(Nuclear) Charge-exchange reaction and opportunities at HIAF

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Nuclear Astrophysics Experiments with HIAF

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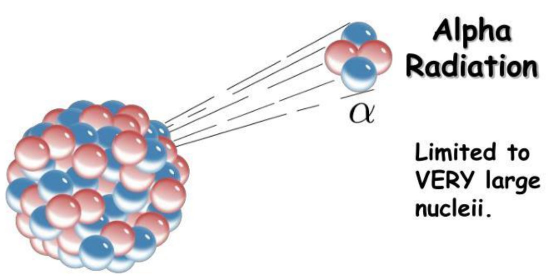
CHINESE ACADEMY OF SCIENCES

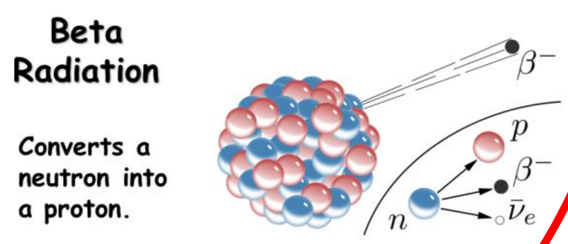
Nuclear decays

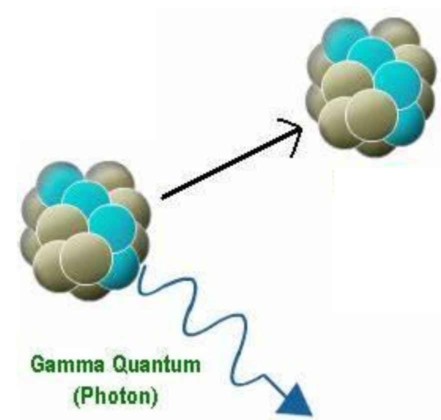
Strong

Weak

Electromagnetic



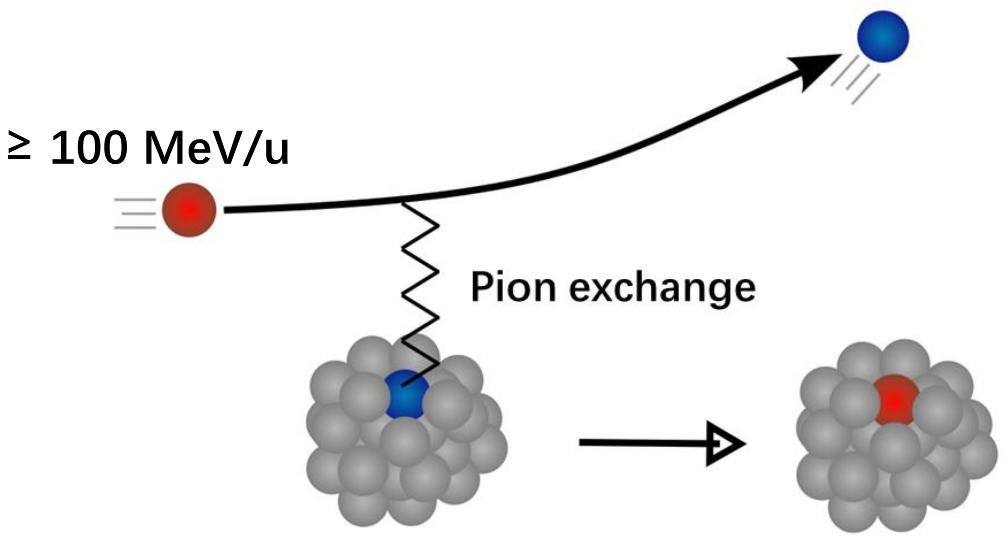




$$\lambda = \frac{\ln 2}{K} \mathrm{B}(GT)\Phi$$

$$\mathrm{B}(GT) = \left(\frac{g_A}{g_V}\right)^2 \frac{<f||\sigma\tau||i>^2}{2J_i+1}$$

Charge-exchange reaction

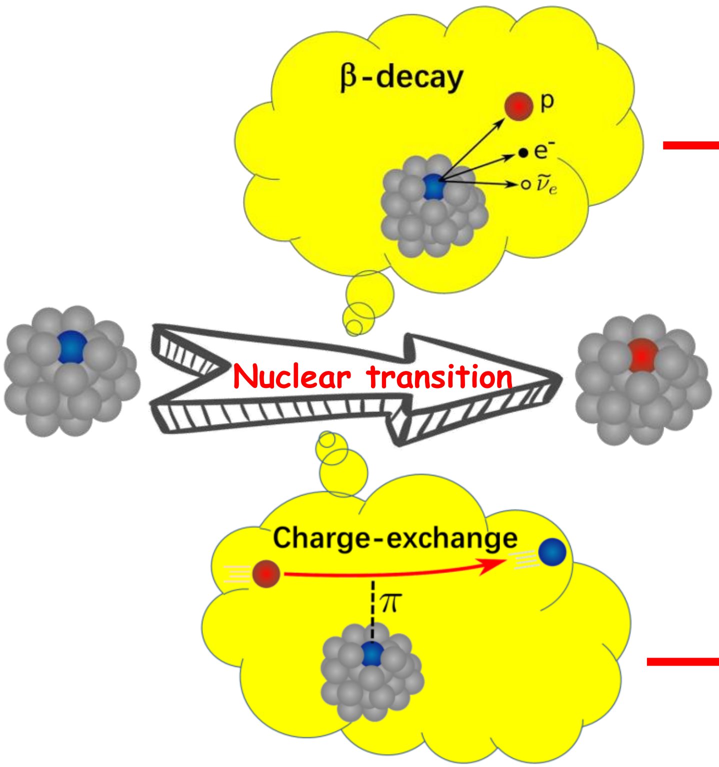


- Direct reaction, single step->easy to extract nuclear structure information
- Beam energy: ≥ 100 MeV/u (inline with the HIAF-HFRS energy region)
- Cross section： $\lesssim$ mb, beam ≥ 10^4 pps
- Probes：(p,n)/(n,p)、(^{3}He,t)/(t,^{3}He)、 (d,^{2}He)

Charge-exchange vs. β-decay

- **The same initial and final states**
- **Very similar operators (στ)**

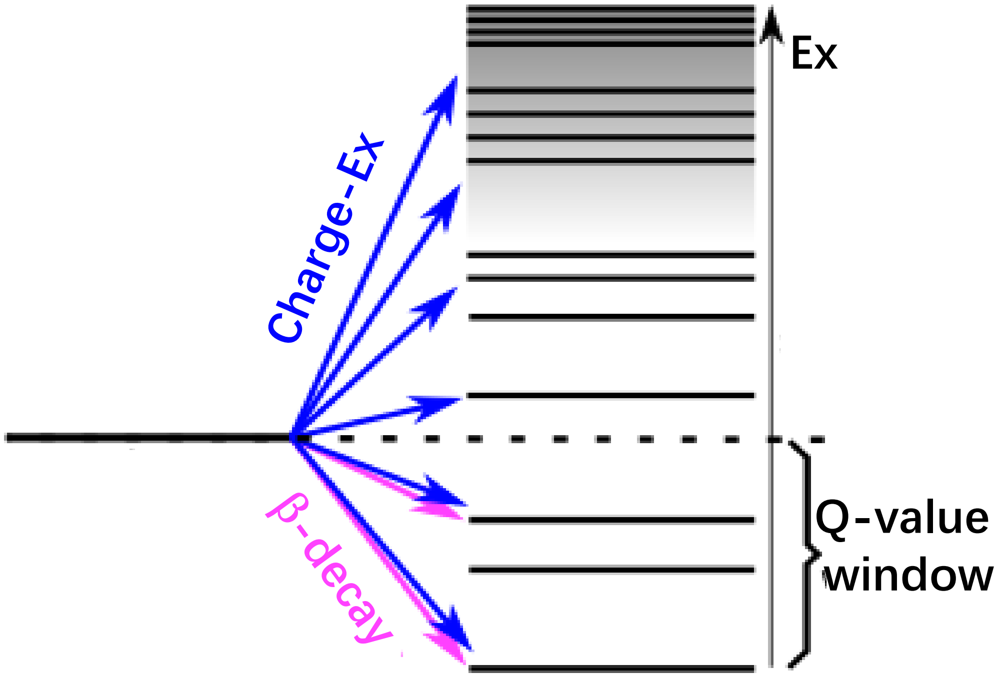
Both charge-exchange reaction and β-decay can study the B(GT)

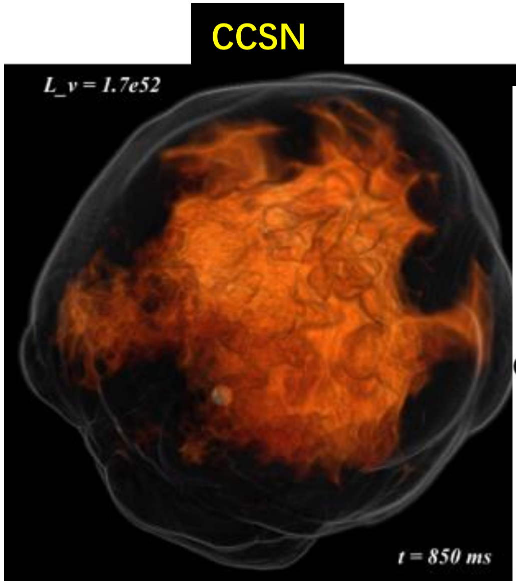


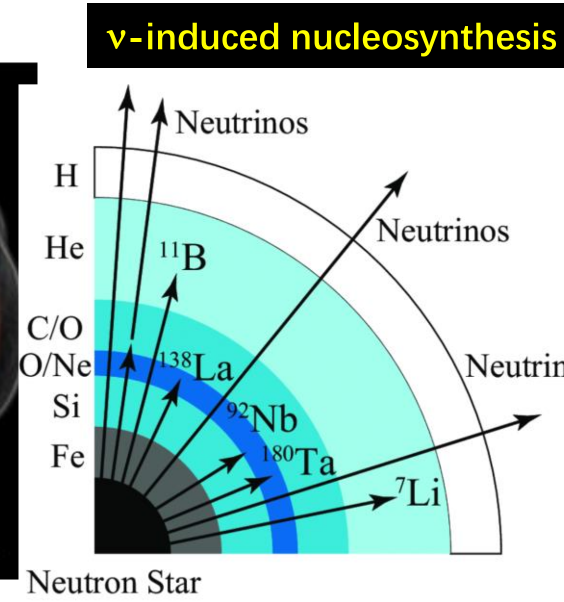
$$\lambda = \frac{\ln 2}{K} |M_{\mathrm{if}}|^2 \Phi$$

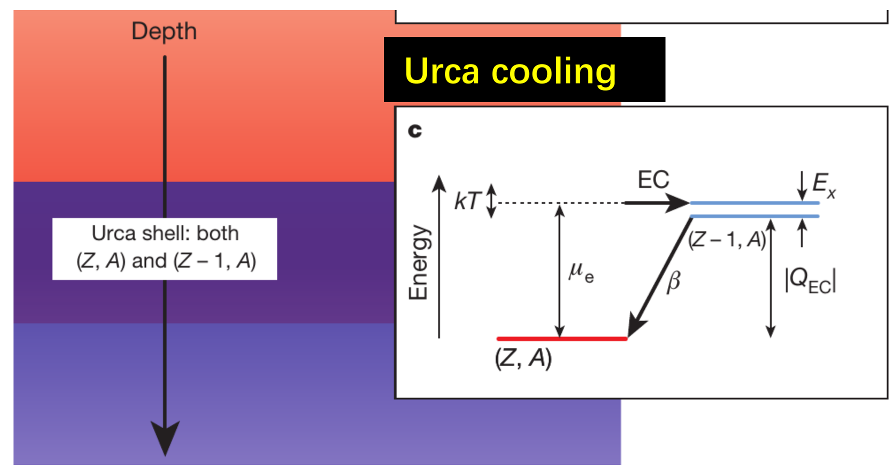
$$\frac{d\sigma}{d\Omega}(q=0) = \hat{\sigma} |M_{if}|^2$$

