ASRC Workshop 2019-3

Heavy Element Synthesis under Explosive Burning on Neutron Stars

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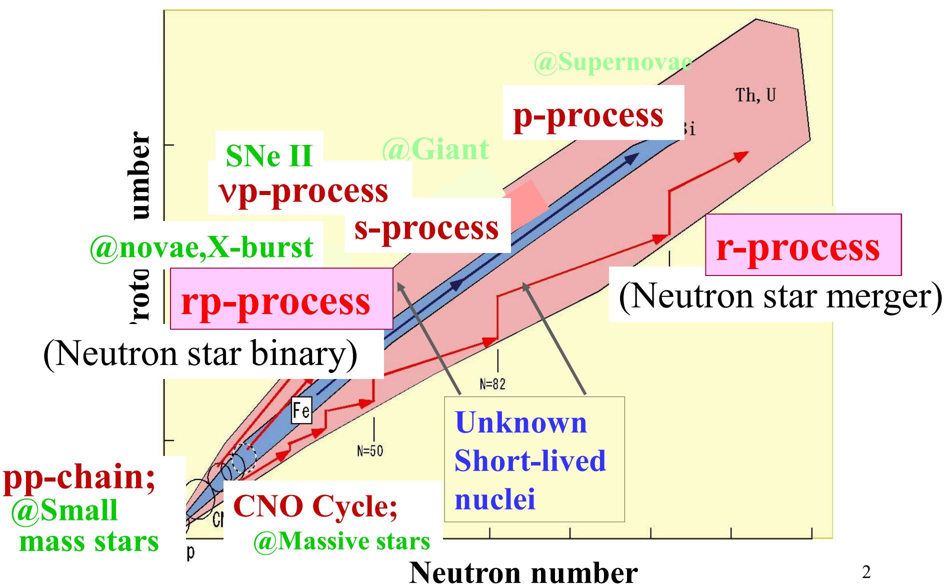
1. Explosive H-burning in X-ray bursts
   - Waiting points, termination process
2. Nuclear Burning in neutron star merger
   - Main energy source of the after glow
3. Scope

Explosive Nucleosynthesis in Neutron stars



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Problems of the rp-Process

- Ignition Process
- Waiting Points/Bottle-Neck
- Termination Process

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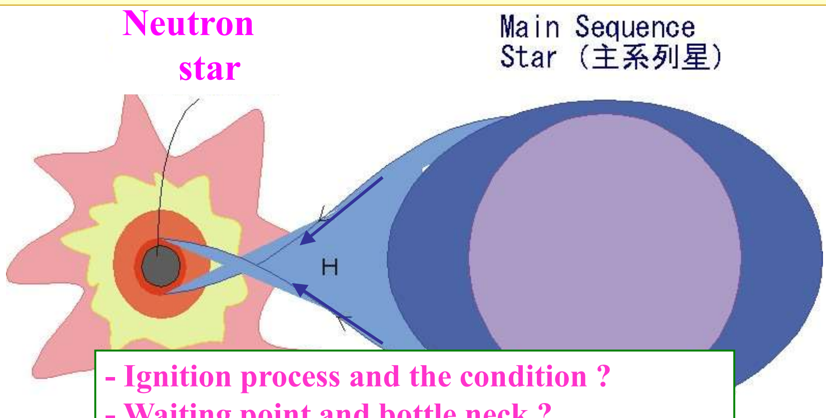
X-ray burst and the Problems



- Ignition process and the condition ?
- Waiting point and bottle neck ?
- Termination process, p-nuclei production？
- Light curve shape ?

[He; pp region] ⟶ A = 40 – 100 Nuclei

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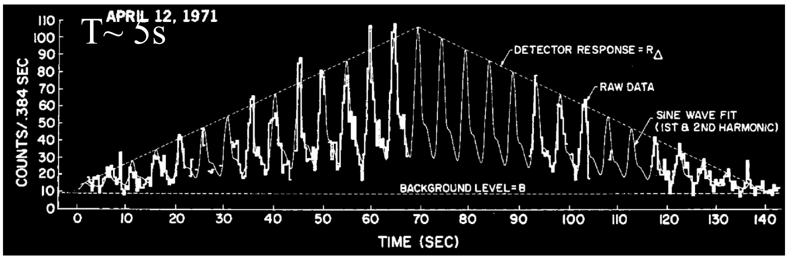
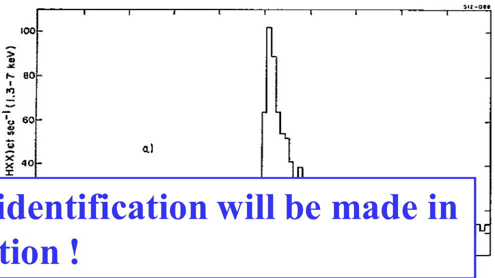
X-ray burst in Accreting Binary Systems

