


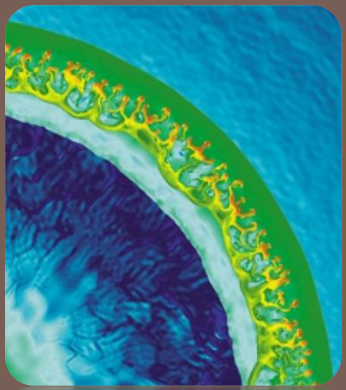


NUCLEAR ASTROPHYSICS AT HIAF

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Lanzhou University and Institute of Modern Physics, CAS




OMEG15, July 2--5, 2019, Kyoto


CIAE@Beijing
IMP@
Lanzhou
JUNA@
Xichang
HIAF@
Huizhou
Mongolia
Kyrgyzstan
Tajikistan
Pakistan
New Delhi
Nepal
Bhutan
Bangladesh
India
Myanmar
(Burma)
China
Beijing
北京
North Korea
Seoul
서울
South Korea
Sea of Japan
Nagoya
名古屋
Japan
Tokyo
東京
Osaka
大阪
Yellow Sea
Shanghai
上海
East China Sea
Taipei
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Taiwan
Hong Kong
香港
Earth
Show imagery
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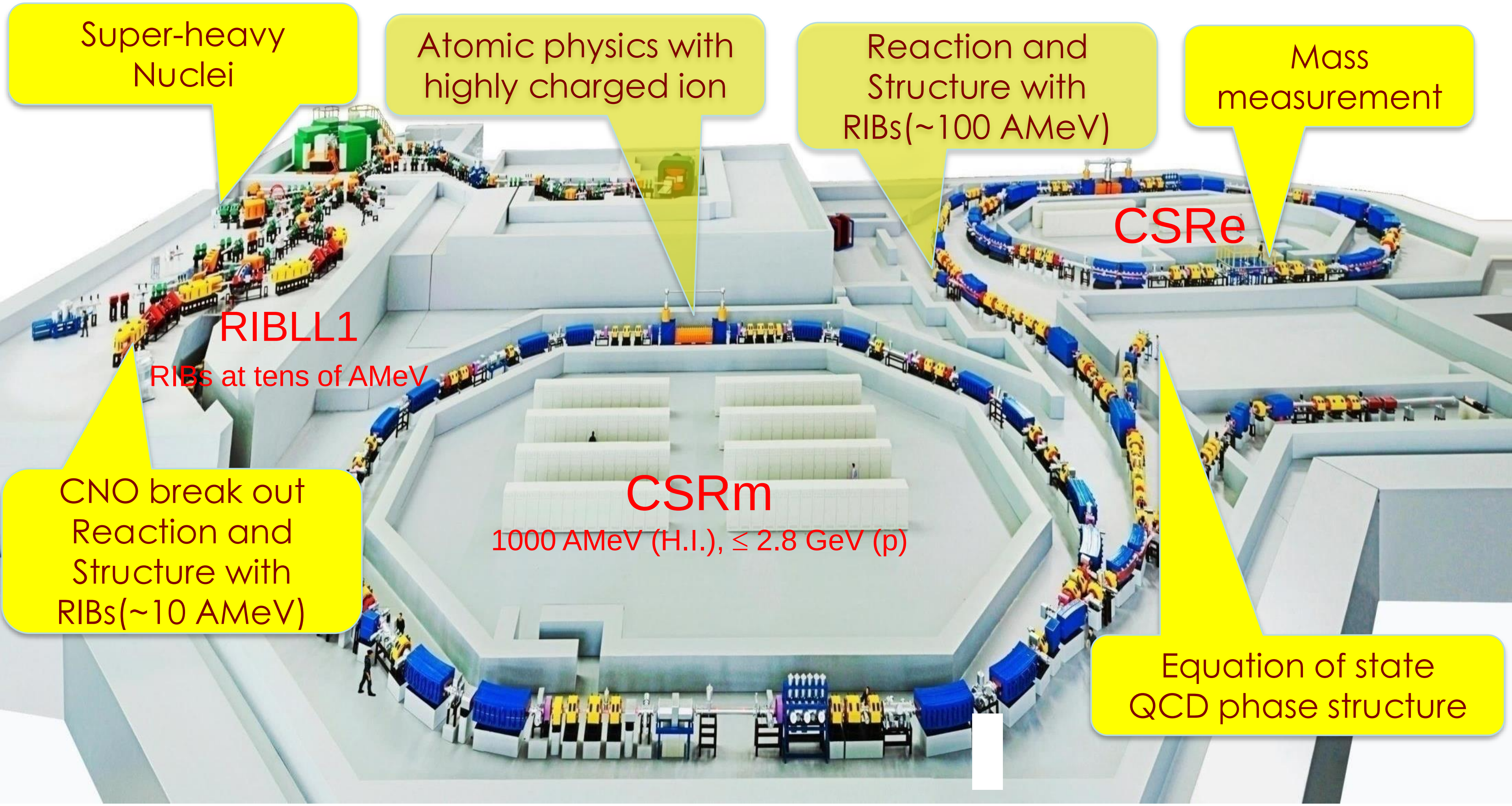
Heavy Ion Research Facility at Lanzhou (HIRFL)



Accelerators: cyclotron(SFC, SSC), synchrontron(CSRm), LINAC(ADS, LEAF)
Research area: rp-process(Mass measurement, CNO breakout), hydrostatic burning(Carbon Fusion Experiment, JUNA), Equation of state (CSR External Experiment), Super-havey Nulceus, nuclear reaction and structure, nuclear data

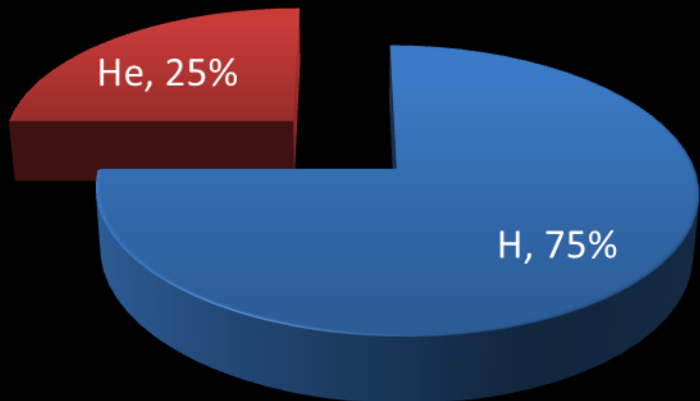
OUTLINE

- Nuclear Physics Problems in Astrophysics
- High Intensity heavy-ion Accelerator Facility (HIAF)
- Opportunities at HIAF

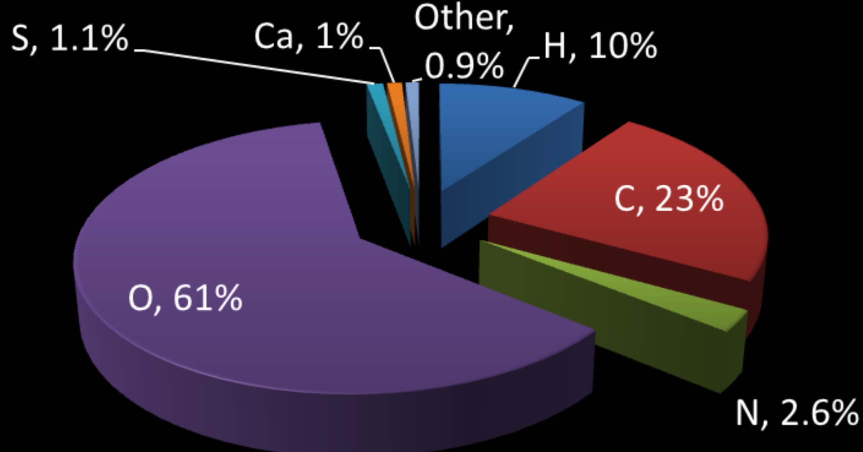
Origin of elements

JUNA

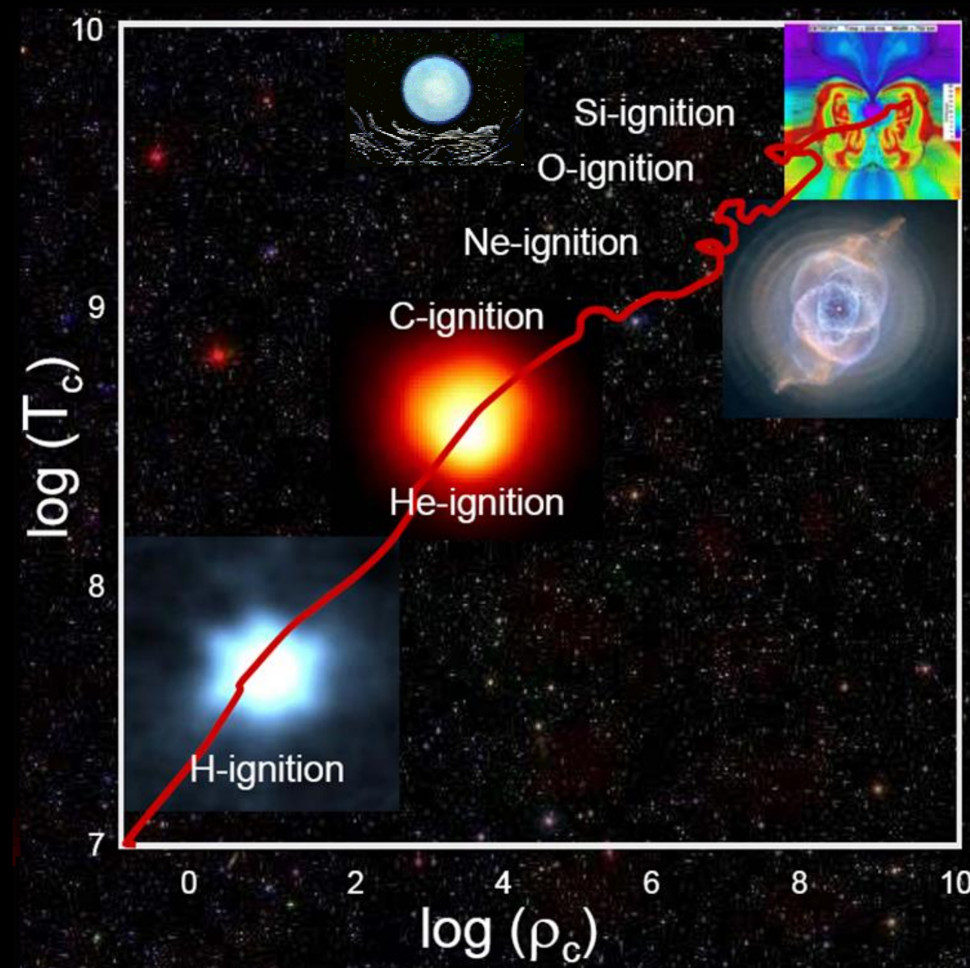
Others (^2H,^3He,^6Li,^7Li)<0.00001



30 mins after BBN

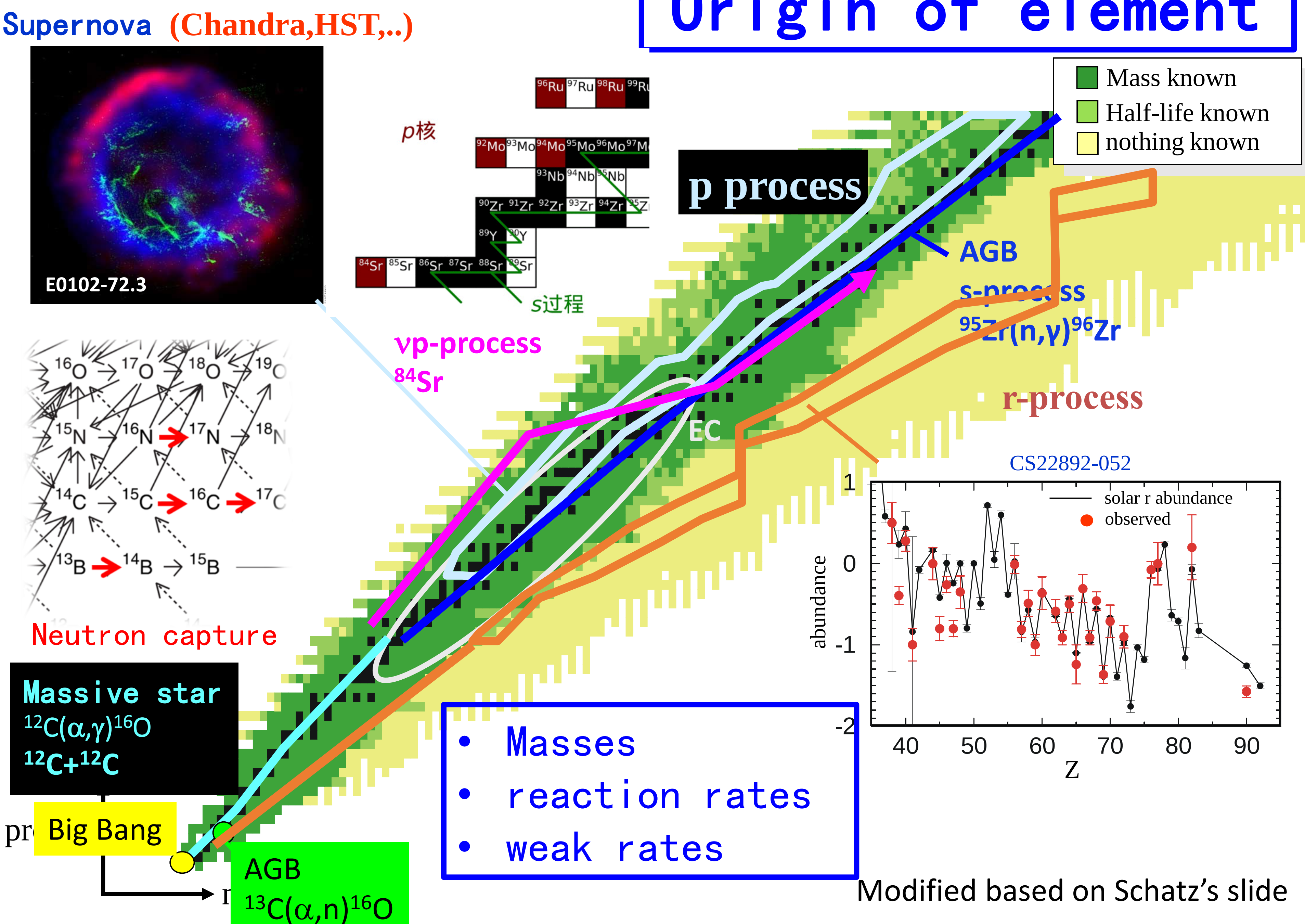


13.4 billions years latter,
Elements within our bodies



We are made of starstuff.

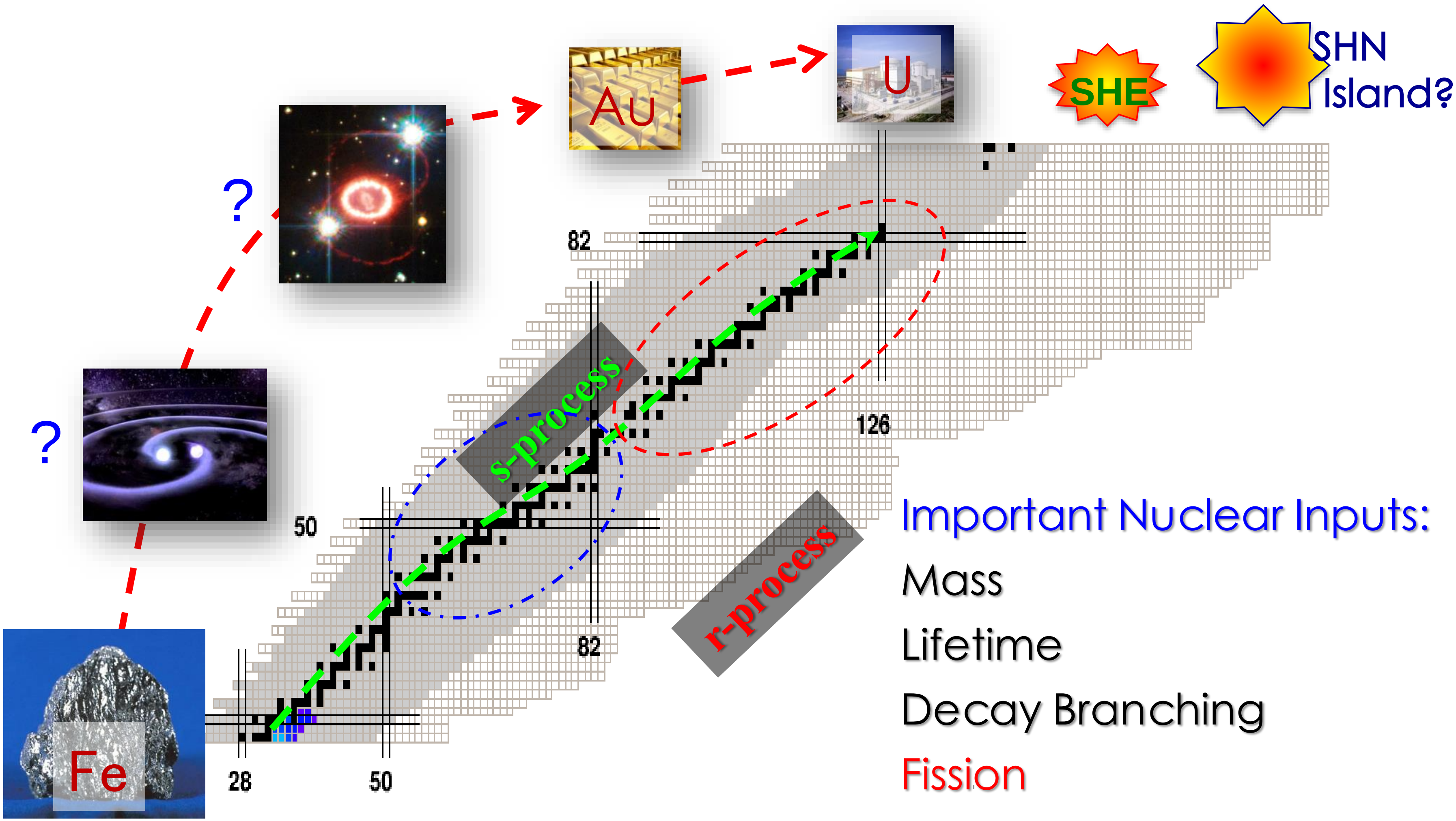
Origin of element



- Masses
- reaction rates
- weak rates

Modified based on Schatz's slide

How were the elements from iron to uranium made ?



Important Nuclear Inputs:

Mass

Lifetime

Decay Branching

Fission

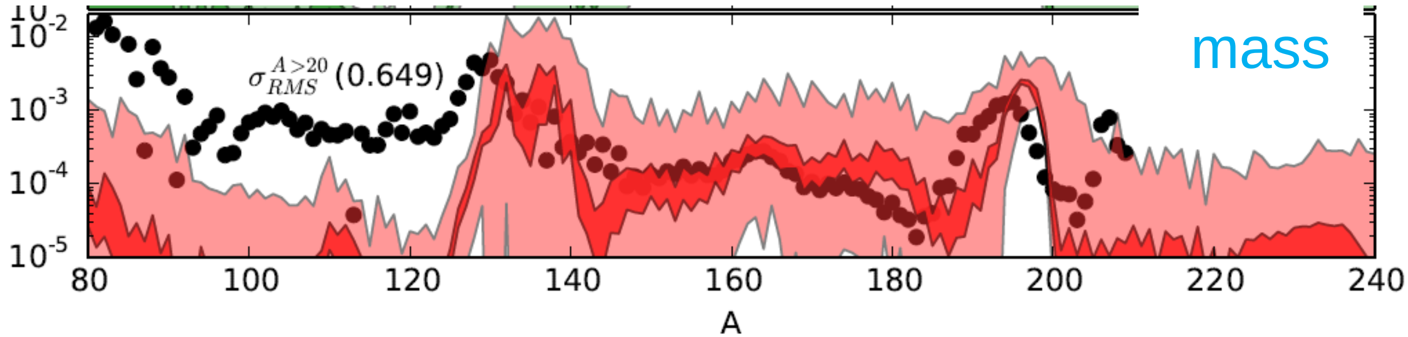
Capture rate

Neutrino interaction

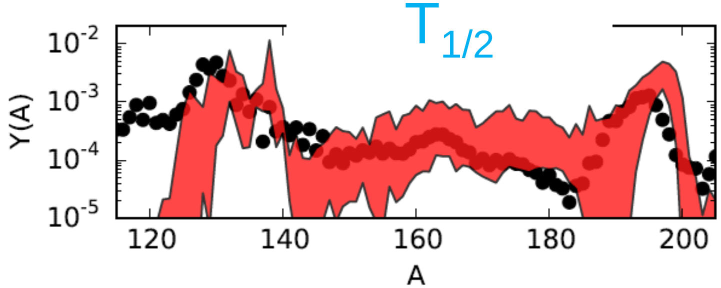
Atomic Spectroscopy is also important!

