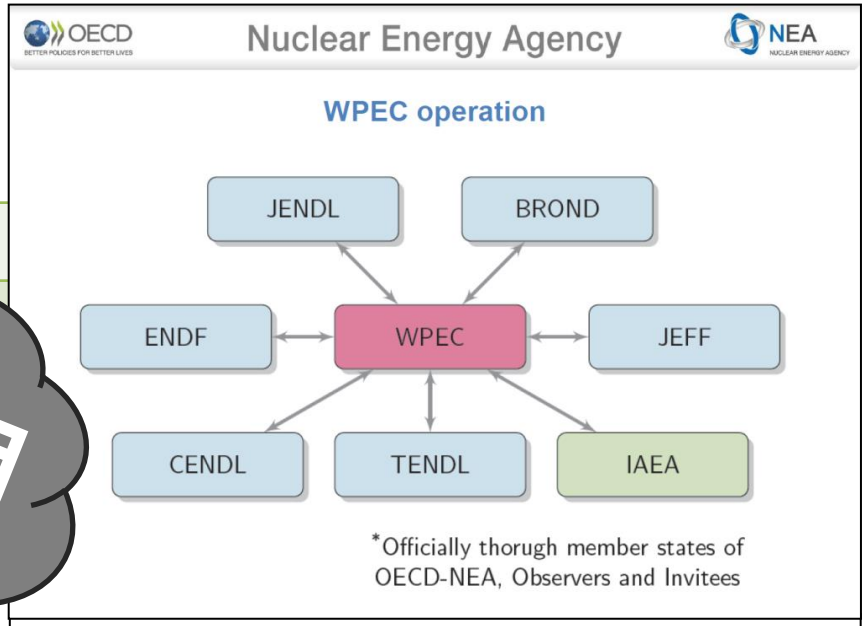
北京大学　裴俊琛课题组

核数据库不断丰富

I. General-purpose evaluated data files

ENDF	USA
JEFF	OECD/NEA Databank
JENDL	JAEA
CENDL	CHINA
BROND	RUSSIA

国际五大通用核数据库



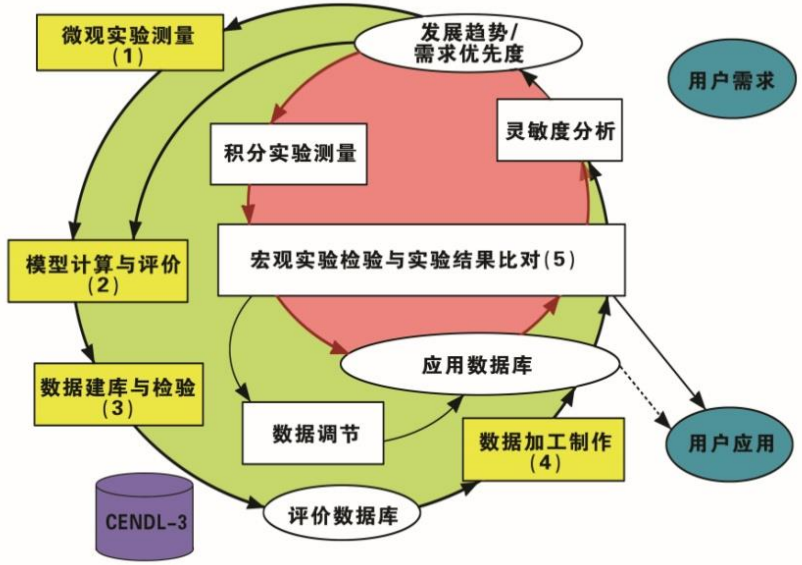
美国：ENDF: http://www.nndc.bnl.gov/
日本：JENDL: http://wwwndc.jaea.go.jp/index.html
欧洲：JEFF: http://www.oecd-nea.org/
中国：CENDL: http://www.nuclear.csdb.cn/cendl32.htm
俄国：BROND: http://www-nds.iaea.org/