First X-ray pulsar: Cen X-3 (Giacconi et al. 1971) with UHURU



Today: ~50

First X-ray burst:
3U 1820-30
(Grindlay et al. 1976)
with ANS

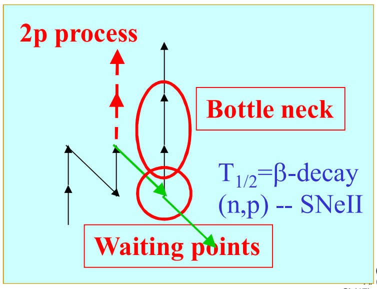


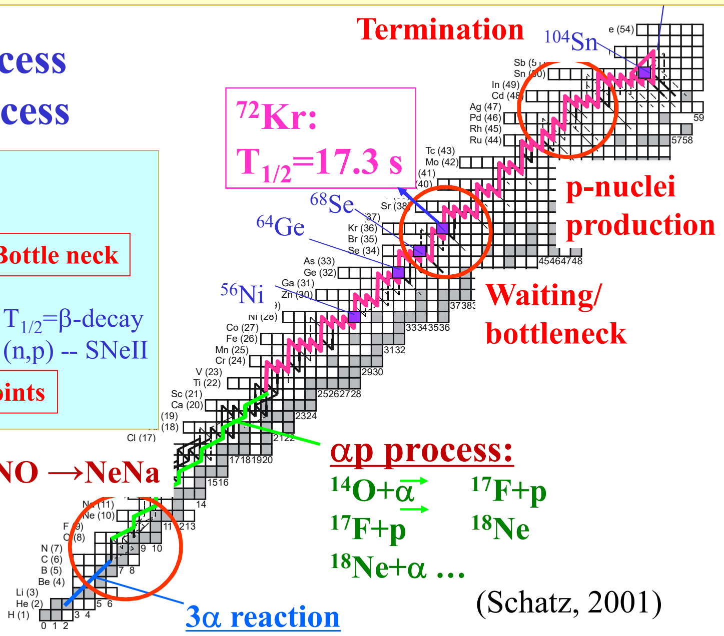
Today: ~40

*** Hevy element identification will be made in X-ray observation !**

High Temperature Hydrogen Burning

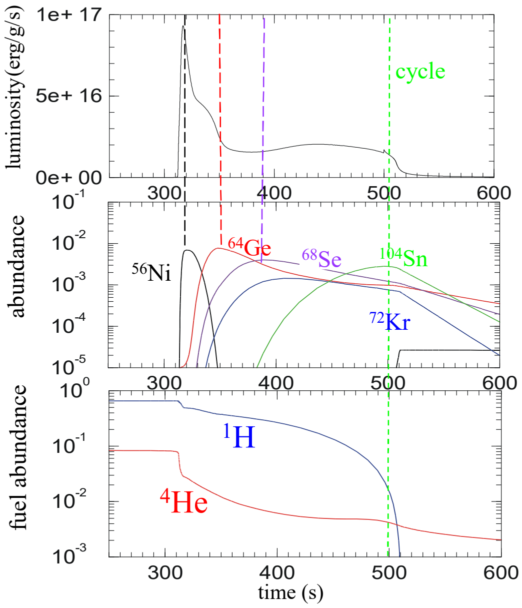
- rp-process
- νp-process





(Schatz, 2001)

X-ray burst: Importance of waiting points-points where the flow is hampered by slow decay or weakly bound nuclei



Problems at the Waiting Points and the Bottle-Neck

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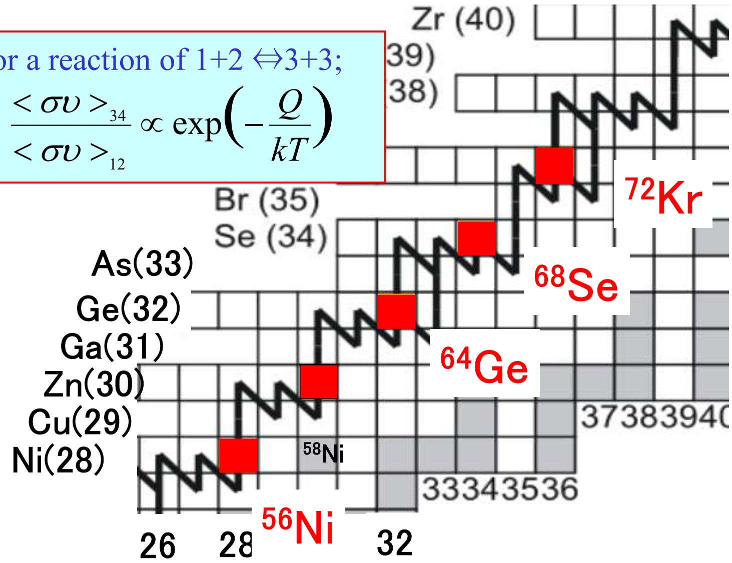
Possible waiting points on the rp-process

