


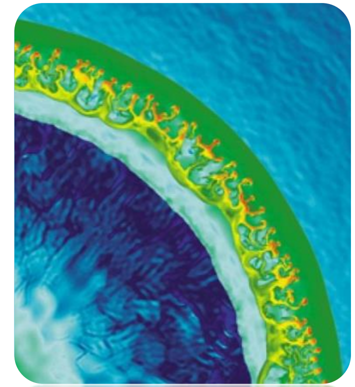


Nuclear reactions in stars

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Chinese Academy of Sciences

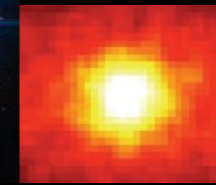
SJTU-JINA winter school **Shanghai, Dec 12 - 17, 2016**


HIRFL@
Lanzhou
JUNA@
Xichang
HIAF@
Huizhou

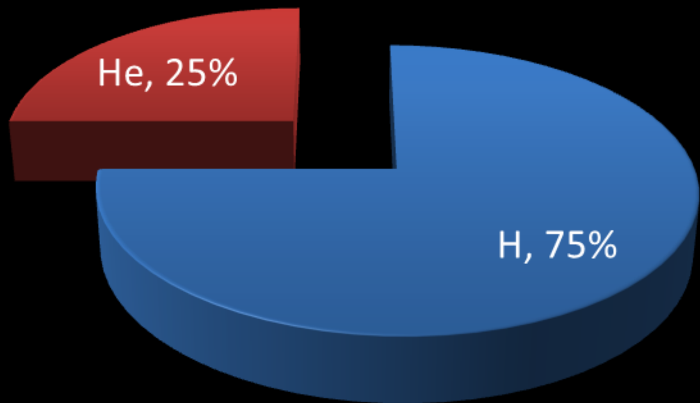
OUTLINE

- Direct measurement at underground (why go underground)
- Carbon fusion reaction
- ^{59}Fe decay in star
- Research with Heavy Ion Research Facility at Lanzhou (HIRFL)
- Research with High Intensity Accelerator Facility (HIAF)

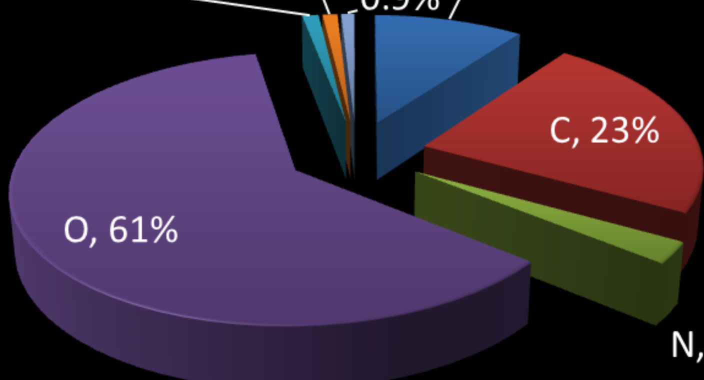
Origin of elements



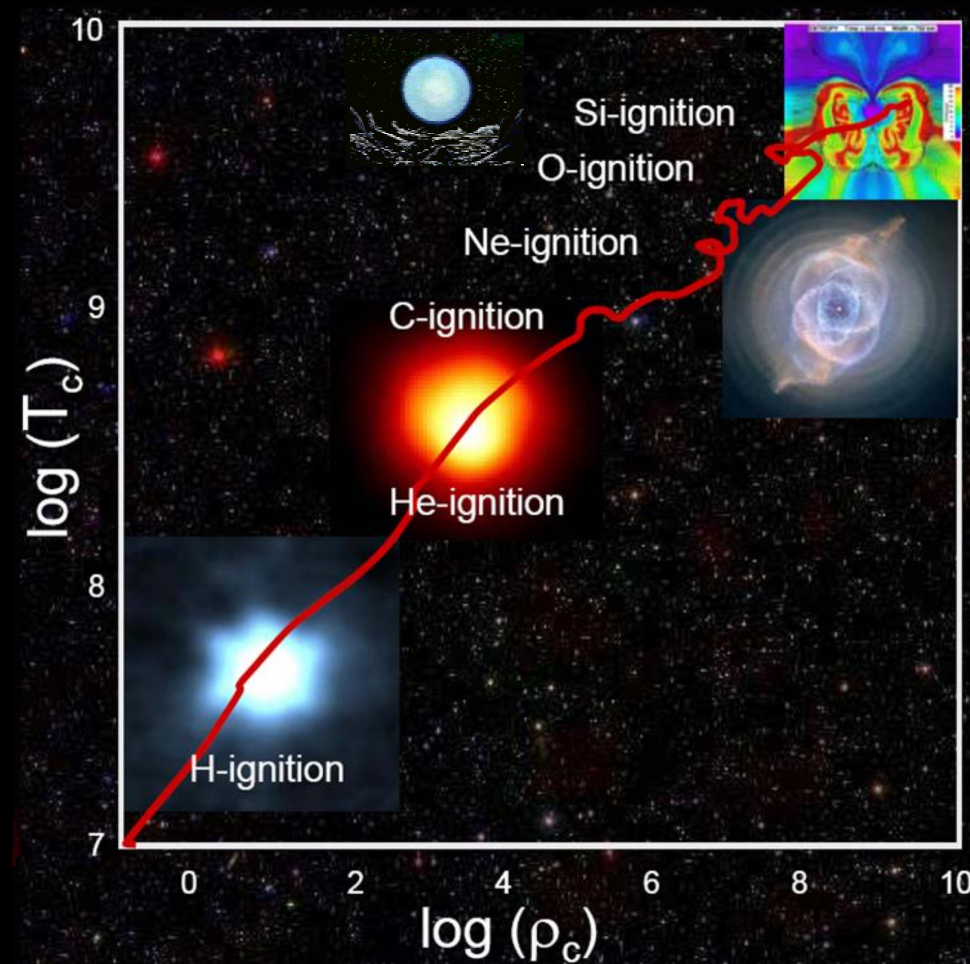
Others (^2H, ^3He, ^6Li, ^7Li)<0.00001



3 mins after BBN



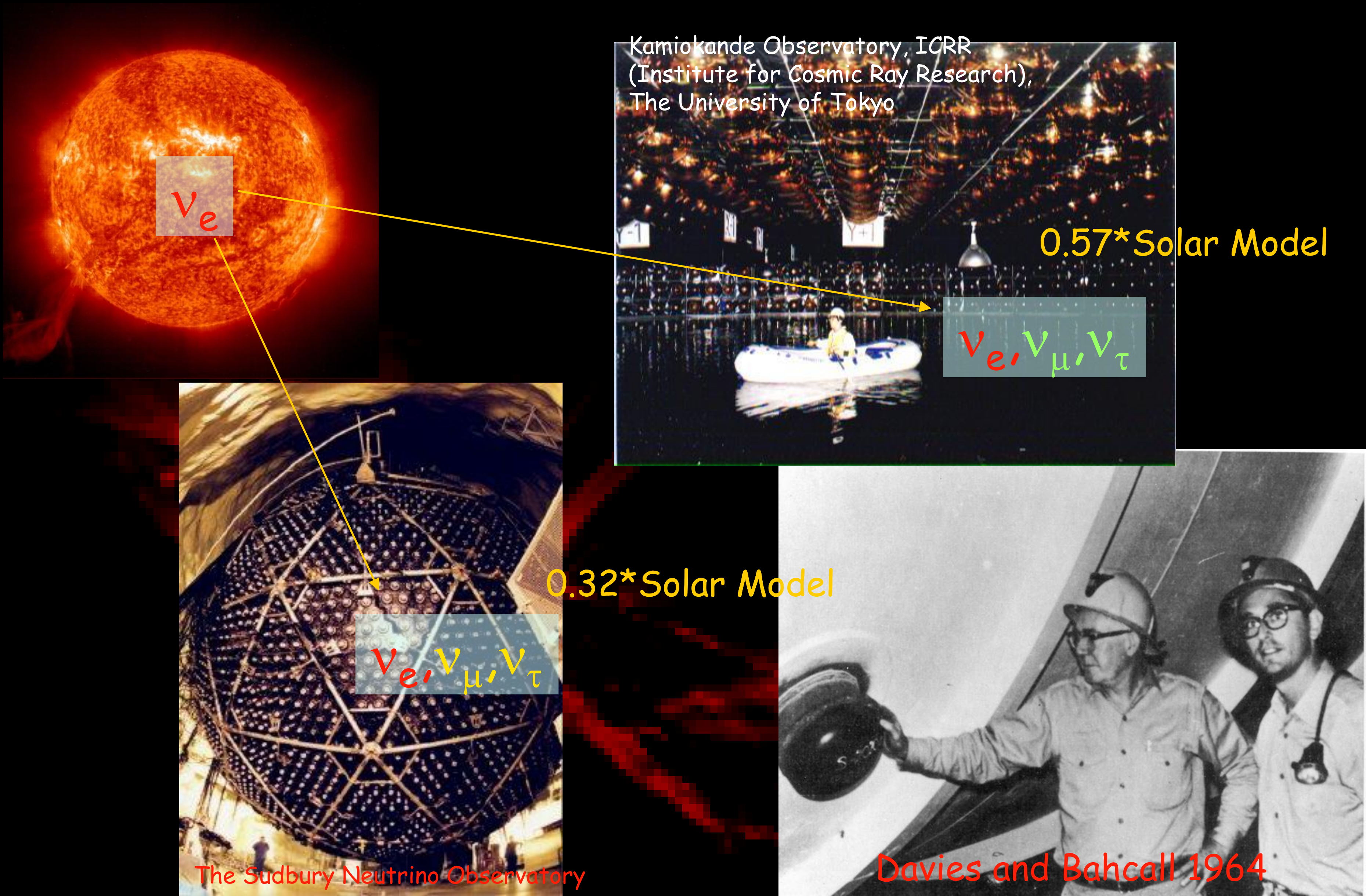
13.4 billions years latter,
Elements within our bodies



We are made of starstuff.