Charge-exchange vs. β-decay





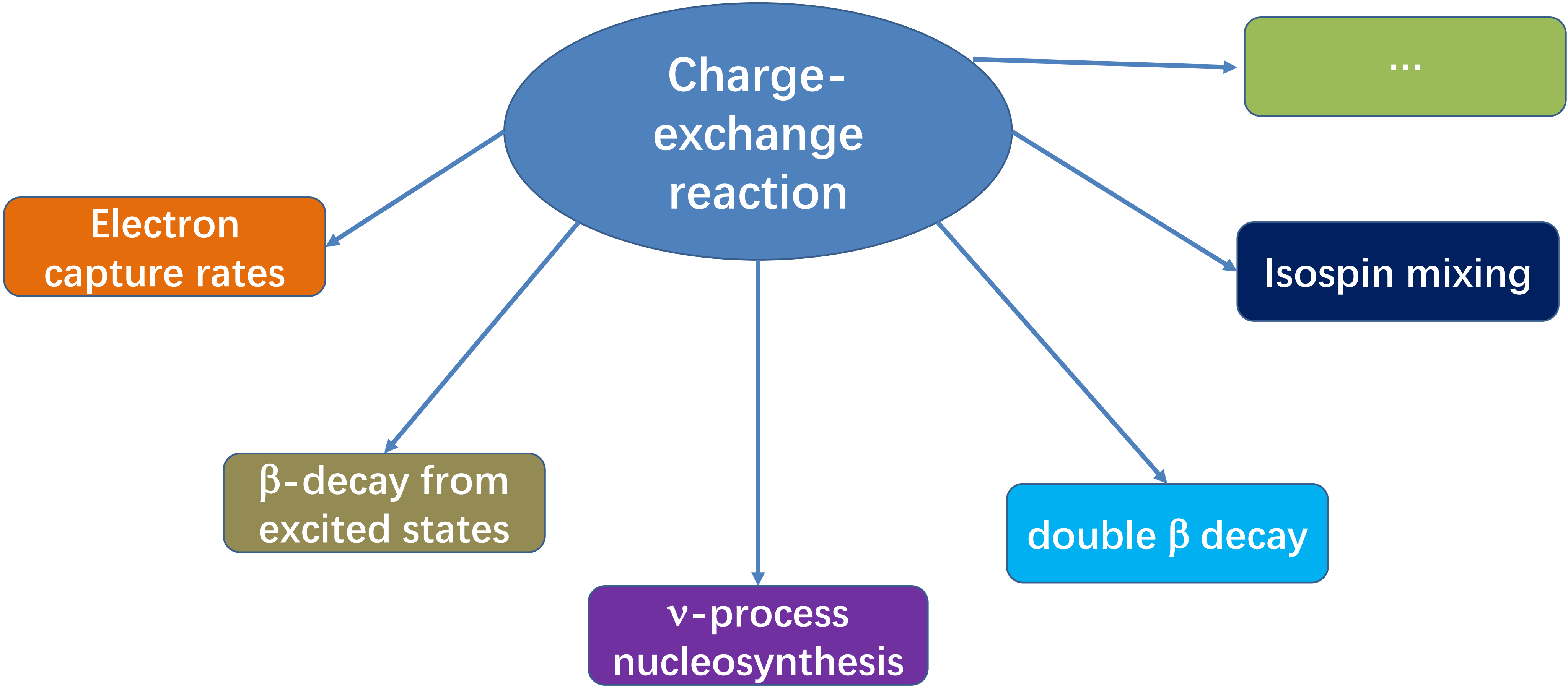




- β-decay is limited by **Q-value window,** only probes low-lying states.
- In stellar environments (high ρ, high T) b-decays have negative Q-value, charge-exchange reaction is the only choice
- Both provide **constraints for theory** development

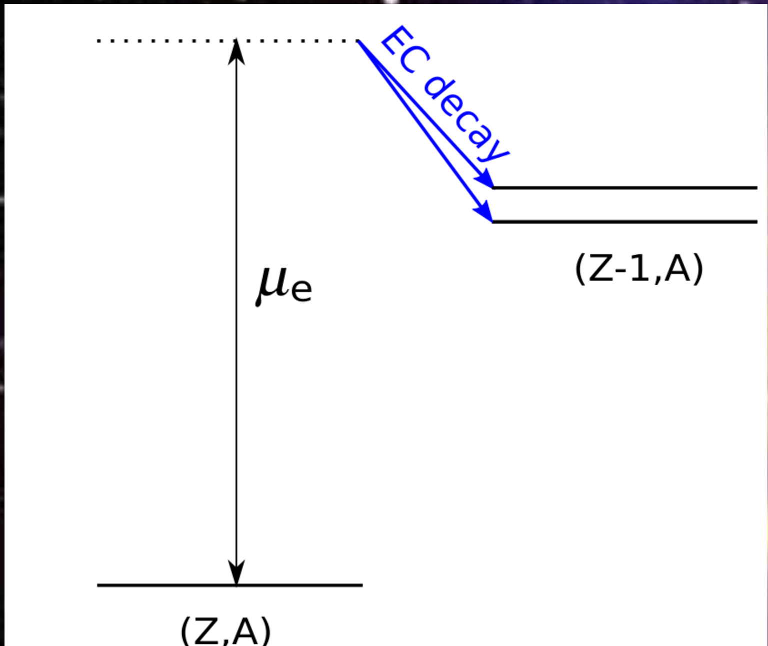
[1] S. M. Couch ApJ 775 1 (2013)
[2] Hayakawa et al., Quantum Beam Sci. 2017,1, 3
[3] Schatz et al., Nature 505, 62 (2014)

Applications



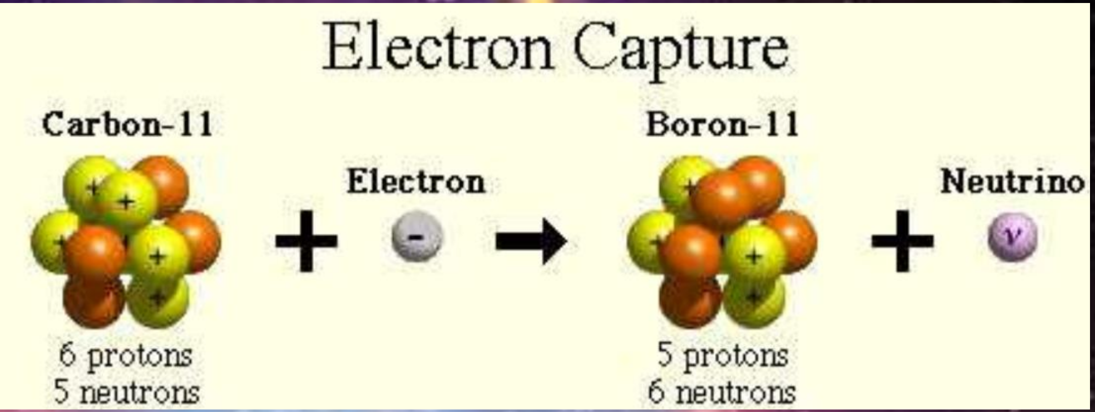
And others…

Electron capture rates in CCSNe



Electron chemical potential μ_e (few MeV) overcomes the negative Q value of EC from neutron-rich nuclides

$$\mu_e = 0.511\text{MeV}\left[\left(1.018\,(\rho_6 Y_e)^{2/3}+1\right)^{1/2}-1\right]$$



Q value:

- Free e-:
  $Q = M_{11C} + M_{e-} - M_{11B}$
- Binding e- (in atomic shell):
  $Q = M_{11C} + M_{e-} - M_{11B} - B_{e-}$
- Degenerate e- (in CCSNe):
  $Q = M_{11B} - M_{11C} - M_{e-} + \mu_{e-}$

Electron capture rates in CCSNe

EC at different stages of CCSNe:

- Pre-supernova
  The iron group
- Deleptonization
  Neutron-rich region around N~50 closed shell
- Neutrino burst
  Free protons

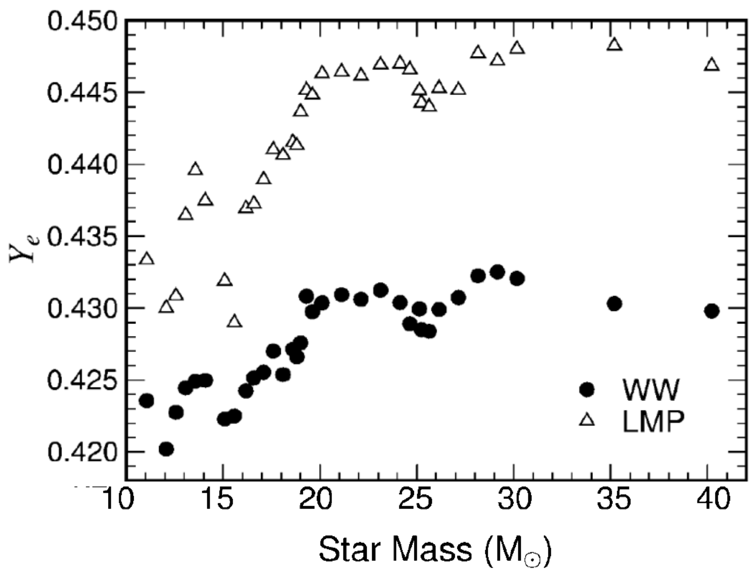
1) Pre-Supernovae (iron group)

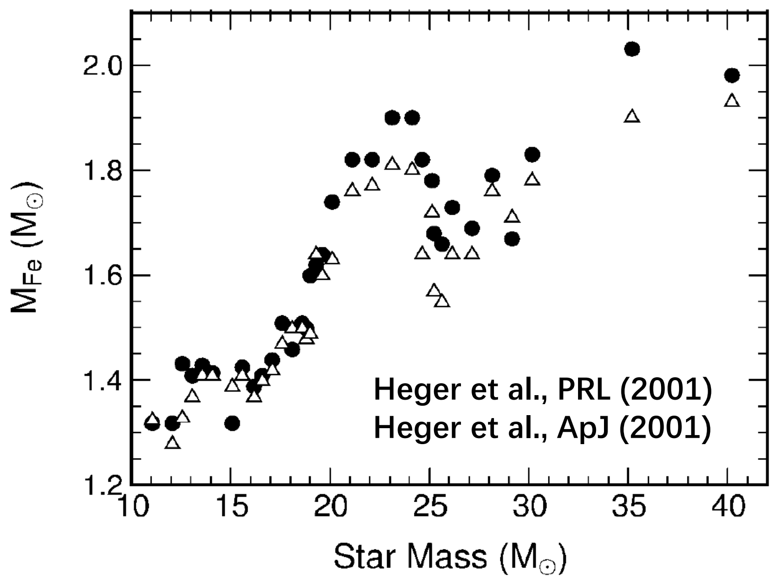
Dominated by Gamow-Teller transitions:

$$\lambda_{EC} = ln2 \sum_{ij} f_{ij}(T, \rho, U_F) B(GT)_{ij}$$

- Independent particle model (FFN rate, 1980s-2000s)
- Interacting Shell Model (LMP rate, 2000s-now)

Note:
Observed neutron star mass lower limit of < 1.2 $M_\odot$ is very difficult to reproduce in stellar models