For a reaction of 1+2 ⇔3+3;

$$\frac{<\sigma\upsilon>_{34}}{<\sigma\upsilon>_{12}} \propto \exp\left(-\frac{Q}{kT}\right)$$



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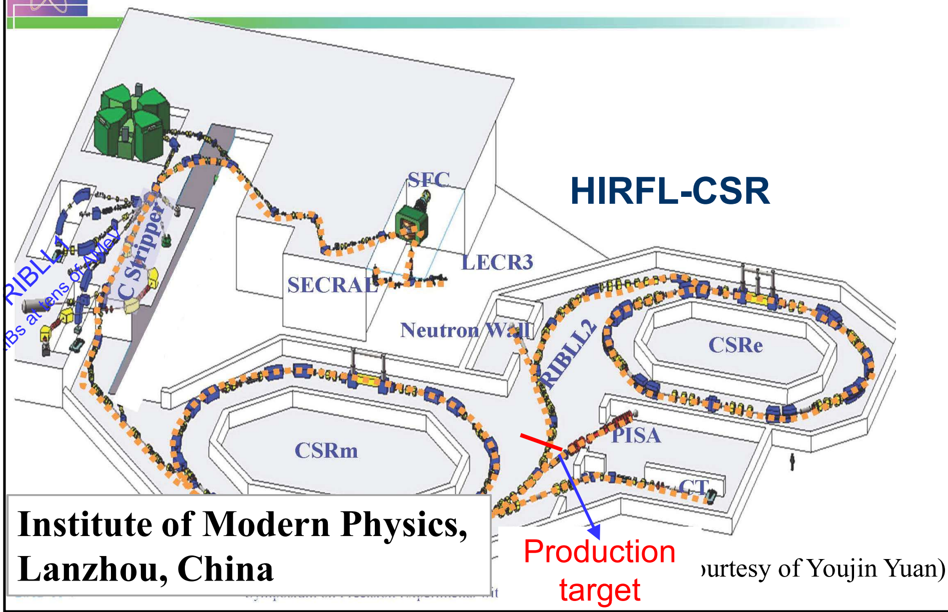
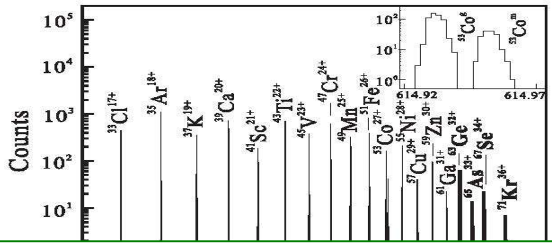
Beam path for routine operation of CSR



Institute of Modern Physics, Lanzhou, China

Mass measurements of nuclei around a possible waiting point ^{64}Ge



(XL Tu, et al., PRL106)

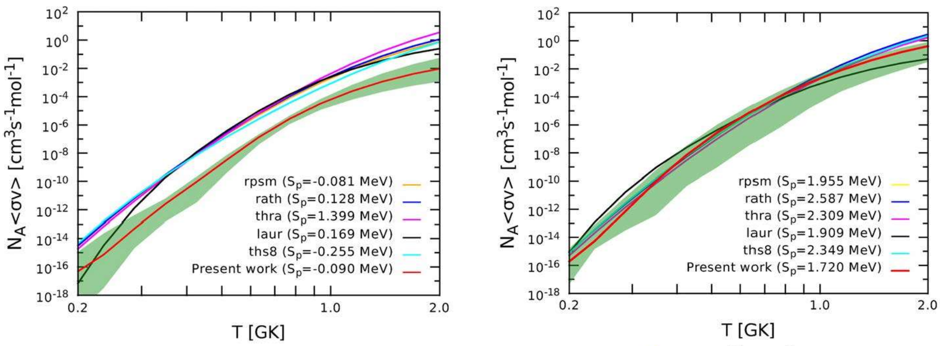
Small unboundness ->
Easier to go; ^{64}Ge -> ^{66}Se by 2p-process !

ved from mirror
ME03 values are

Atom	ME_{CSRe} [keV]	S_p [keV]	ME_{CDE} [keV]	ME_{AME03} [keV]
^{63}Ge	−46 921(37)	2210(46)	−46 945(100)	−46 910(200)#
^{65}As	−46 937(85)	−90(85)	−46 776(100)	−46 980(300)#
^{67}Se	−46 580(67)	1851(74)	−46 548(100)	−46 490(200)#
^{71}Kr	−46 320(141)	2184(142)	−46 025(100)	−46 920(650)