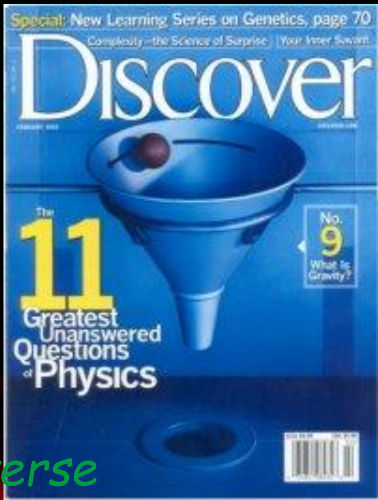
From big bang to De Vinci

Impact on fundamental physics



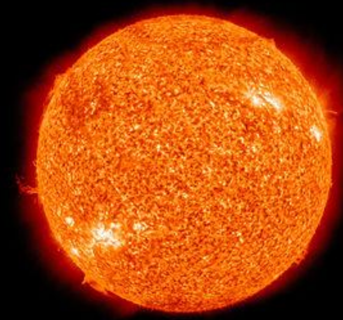
11 physics questions for the new century

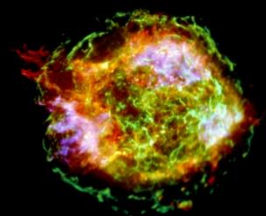
1. *What is dark matter?*
2. *What is dark energy?*
3. *How were the heavy elements from iron to uranium made?*
4. *Do neutrinos have mass?*
5. *Where do ultra-energy particles come from?*
6. *Is a new theory of light and matter needed to explain what happens at very high energies and temperatures?*
7. *Are there new states of matter at ultrahigh temperatures and densities?*
8. *Are protons unstable?*
9. *What is gravity?*
10. *Are there additional dimensions?*
11. *How did the Universe begin?*



the National Research Council's Committee on Physics of the Universe

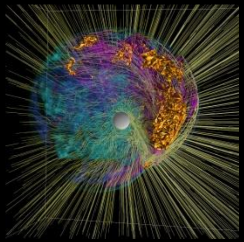
Hydrostatic burning in stars
High intensity, low energy, stable beam facility



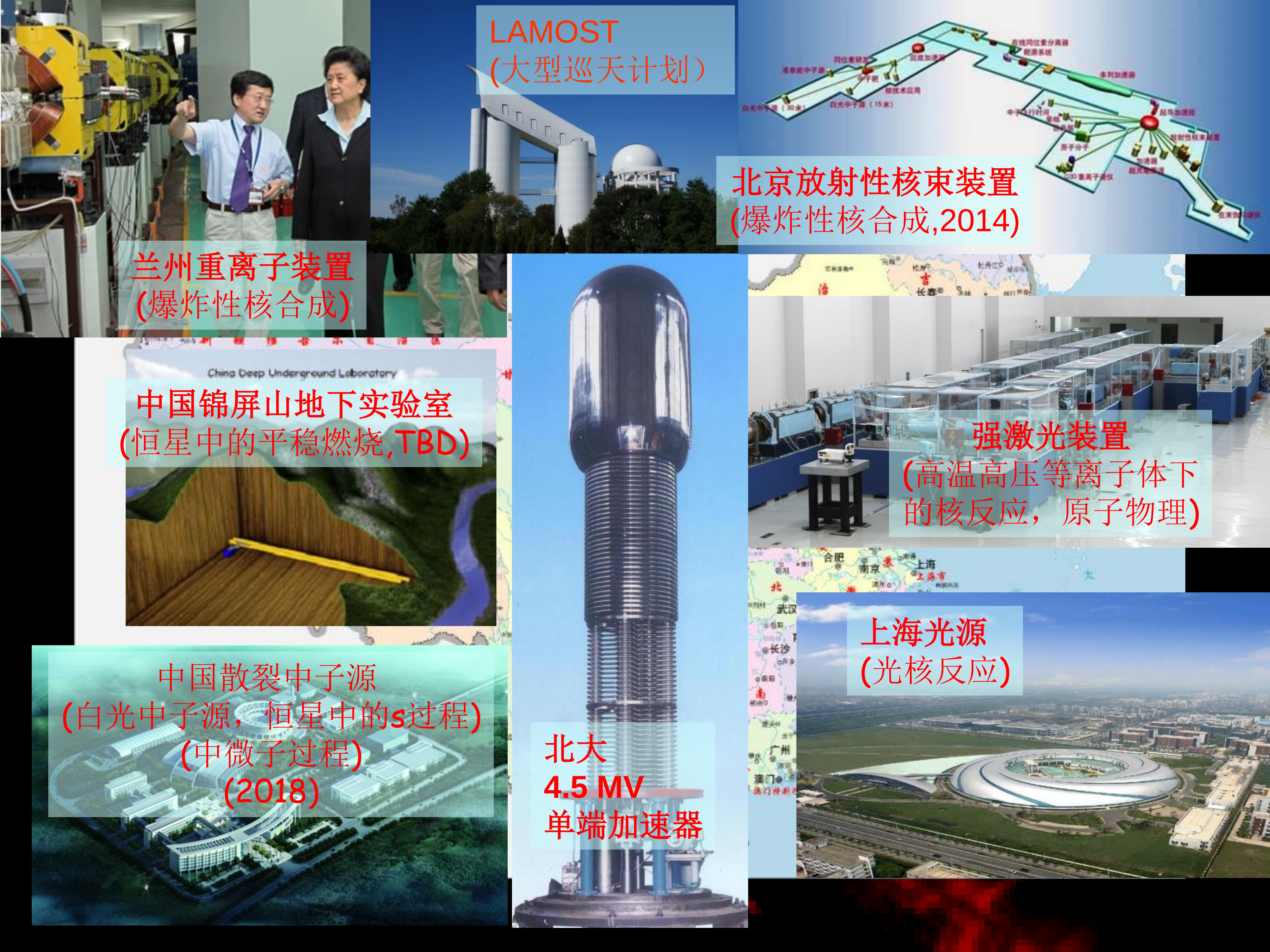


Explosive nucleosynthesis (supernova, X-ray burst)
Radioactive ion beam facility

S-process in AGB stars and massive stars
Neutron facility



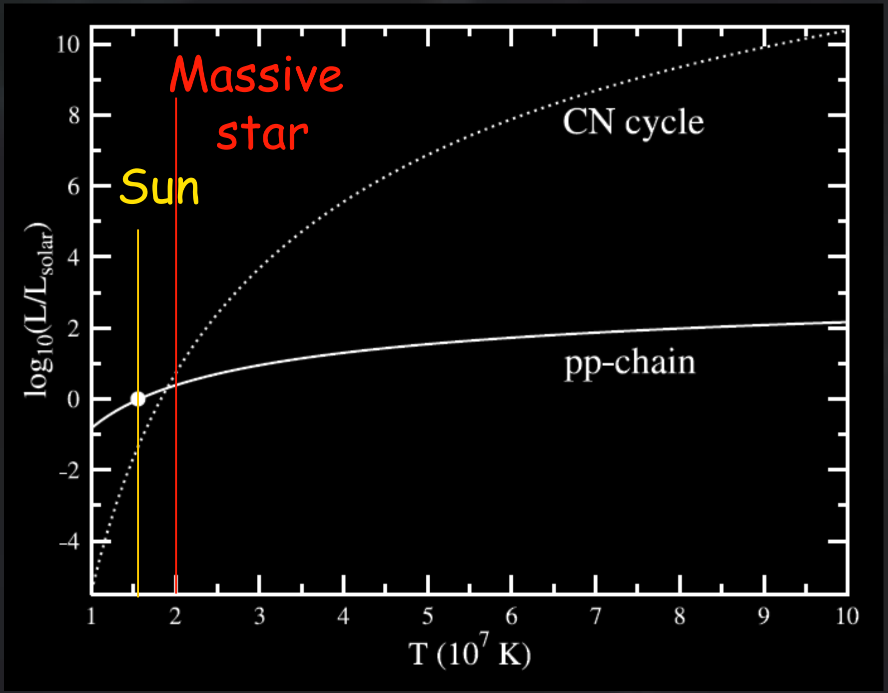
Stellar Neutrino (hydrostatic and explosive)
Neutrino facility

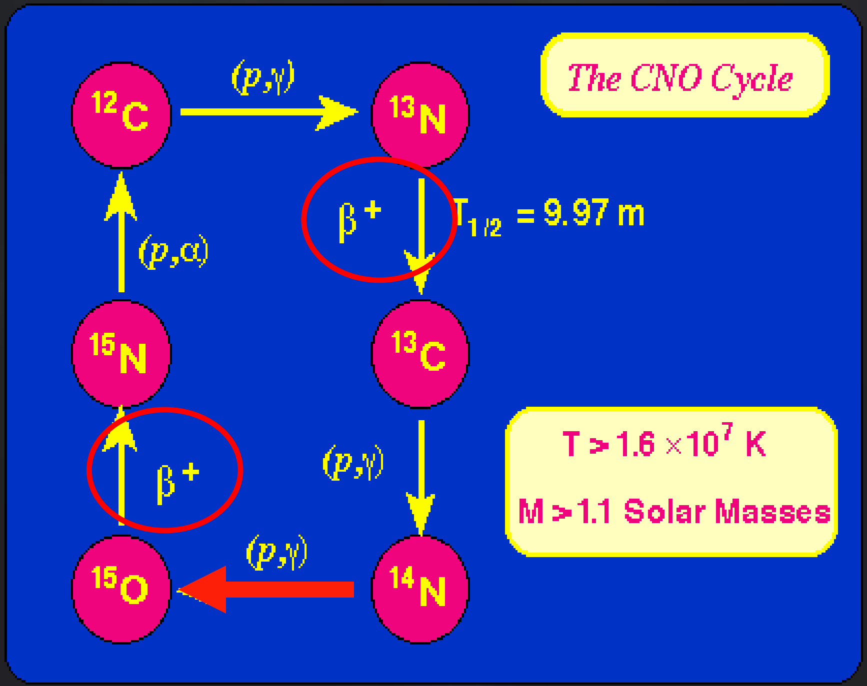

LAMOST
(大型巡天计划）
北京放射性核束装置
(爆炸性核合成,2014)
兰州重离子装置
(爆炸性核合成)
China Deep Underground Laboratory
中国锦屏山地下实验室
(恒星中的平稳燃烧,TBD)
强激光装置
(高温高压等离子体下
的核反应，原子物理)
中国散裂中子源
(白光中子源，恒星中的s过程)
(中微子过程)
(2018)
北大
4.5 MV
单端加速器
上海光源
(光核反应)