Nuclear uncertainties limit predictions

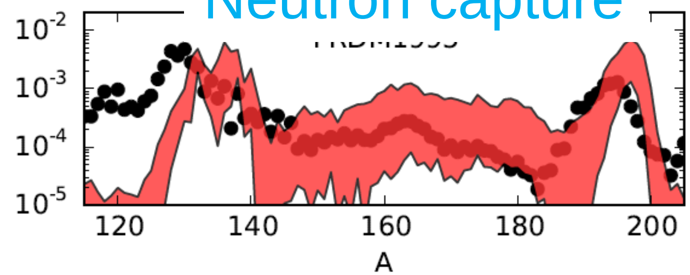
mass



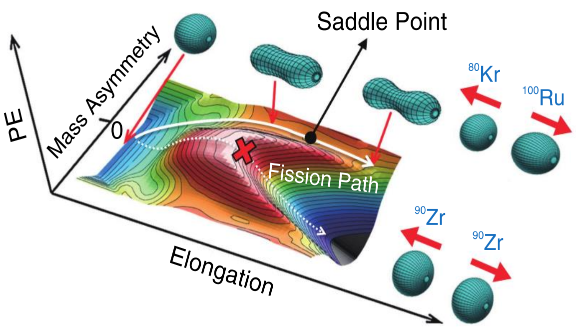
$T_{1/2}$



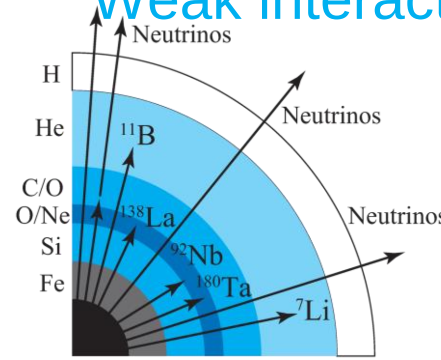
Neutron capture



Fission

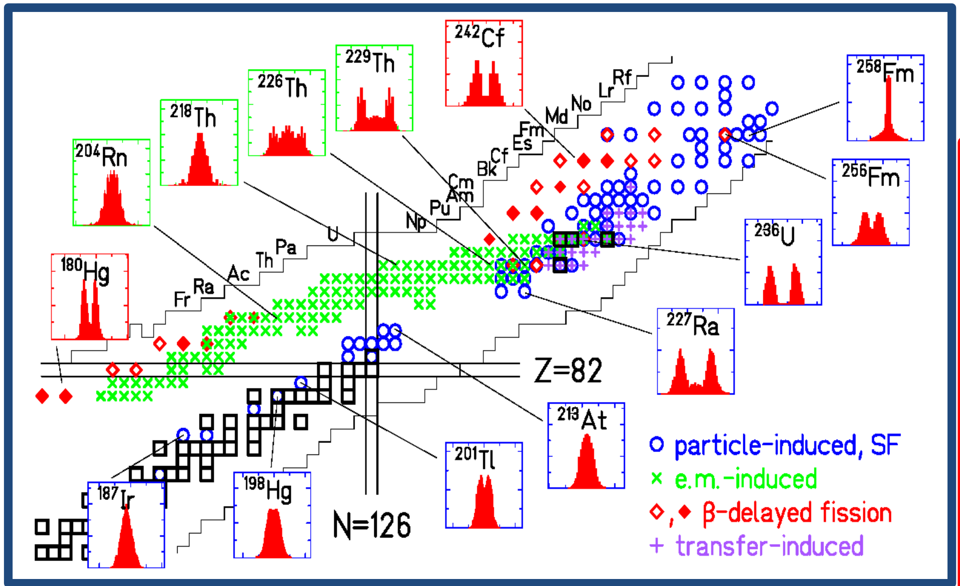


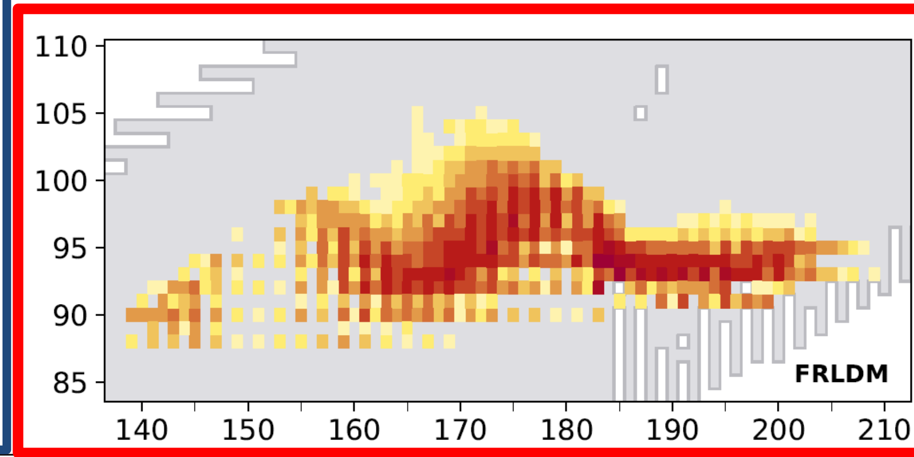
Weak interaction

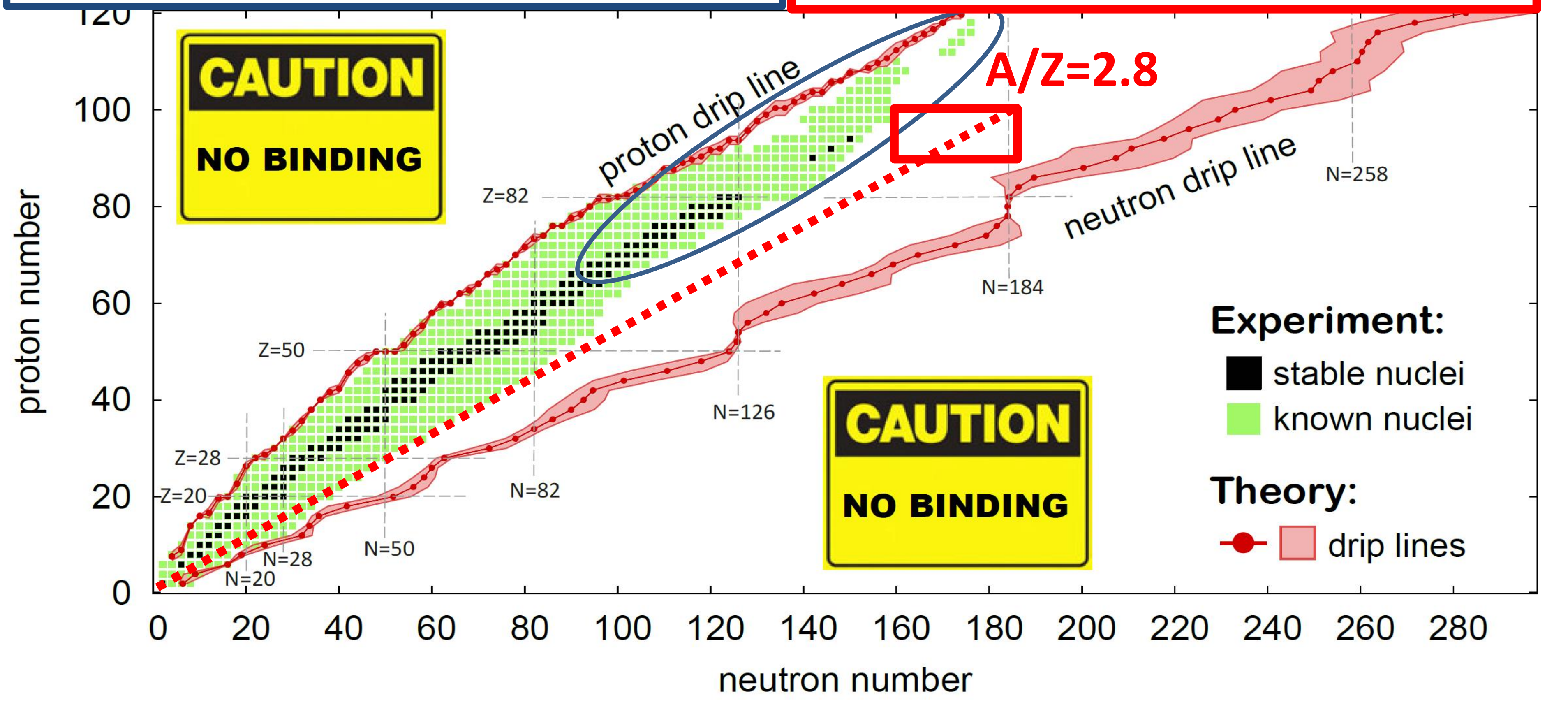


Important (n,f) in r-process

Vassh et al., arXiv:1810.08133v1

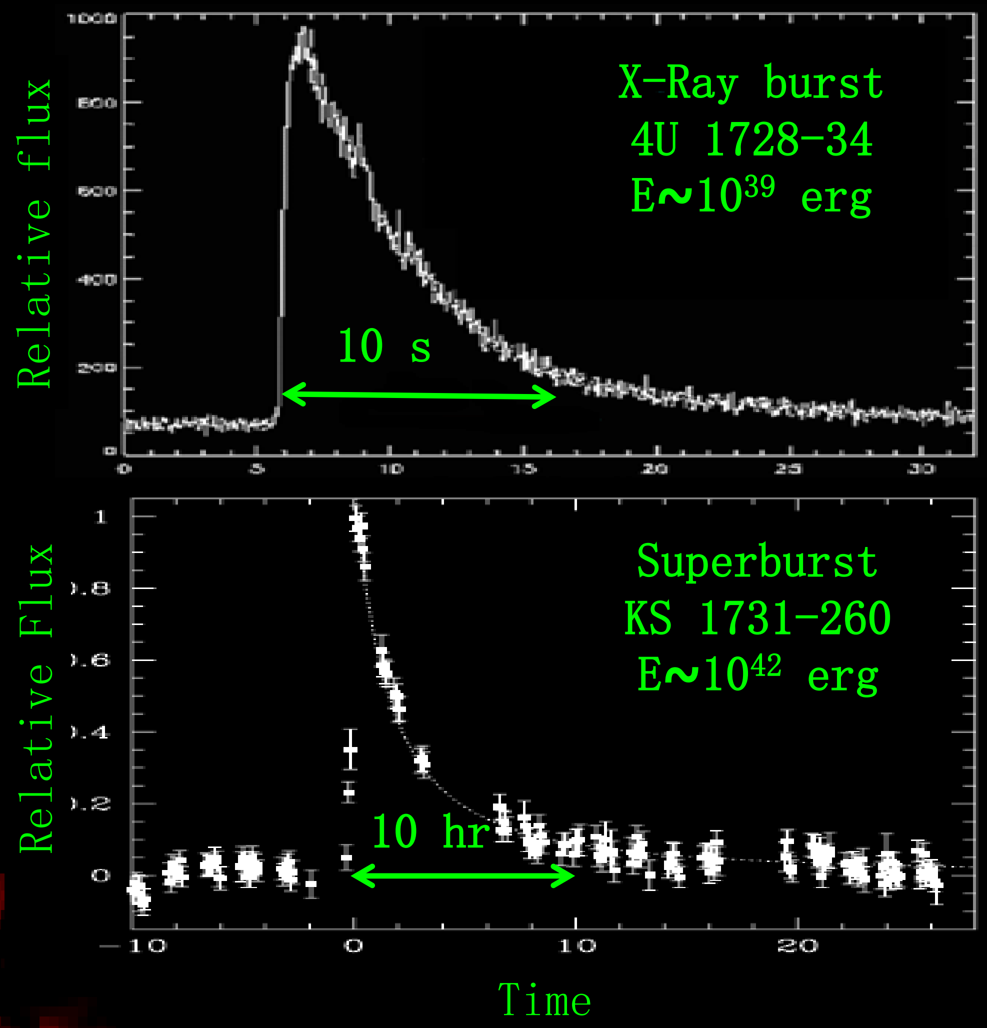




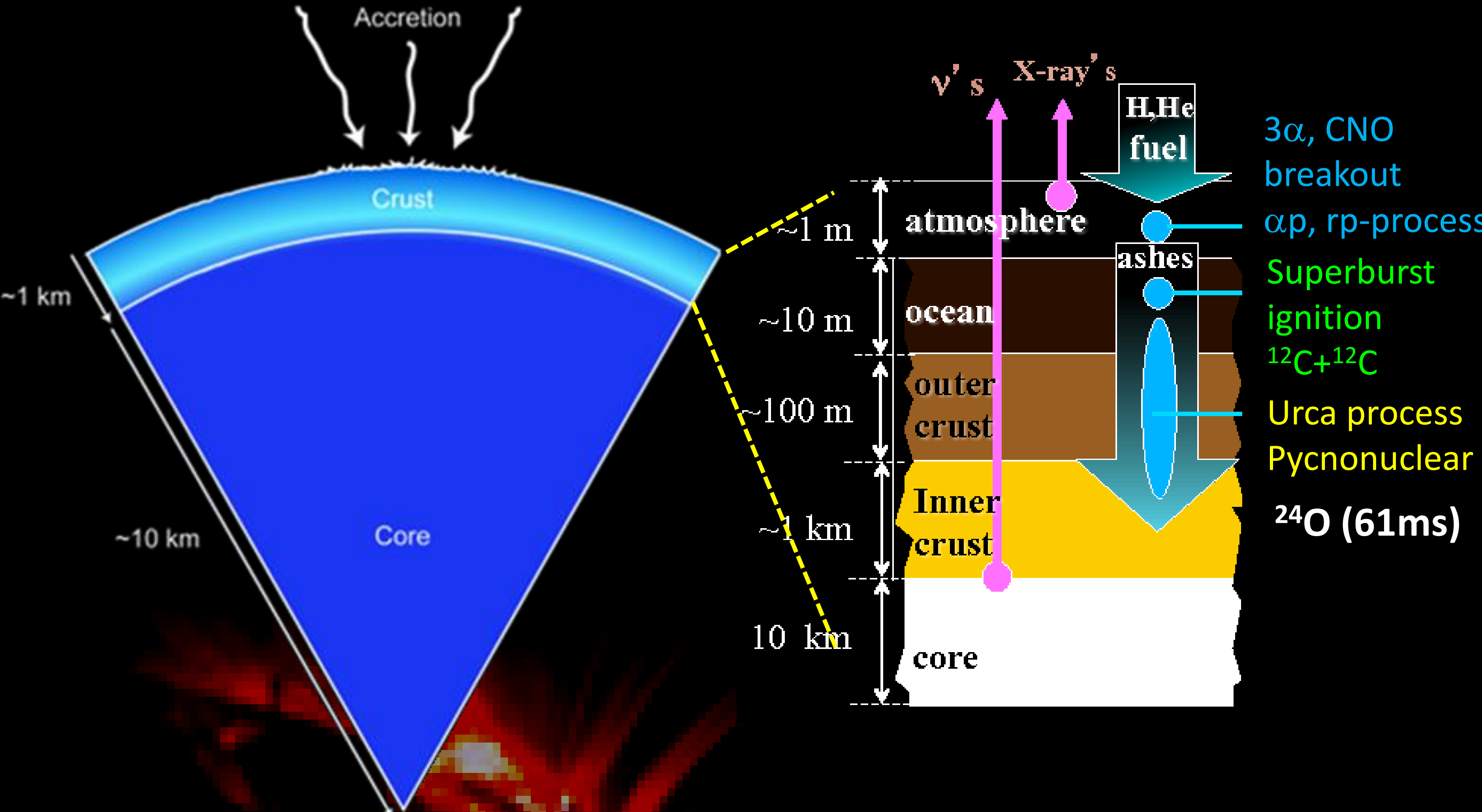


X-Ray burst

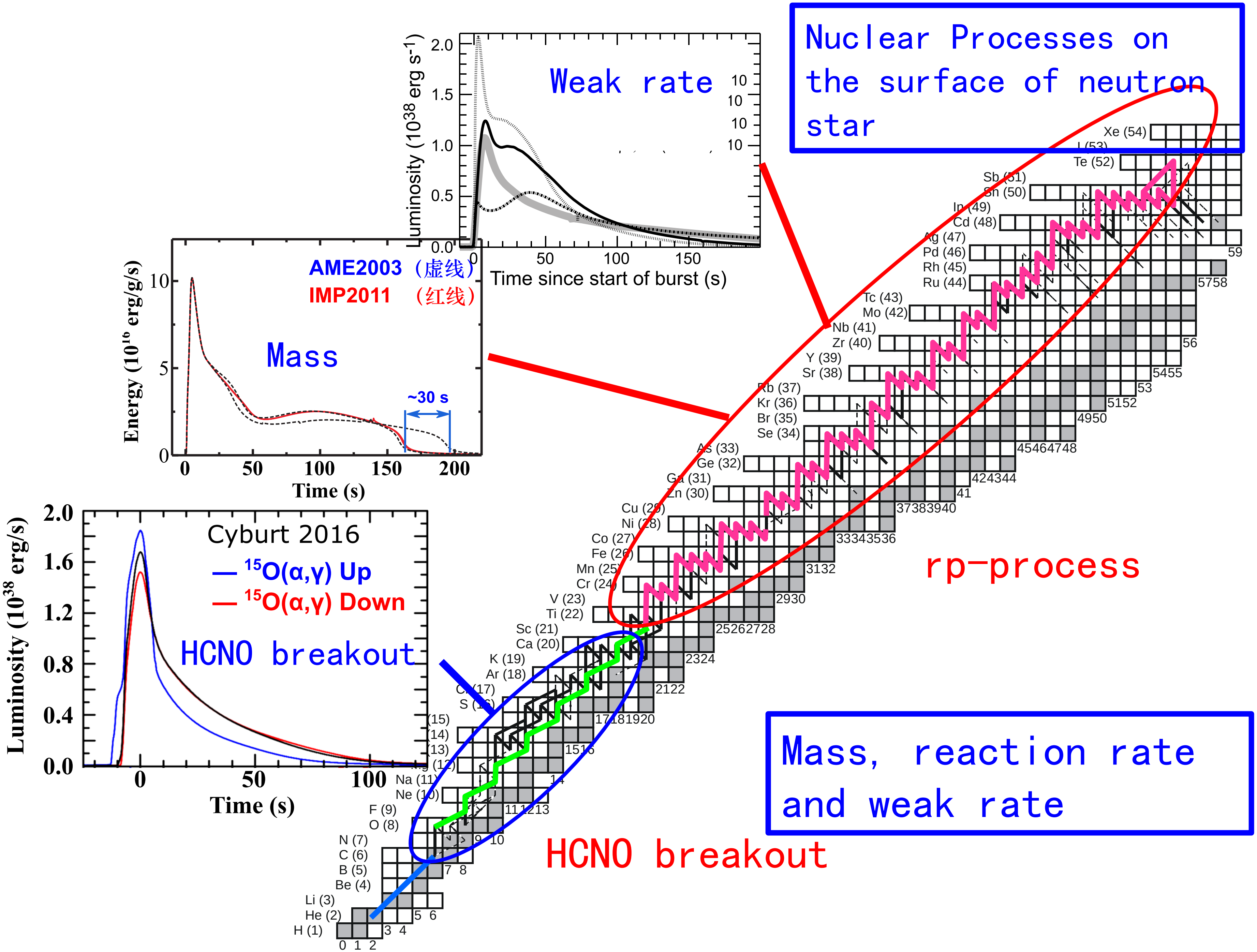

Companion star
Neutron star


X-Ray burst
4U 1728-34
E~10^39 erg
10 s
Relative flux
Superburst
KS 1731-260
E~10^42 erg
10 hr
Relative Flux
Time

X-Ray: Messenger from neutron star

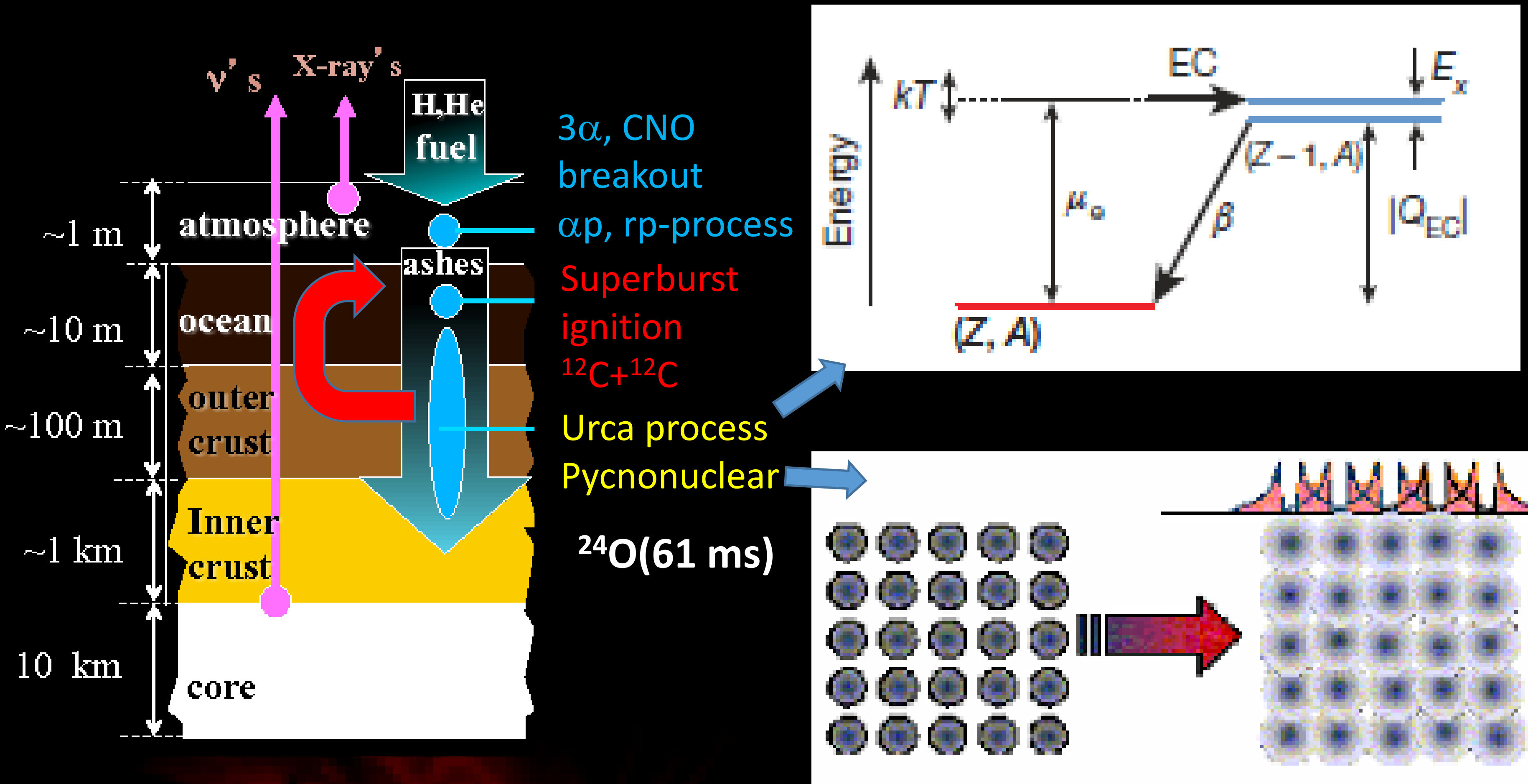


Energy spectra and light curve depends strongly on the nuclear processes in the curst.