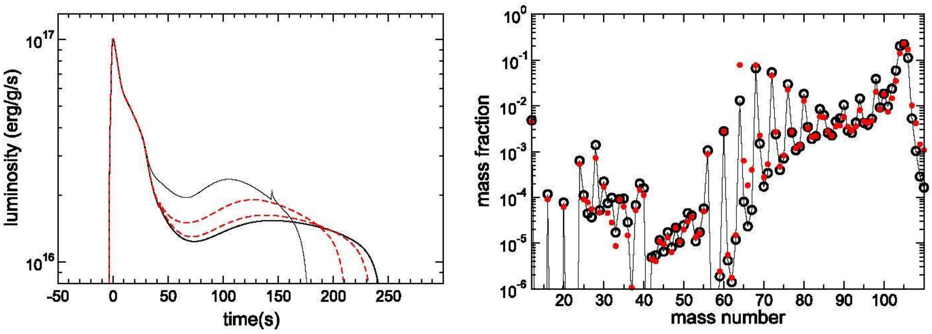
Estimate ^{64}Ge(p,g)^{65}As(p,g)^{66}Se Rate

Lam, APJ 818 (2016)



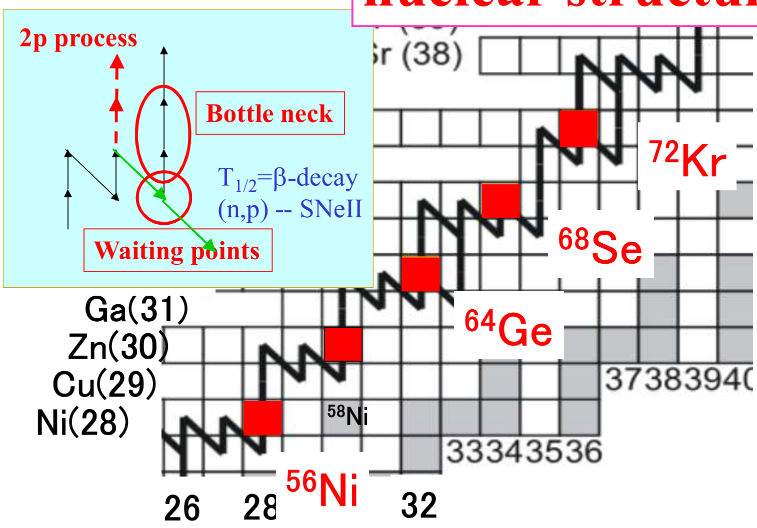
Impact to the rp-process; light curve and abundances

Lam, APJ 818 (2016)



Possible waiting points on the rp-process

Masses + nuclear structure!



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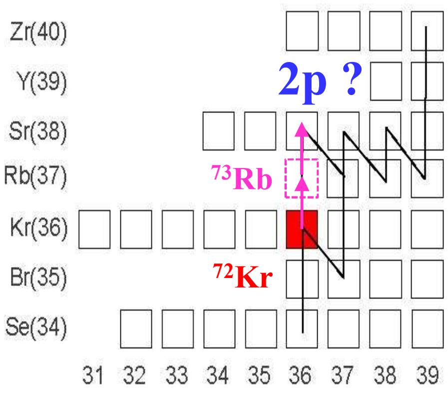
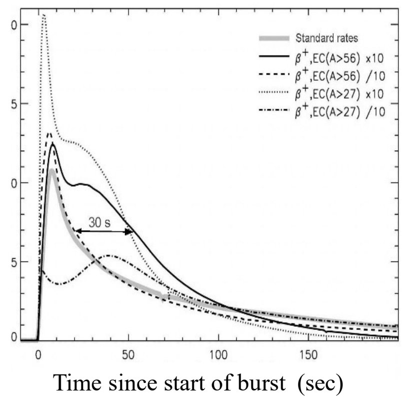
Possible Waiting Point at ^{72}Kr

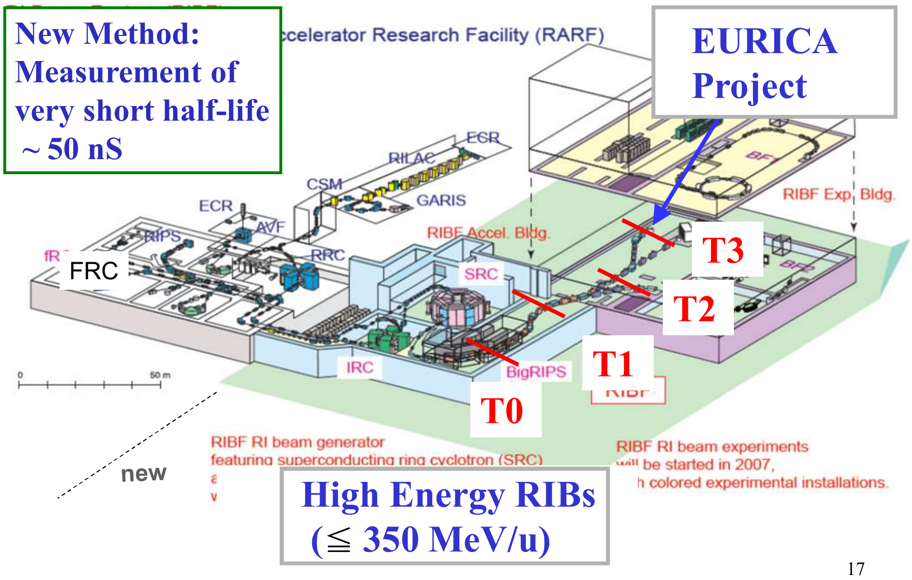
Bypath by 2p-process at ^{72}Kr ?