Why go to underground lab

$^{14}N(p,\gamma)^{15}O$: slowest reaction in the CN cycle

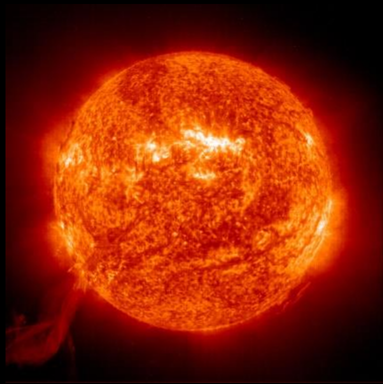
Fuel	Primary Products	Secondary products	Approximate temperature (10^9 K)	Approximate duration
Hydrogen →	^{4}He	^{14}N	0.02	10^7 yr



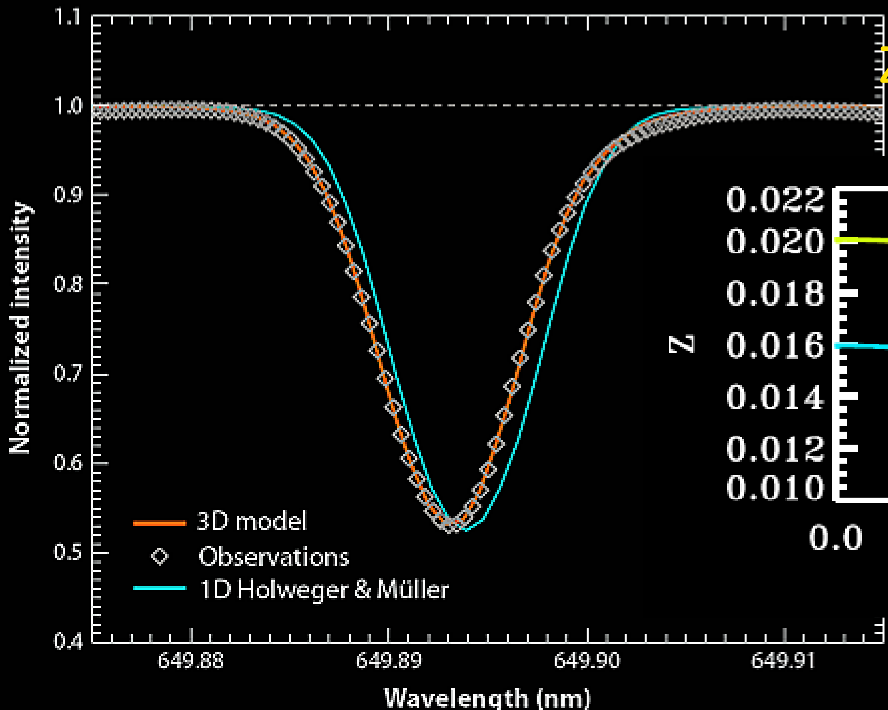


- *Massive MS stars: energy production and their lifetime*

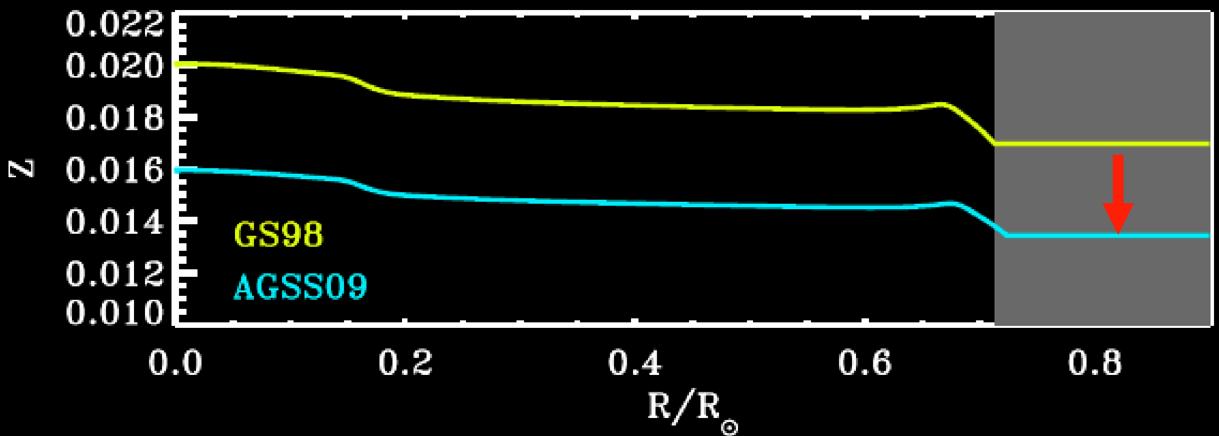
solar metallicity puzzle



- New 3D hydrodynamic models of the solar atmosphere
- Parameter free
- significantly improving consistency of line analysis
- Makes sun more consistent with similar stars in local neighborhood



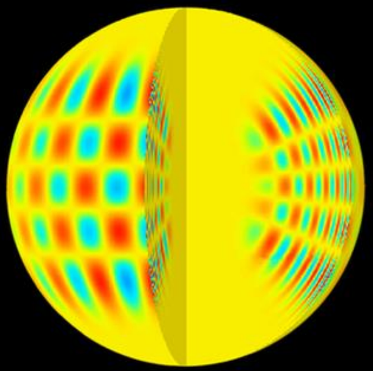
Z: Percentage of metal (heavier than Helium)