Nuclear Processes on the surface of neutron star
Weak rate
Luminosity (10^{38} erg s^{-1})
Time since start of burst (s)
AME2003（虚线）
IMP2011 （红线）
Mass
~30 s
Energy (10^{16} erg/g/s)
Time (s)
Cyburt 2016
$^{15}O(\alpha,\gamma)$ Up
$^{15}O(\alpha,\gamma)$ Down
HCNO breakout
Luminosity (10^{38} erg/s)
Time (s)
rp-process
HCNO breakout
Mass, reaction rate and weak rate
H (1)
He (2)
Li (3)
Be (4)
B (5)
C (6)
N (7)
O (8)
F (9)
Ne (10)
Na (11)
Ca (20)
Sc (21)
Ti (22)
V (23)
Cr (24)
Mn (25)
Fe (26)
Co (27)
Ni (28)
Cu (29)
Zn (30)
Ga (31)
Ge (32)
As (33)
Se (34)
Br (35)
Kr (36)
Rb (37)
Sr (38)
Y (39)
Zr (40)
Nb (41)
Mo (42)
Tc (43)
Ru (44)
Rh (45)
Pd (46)
Ag (47)
Cd (48)
In (49)
Sn (50)
Sb (51)
Te (52)
I (53)
Xe (54)

Problems in superburst model



- Cooling: Urca pair (Electron Capture vs. β-decay, ^{29}Mg ←→ ^{29}Na)
- Heating: Density driven fusion reaction (eg. ^{24}O+^{24}O, ^{34}Ne+^{34}Ne)
- Ignition: temperature is too low to ignite reaction (^{12}C+^{12}C)

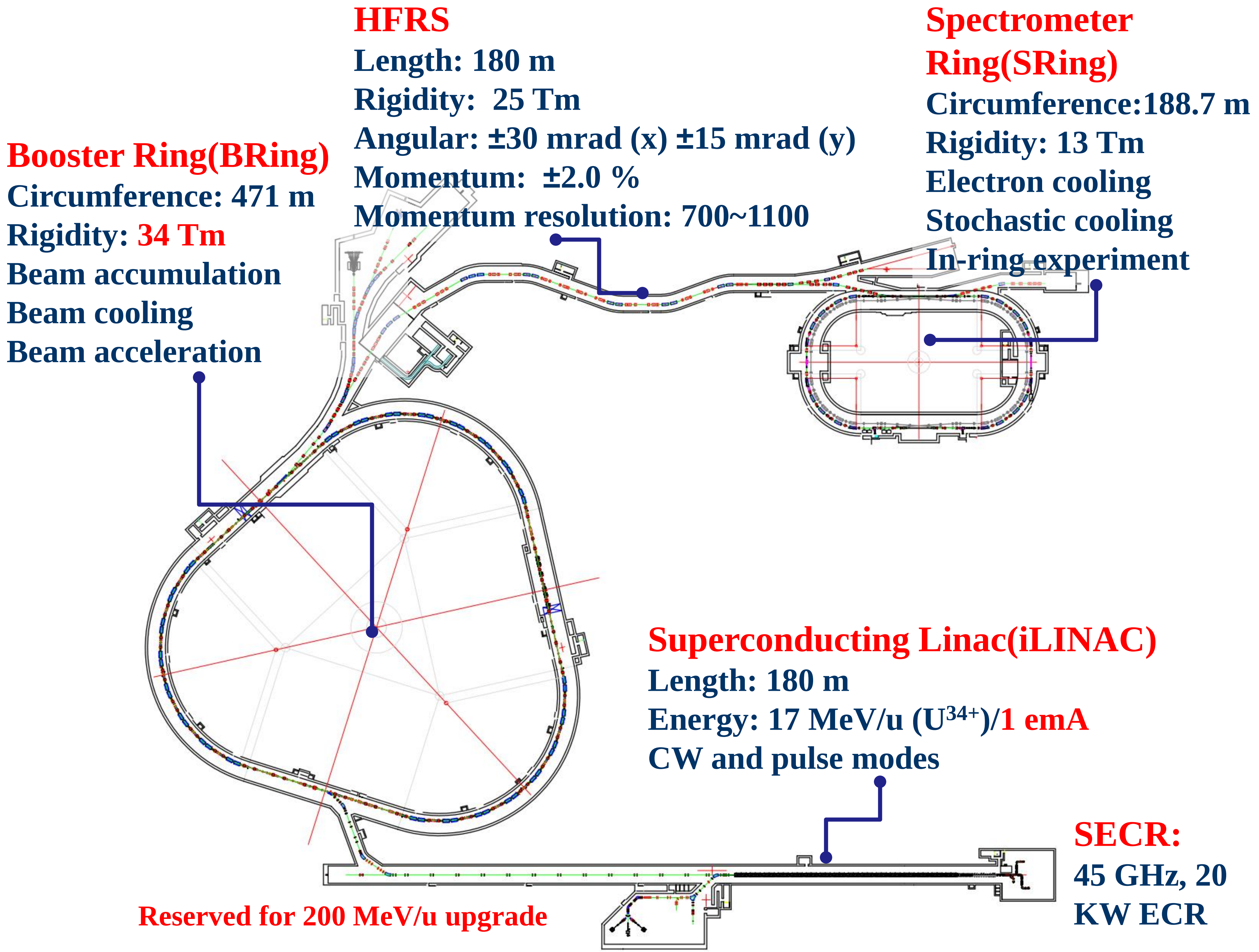
Nuclear Astrophysics with HIAF

- **Expanding nuclear landscape:**
  - **new isotopes**
- **Studying basic properties:**
  - **nuclear mass, $T_{1/2}$, J^{π}, decay branching, new magic number, giant resonances, dipole polarizabilities, and neutron skin**
- **Nuclear reactions:**
  - **neutron capture reaction, weak interaction, fission**

- **Equation of State of neutron star:**
  - **Heavy Ion Collision, Hypernucleus**

- **Atomic spectroscopy of highly charged ion**
- **Nuclear force**

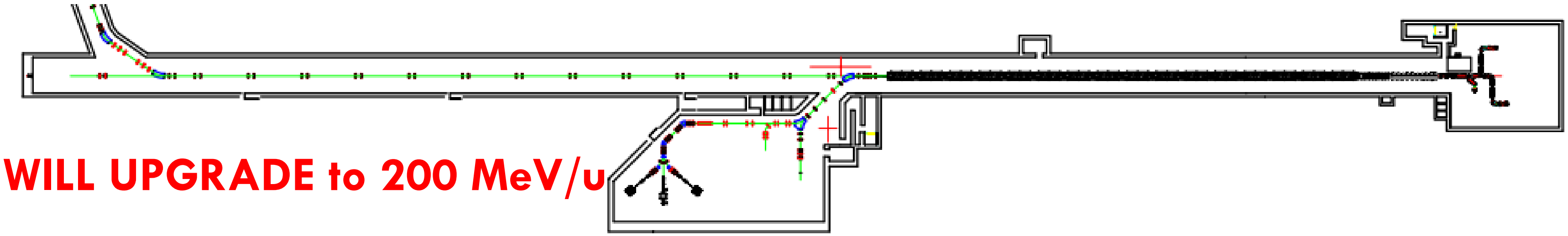
HIAF@2018-2025
CiADS@2019-2025
High Intensity heavy-ion Accelerator Facility (HIAF)



HFRS
Length: 180 m
Rigidity: 25 Tm
Angular: ±30 mrad (x) ±15 mrad (y)
Momentum: ±2.0 %
Momentum resolution: 700~1100
Spectrometer Ring(SRing)
Circumference:188.7 m
Rigidity: 13 Tm
Electron cooling
Stochastic cooling
In-ring experiment
Booster Ring(BRing)
Circumference: 471 m
Rigidity: 34 Tm
Beam accumulation
Beam cooling
Beam acceleration
Superconducting Linac(iLINAC)
Length: 180 m
Energy: 17 MeV/u (U34+)/1 emA
CW and pulse modes
SECR:
45 GHz, 20 KW ECR
Reserved for 200 MeV/u upgrade

Typical beams from iLinac

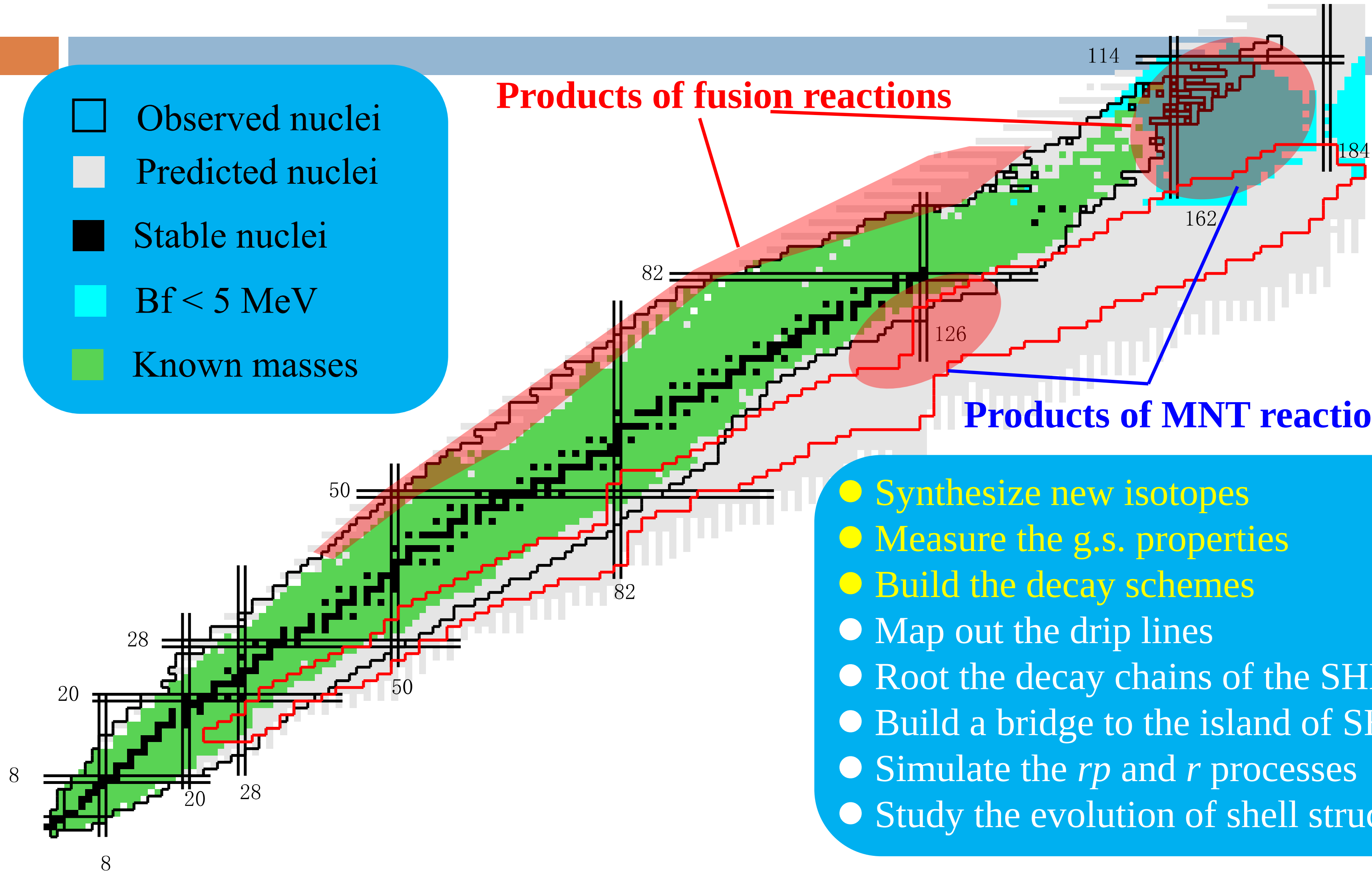
Ions	Intensity (emA)	Energy (MeV/u)
$^{238}U^{34+}$	1.0	17
$^{129}Xe^{27+}$	1.0	30
$^{78}Kr^{19+}$	1.0	30
$^{18}O^{6+}$	1.0	36
H_2^+	1.0	48



WILL UPGRADE to 200 MeV/u

Low Energy High current: 1 emA

New Isotopes with Low Energy Beams

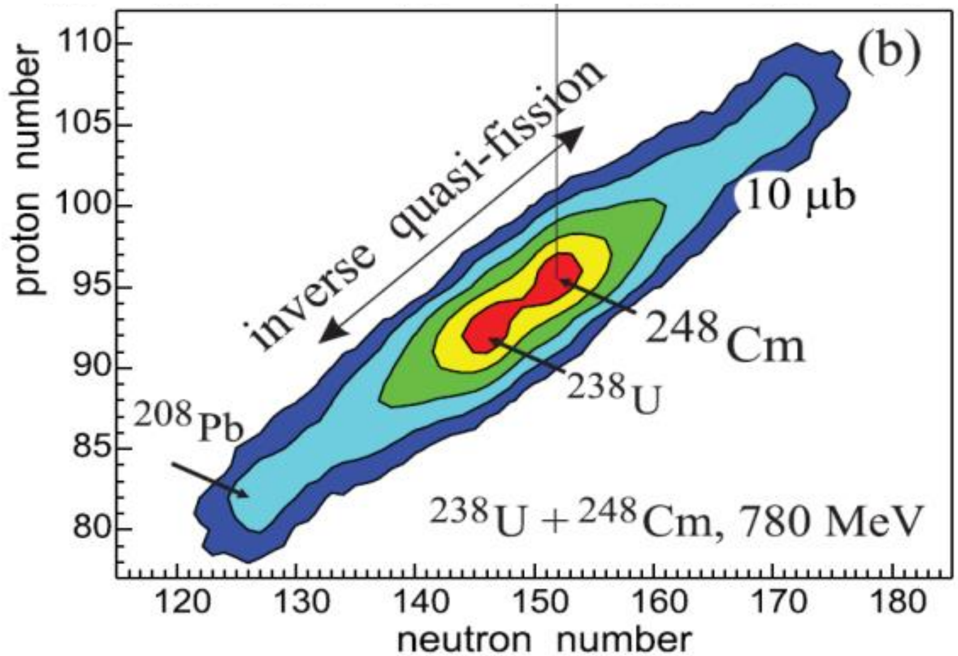


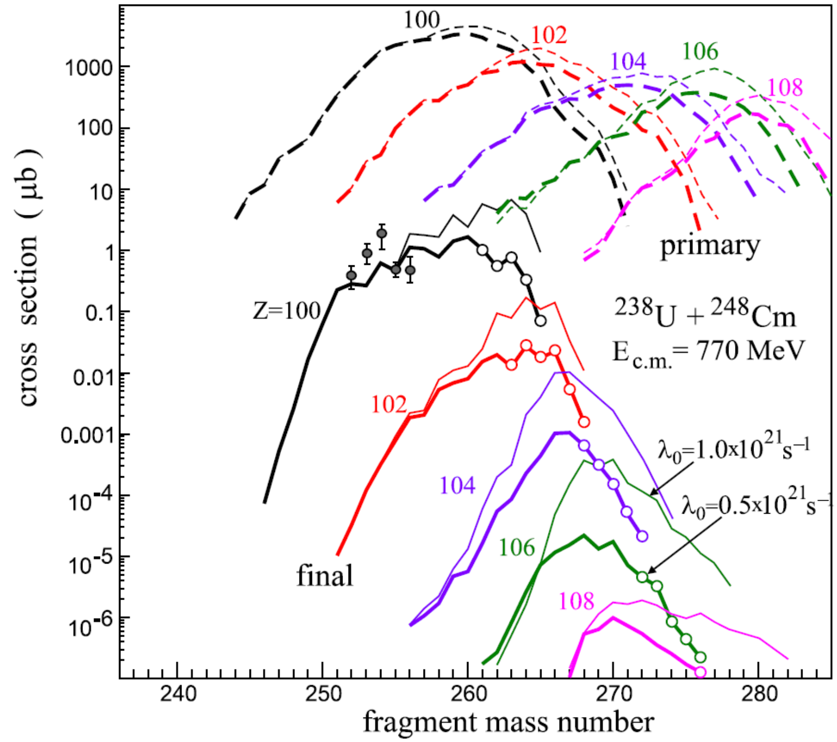
- Synthesize new isotopes
- Measure the g.s. properties
- Build the decay schemes
- Map out the drip lines
- Root the decay chains of the SHE
- Build a bridge to the island of SHN
- Simulate the *rp* and *r* processes
- Study the evolution of shell structure

The low-energy intense beams will enable producing very n-deficient nuclei by fusion reactions and particularly heavy and super-heavy n-rich nuclei by multi-nucleon transfer reactions.

Producing new trans-fermium(Z>100) isotopes

V. I. Zagrebaev et al. PRC 87, 034608 (2013).

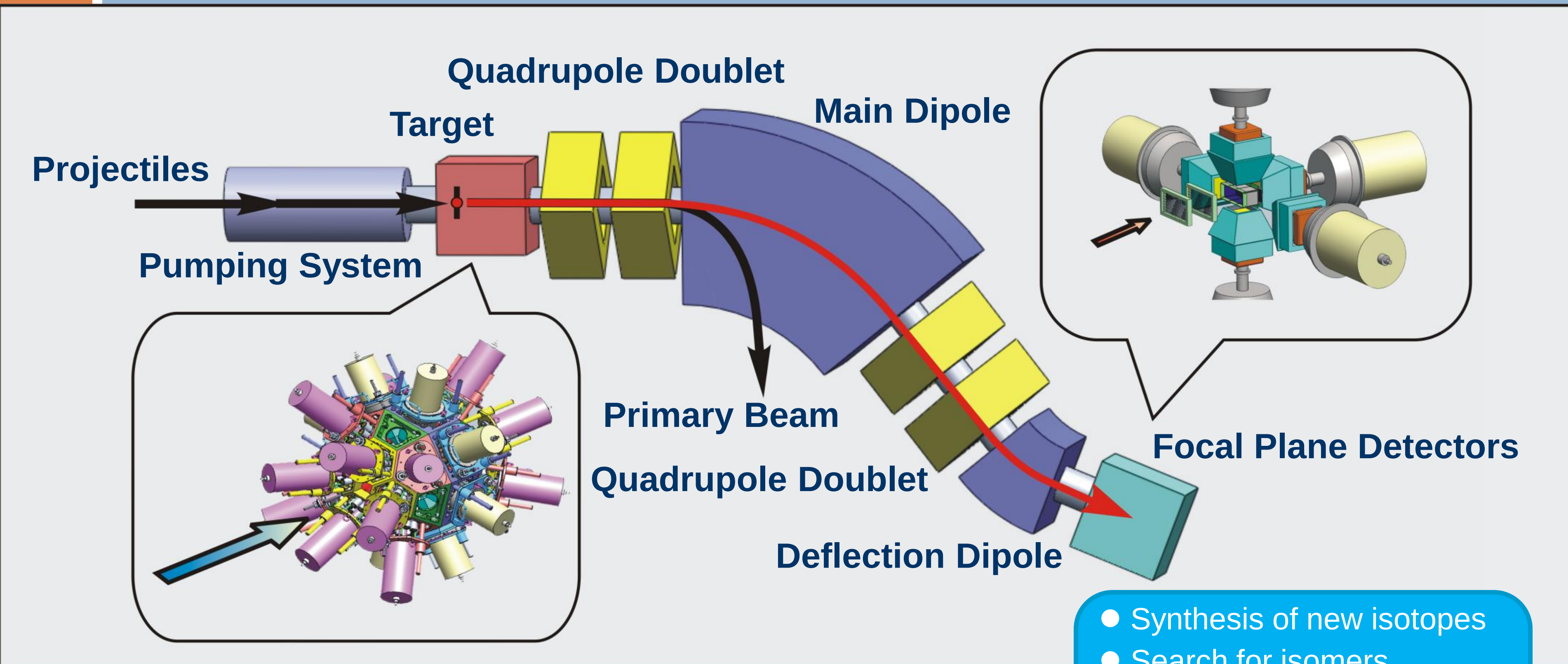




open circles: New isotopes

- new isotopes of transfermium elements (open circles) are produced with xsec ranging from ub to nb
- Lacking of data limits the reliability to the prediction

Gas-Filled Spectrometer

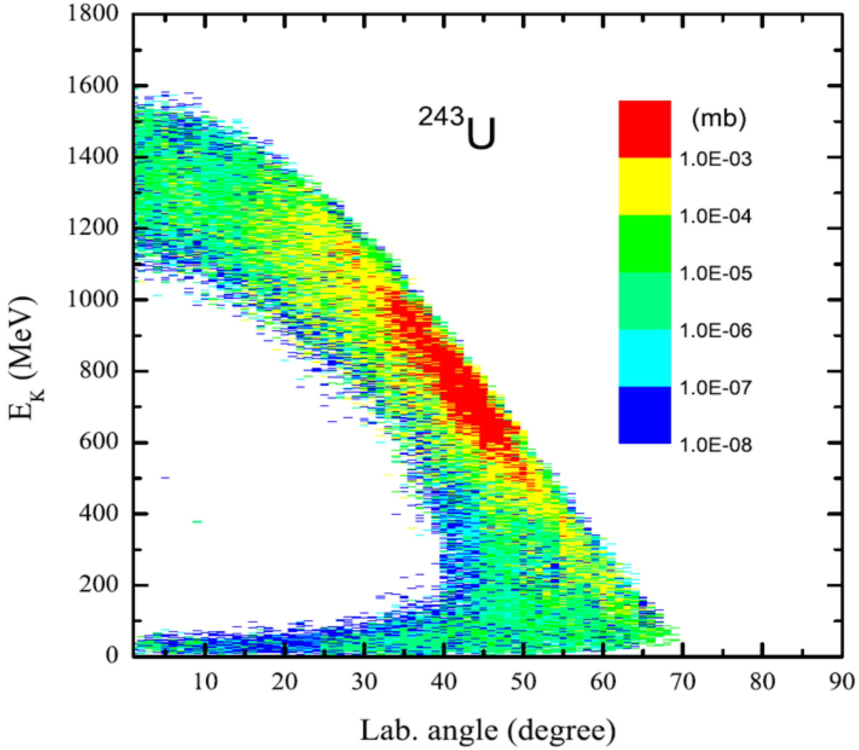


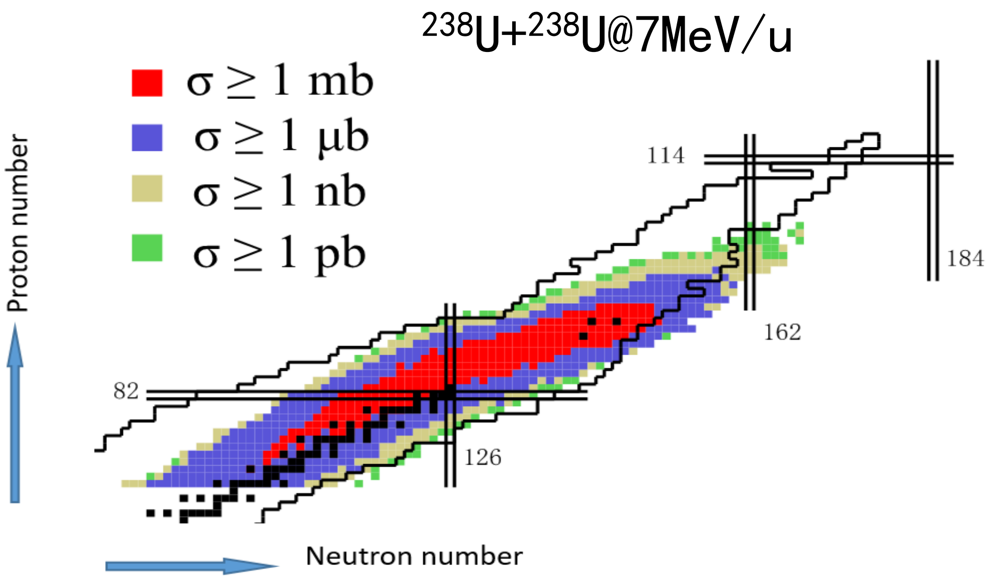
- Synthesis of new isotopes
- Search for isomers
- Decay spectroscopy
- In-beam spectroscopy
- Nuclear chemistry

A fast and high-efficient separator for fusion products.