II. Special-purpose libraries

CINDA	bibliographic
ENSDF	nuclear structure
EXFOR	experimental
FENDL	fusion applications
IBANDL	ion beam analysis
RIPL	reference input parameters for modeling
Other	Activation data, Medical Application, Safeguards, Standards …

核数据宏观检验

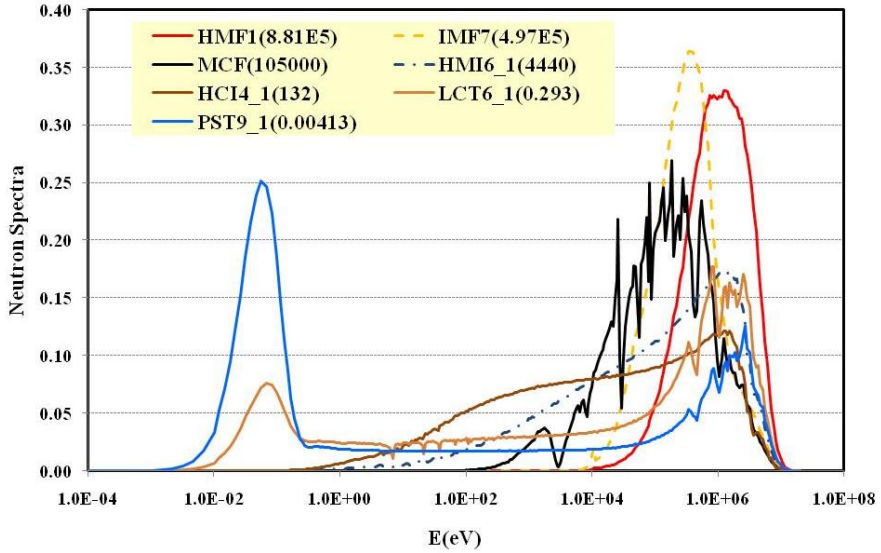
- 核数据宏观检验的作用
  - 评估质量，确定不确定度
  - 指导微观实验测量和评价
  - 为核数据改进提供反馈。