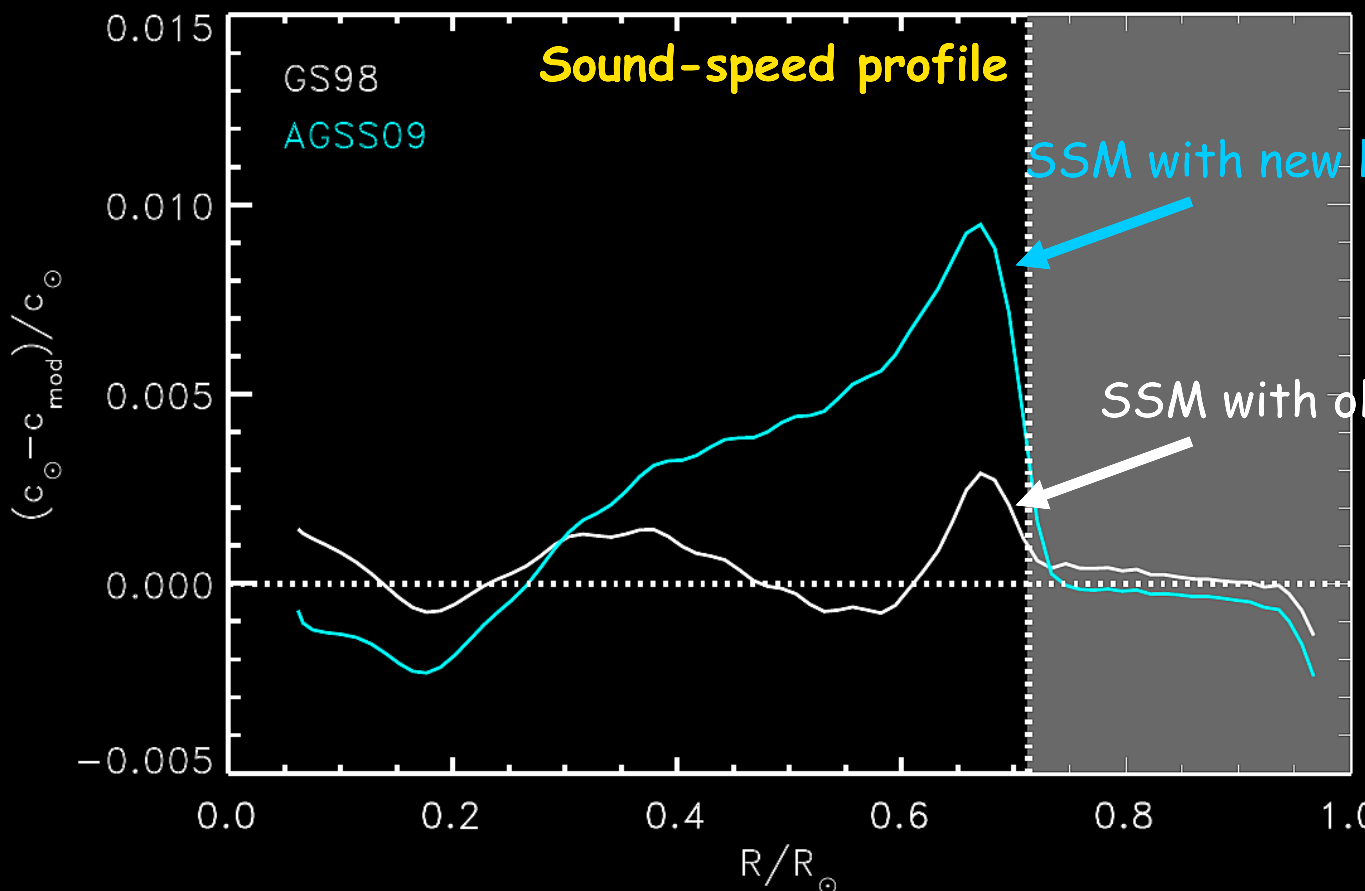


But abundances in the photosphere significantly reduced Z: 0.0169 ⇒ 0.0122

M. Asplund et al., Annu. Rev. Astro. Astrophys. 47 (2009) 481

Better determined metallicity leads to problems





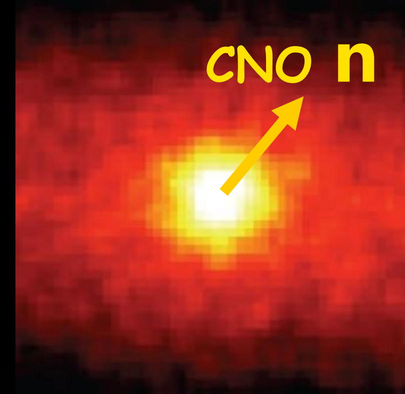
Sound speed – Precision 10^{-4}

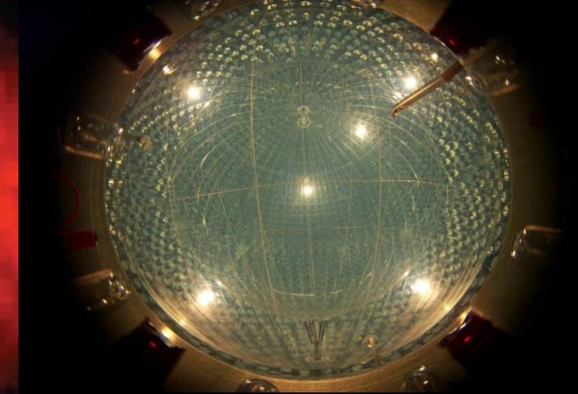
SSM: standard solar model

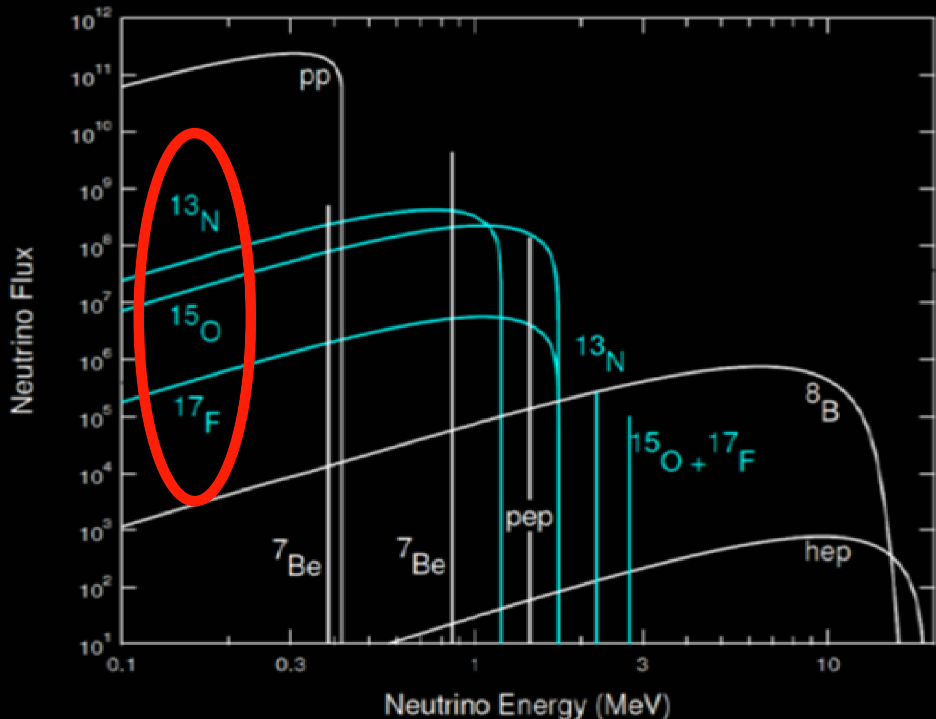
Serenelli, Haxton, Peñay-Garay (2011)

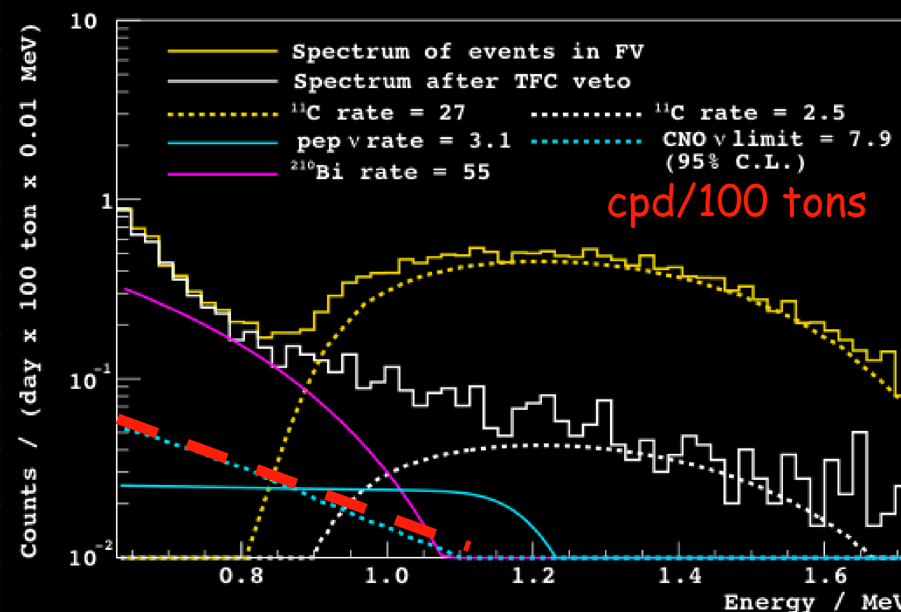
$^{14}N(p,\gamma)^{15}O$

key to solve the mystery









Neutrino observed by Borexino

$$\phi_{\nu}^{CN} = F[S_{^{14}N+p};\ \ T;\ \ \theta_{12};\ \ CN]$$

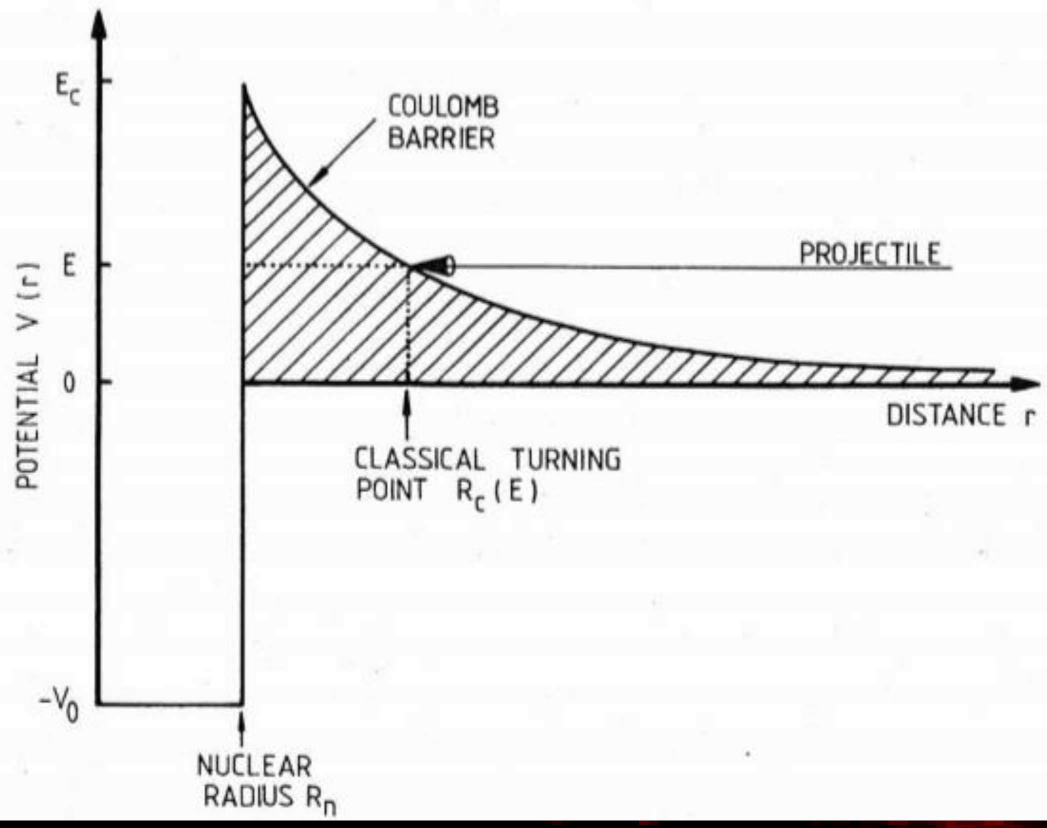
S_{14N+p}: $^{14}N(p,g)^{15}O$ S factor

- *solar CNO neutrino flux →solar core metallicity*

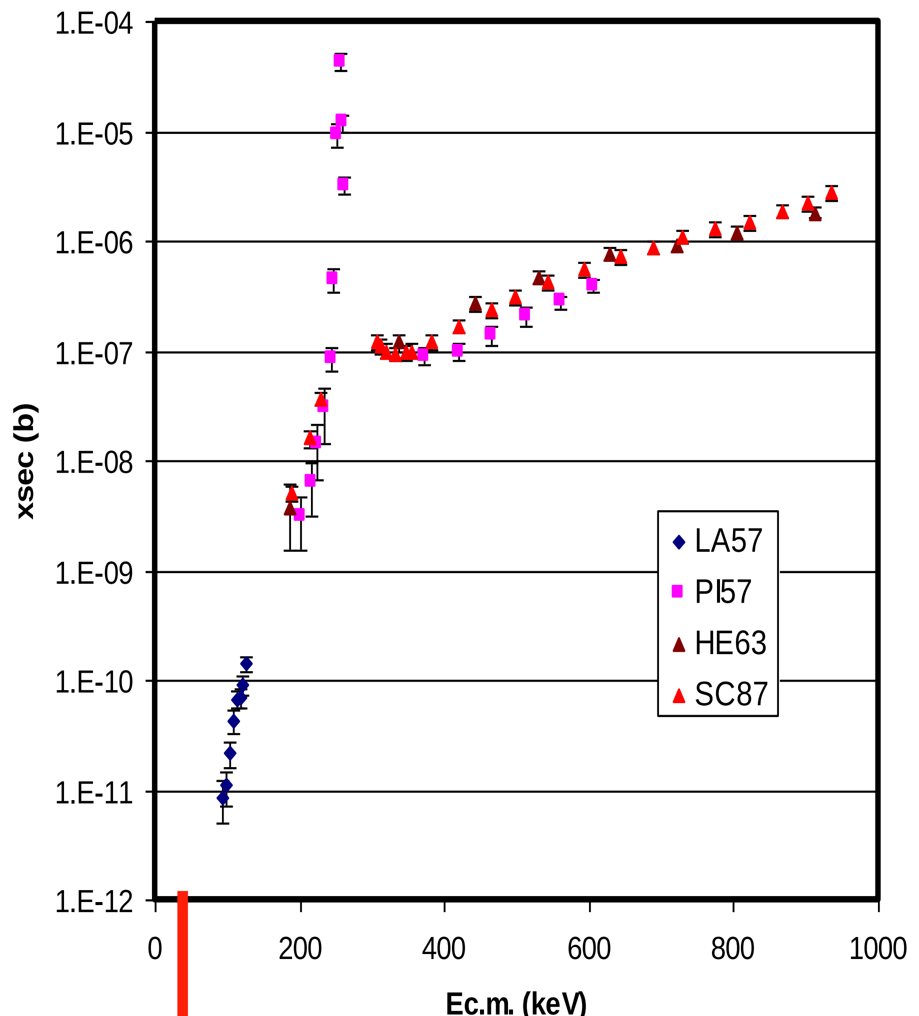
W. Haxton and A. Serenelli Ap J 687 (2008) 678