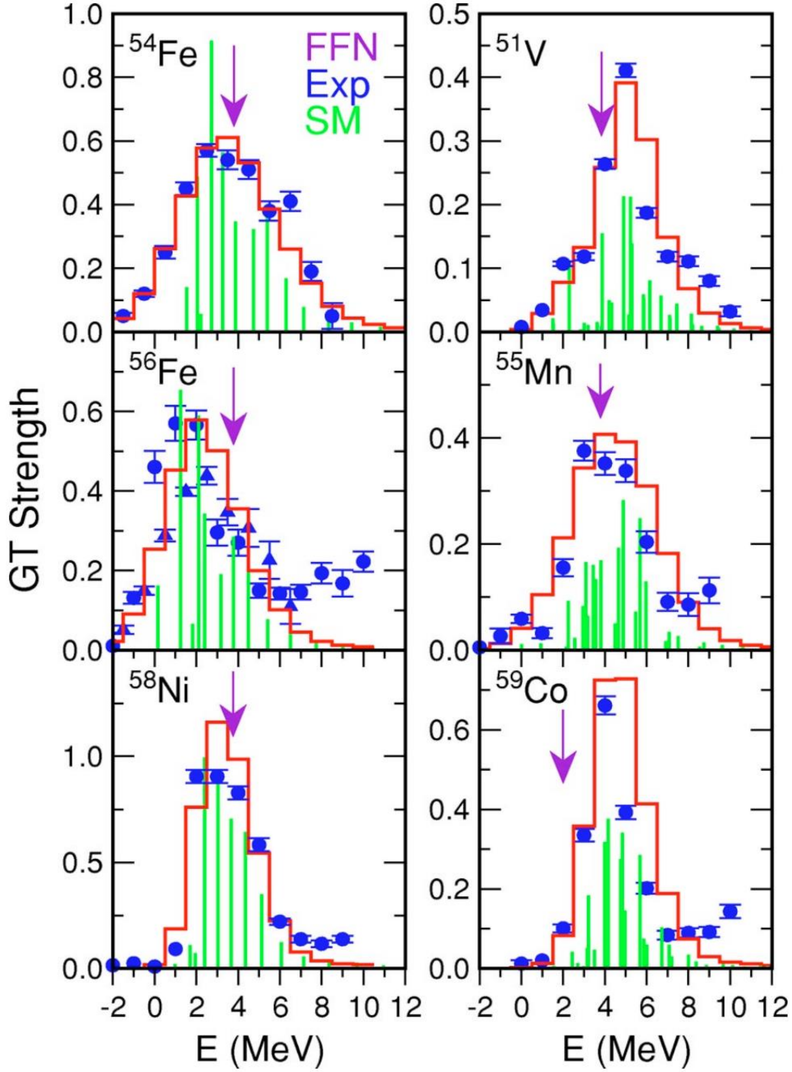




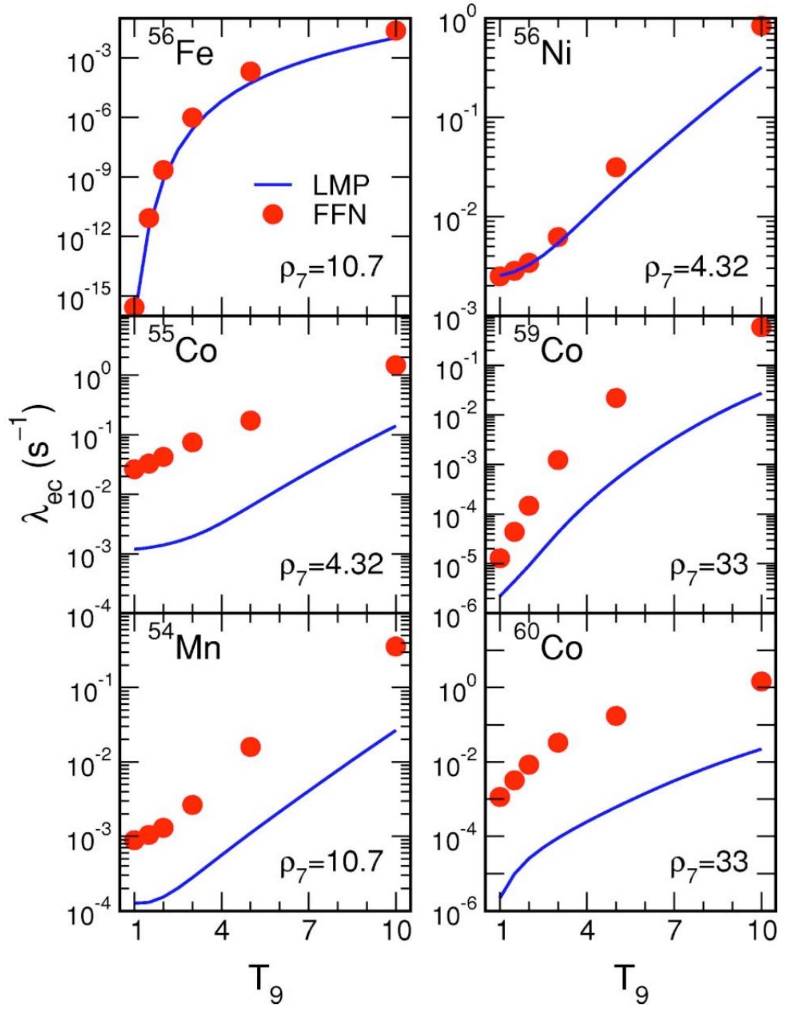
Significant change of the Pre-SN structure (e.g. Y_e, M_{Fe}) due to the new EC rates

FFN, LMP and experimental data

Comparisons to charge-exchange data:



EC rates change by more than x10:



K. Langanke and G. Martínez-Pinedo, RMP (2003)

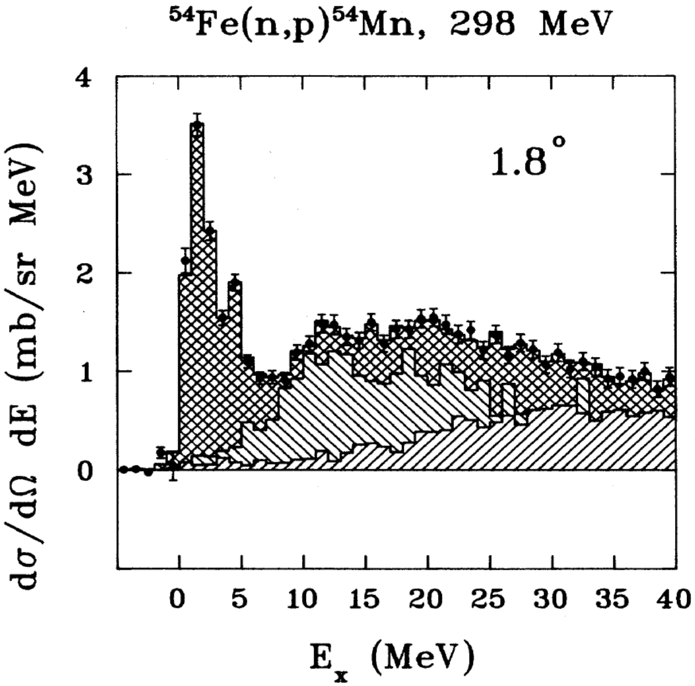
Importance of high-resolution data

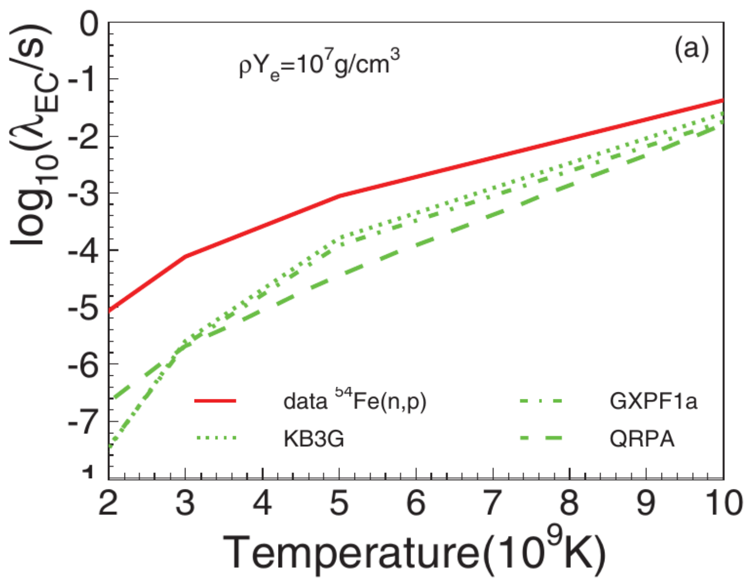
Most important EC nuclei in pre-SN

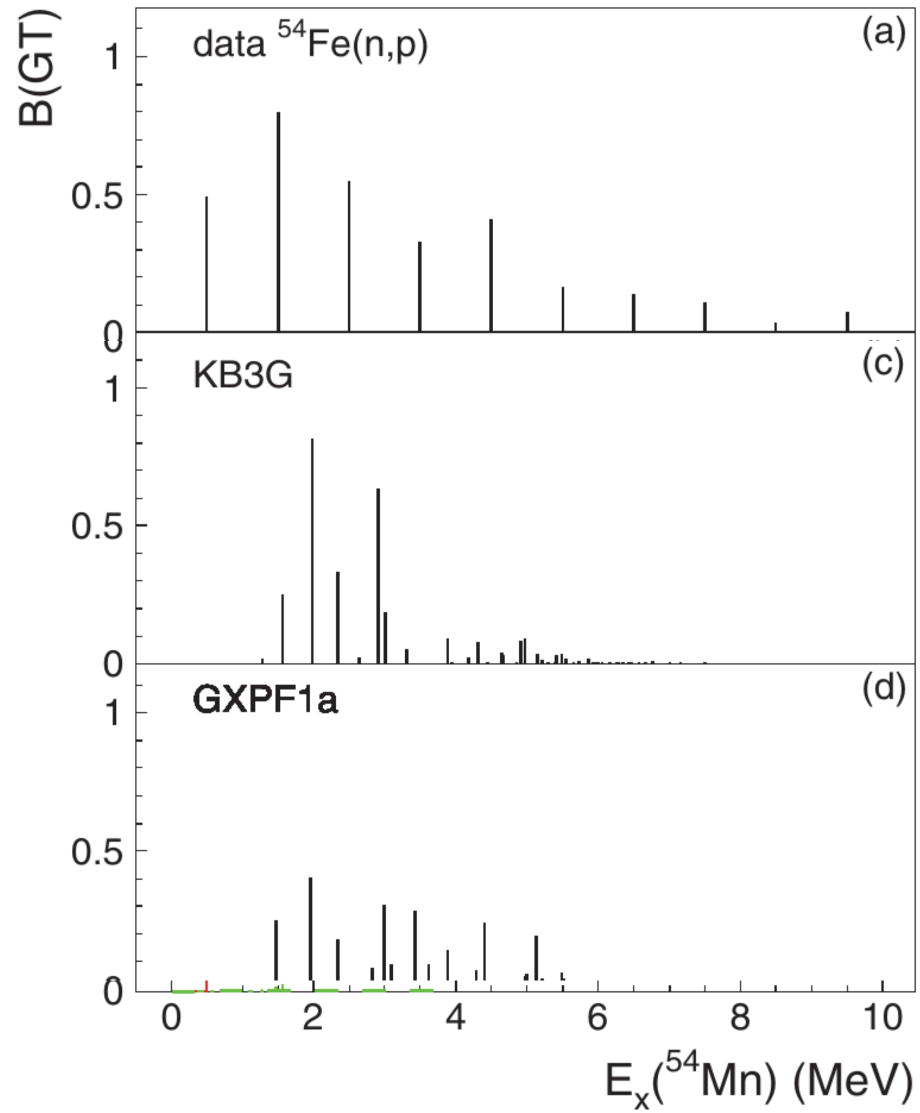
T (K)	ρ (g cm^{-3})	Y_e	λ_{ec} (s^{-1})	Electron capture		
					$15M_\odot$	
3.39×10^9	4.50×10^7	0.480	5.17×10^{-7}	^{54}Fe (29)	^{55}Fe (25)	^{53}Mn (11)
3.82×10^9	7.26×10^7	0.464	3.30×10^{-7}	^{55}Fe (41)	^{57}Co (10)	^{53}Mn (9)
4.13×10^9	2.89×10^8	0.450	6.86×10^{-7}	^{57}Fe (54)	^{61}Ni (21)	^{56}Fe (14)
4.41×10^9	1.30×10^9	0.442	7.57×10^{-6}	^{57}Fe (22)	^{53}Cr (14)	^{55}Mn (13)
7.25×10^9	9.36×10^9	0.432	9.21×10^{-3}	^{65}Ni (14)	^{59}Fe (7)	^{52}V (7)
					$25M_\odot$	
3.79×10^9	2.89×10^7	0.487	3.18×10^{-6}	^{53}Fe (23)	^{55}Co (20)	^{56}Ni (19)
4.17×10^9	3.71×10^7	0.476	4.23×10^{-6}	^{54}Fe (21)	^{55}Co (14)	^{55}Fe (11)
5.03×10^9	1.82×10^8	0.456	3.84×10^{-6}	^{56}Fe (17)	^{55}Fe (13)	^{61}Ni (10)
5.57×10^9	5.05×10^8	0.449	1.45×10^{-5}	^{57}Fe (16)	^{56}Fe (11)	^{53}Cr (9)
7.75×10^9	2.42×10^9	0.445	1.95×10^{-3}	^{1}H (32)	^{53}Cr (9)	^{57}Fe (7)