(S. E. Woosley et al., Astrophy. J. Suppl. 151 (2004))

RIKEN RIBF Facility



New Method:
Measurement of
very short half-life
~ 50 nS

EURICA
Project

High Energy RIBs
(≦ 350 MeV/u)

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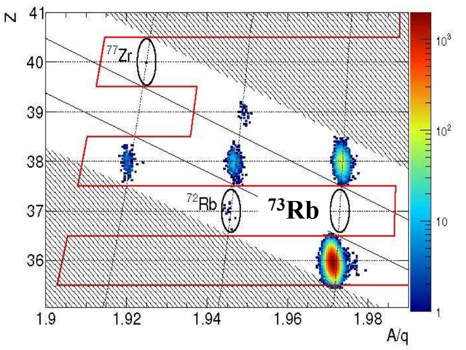
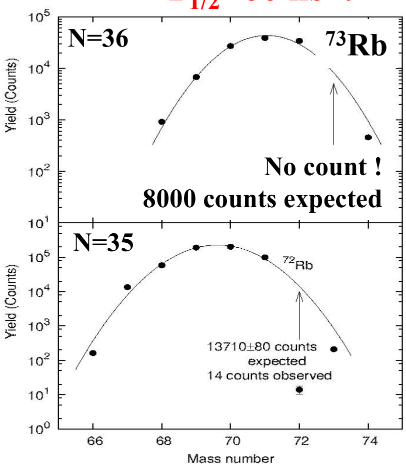
Bypath by 2p-process at ^{72}Kr ?

EURICA/ H. Suzuki, PRL 119 (2017)

$T_{1/2}$<60 ns !





Primary beam; ^{124}Xe 345 AMeV
30-40 pnA
Be prod. target; 740 mg/cm2
EURICA+WAS3ABi @F11/BigRIPS/RIKEN

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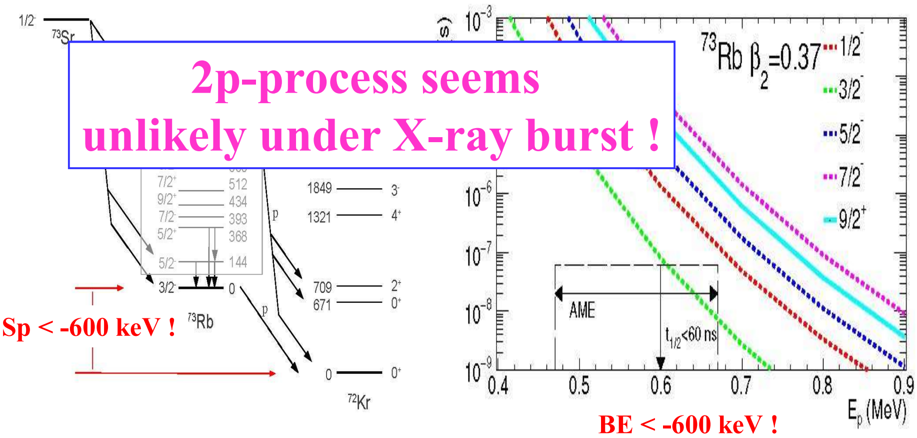
Bypath by 2p-process at ^{72}Kr ?



2p-process seems unlikely under X-ray burst !

Sp < -600 keV !

BE < -600 keV !

*** Half tone levels = the levels taken from the mirror the mirror nucleus except for the IAS.**

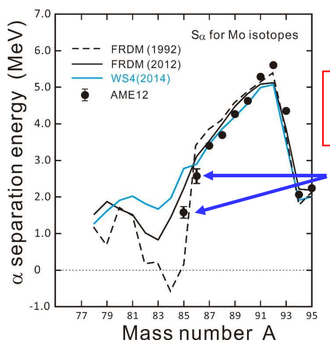
Problems of the Termination Process

- Where it terminates
- Abundance of the termination element

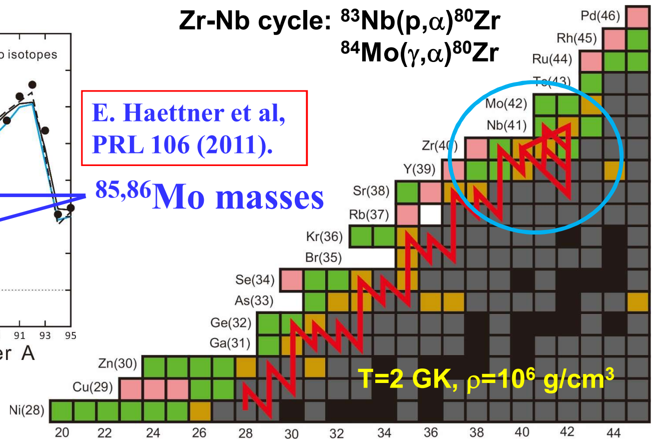
Impact on the studies of nuclear astrophysics