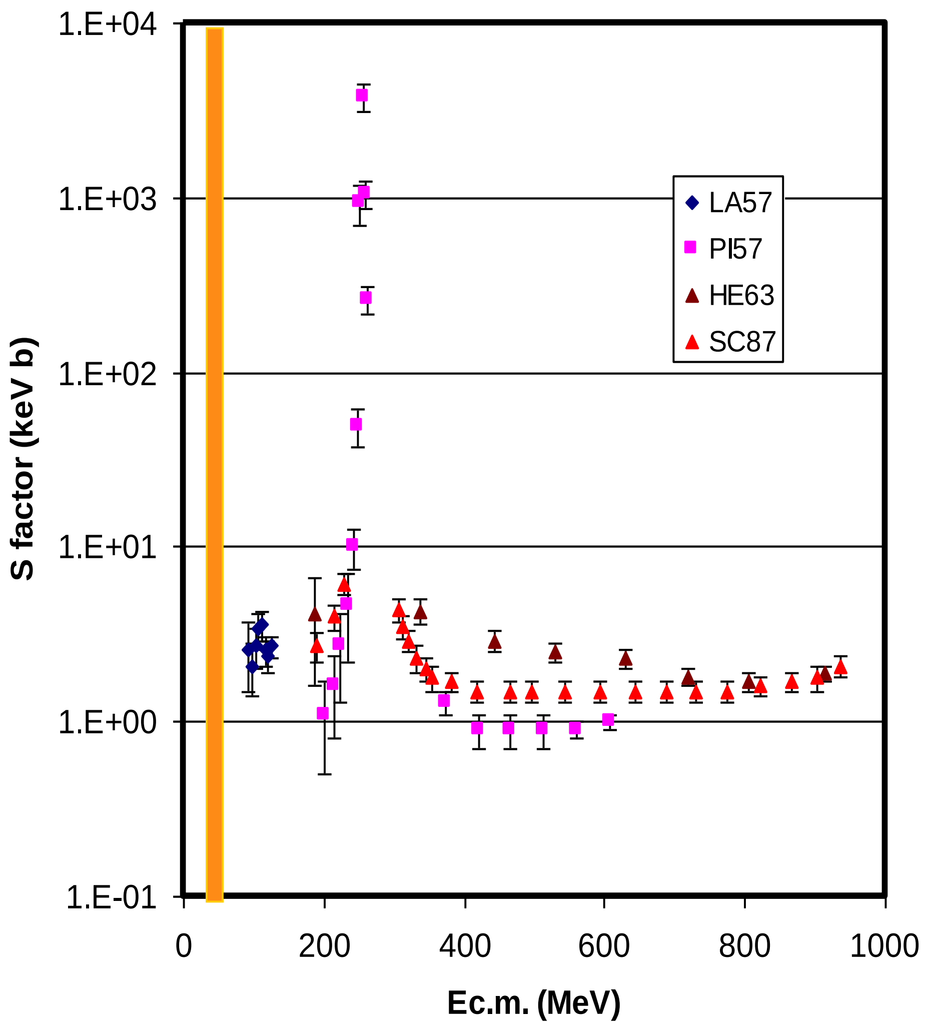
Coulomb barrier: enemy at low energy

$$V_C(r) = \frac{Z_1 Z_2 e^2}{r},$$



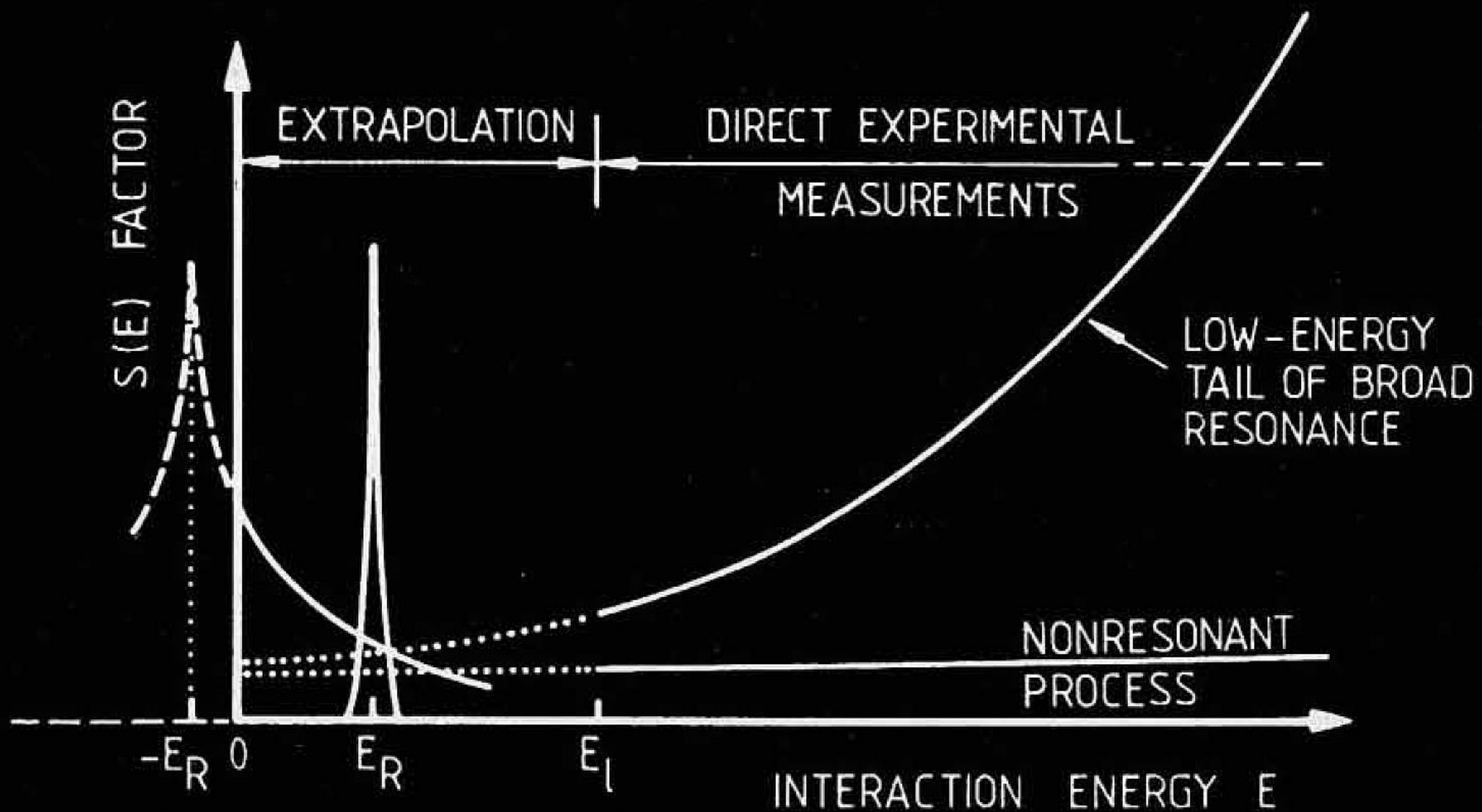
$^{14}N(p,\gamma)^{15}O$ before Underground Lab





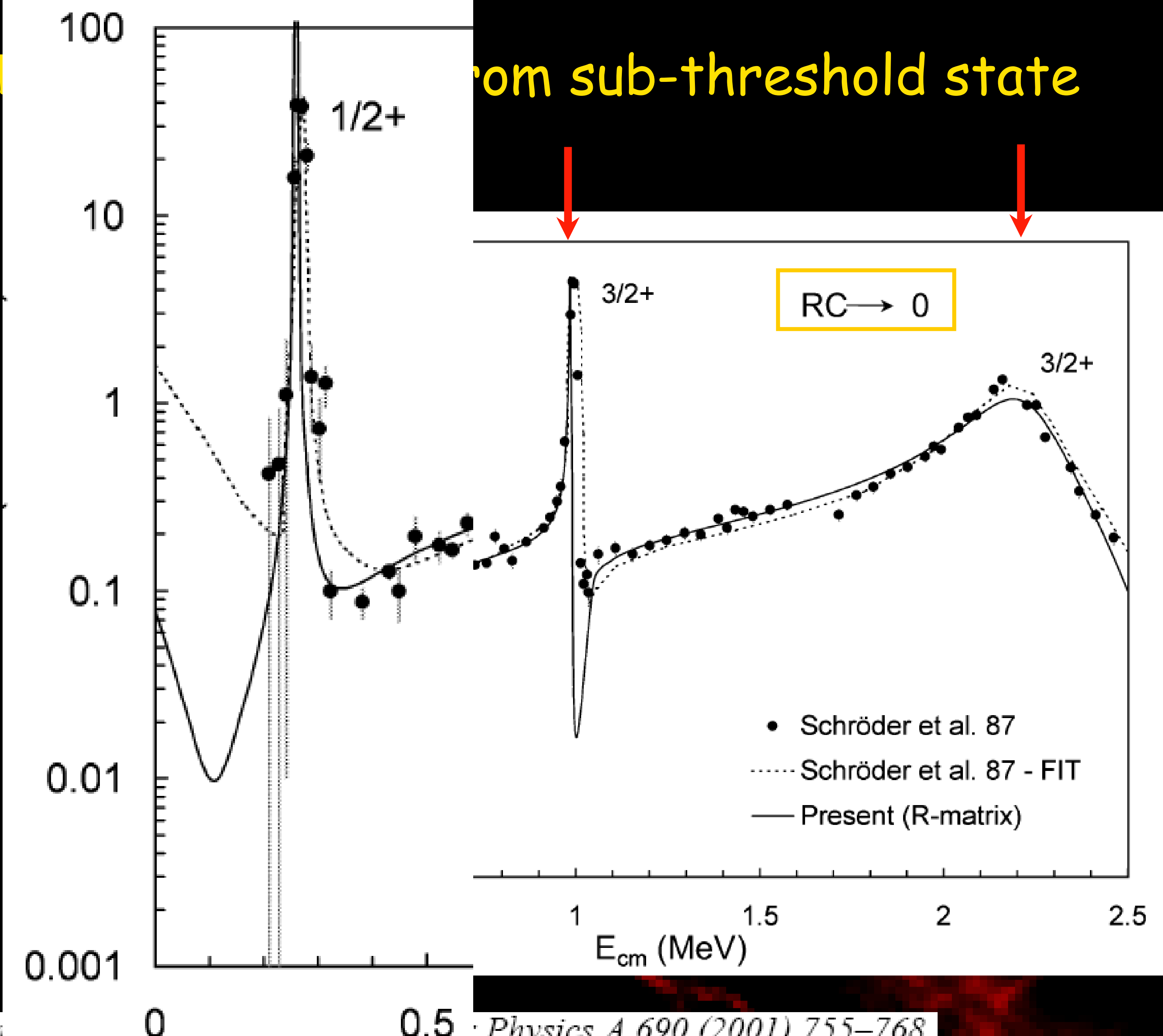
$$S(E)=E*\exp(2\pi\eta)*\sigma(E)$$
$$2\pi\eta=31.29*Z_1*Z_2*(m_1/E_1)^2$$