Heger et al., PRL (2001)

Importance of high-resolution data







M. C. Vetterli et al., PRC 40, 559 (1989)
A. L. COLE et al. PRC 86, 015809 (2012)

Charge-exchange & γ-ray spectrascopy

The Coupled-Cyclotron Facility (CCF) and S800 spectrometer + GRETINA at NSCL/FRIB

Measure cross section, then obtain B(GT):

$$\left(\frac{d\sigma}{d\Omega}(q=0)\right)_{(t,{}^3He)} = \hat{\sigma}\, B(GT)$$

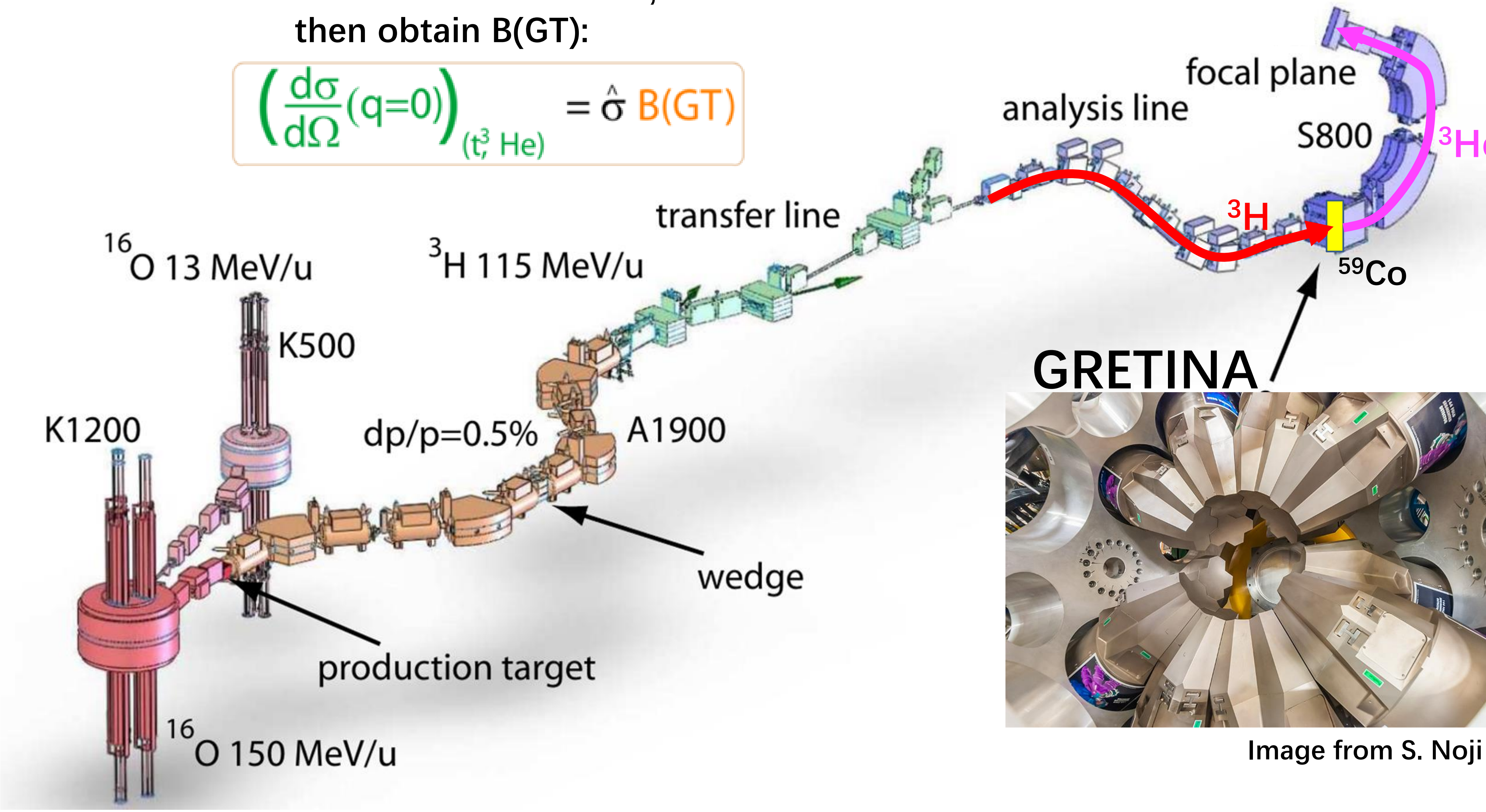
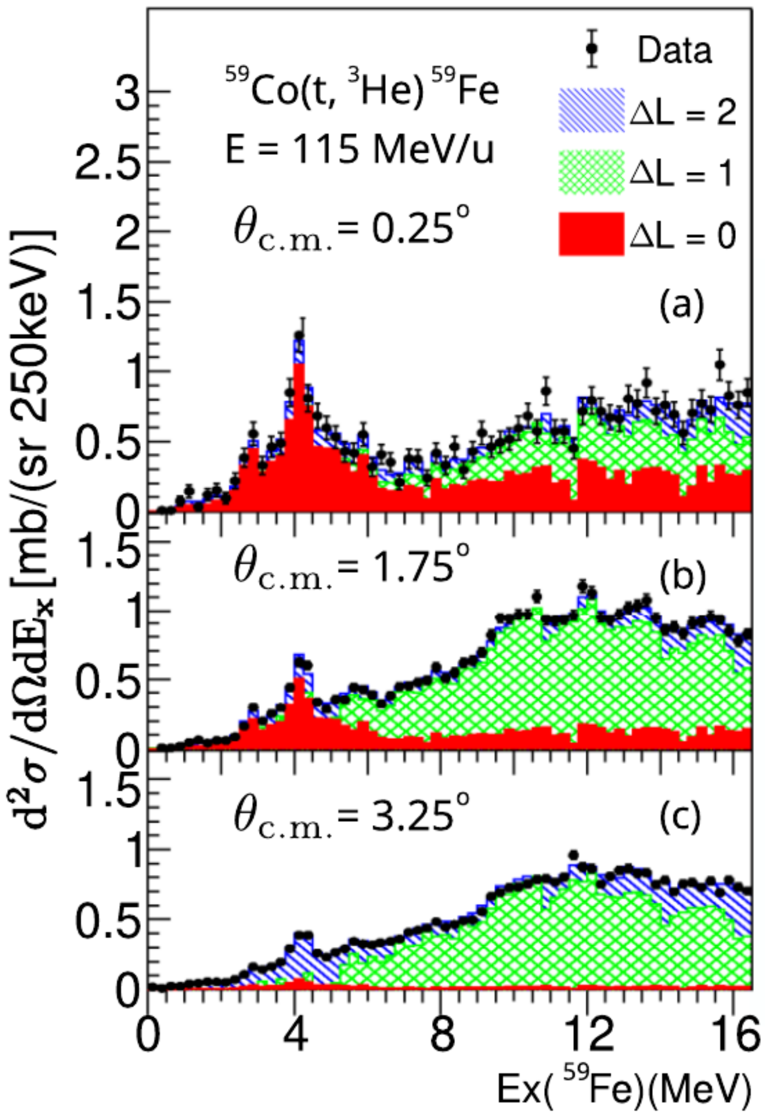


Image from S. Noji

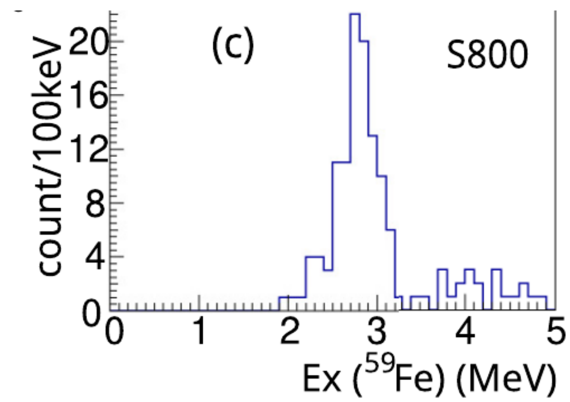
Charge-exchange & γ-ray spectroscopy

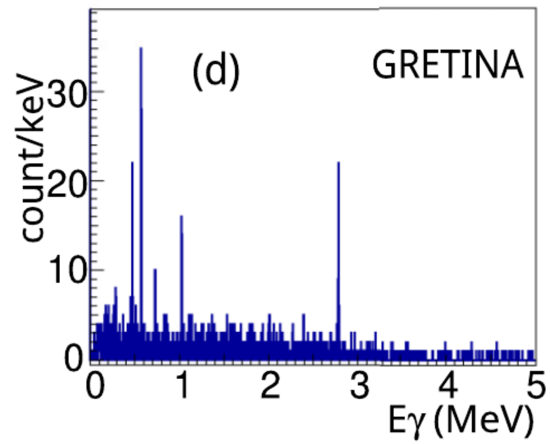
B.Gao et al., PRC 112, 024615 (2025)