→ Zr-Nb cycle in the rp-process

Zr-Nb cycle was proposed by H. Schatz et al, Phys. Rep. 294, 167 (1998) based on the FRDM mass prediction in 1992, which show a very low or even negative α separation energy of ^{84}Mo.



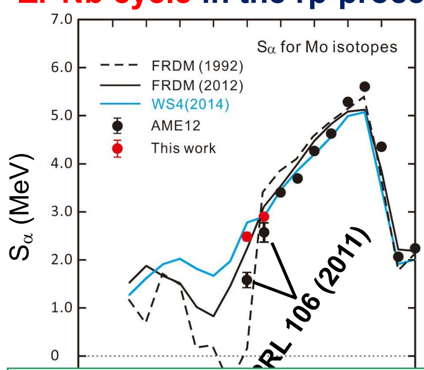
Zr-Nb cycle: ^{83}Nb(p,α)^{80}Zr
^{84}Mo(γ,α)^{80}Zr



(Courtesy of Y. Zhang)

Impact on the studies of nuclear astrophysics

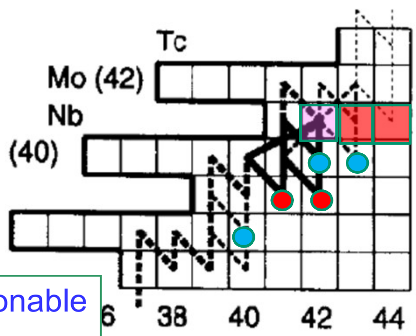
→ Zr-Nb cycle in the rp-process



From our S_α values and reasonable extrapolation to ^{84}Mo,
the Zr-Nb cycle should be weaker or disappears.

Zr-Nb cycle: ^{83}Nb(p,α)^{80}Zr
^{84}Mo(γ,α)^{80}Zr

T=2 GK, ρ=10^6 g/cm^3

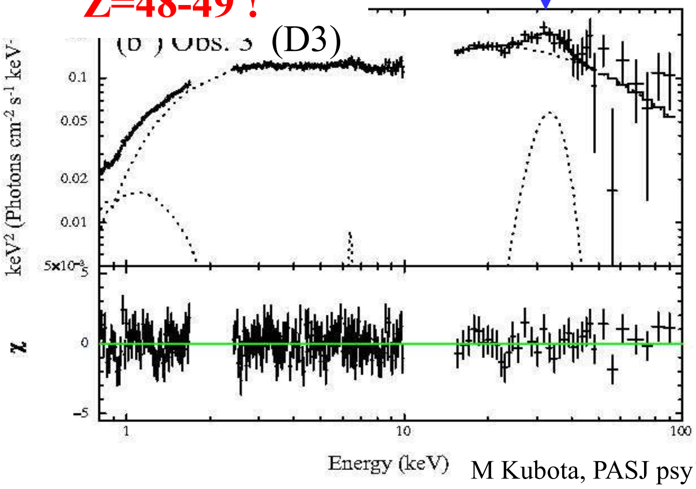


(Courtesy of Y. Zhang)

Suzaku Spectra of Aquila X-1

K edge of elements
Z=48-49 !

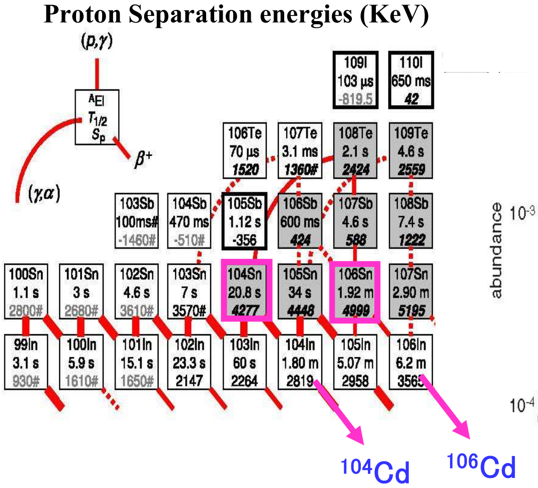
Hump ~ 30 keV



M Kubota, PASJ psy148 (2019)

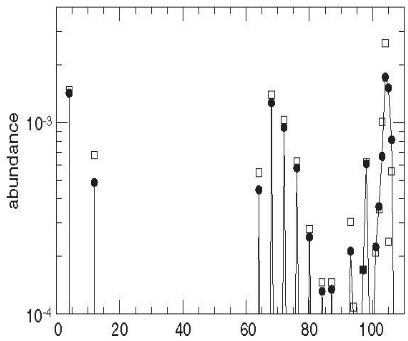
Possible end point on the rp-process

Proton Separation energies (KeV)



Elomaa, PRL 102 (2009)

● with new masses



Kilonova observation in the neutron star mergers

- How far the r-process run ?
Gold is really produced ?