Extrapolation and its risk



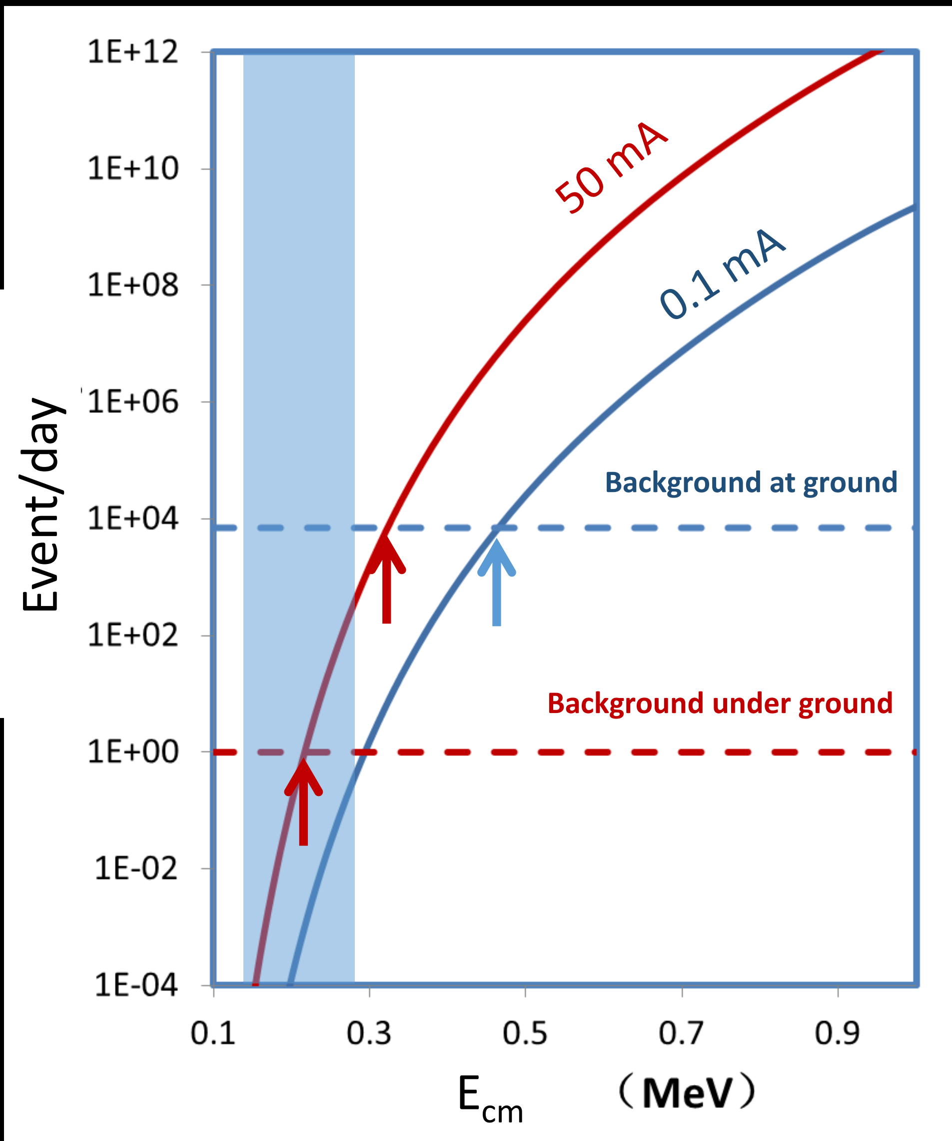
Adopted from "Cauldrons in Cosmos"