Singles data

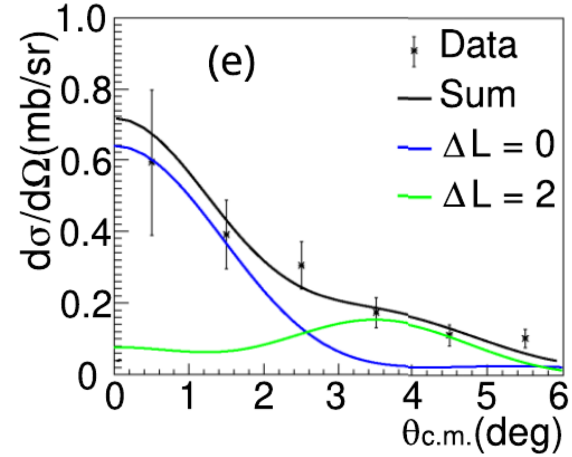


Coincident data

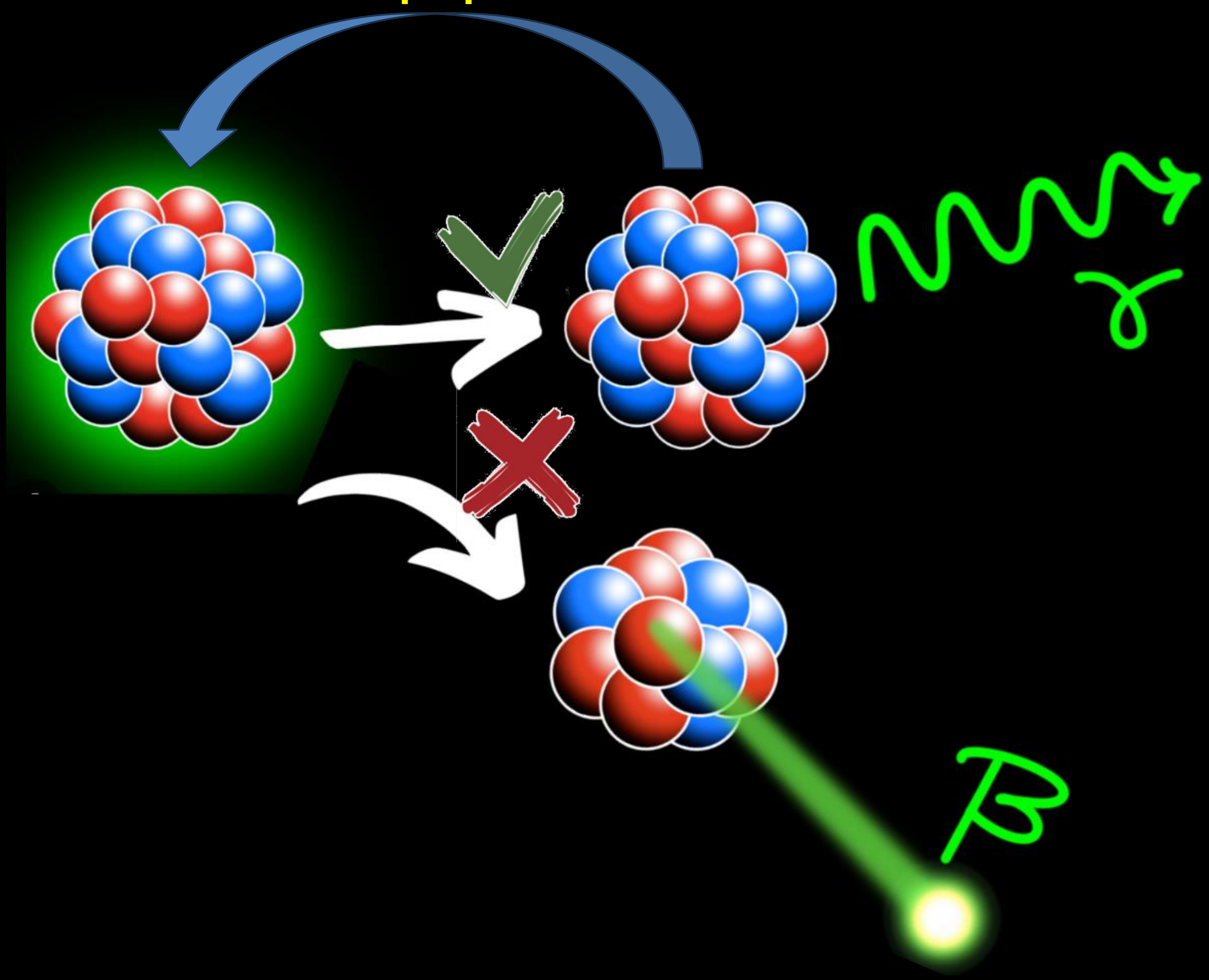




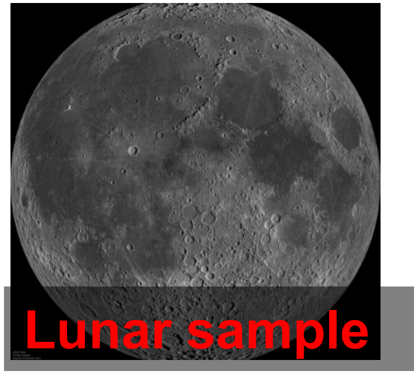
Angular distribution



beta decay from excited states

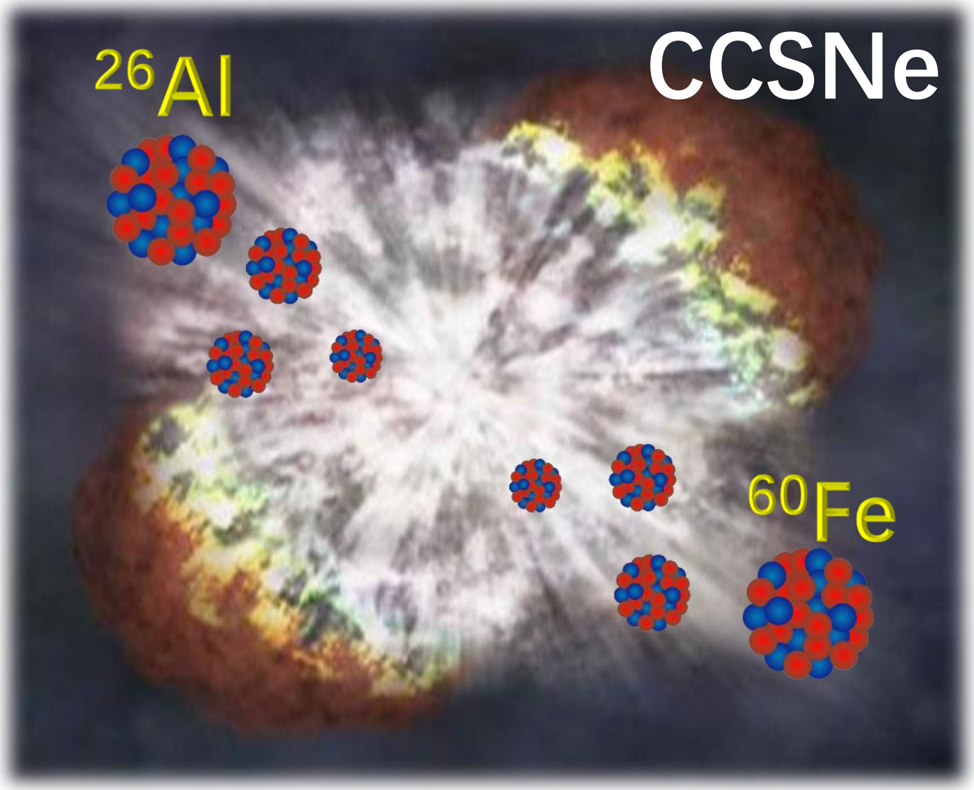


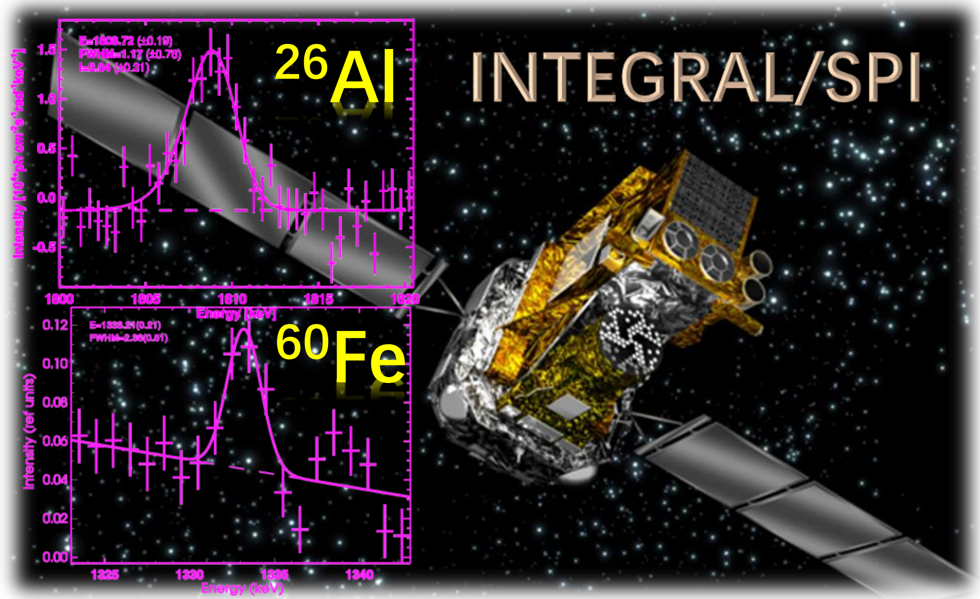
^{60}Fe in astrophysics



^{60}Fe wanted by astrophysical scientists, dead or alive, high up in the sky, on the moon or deep under the sea!

The $^{60}Fe/^{26}Al$ Puzzle





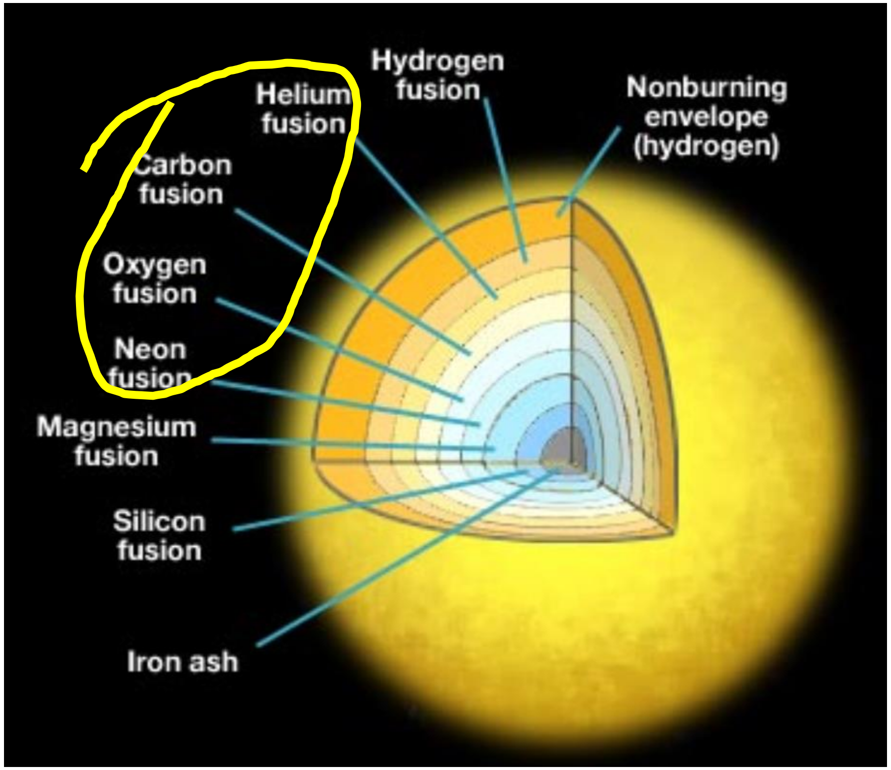
Observation: $^{60}Fe/^{26}Al = 0.184(42)$

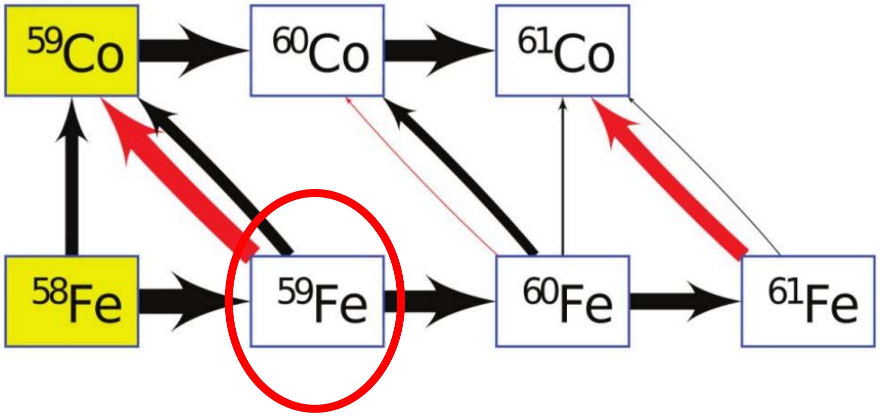
Theory prediction: $^{60}Fe/^{26}Al = 0.45$