By coupling with a gas cell followed by a RFQ cooler and buncher, pulsed high-quality low-energy beams are available for ion trap and collinear laser spectrometer.

Challenges in Multi-Nucleon Transfer Exp.



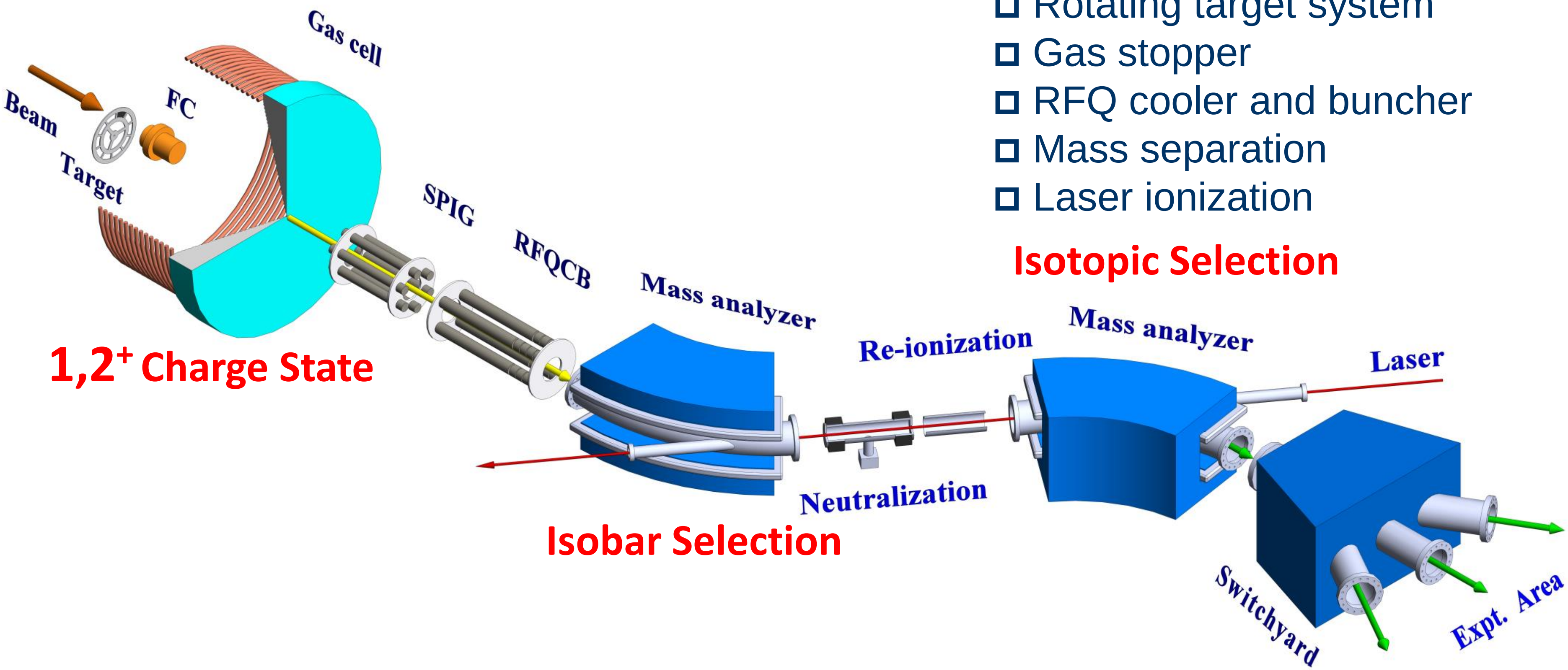


K. Zhao (CIAE)

- Large scattering angular range
- Large momentum spread
- Small yield for interesting isotopes

Multi-Nucleon Transfer spectromter

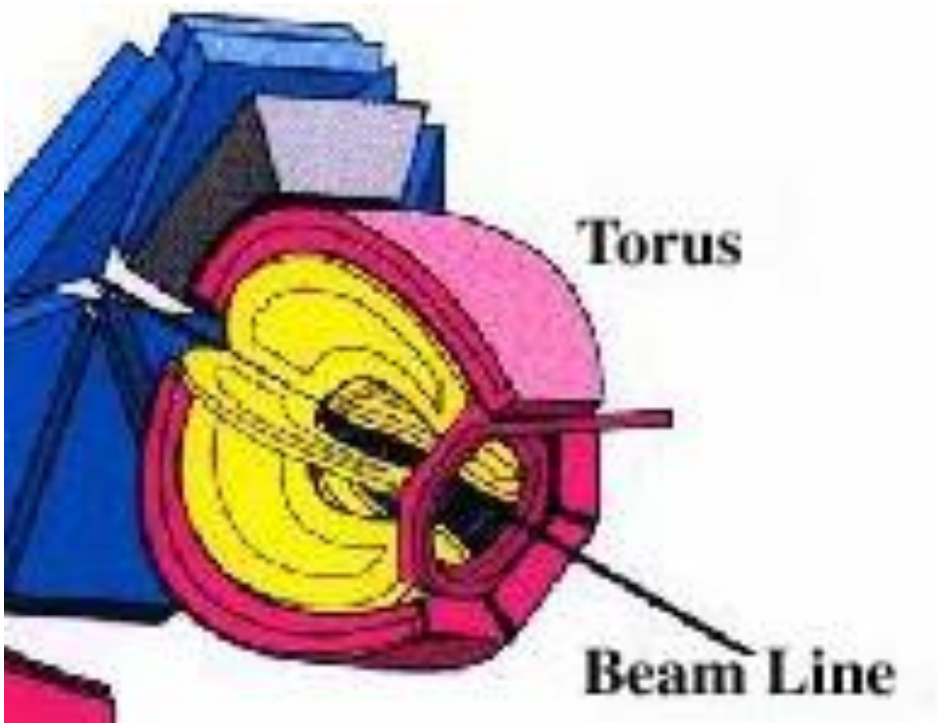
- Rotating target system
- Gas stopper
- RFQ cooler and buncher
- Mass separation
- Laser ionization



Pre-Separator is needed to use HIGH CURRENT

Ion trap
Collinear Laser Spectroscopy
Decay Spectroscopy
Post acceleration

Multi-Nucleon Transfer@7 MeV/u



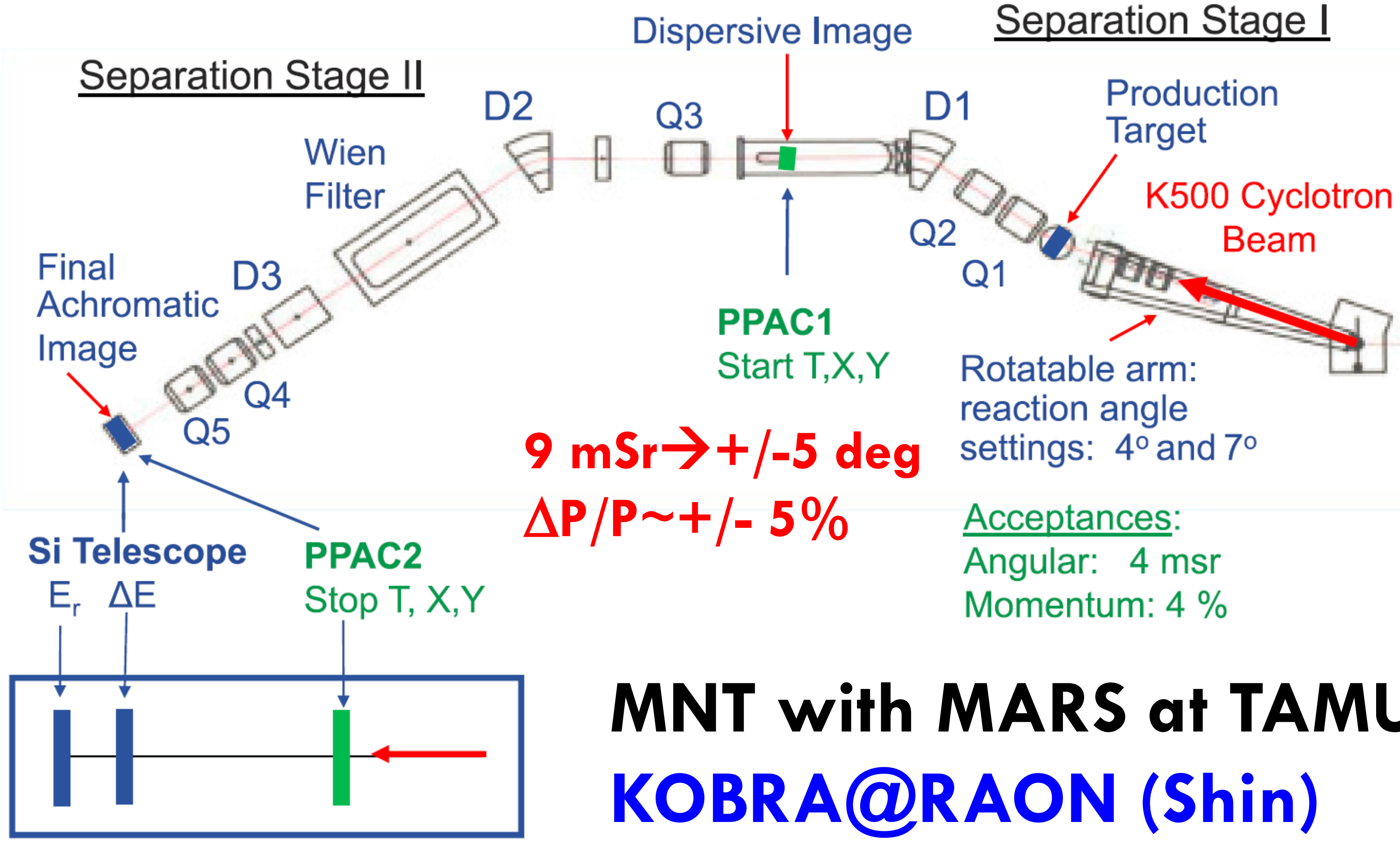
Large Acceptance Spectrometer

Miyatake, Kubono et al.

Multi-Nucleon Transfer@15 MeV/u

G. A. Souliotis, PHYSICAL REVIEW C **84**, 064607 (2011)

^{86}Kr at 15 MeV/u



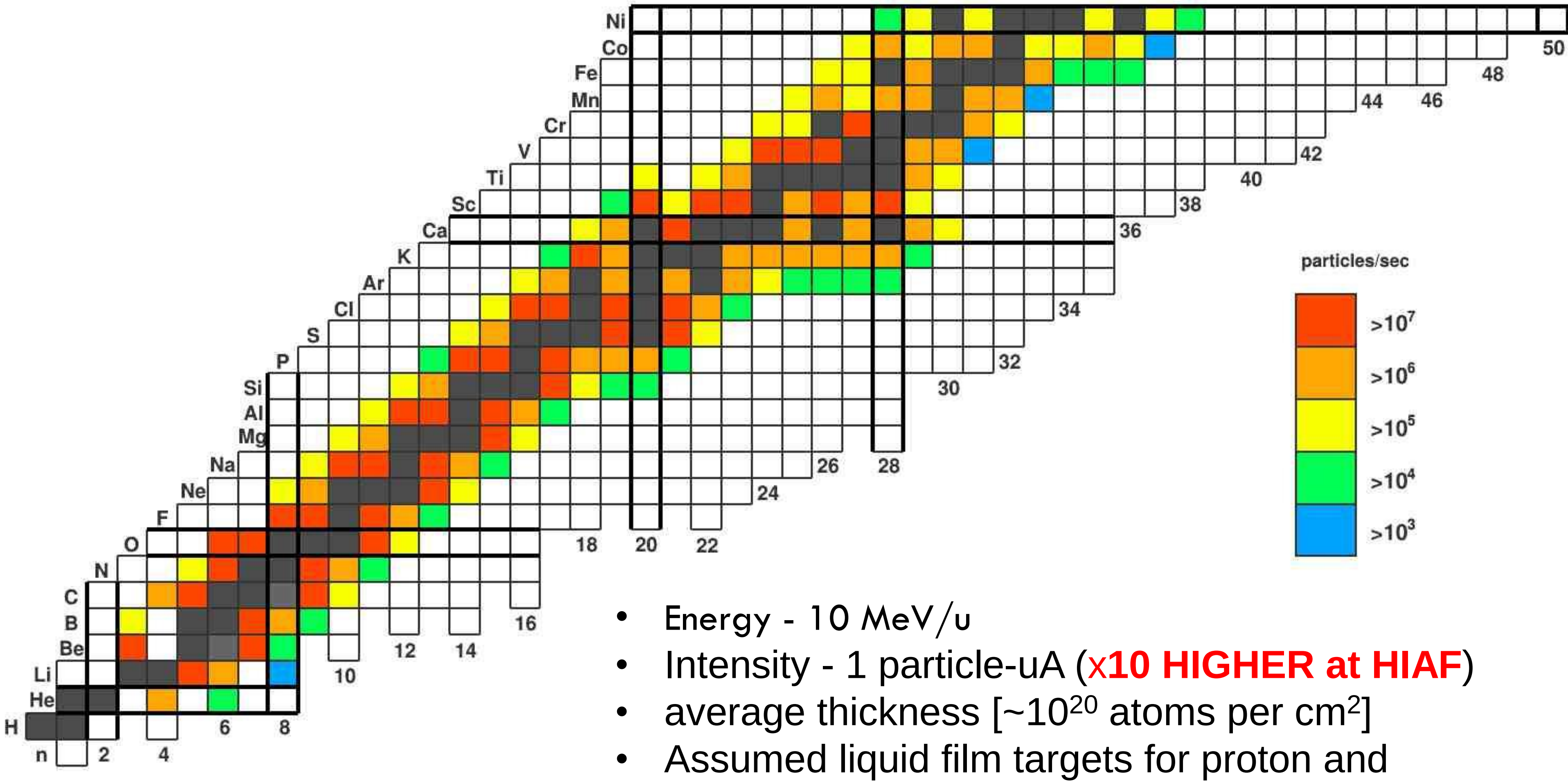
9 mSr→+/-5 deg

ΔP/P~+/- 5%

MNT with MARS at TAMU

KOBRA@RAON (Shin)

In-flight RIBs at low energies

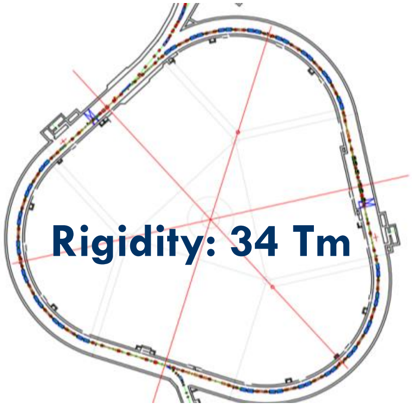


- Energy - 10 MeV/u
- Intensity - 1 particle-uA (x**10 HIGHER at HIAF**)
- average thickness [~10^{20} atoms per cm^2]
- Assumed liquid film targets for proton and deuterons and solid rotating targets for Be and C

https://www.phy.anl.gov/airis/rates_expected.html

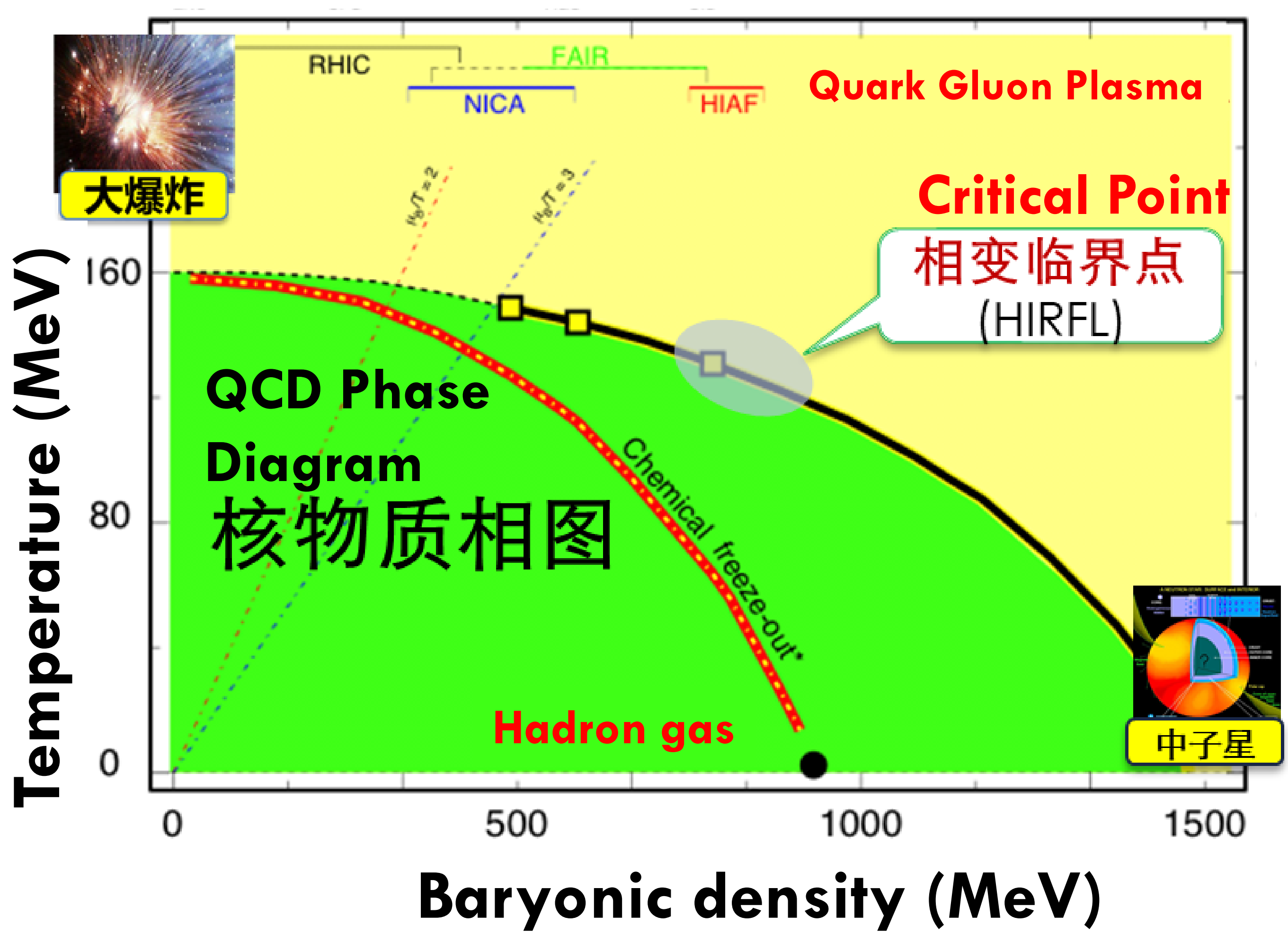
Typical beams from BRing

Ions	Intensity (ppp)	Energy (MeV/u)
$^{238}U^{34+}$	1.0×10^{11}	800
$^{129}Xe^{27+}$	1.8×10^{11}	1400
$^{78}Kr^{19+}$	3.0×10^{11}	1750
$^{40}Ar^{12+}$	5.0×10^{11}	2300
$^{18}O^{6+}$	6.0×10^{11}	2600
p	2.0×10^{12}	9300