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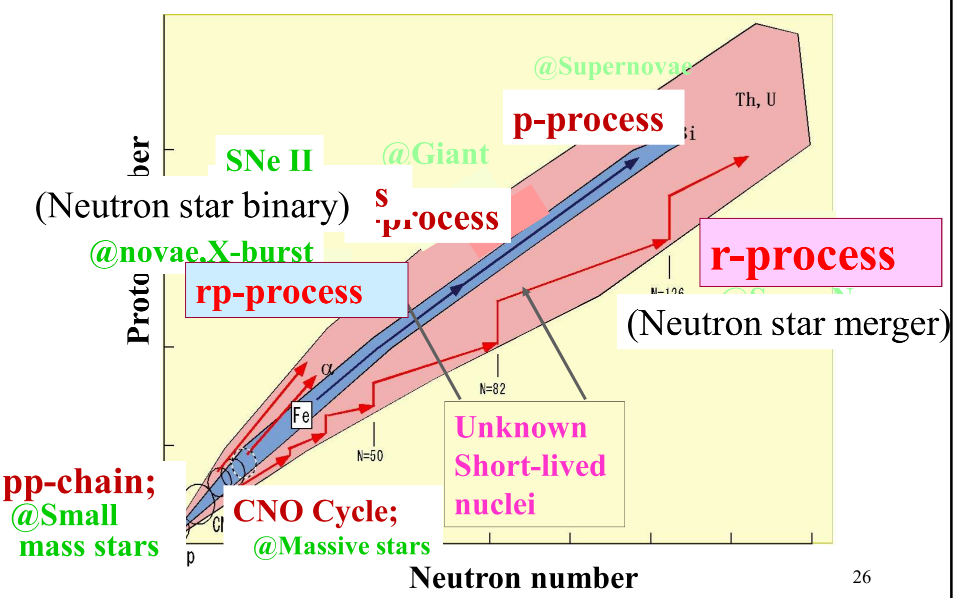
Explosive Nucleosynthesis in Neutron stars



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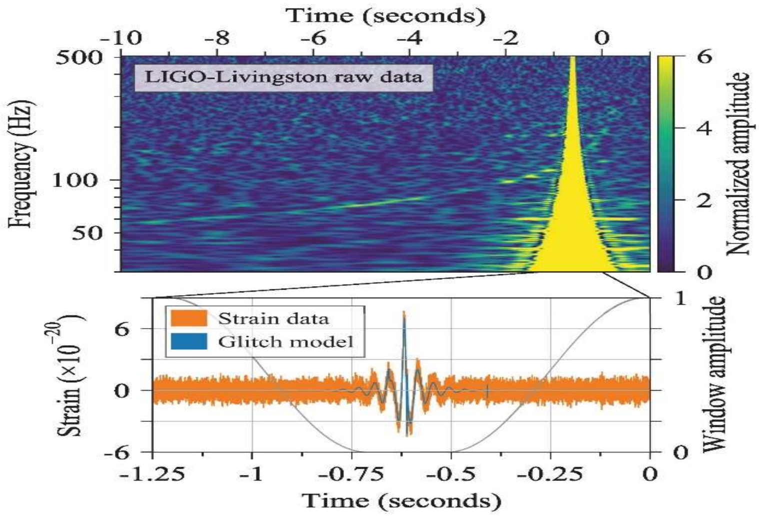
Detection of Gravitational Wave from Binary Neutron Star Merger (GW170817)

LIGO+Virgo, PRL 119 (2017)