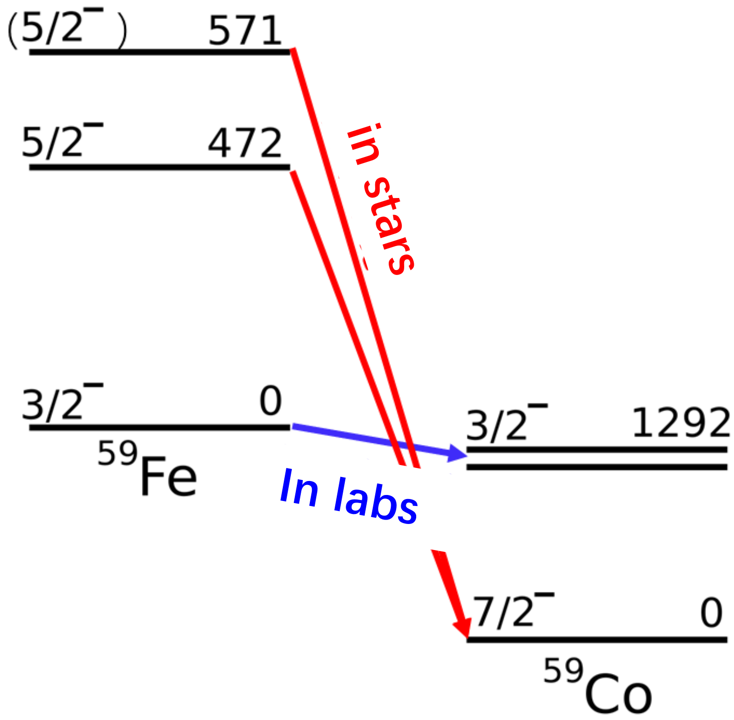
[1] W. Wang, et al. ApJ 889, 169 (2020).
[2] S. E. Woosley and A. Heger, Phys. Rep. 442, 269 (2007)

^{60}Fe synthesized in stars

^{60}Fe produced in:

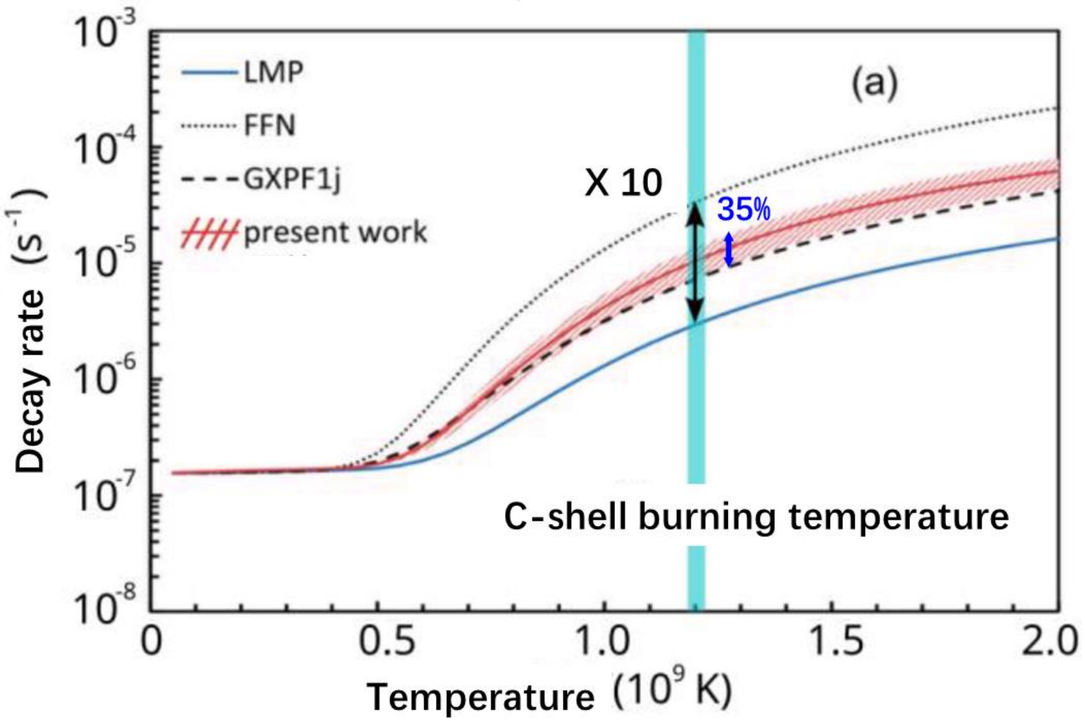


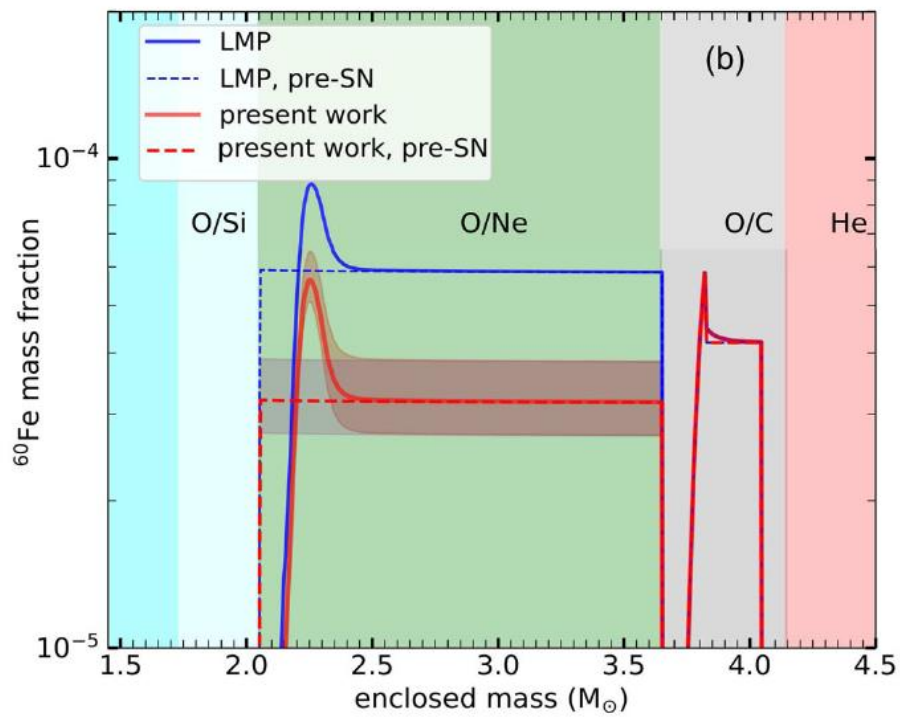




- Competition between β-decay and n-capture of ^{59}Fe determines yield of ^{60}Fe
- Highly uncertain β-decay rate of ^{59}Fe, cannot accurately predict yield of ^{60}Fe
- Direct measurement of ^{59}Fe decay rate from excited states impossible.

Stellar decay rate of ^{59}Fe



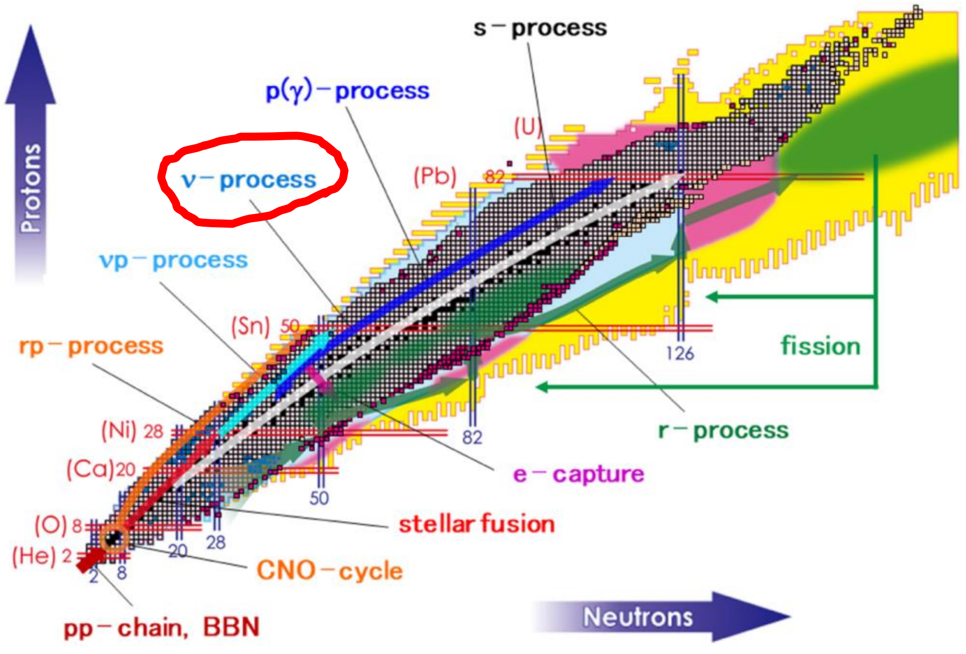


- The uncertainty of ^{59}Fe decay rate is significantly reduced (from a factor of 10 to 35%), 3 times faster than previously used value.
- 18 solar mass model calculation shows a decrease of ^{60}Fe production by 40%, reducing the tension between observation and calculation (systematic calculations needed to fully investigate the impact of the new ^{59}Fe decay rate)

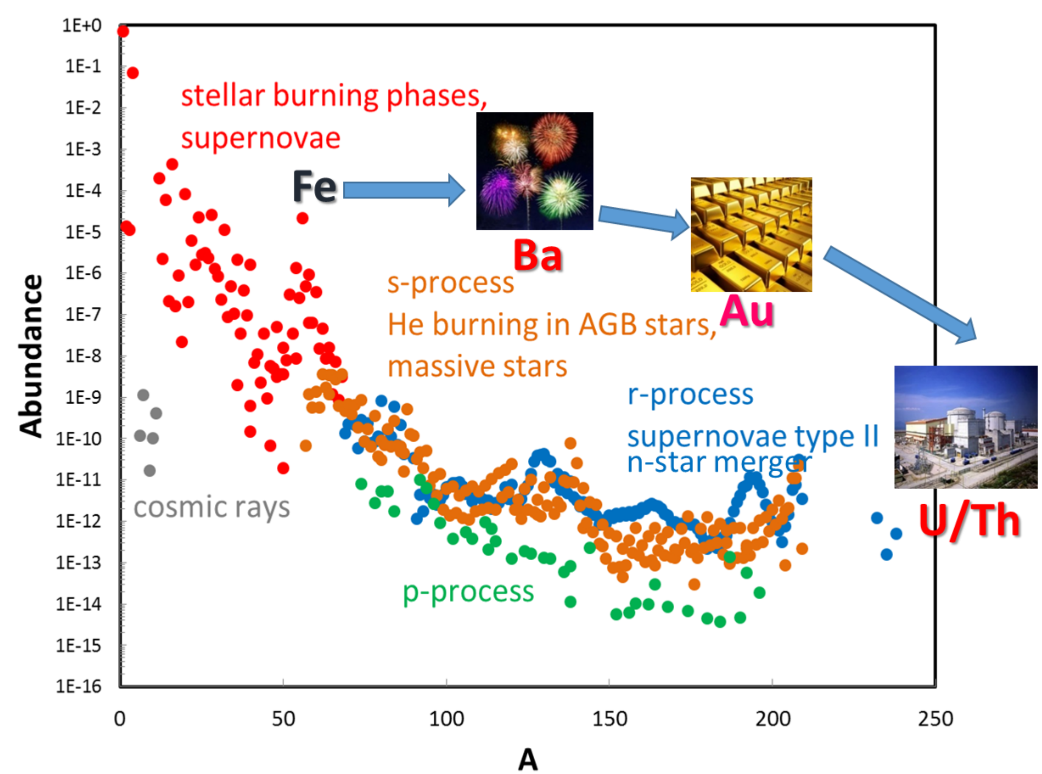
B. Gao *et al.*,PRL. 126, 152701 (2021)

ν-process

- The origin of elements in the Universe：BBN, stellar fusion, r-process, s-process, i-process, rp-process, νp-process, ν-process, p/γ-process, …
- Dominated by BBN (up to Li), stellar fusion (up to iron), s and r-process (heavier than iron)
- ν-process: important only when other processes are blocked (CCSNe): ^{7}Li, ^{11}B, ^{138}La, ^{180}Ta, ^{92}Nb, ^{98}Tc, ^{19}F, ^{50}V, ^{53}Mn。Their abundances in meteorites provide valuable constraints on stellar models