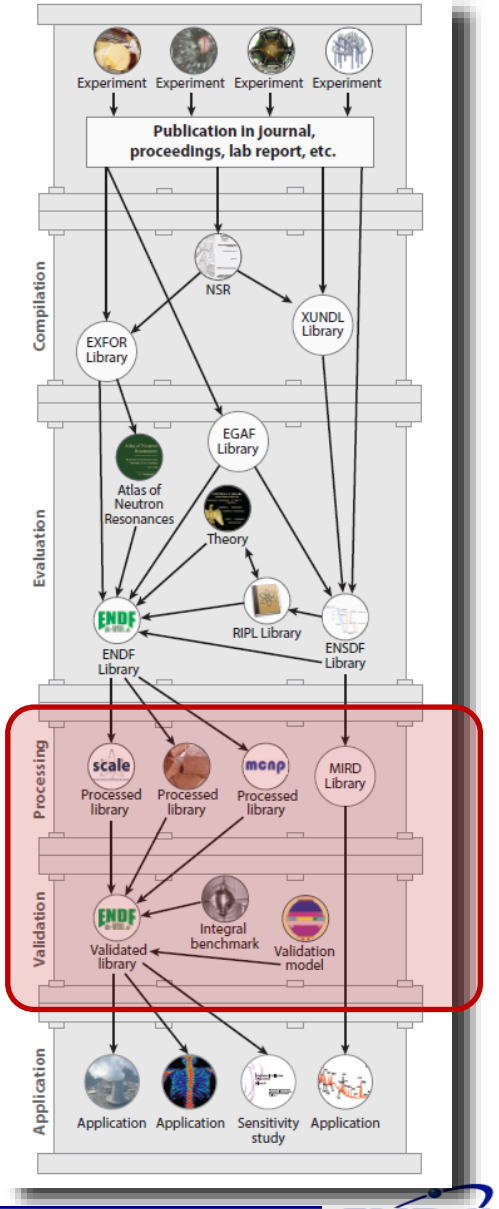


核数据工作流程

- 宏观检验的范围和有效性
  - 基准实验、分析技术

需要利用大量、多种类型的基准实验和积分量检验核数据的不同方面！

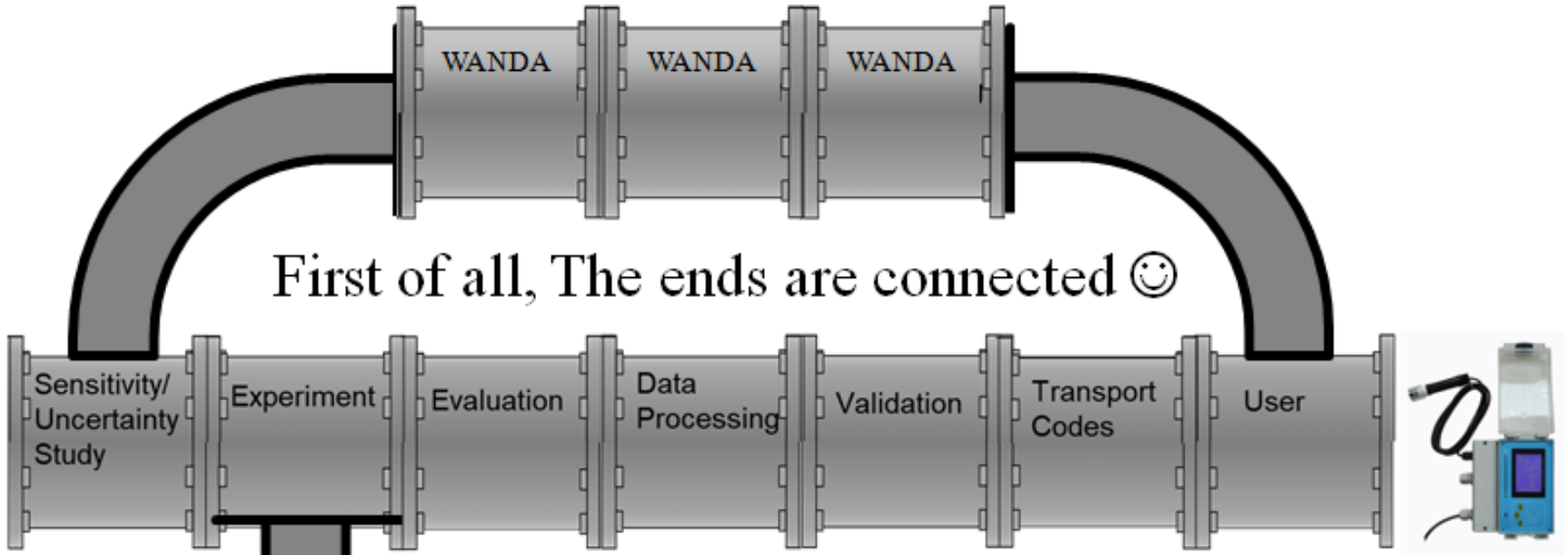


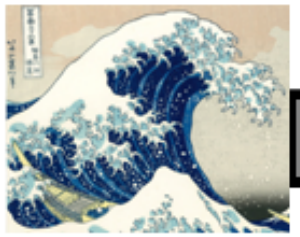


最后一道屏障：所有投入应用的核数据库，必须经过宏观检验验证其准确性，才能被用户所接受。**核反应堆和核技术应用成功的重要因素之一！**

"On the other hand the Pipeline has lots of great features, I (We) didn't know about..."