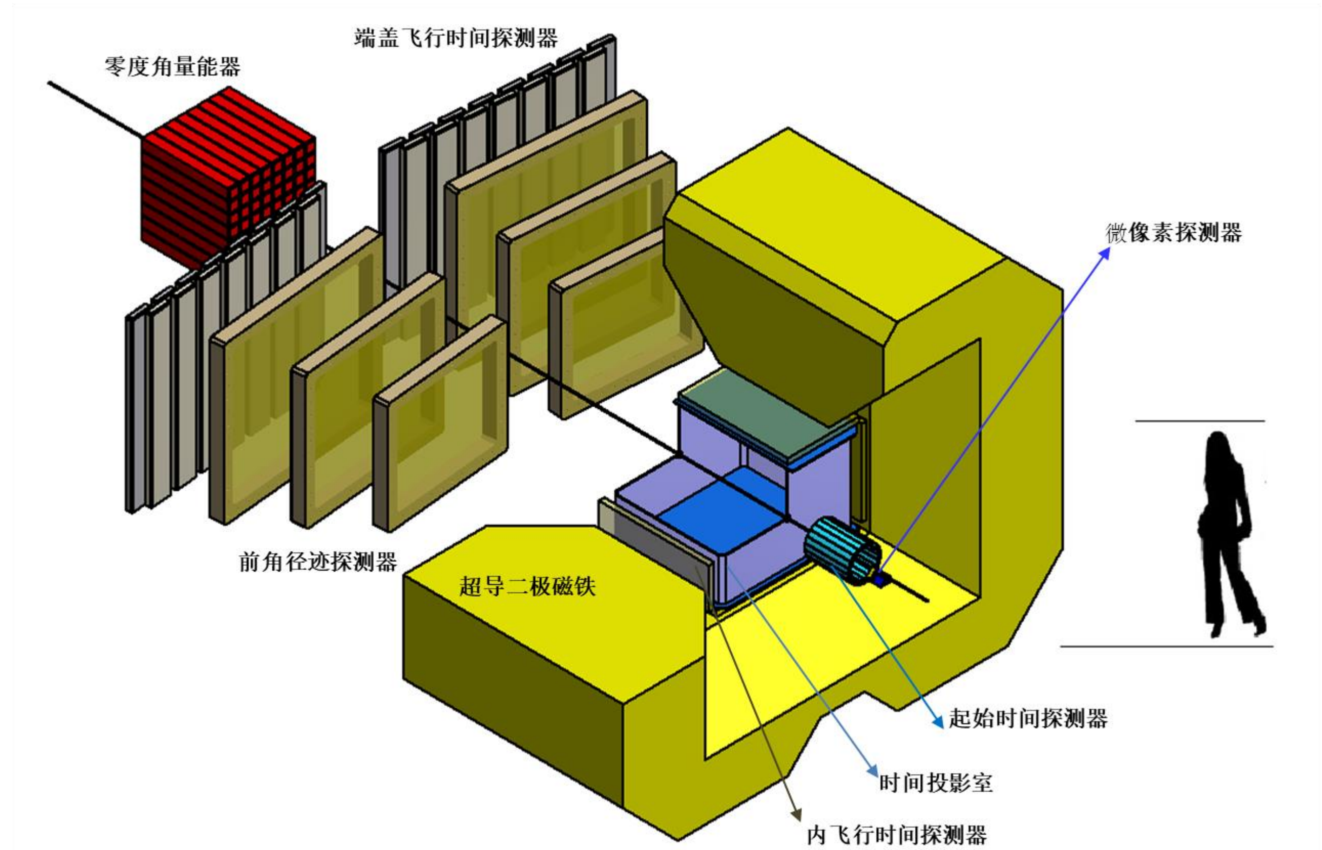


- Higher energies than RIBF and FRIB
- Even higher energies could be available with stripper
- 1% beam from iLINAC
- iLINAC+Bring sharing beams with similar A/Q

Searching critical point of strongly interacting matter

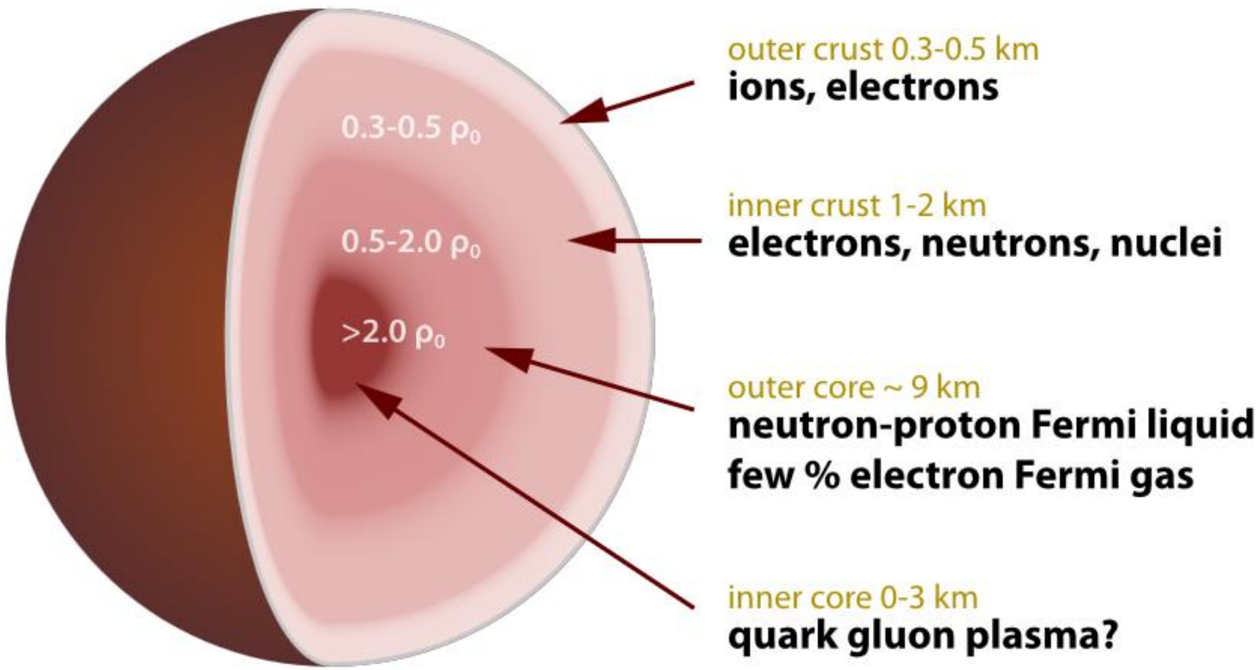


CEE Spectrometer



Courtesy of N. Xu (IMP)

Hypernucleus

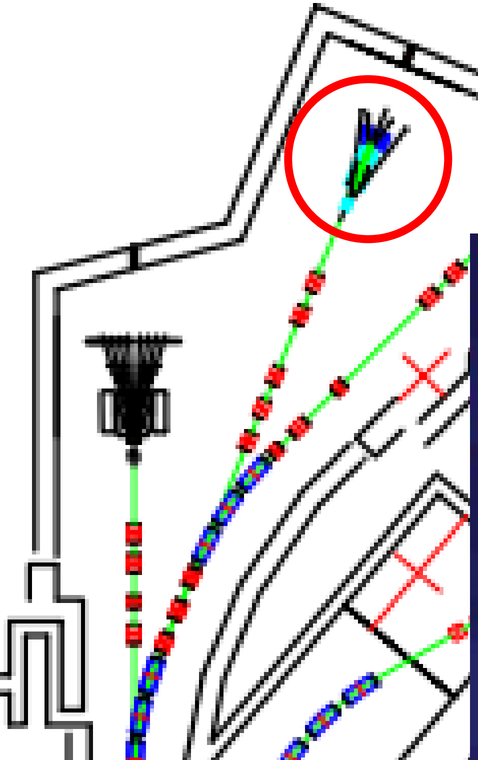


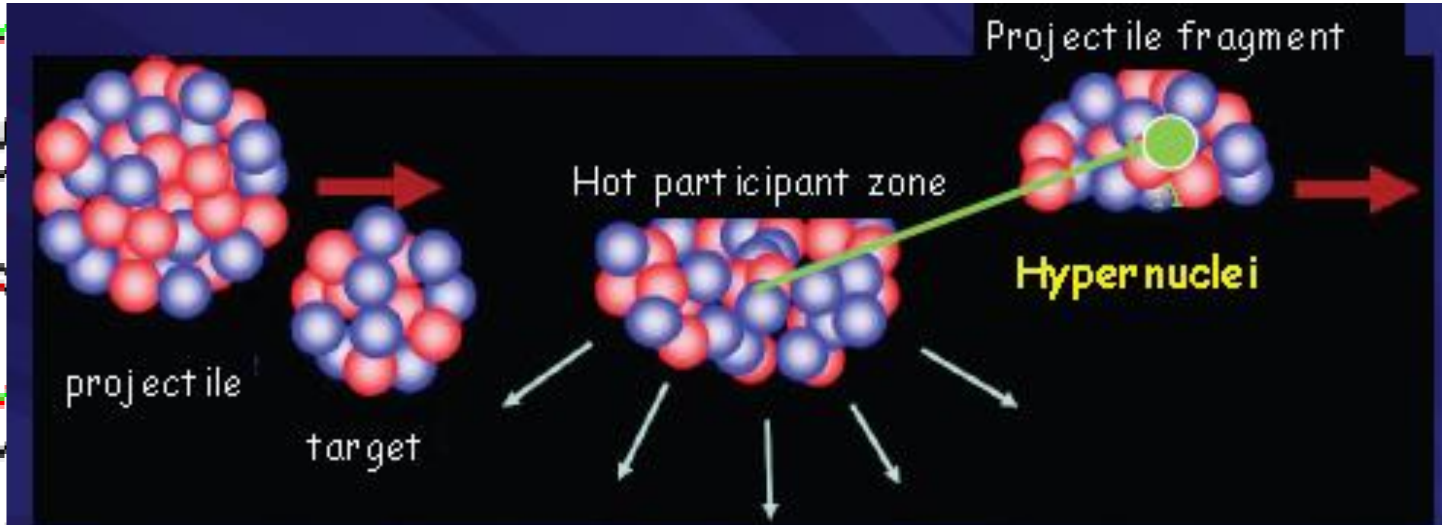
Strong quarks may exist in the core of Neutron Star

EOS can impact r-process nucleosynthesis (Wanajo)

ΛN interaction is needed

Hypernucleus

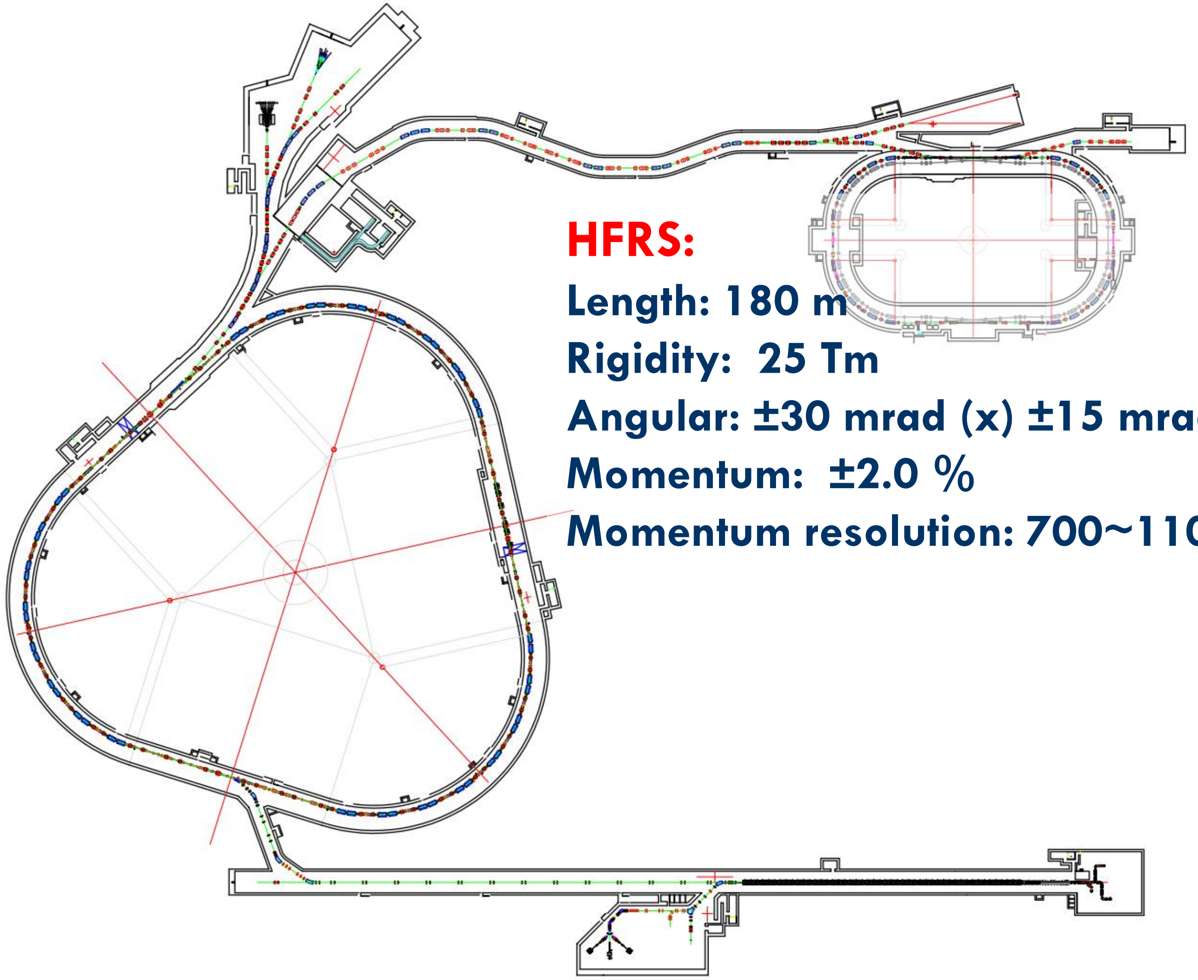




- AT HIAF
  - At 4.25 A GeV. Higher energy than NuSTAR/FAIR (2 A GeV)
  - Single- and double-Λ hypernuclei
  - Triple-Λ hypernuclei with proton beams (9 GeV)
  - Dedicated permenent setup in high energy cave
  - Flexibility for R&D

T. Saito(RIKEN)

HIAF Fragment Separator (HFRS)



HFRS:

Length: 180 m

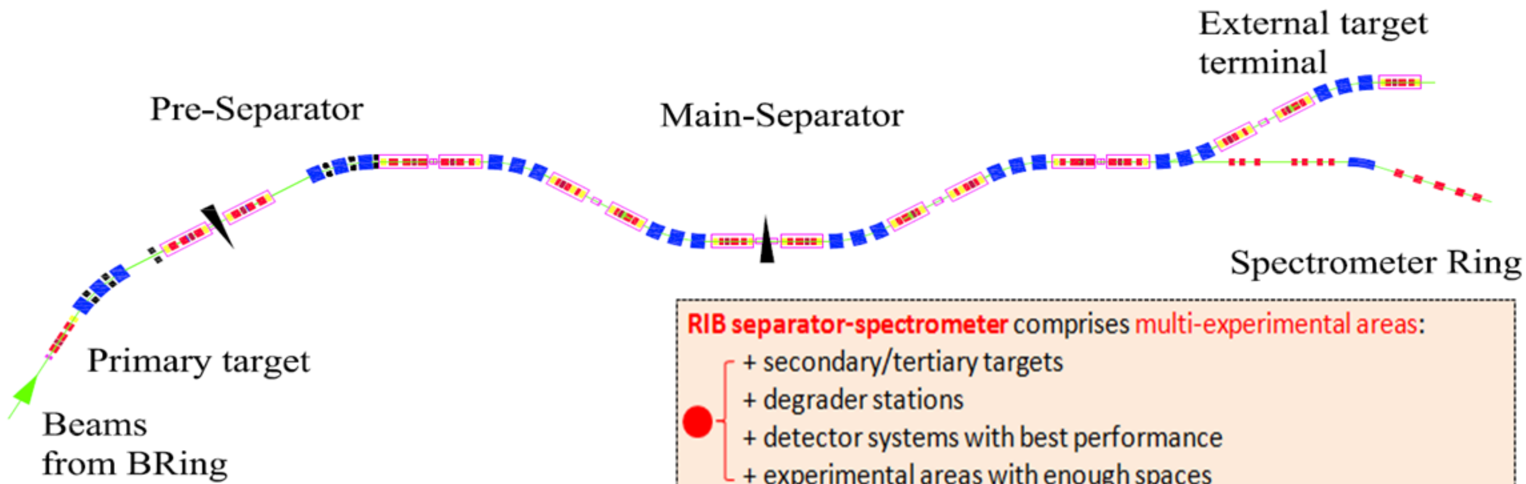
Rigidity: 25 Tm

Angular: ±30 mrad (x) ±15 mrad (y)

Momentum: ±2.0 %

Momentum resolution: 700~1100

HIAF Fragment Separator (HFRS)



HFRS:

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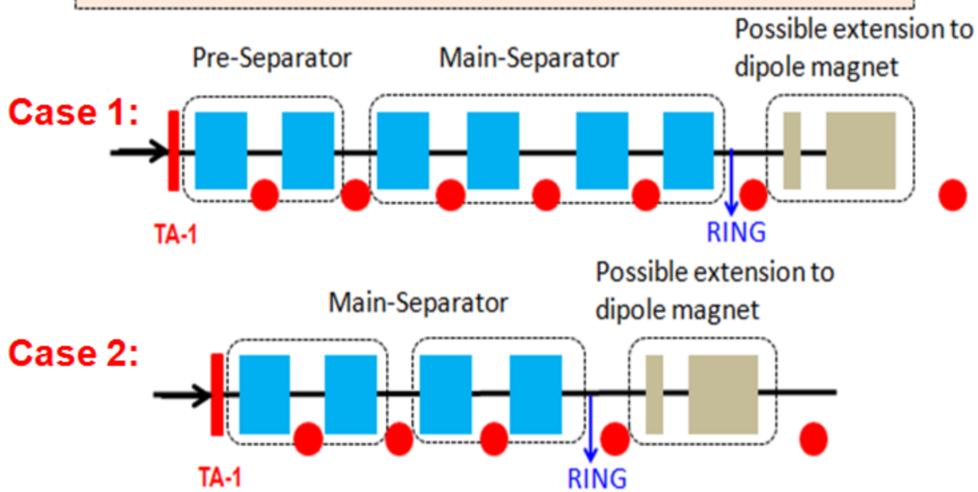
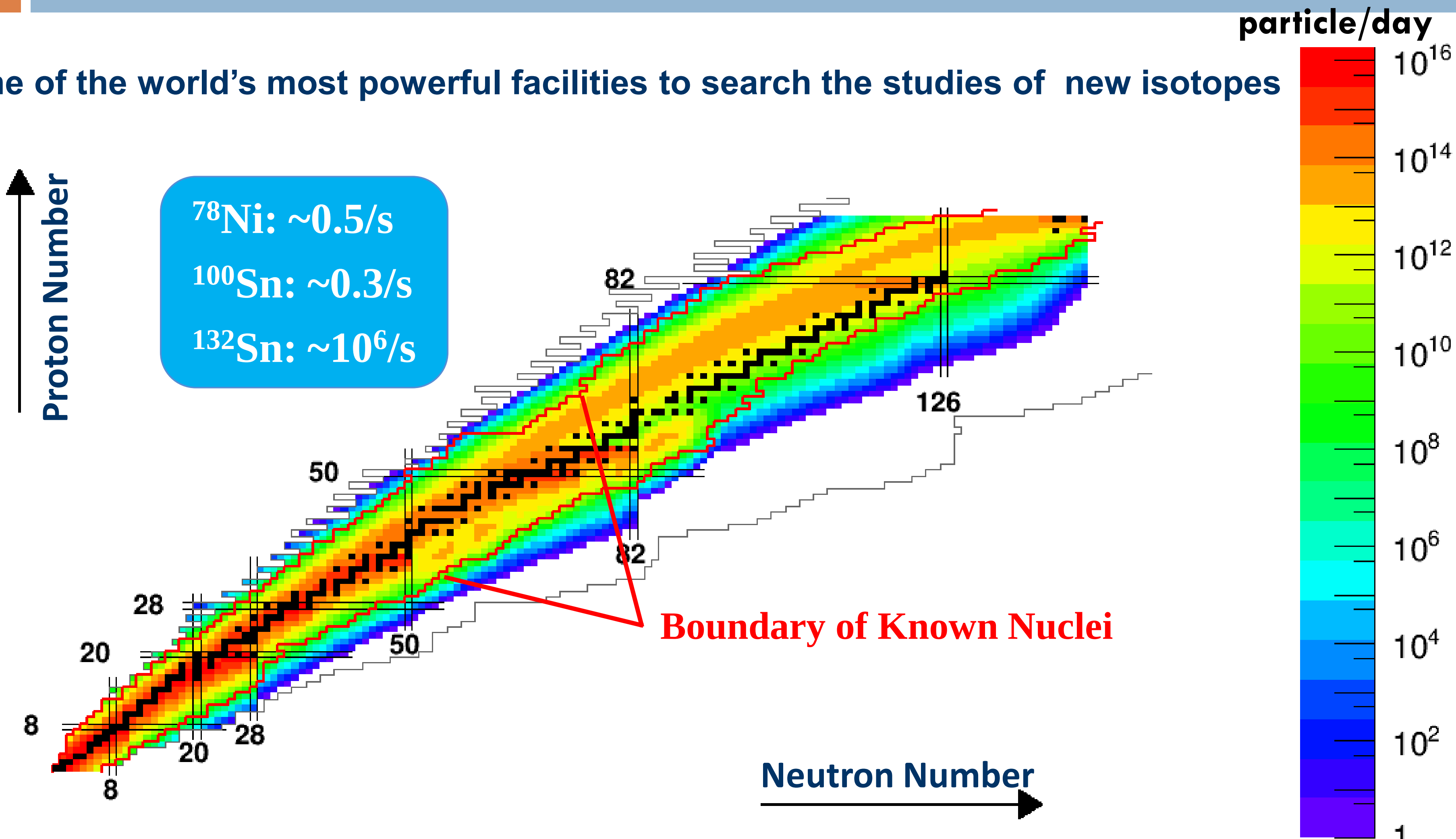