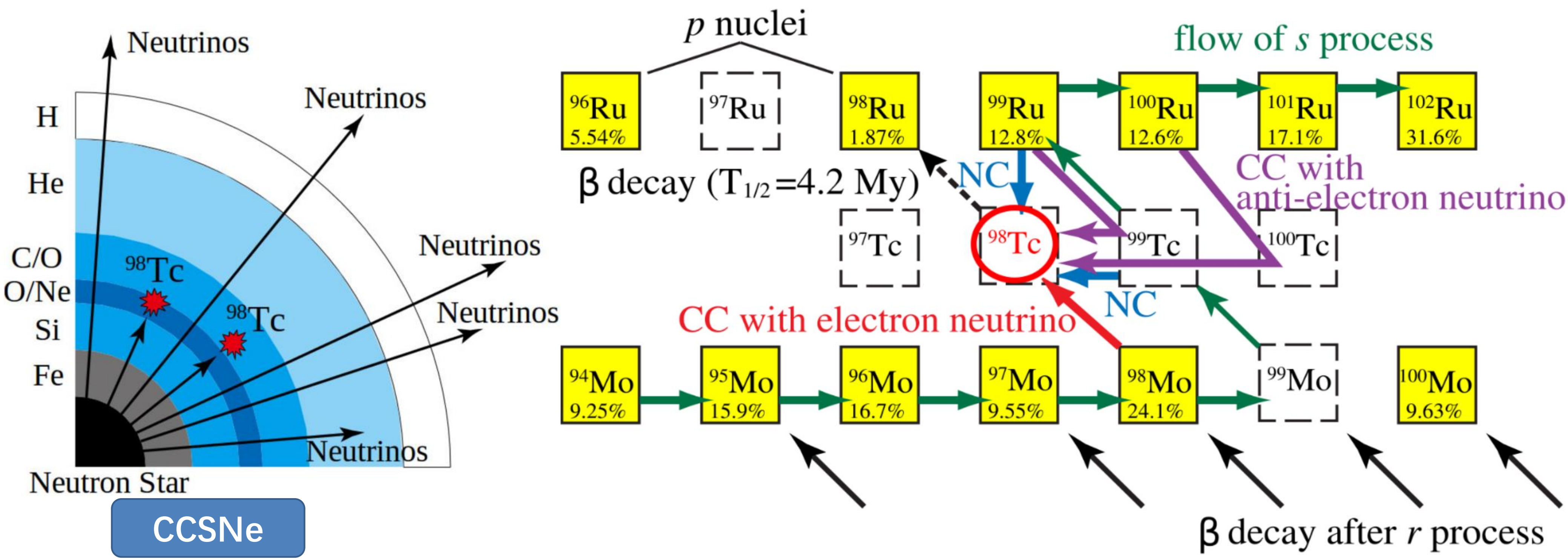


Aziz et al. AAPPS Bulletin (2021)



Based on West and Heger, ApJ(2013)

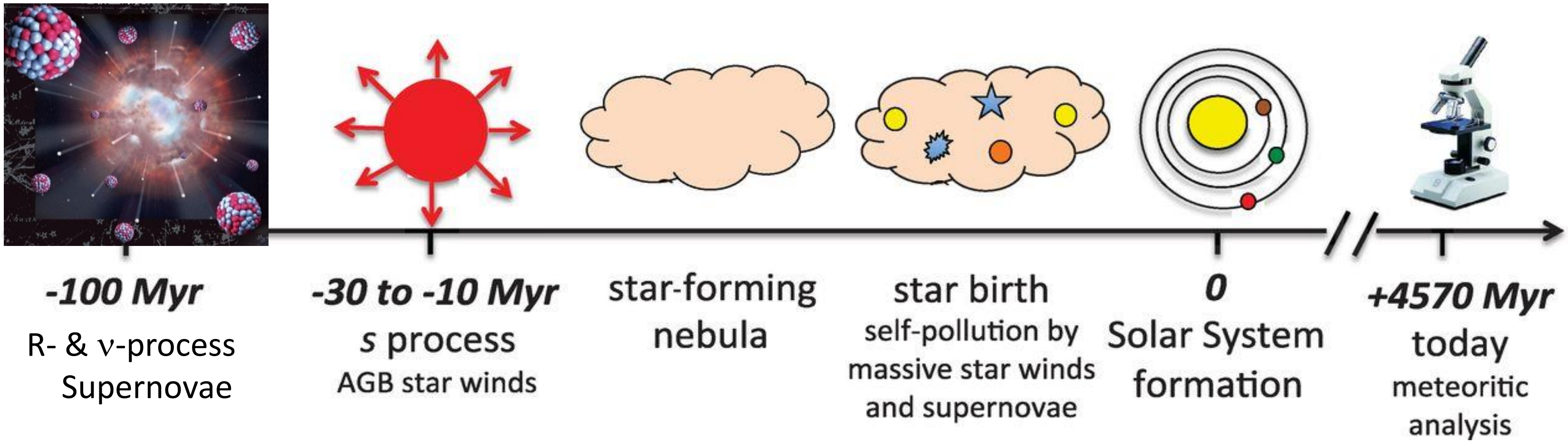
ν-nucleus: ^{98}Tc

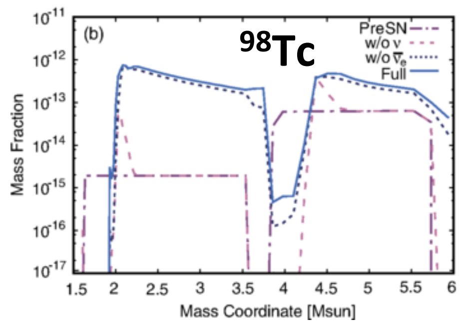


- Cannot be produced by s-,r- or rp-processes
- ν-process is proposed to be the main mechenism: ^{98}Mo(ν_e,e^-)^{98}Tc in some model calculations
- Provides constraints on n spectra in CCSNe and evolution history (~My) of the solar system

T. Hayakawa et al., Phys. Rev. Lett. 121, 102701 (2018)

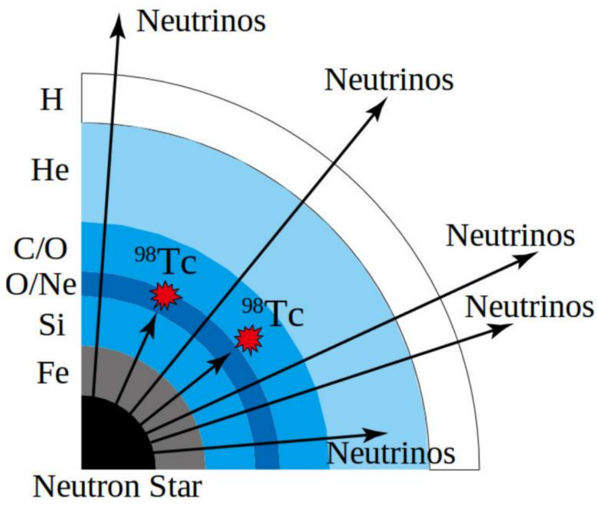
Solar system archaeology





- **^{98}Tc ($T_{1/2}$=4.2 My) decays with comparable time scale as the last SN event before formation of the solar system**
- **Calculate the yield of ^{98}Tc from SN, measure the abundance in pre-solar meteorites, then compare the two, see how much ^{98}Tc decayed and obtain the time duration**

ν-nucleus interaction cross section

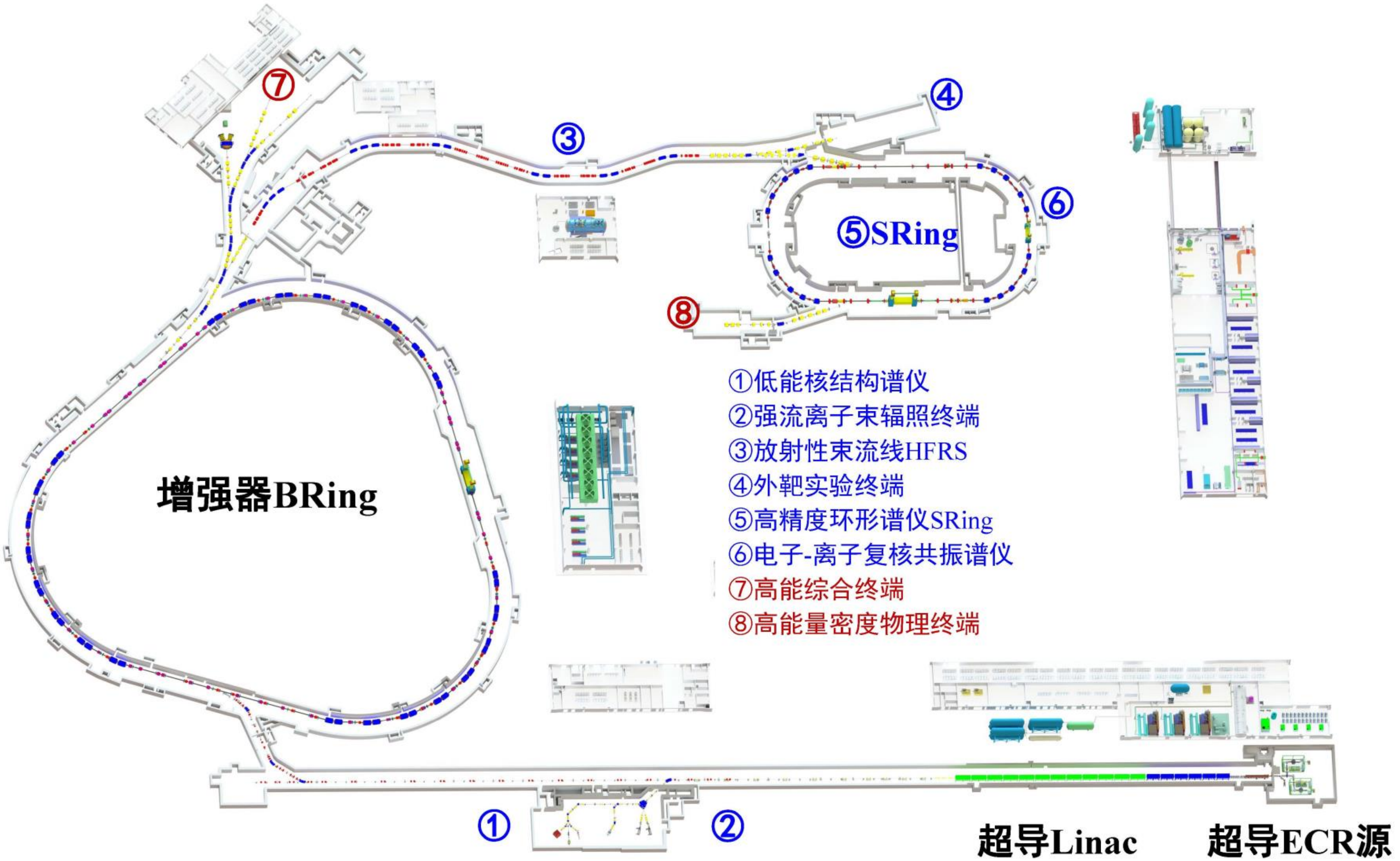


ν-process cross section：

$$\sigma(E_{\nu_e}) = \frac{(G_F \cos\theta_c)^2}{4\pi}[B(F) + g_A^2 B(GT)]E_e'|p_e'|F(Z, E_e')$$

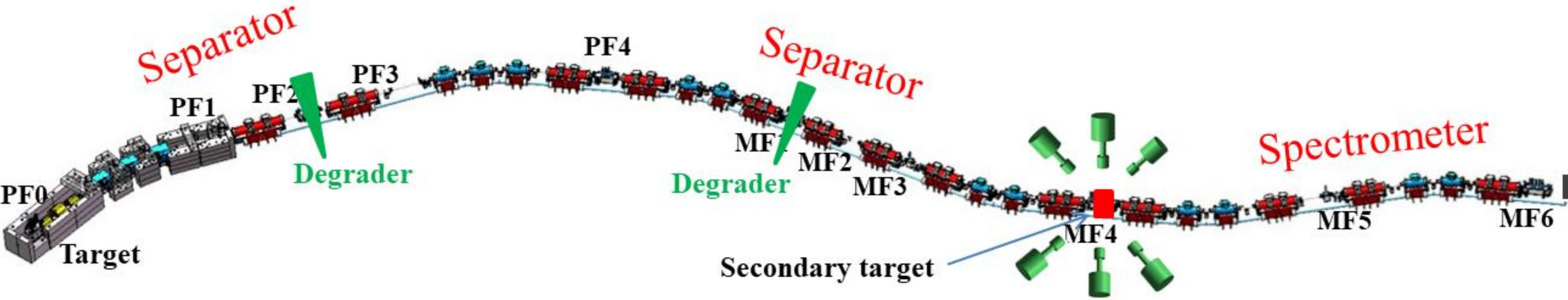
- **B(GT) depends on nuclear structure, to be determined via ^{98}Mo(^{3}He,t)^{98}Tc charge-exchange reaction (RCNP)**
- **Other terms are well-known constants or readily calculable factors**