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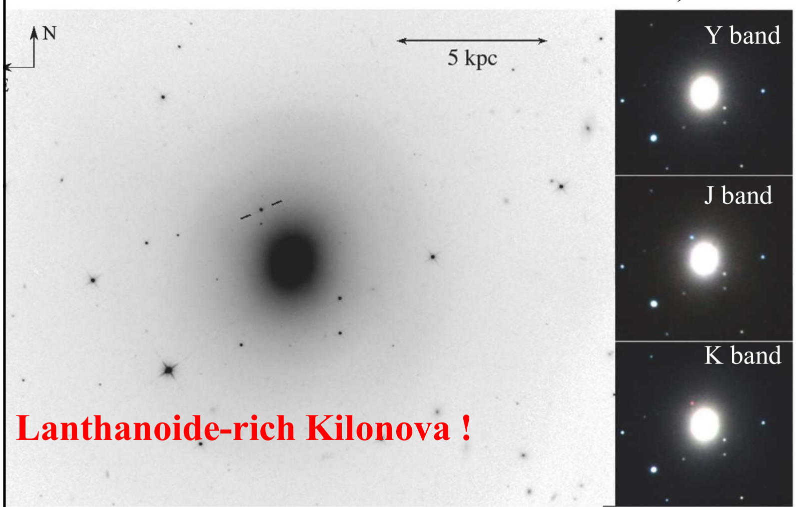
Optical observation of the neutron-star merger (GW170817)

Tanvir, APJ L 848



Before

Right after

8.5 days after

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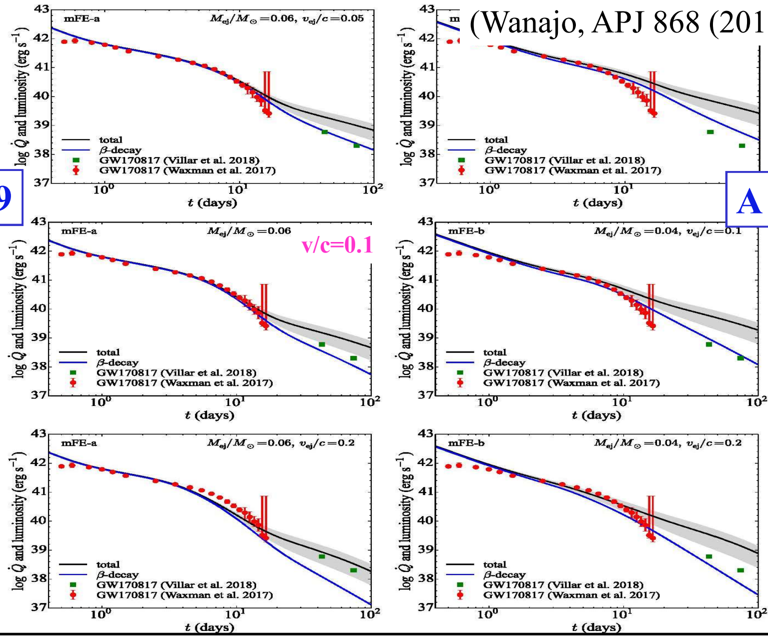
Afterglow of Kilonova; Role of ^{254}Cf

(Wanajo, APJ 868 (2018))

A≧69

A≧90



Afterglow of Kilonova; Role of each isotope

^{66}Ni (54.6 h)

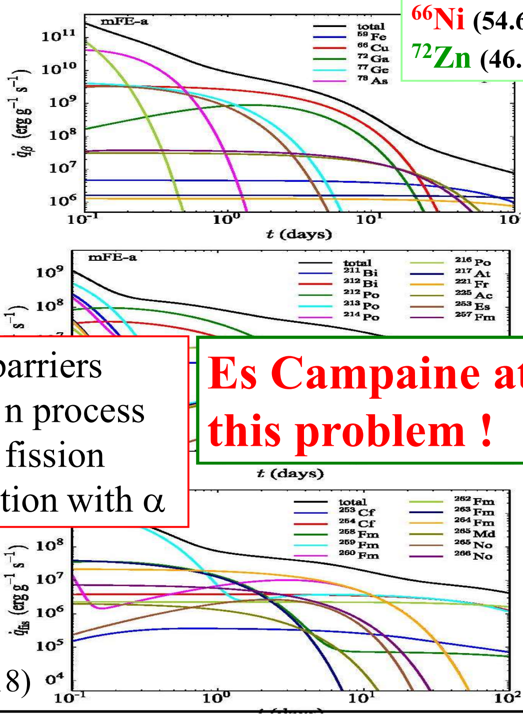
^{72}Zn (46.5h)

Total

β Decays

Alpha decays

Fissions



- Fission barriers
- Delayed n process
- Delayed fission
- Competition with α

Es Campaine attacks this problem !

Wanajo, APJ 868 (2018)

Summary

-Explosive burning on neutron stars-

1. For x-ray bursts, **a new observation suggests that the rp-process runs up to A~100 region**.
2. **^{72}Kr could be a serious waiting point** for the rp-process. Nuclear physics (masses and nuclear structures) of nuclei around the waiting points and the bottle necks need to be investigated carefully
3. **The Zr-Nb cycle suggested before possibly does not exist**, and thus the rp-process may extend to A~100 region, if the waiting point at ^{72}Kr is not so serious.
4. The afterglow of neutron star merger will give a good proof of the r-process for heavy element production, but it **needs the physics of actinides, esp. β, α, n, fission decays.**

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