T… rom sub-threshold state



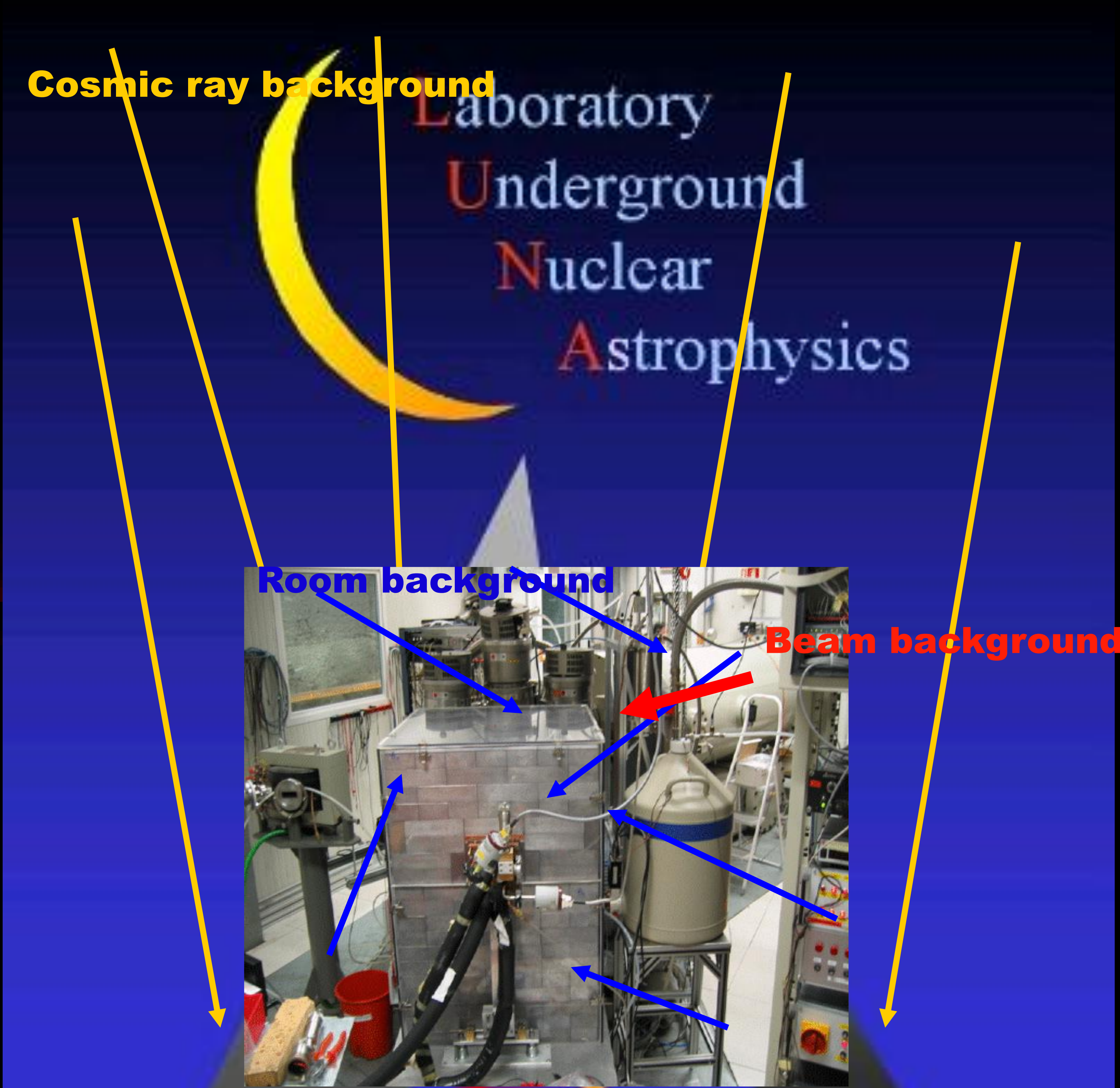
C. An… Physics A 690 (2001) 755–768

Challenging the tiny cross sections

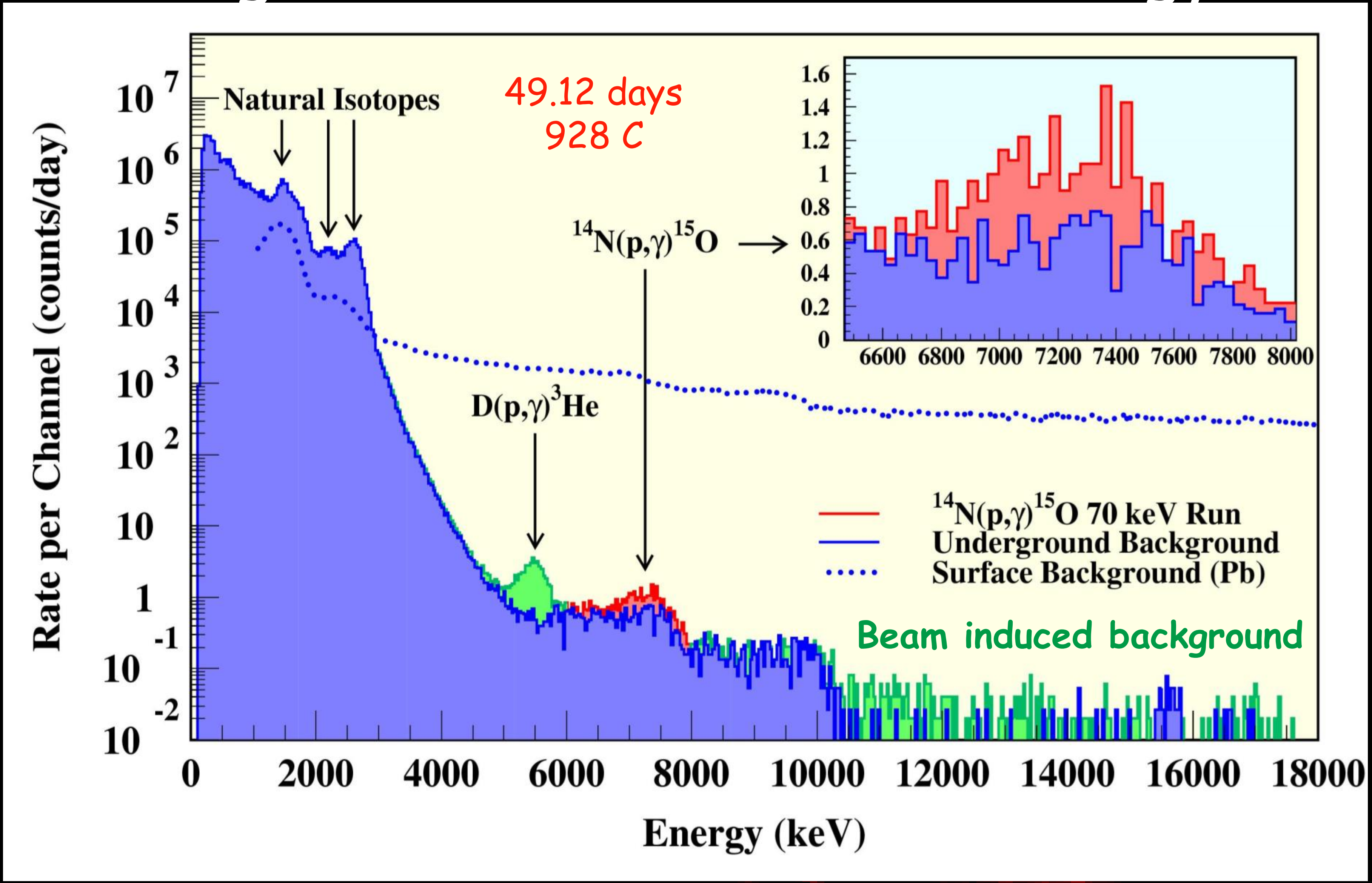


Background reduction in LNGS
(shielding ≡ 4000 m w.e.)

Radiation	LNGS/surface
Muons	10^{-6}
Neutrons	10^{-3}
Photons	10^{-1}

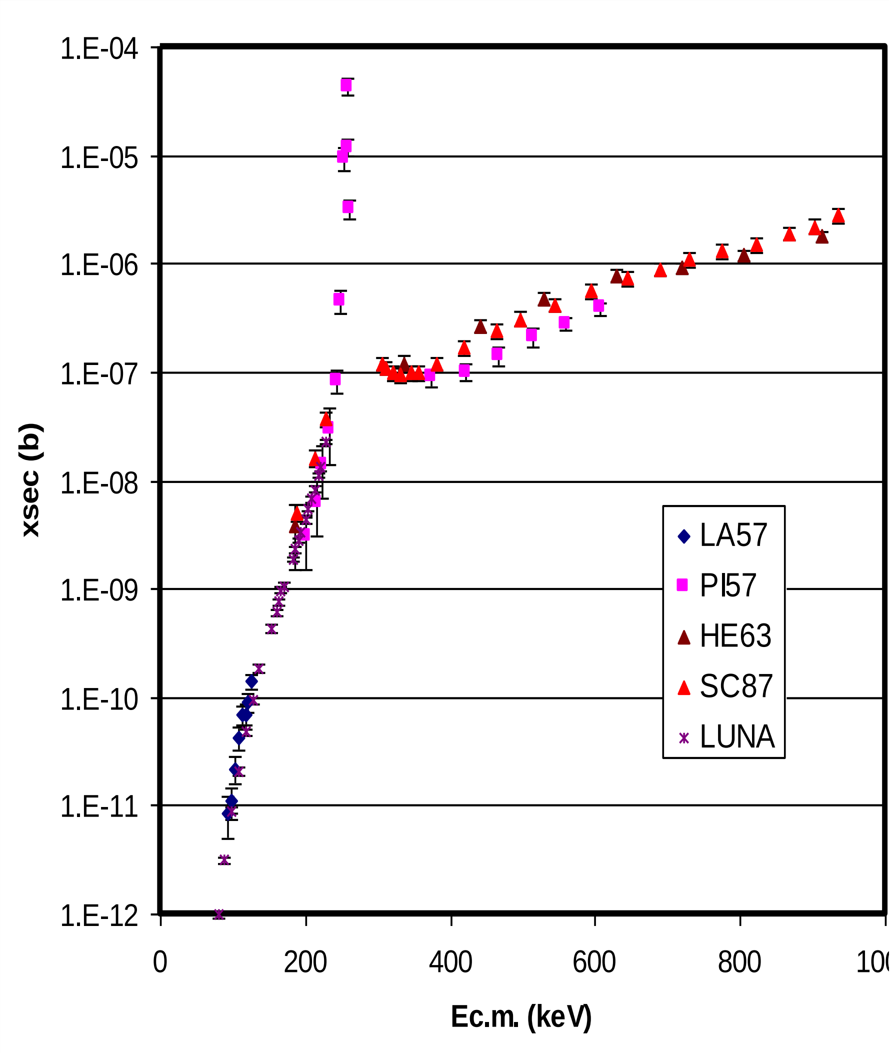

Cosmic ray background
Laboratory
Underground
Nuclear
Astrophysics
Room background
Beam background