Opportunities at HIAF



Opportunities at HIAF

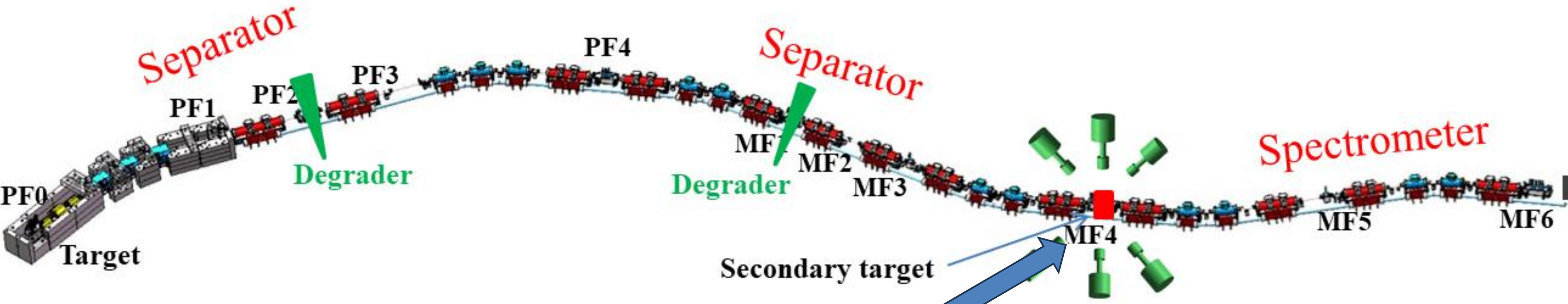
Operation mode: Separator + Separator + Spectrometer

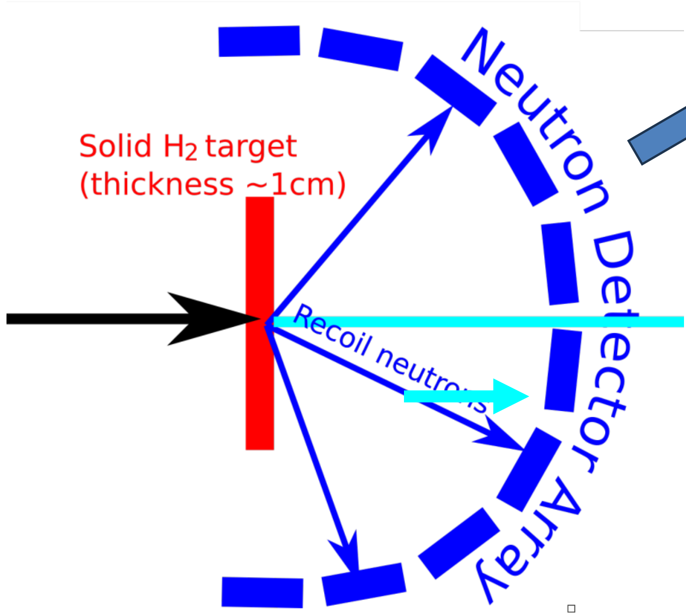


By operating the HIRIBL as a Separator + Spectrometer, (t,^{3}He) reactions are readily possible!

Opportunities at HIAF

Operation mode: Separator + Separator + Spectrometer

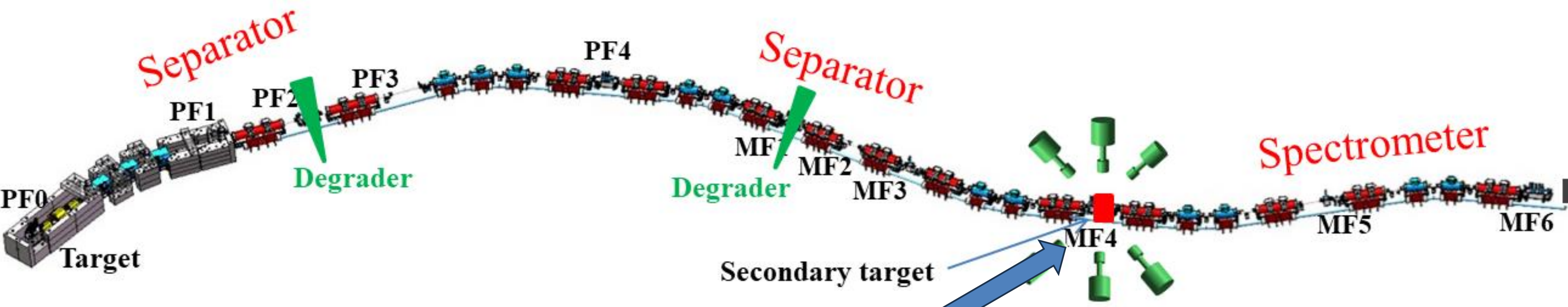


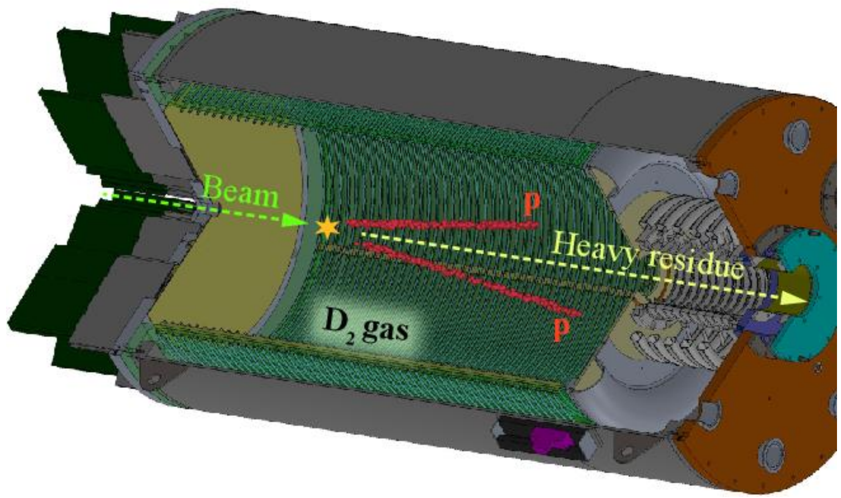


(p,n) reaction in inverse kinematics is possible!

Opportunities at HIAF

Operation mode: Separator + Separator + Spectrometer





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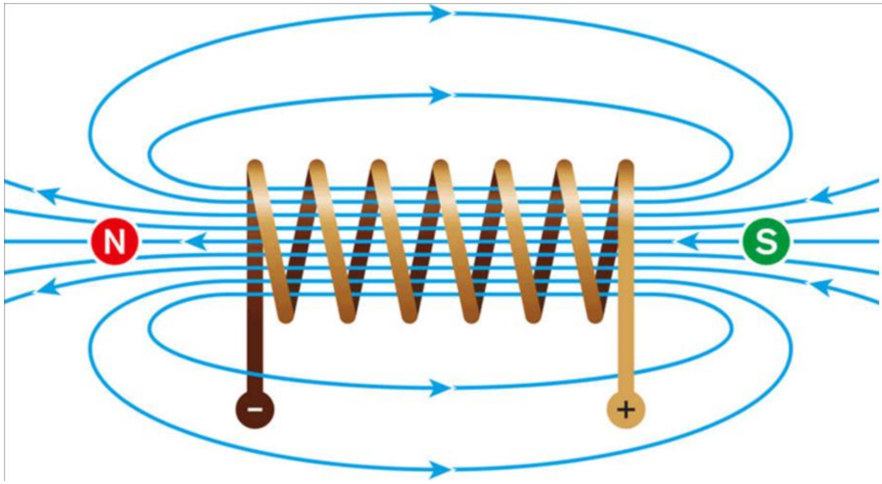
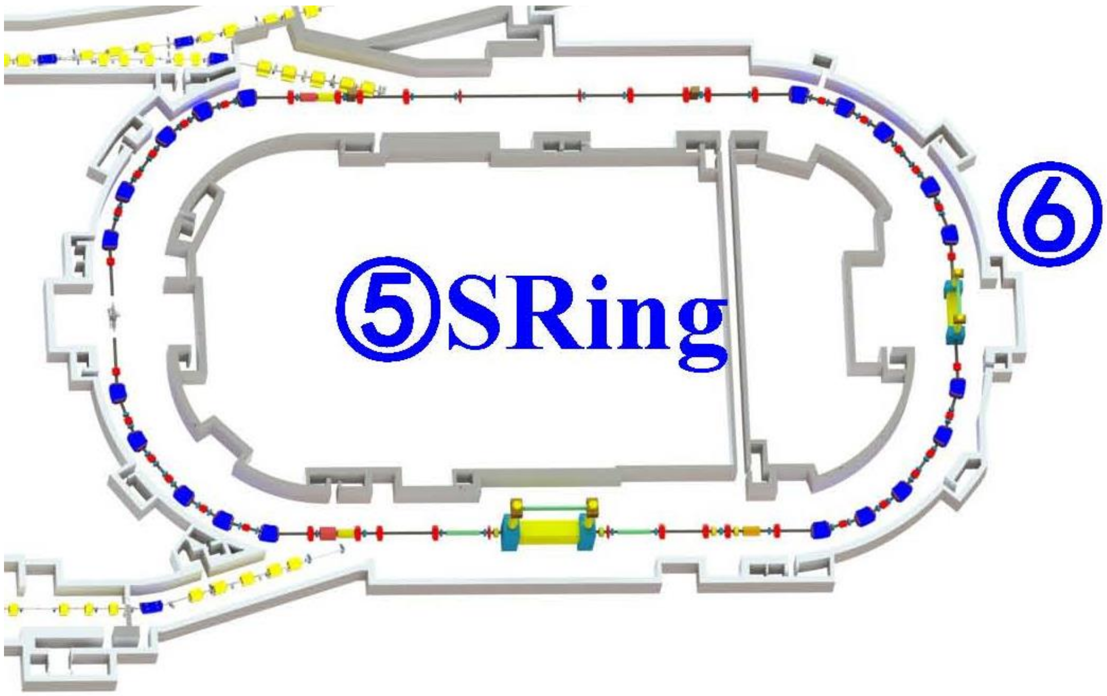
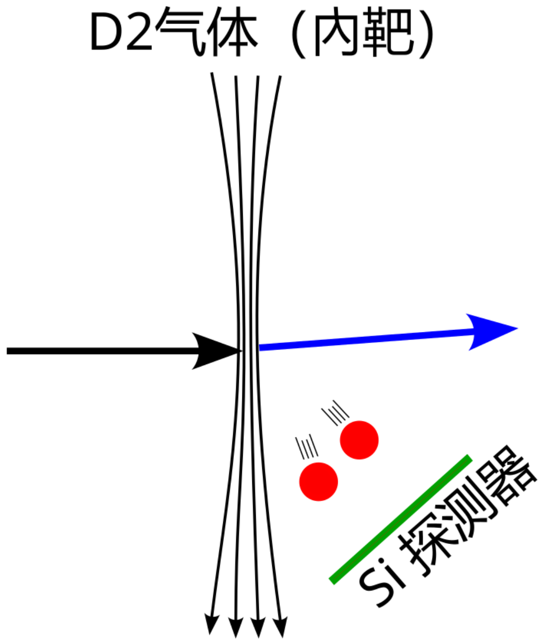


(d,^{2}He) and (3He, t) in inverse kinematics is possible by using TPC

Opportunities at HIAF



(d,^{2}He), (^{3}He,t) using internal target are possible !



Thanks!