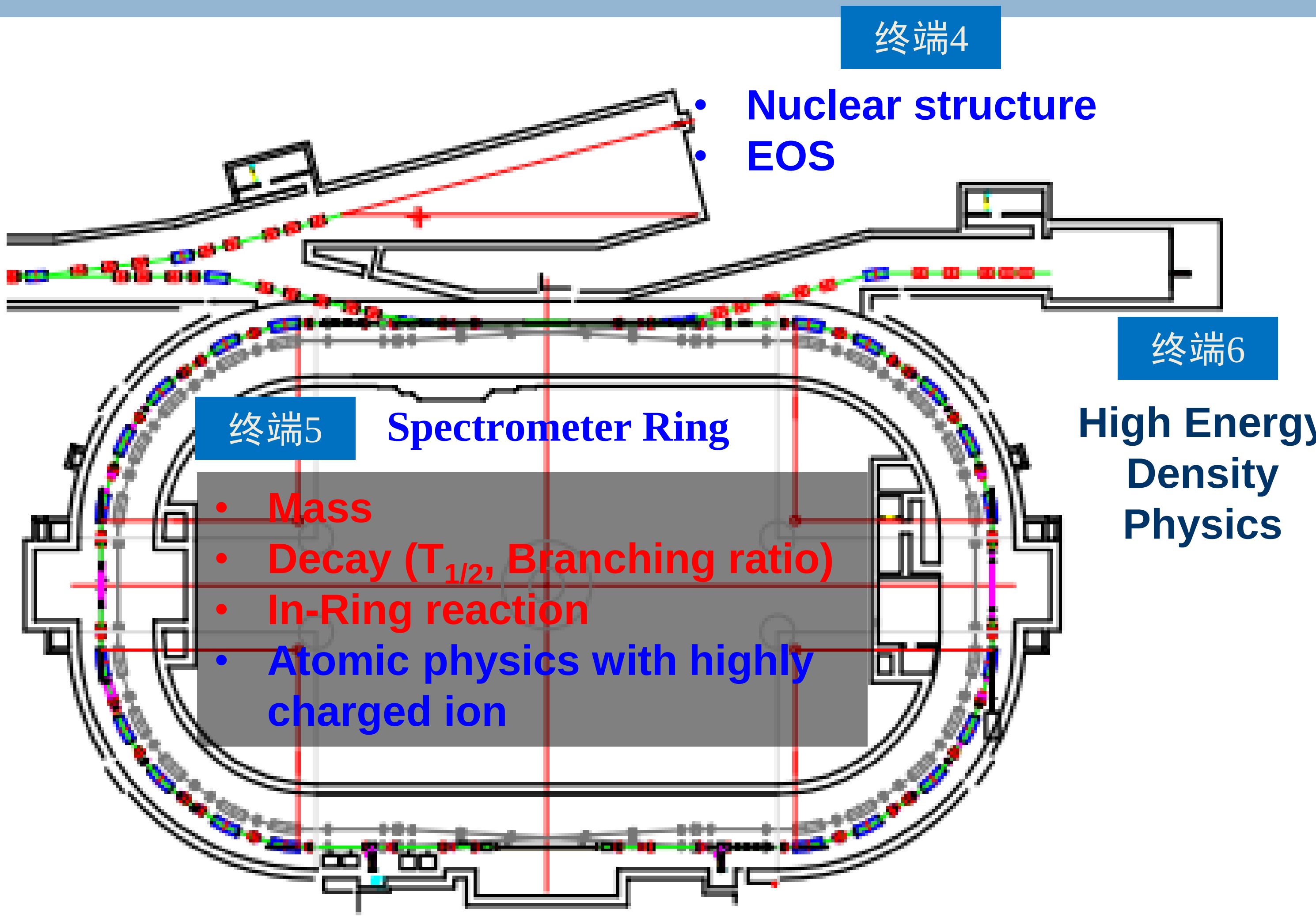
In collaboration with Beihang University.

RIBs Available at HFRS

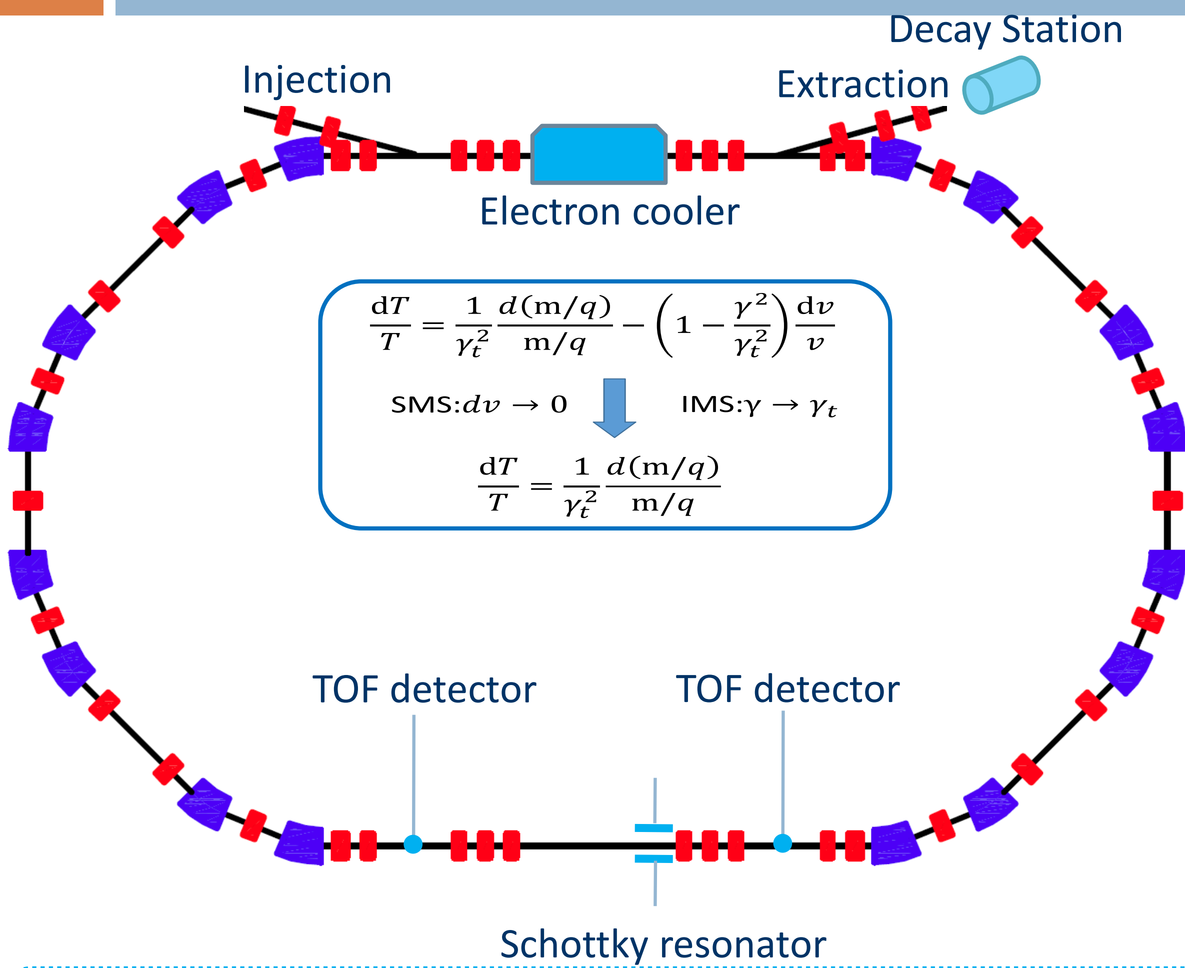
One of the world's most powerful facilities to search the studies of new isotopes



Physics terminals after HFRS



Spectrometer Ring (SRing)



Isochronous Mass Spectrometry

Masses and isomers

With double TOF detectors, improve precision by velocity correction

Single ion sensitivity

Schottky Spectrometry

Masses, lifetimes, and rare decays

In isochronous mode, measure masse and lifetimes simultaneously

Single ion sensitivity

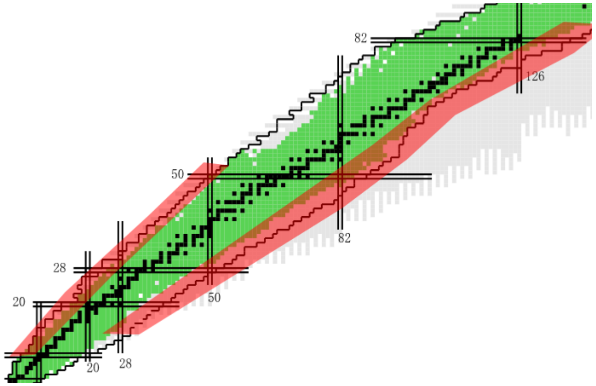
Dielectronic Recombination Spectrometry

Fine atomic spectroscopy for QED effect, nuclear charge radii, etc.

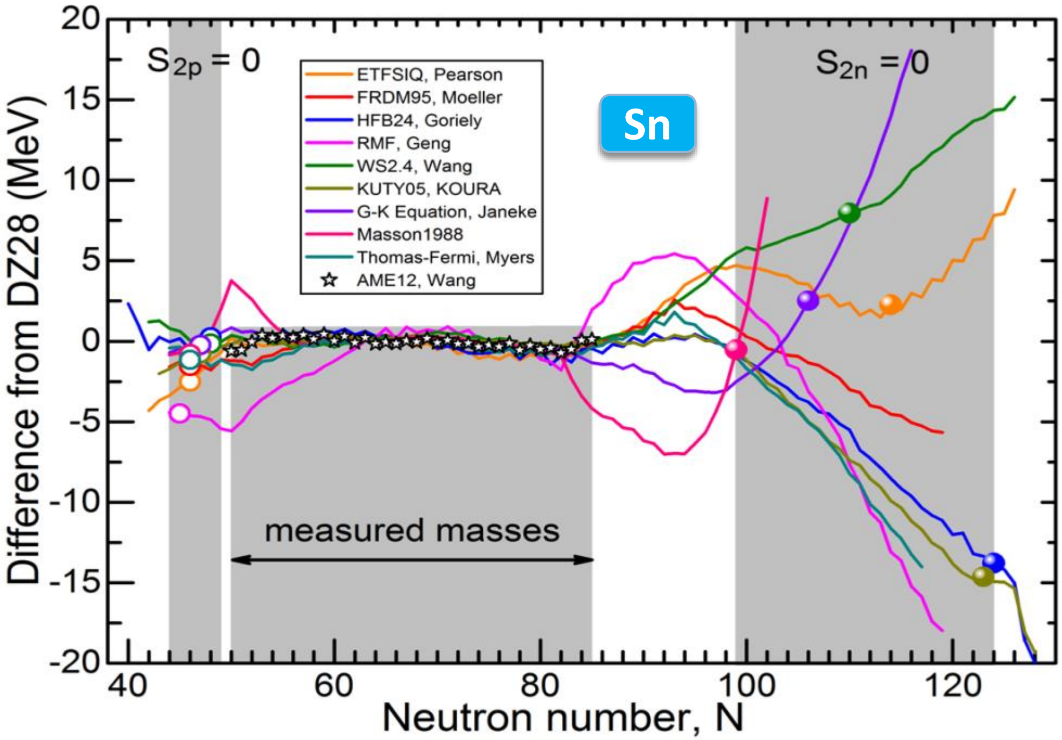
Useful input for X-Ray astronomy

Measurements of precision nuclear masses and lifetimes of nuclei located far away from the stability line, and rare decay modes of highly charged ions.

Mass measurement @SRing



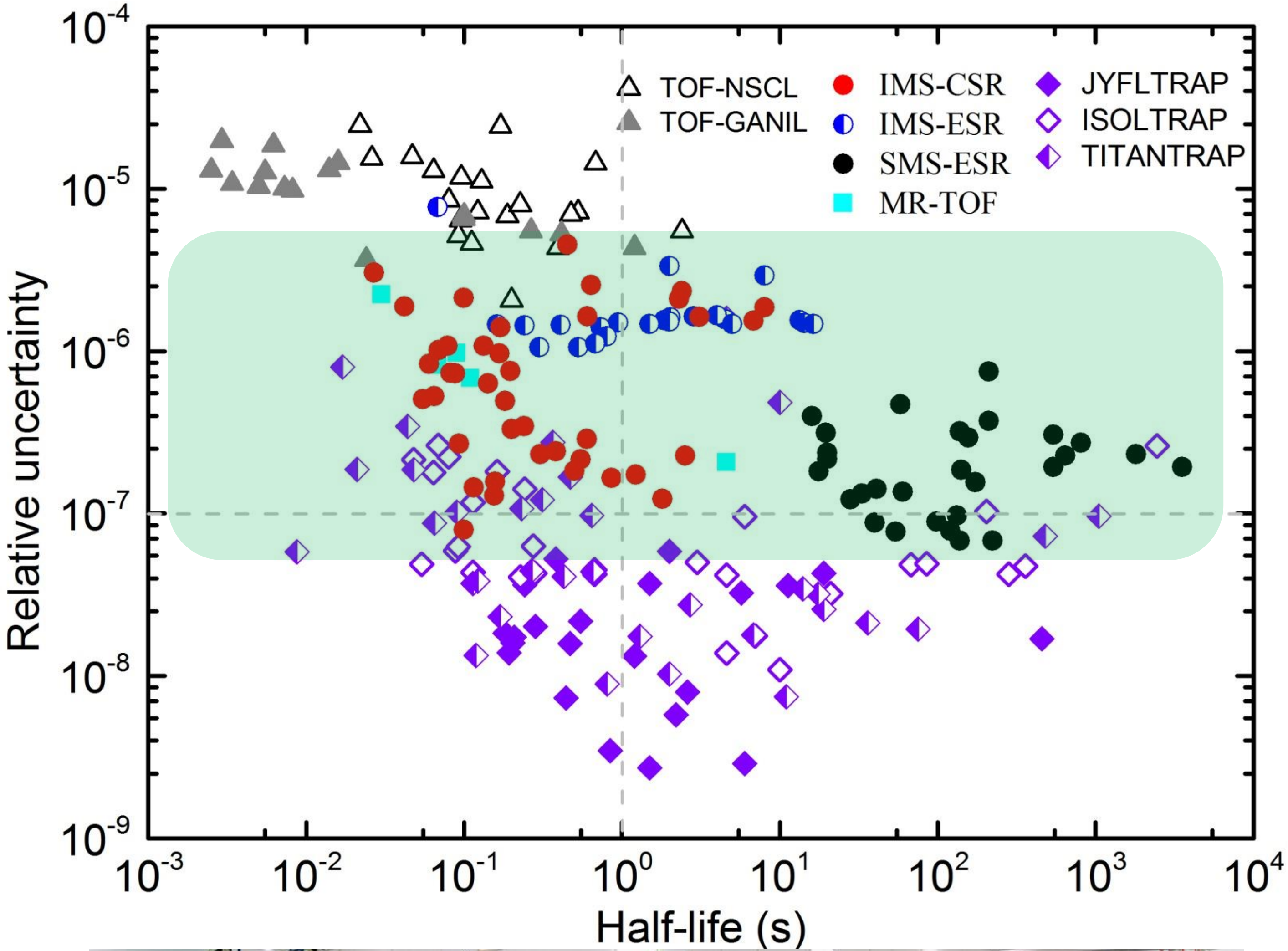
Systematically measure nuclear masses in broad regions.



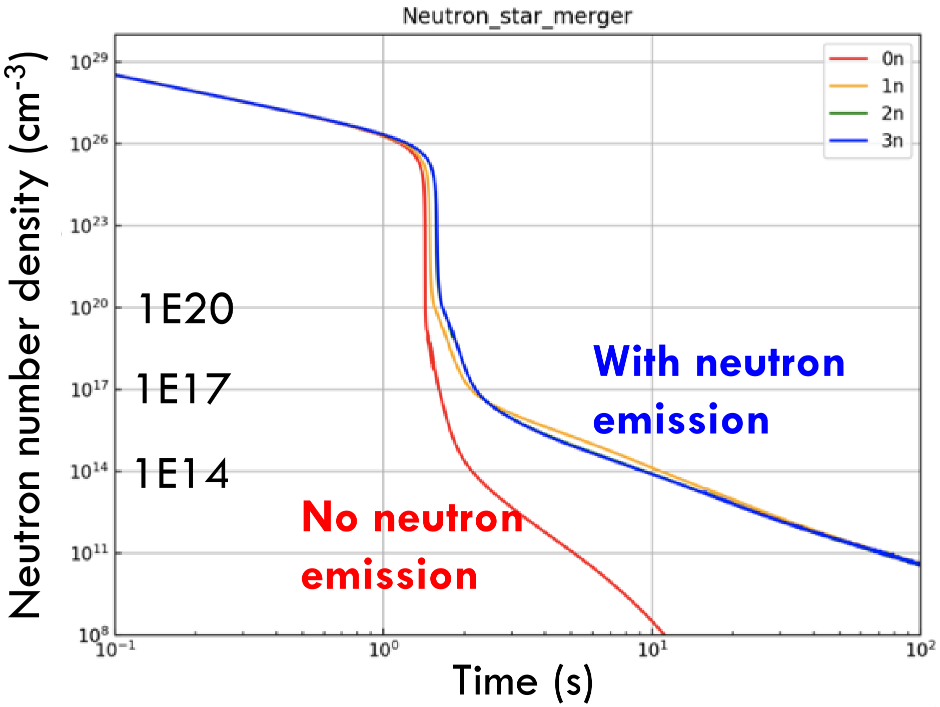
Physics:

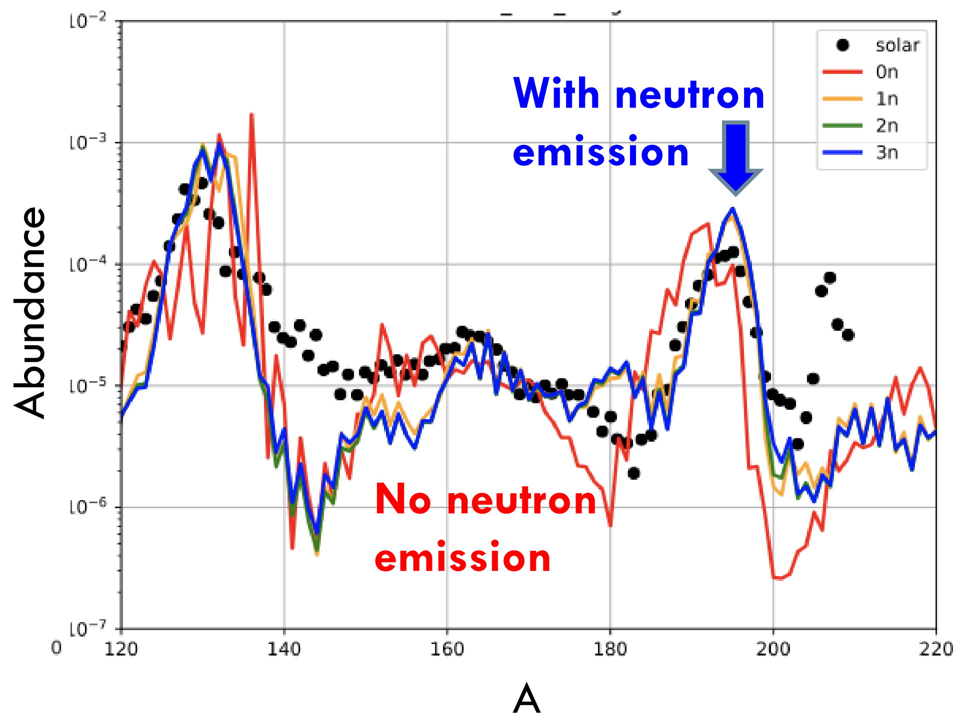
- Map out the mass surface in broad region, and determine the position of the drip lines
- Reveal the evolution of the nuclear effective interactions while changing the N/Z ratios
- Study the quenching of the known shell gaps and development of new ones
- Find out the deformation change, the onset of exotic shapes, etc. along isotopic chains
- Simulate the *rp* process and *r* process