by L.A.Bernstein

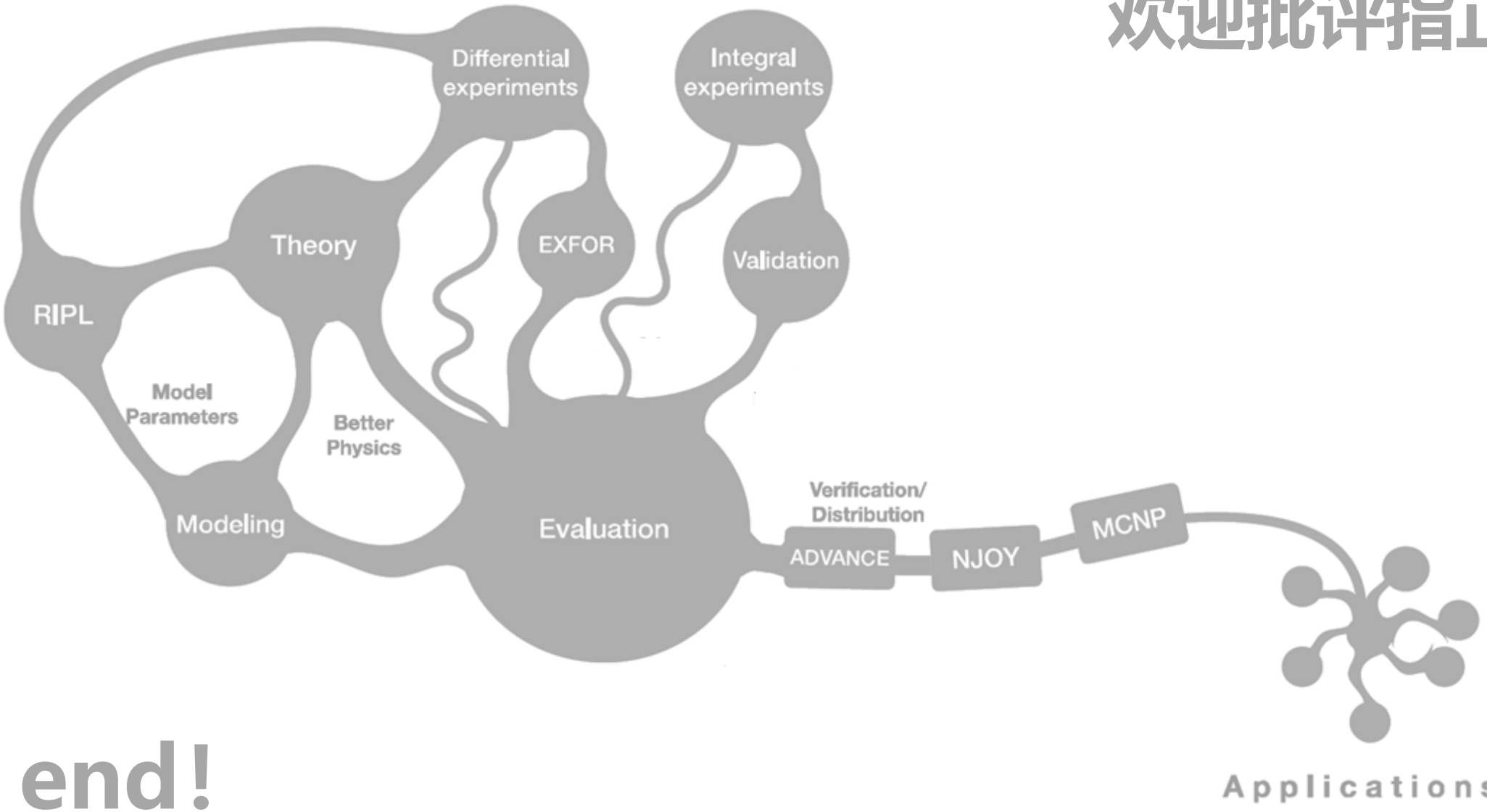




There is a torrent of new, high-quality data entering the system

Water quality sensors (many of whom are in this room) are an integral part of the pipeline

欢迎批评指正！



The end!