New mass measured at IMP



β-delayed neutron emission

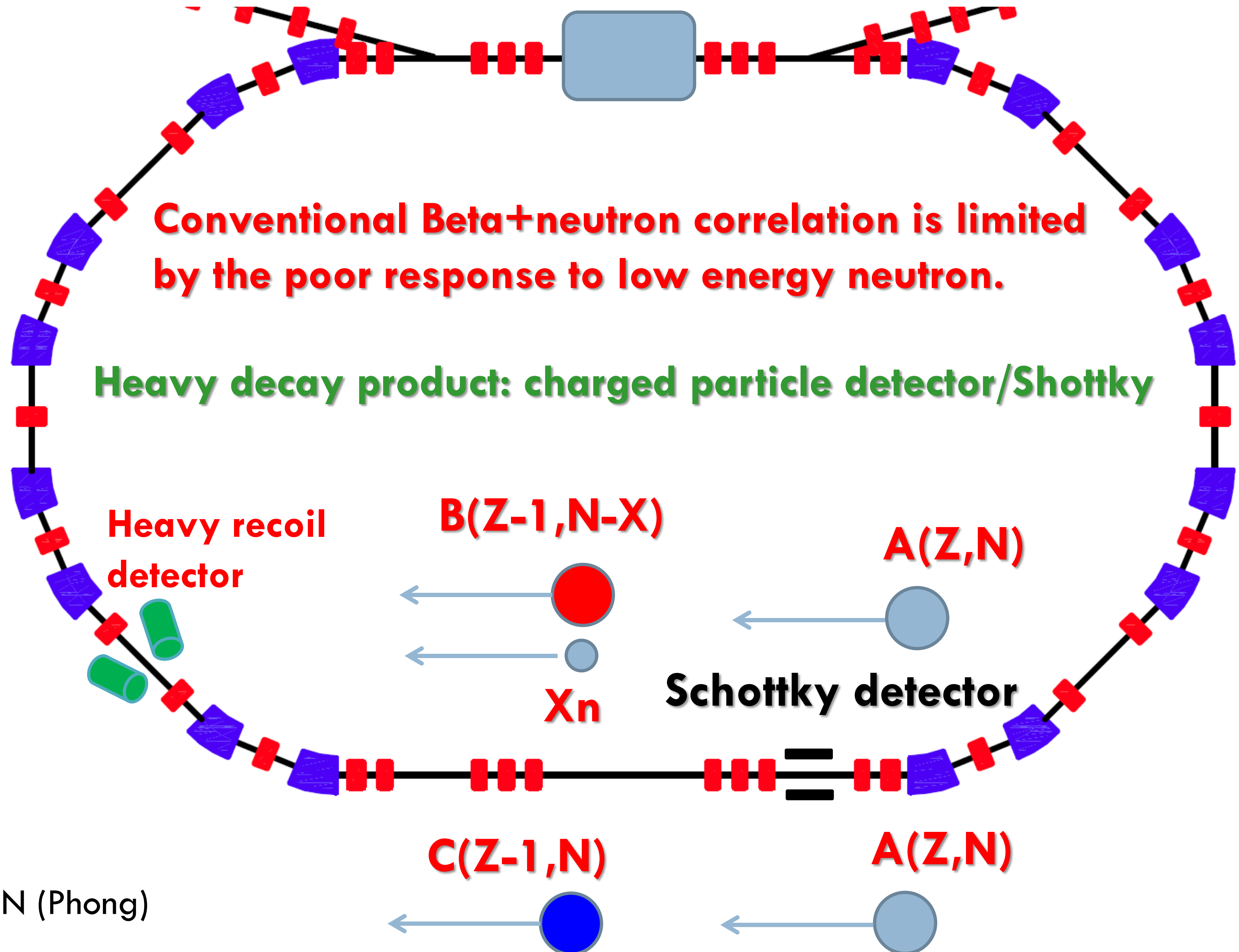




- β-delayed neutron emission plays an important role in a later time
- Peak at A~130 shifts downwards in mass while Peak at A~190 shifts upwards
- The neutron emission multiplicity play less significant role

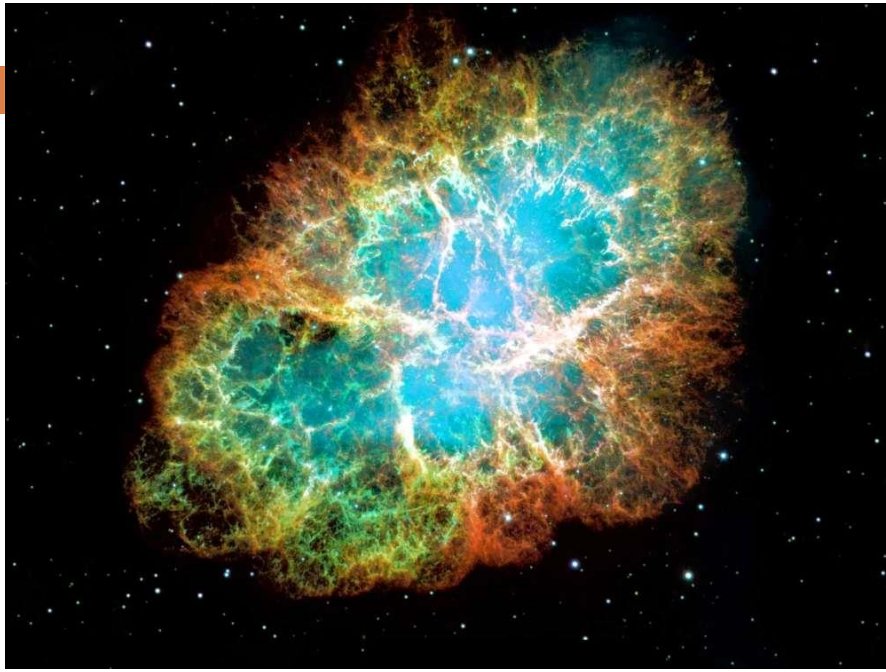
L.H. Ru and D.L. Fang (IMP)

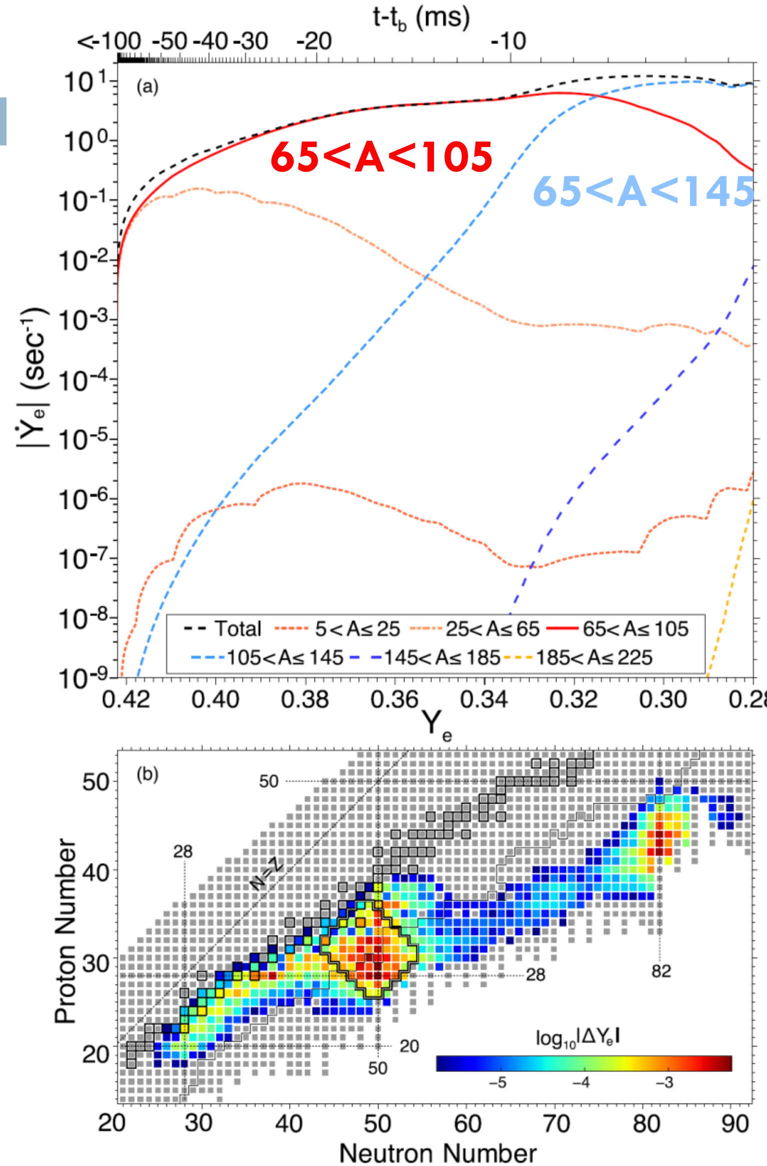
Decay measurement @SRing



BRIKEN (Phong)

Electron capture process in SNe



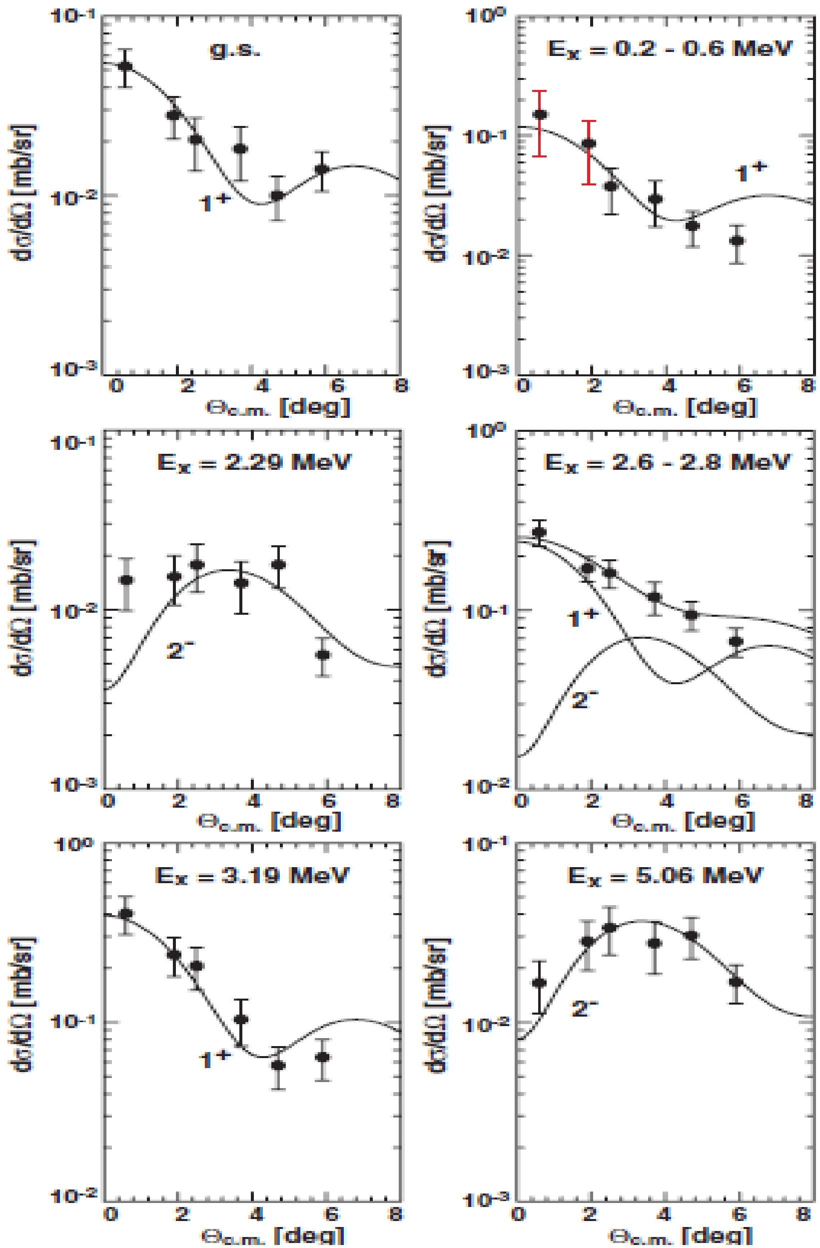


- Electron-capture reactions play a prominent role in the late stages of massive star evolution

- No experimental B(GT+) of n-rich isotopes

Sullivan et al., ApJ, 816:44 , 2016

$^{64}Zn(d,^{2}He)^{64}Cu$@183MeV



GT (στ) :

Important weak response

β decay :

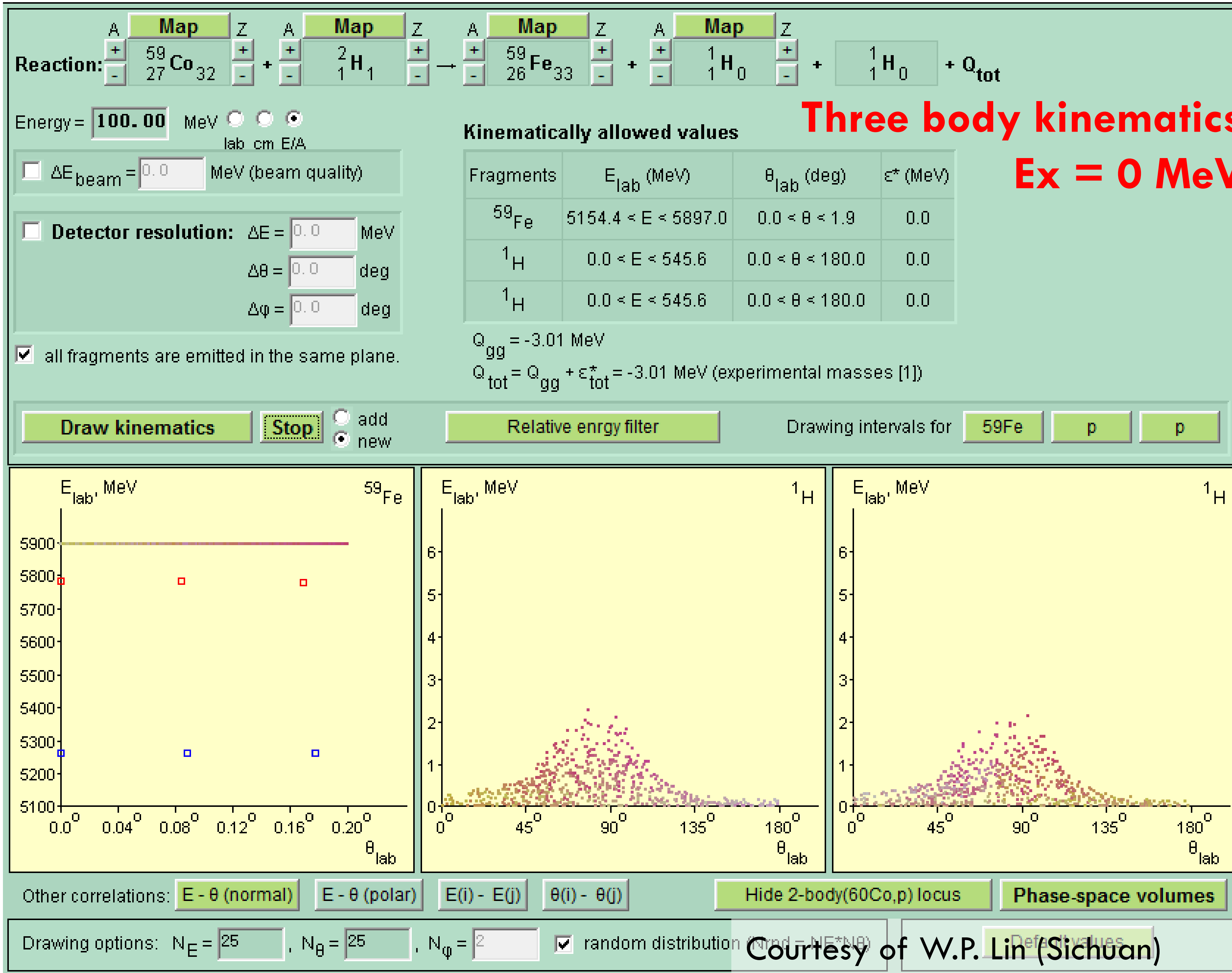
absolute B(GT), limited to low-lying state

CE reaction :

relative B(GT), highly E_x region

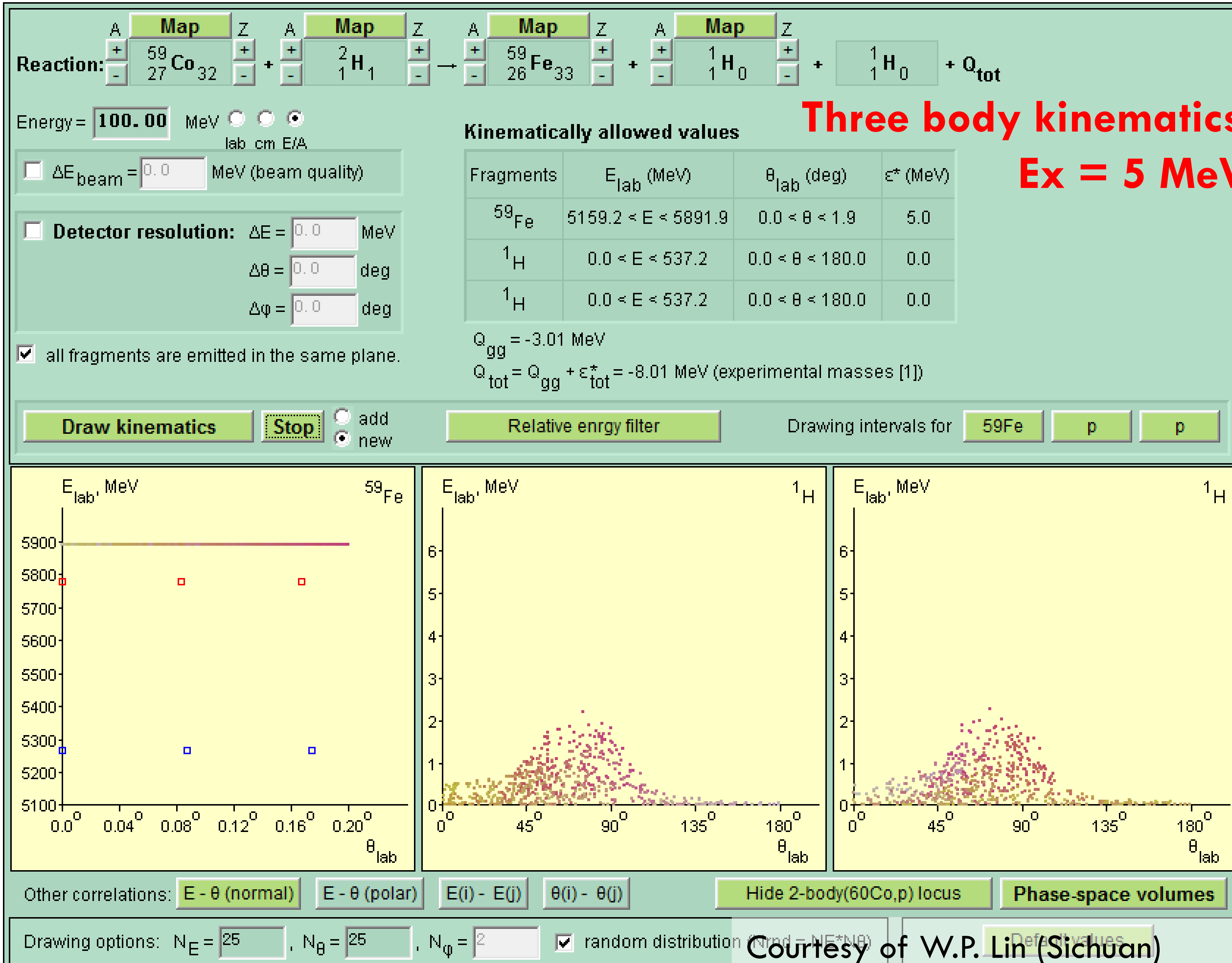
E. W. GREWE *et al.* PHYSICAL REVIEW C ***77***, 064303 (2008).

$^{59}Co + ^{2}H \Rightarrow ^{59}Fe^{*} + ^{1}H + ^{1}H$ reaction at 100A MeV



Courtesy of W.P. Lin (Sichuan)

$^{59}Co + ^{2}H \Rightarrow ^{59}Fe^{*} + ^{1}H + ^{1}H$ reaction at 100A MeV

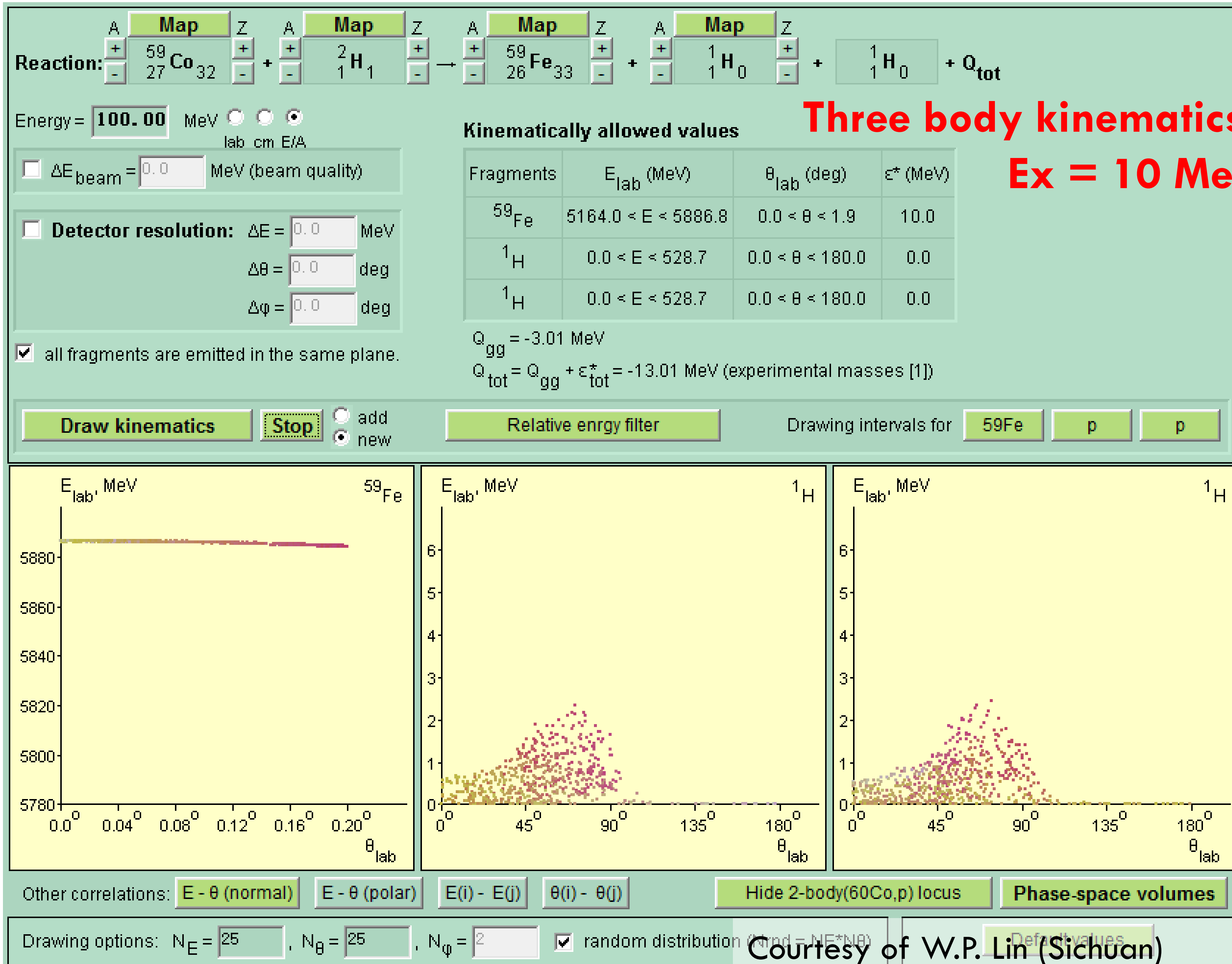


Three body kinematics

Ex = 5 MeV

Courtesy of W.P. Lin (Sichuan)

$^{59}Co + ^{2}H \Rightarrow ^{59}Fe^{*} + ^{1}H + ^{1}H$ reaction at 100A MeV



Fragments	E_{lab} (MeV)	θ_{lab} (deg)	ε* (MeV)
^{59}Fe	5164.0 < E < 5886.8	0.0 < θ < 1.9	10.0
^{1}H	0.0 < E < 528.7	0.0 < θ < 180.0	0.0
^{1}H	0.0 < E < 528.7	0.0 < θ < 180.0	0.0

Three body kinematics

Ex = 10 MeV

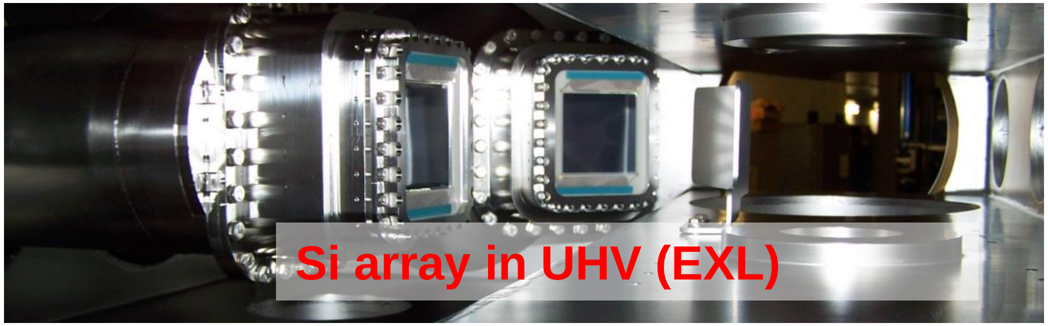
Courtesy of W.P. Lin (Sichuan)

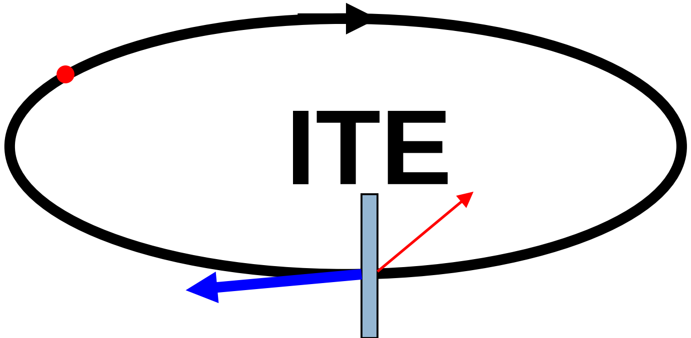
Internal target experiment

- Boost beam current (10^8 particles, 10^6 Hz → max effective intensity : 10^{14} pps)
- Free of beam induced background
- Ultra-thin target (10^{13} atoms/cm^2)

  Conventional target: 10 μg/cm^2 Carbon foil → >10^{17} atoms/cm^2

- Allow low energy particle escaping from the target
- Minimize beam particle energy loss in target



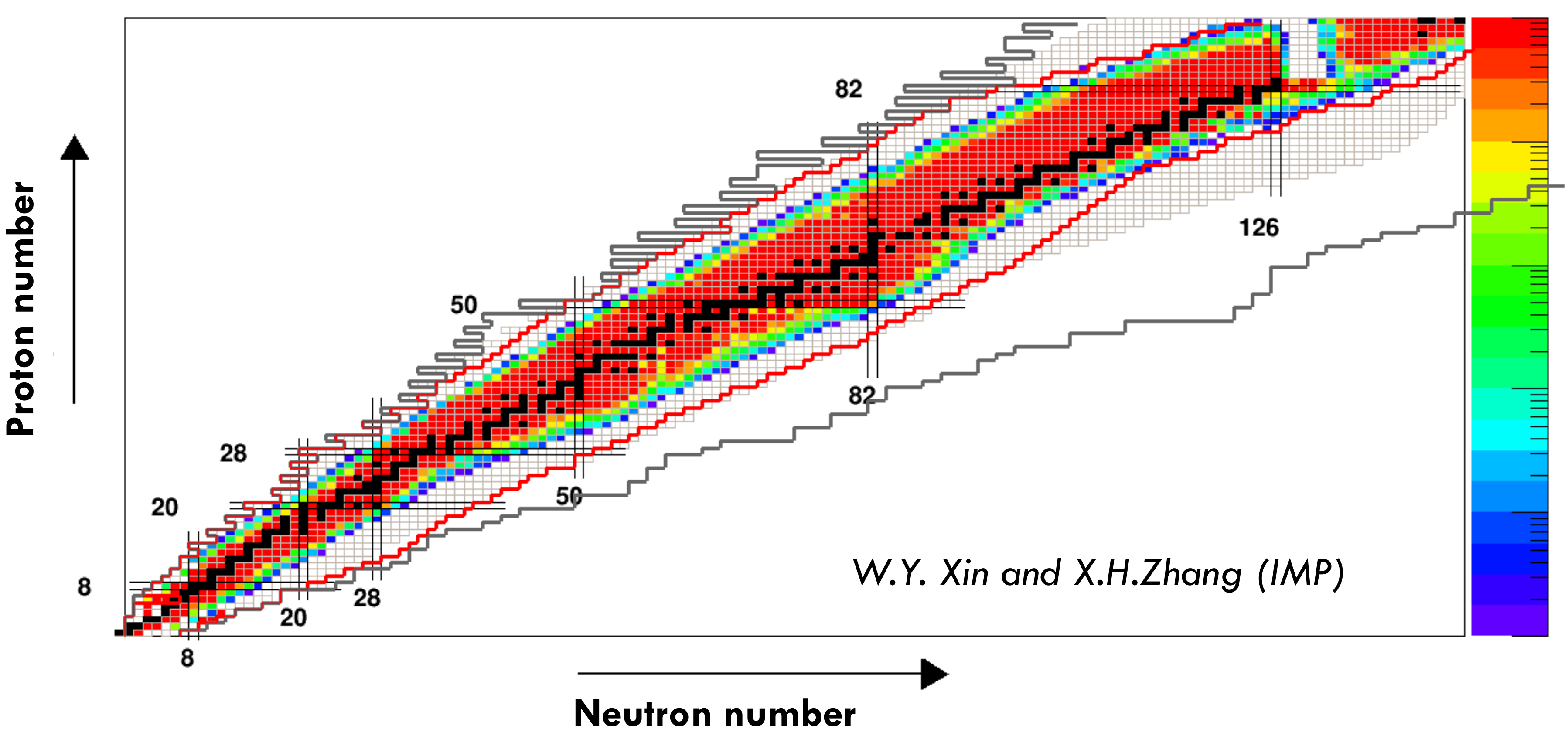


A case study

^{132}Sn ($T_{1/2}$=40 s)

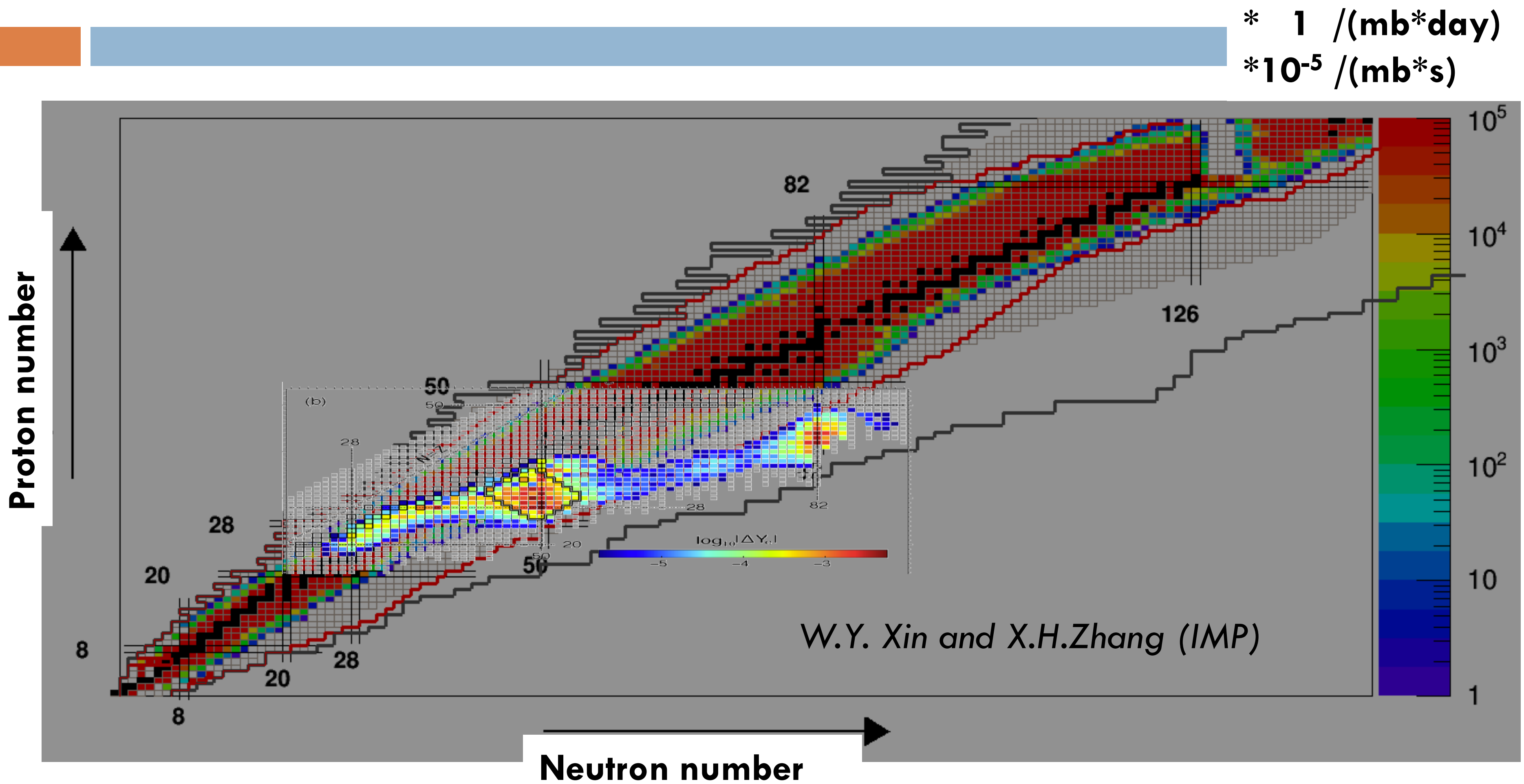
- HIAF: 3.5E6 pps→stored ion: 2.2E8 particles
  Effective intensity: 2.2E14 pps
- RIBF: 3E6 pps
- FRIB: 1E8 – 1E9 pps
- EURISOL: 4E11 pps
- BEIJING ISOL(CARIF): 5E10 pps

HIAF S-Ring Luminosity



- **100% injection into S-Ring, no beam loss except decay**
- **Target thickness of 1×10^{12} cm^{-2}**

HIAF S-Ring Luminosity



- **100% injection into S-Ring, no beam loss except decay**
- **Target thickness of 1×10^{12} cm^{-2}**

Light ion induced direct reactions

elastic scattering (p,p), (α,α), …
nuclear matter distribution ρ(r), skins, halo structures

inelastic scattering (p,p'), (α,α'), …
giant resonances, deformation parameters, B(E2) values, transition densities

charge exchange reactions (p,n), (^{3}He,t), (d, ^{2}He), …
Gamow-Teller strength

transfer reactions (p,d), (p,t), (p, 3He), (d,p), …
single particle structure, spectroscopic factors
spectroscopy beyond the driplines
neutron pair correlations
nuclear structure relevant to nuclear reactions at stellar energy (ANC, energy, spin, J^π, decay branching ratio)

knock-out reactions (p,2p), (p,pn), (p,p 4He)…
ground state configurations, nucleon momentum distributions, cluster correlations

*Modified based on **Egelhof's talk***

2018-2025

HIAF 强流重离子加速器装置

High Intensity heavy-ion Accelerator Facility

Ground breaking ceremony, Dec. 23, 2018

2018-2025

HIAF 强流重离子加速器装置

High Intensity heavy-ion Accelerator Facility

Rock Blasting @June 9, 2019

2018-2025

HIAF 强流重离子加速器装置

High Intensity heavy-ion Accelerator Facility

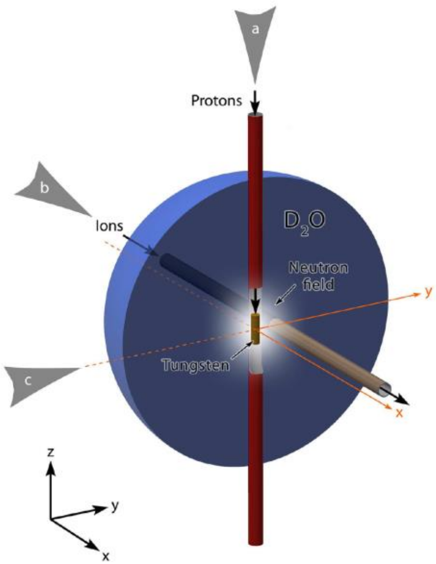
- Nuclear Astrophysics
- Super-heavy Nuclei
- Nuclear Structure
- Nuclear Reaction
- Hyper-nucleus
- QCD phase structure

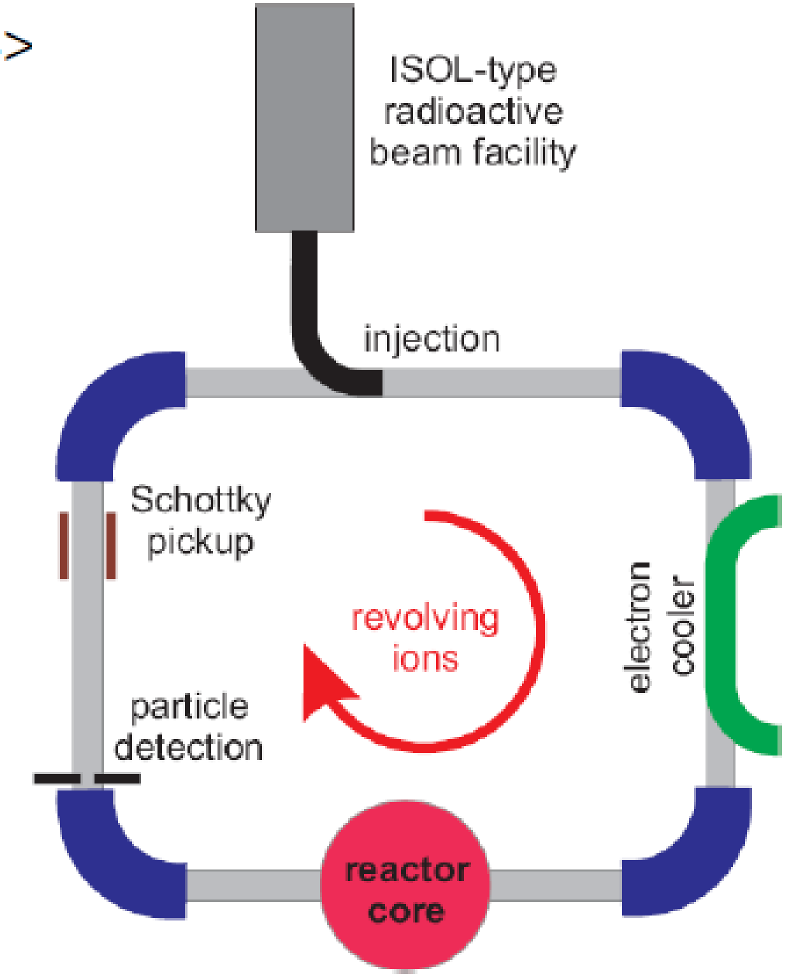
Neutron captures in inverse kinematics

Indirect measurement(Imai)

- Neutron density: 10^{14} n/cm^2/s ->
- Neutron target: 2 10^{10} n/cm^2
- 10^7 ions, 1 MHz: 10^{13} ions/s

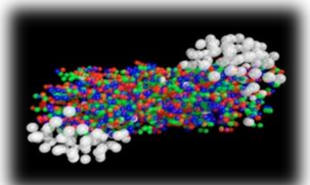
- **Counts per day: 20 σ / mb**

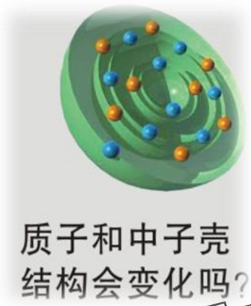


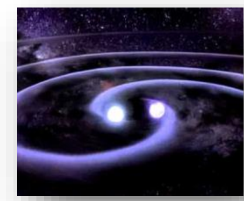


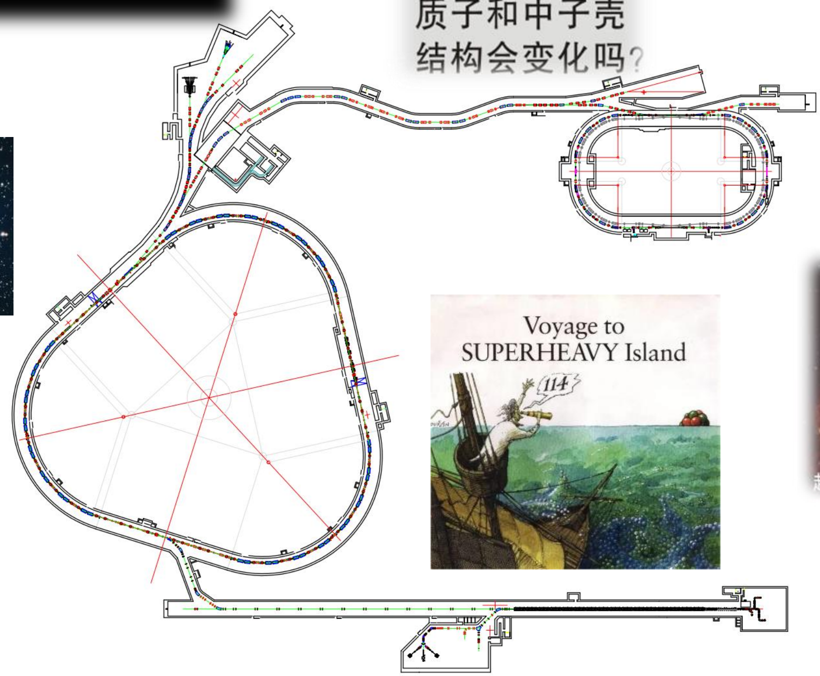
(Reifarth & Litvinov , Phys. Rev ST Accelerator and Beams, 17 (2014) 014701)

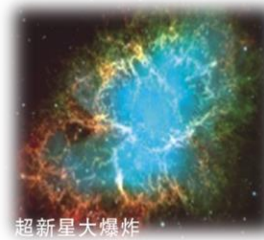
Opportunities with HIAF







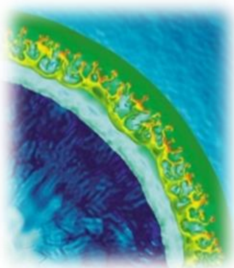


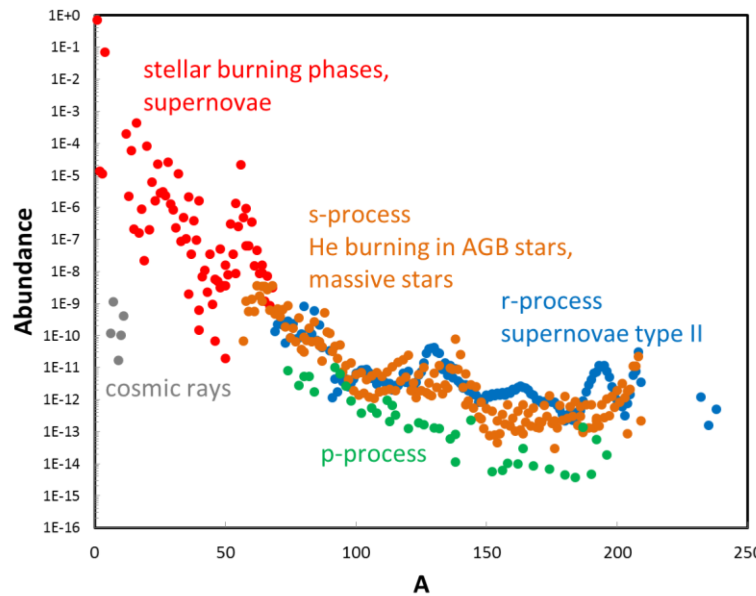


- **High current (HIAF-I)@Low E (n-rich heavy isotopes)**
- **High energy (HIAF-I) (higher than RIBF, FRIB) (hypernucleus, QCD phase structure, Mass, decay, weak interaction)**
- **More n-rich beams at HIAF-U**

Nuclear Experiment

Nuclear Theory





Observation
Atomic Physics