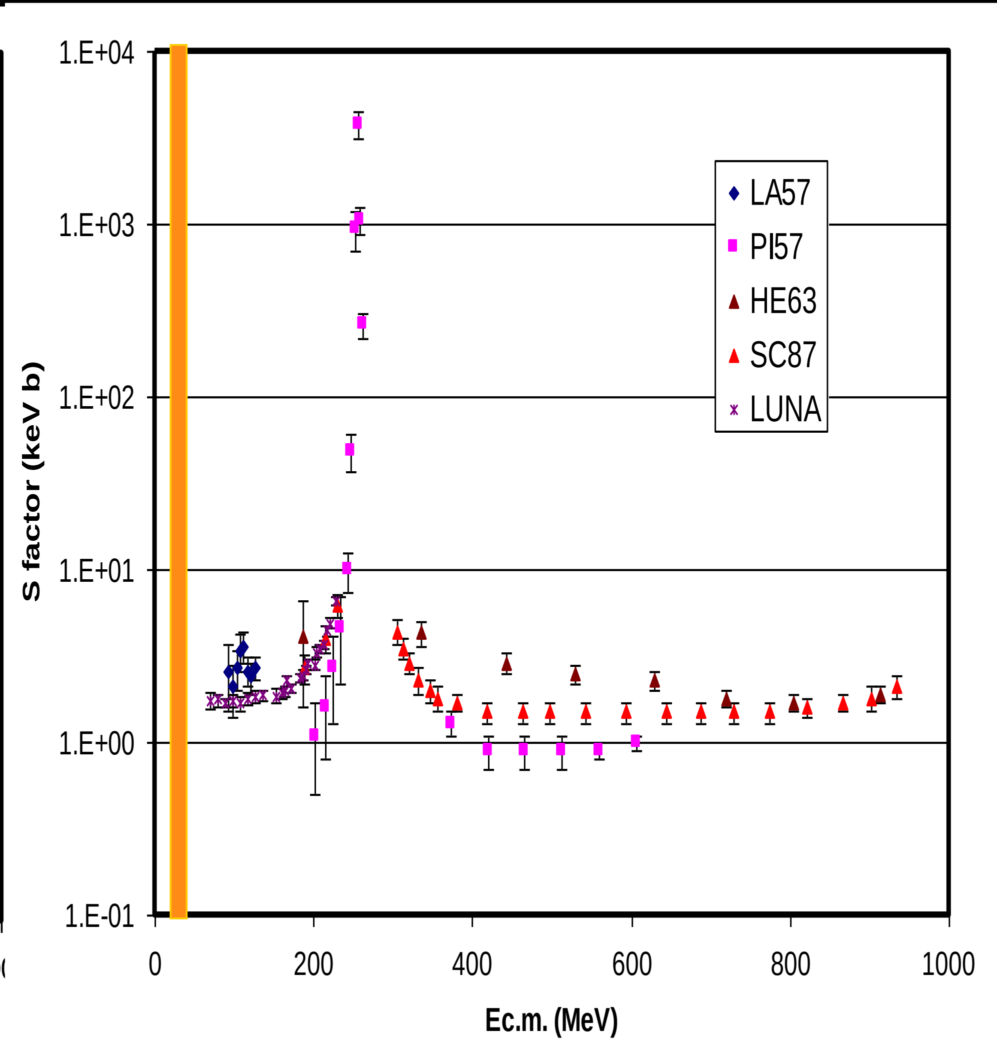
Backgrounds at the lowest energy



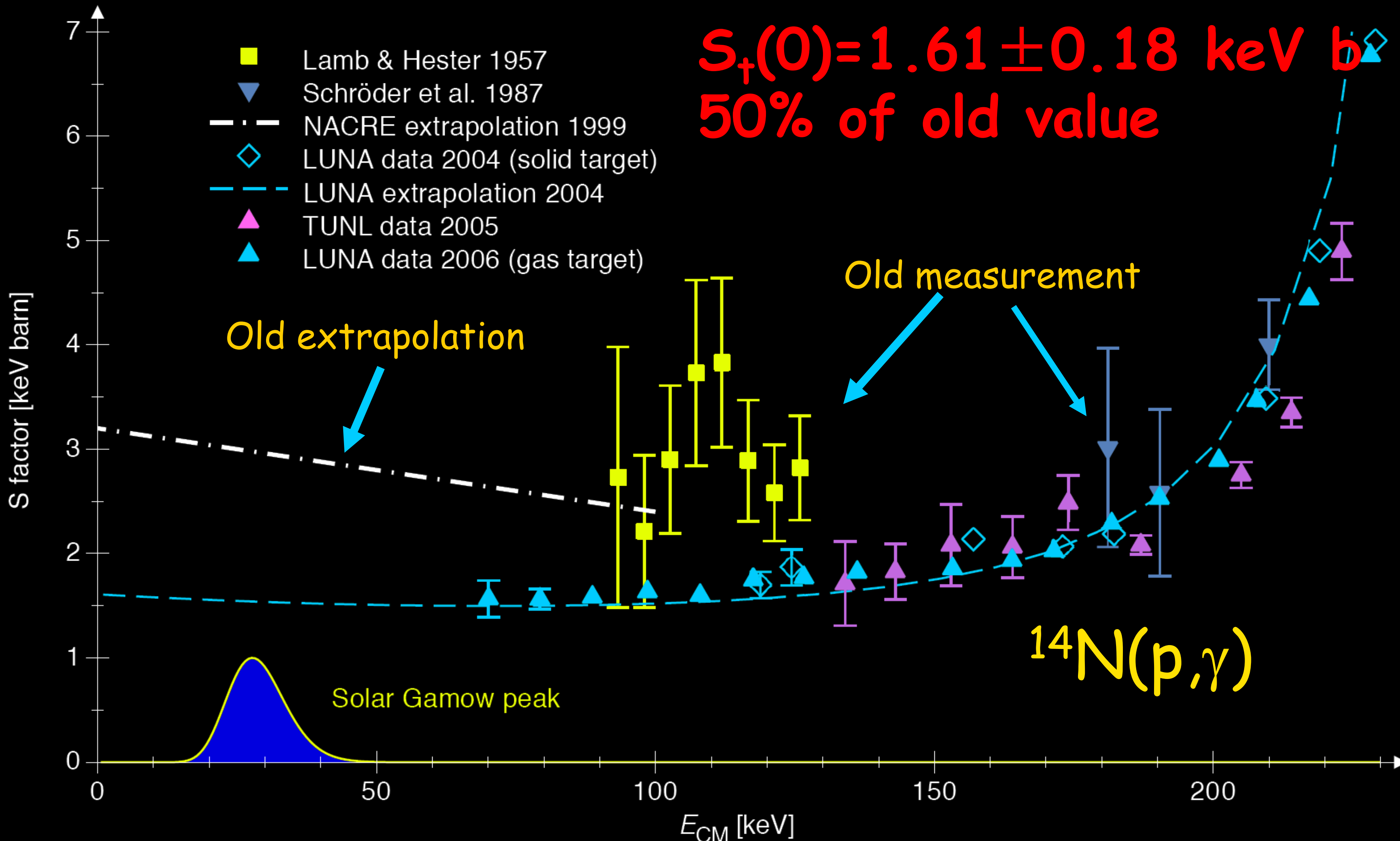
LUNA Collaboration / Nuclear Physics A 779 (2006) 297–317

$^{14}N(p,\gamma)^{15}O$





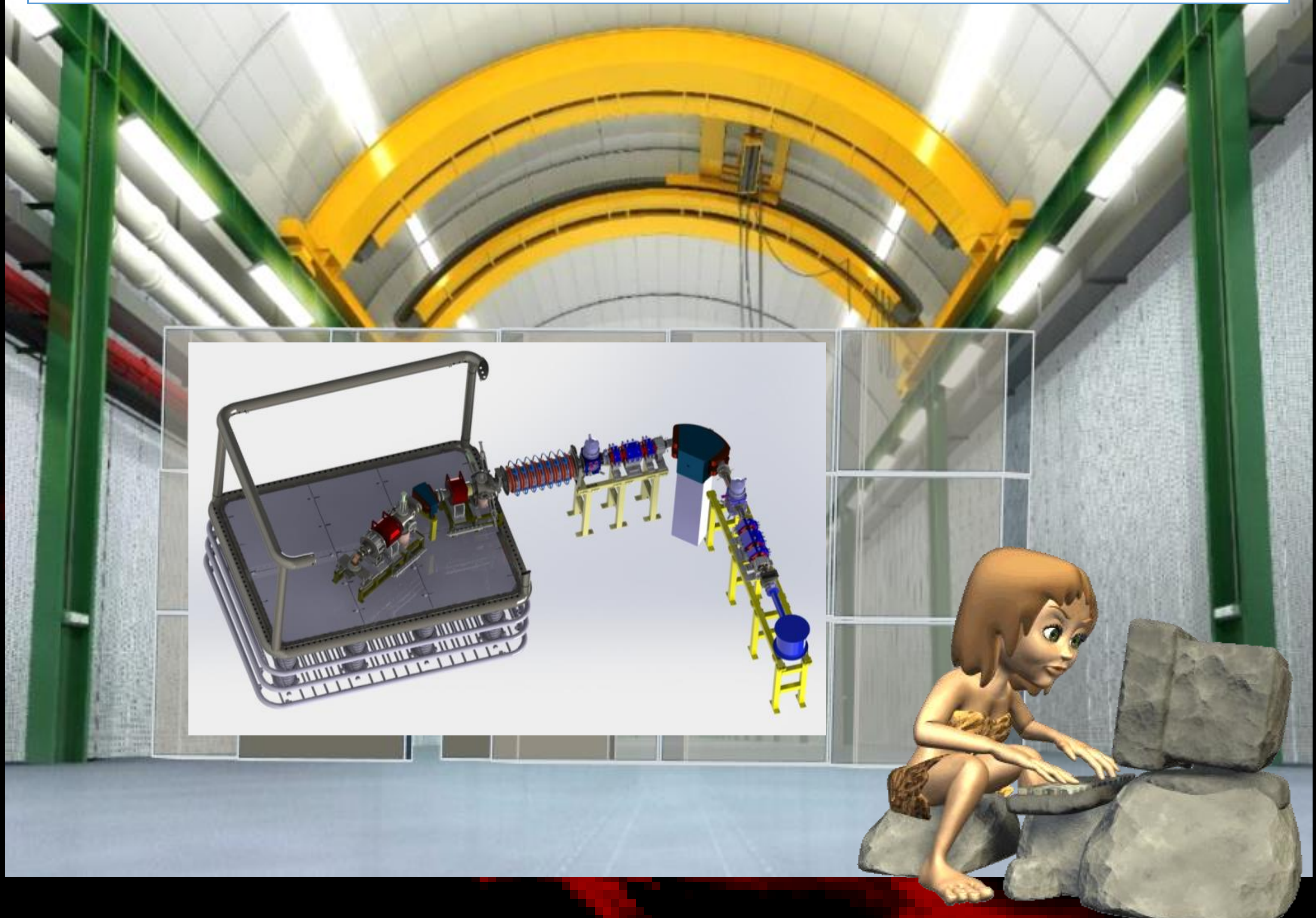
$S_t(0)=1.61 \pm 0.18$ keV b
50% of old value



ν_{cno} reduced by ~ 2 with 8% error (precise core metallicity)
Globular cluster age increased by 0.7-1 Gy

Phys. Lett. B591 (2004) 61-68/*Nuclear Physics A 779 (2006) 297-317*

**Jinping Underground laboratory for Nuclear Astrophysics (JUNA)
the deepest underground lab**



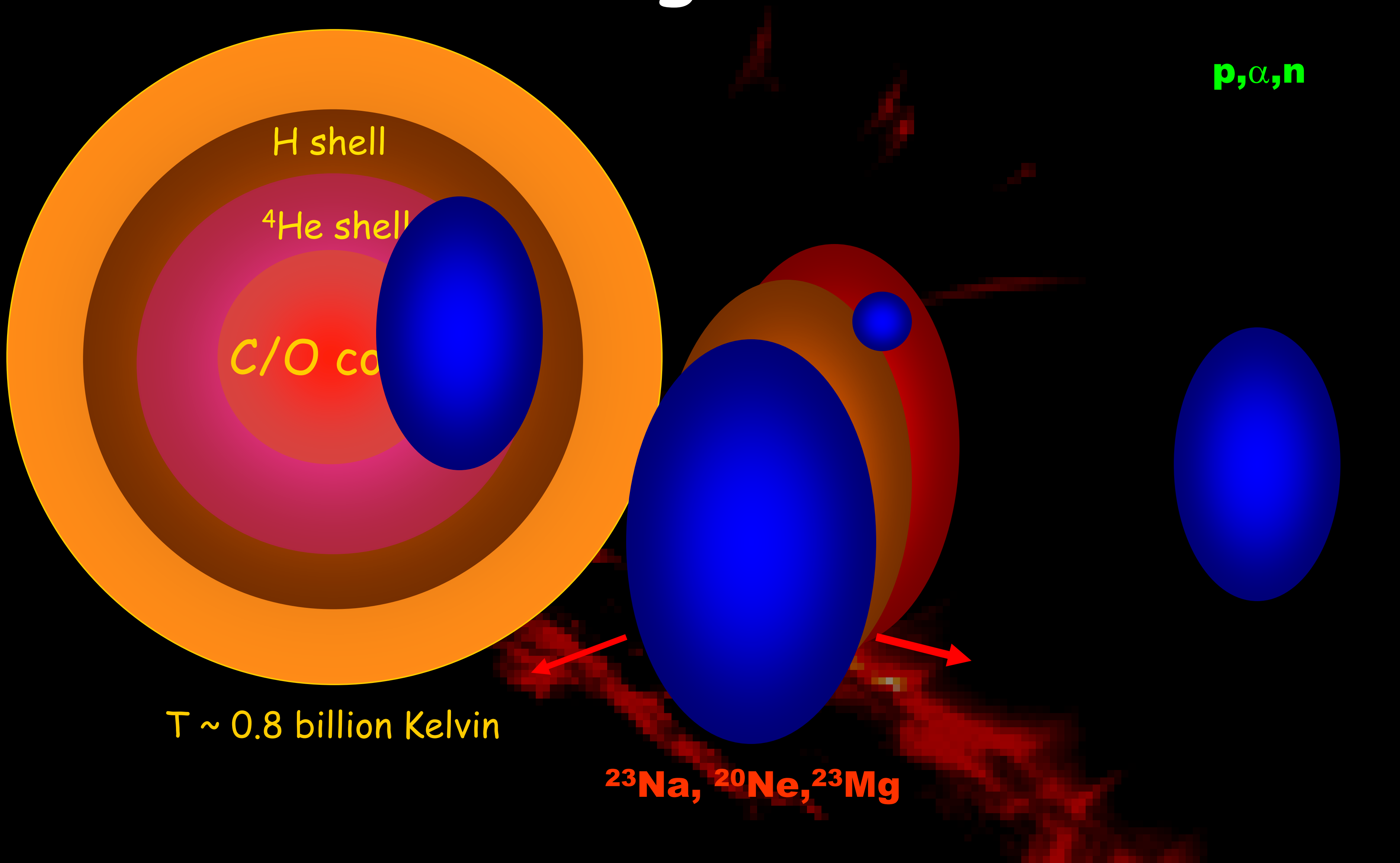
2017: installation of accelerator in Jinping

2018-2019: ^{19}F(p,a), ^{25}Mg(p,g), ^{13}C(a,n), ^{12}C(a,g) (see W.P. Liu's talk)

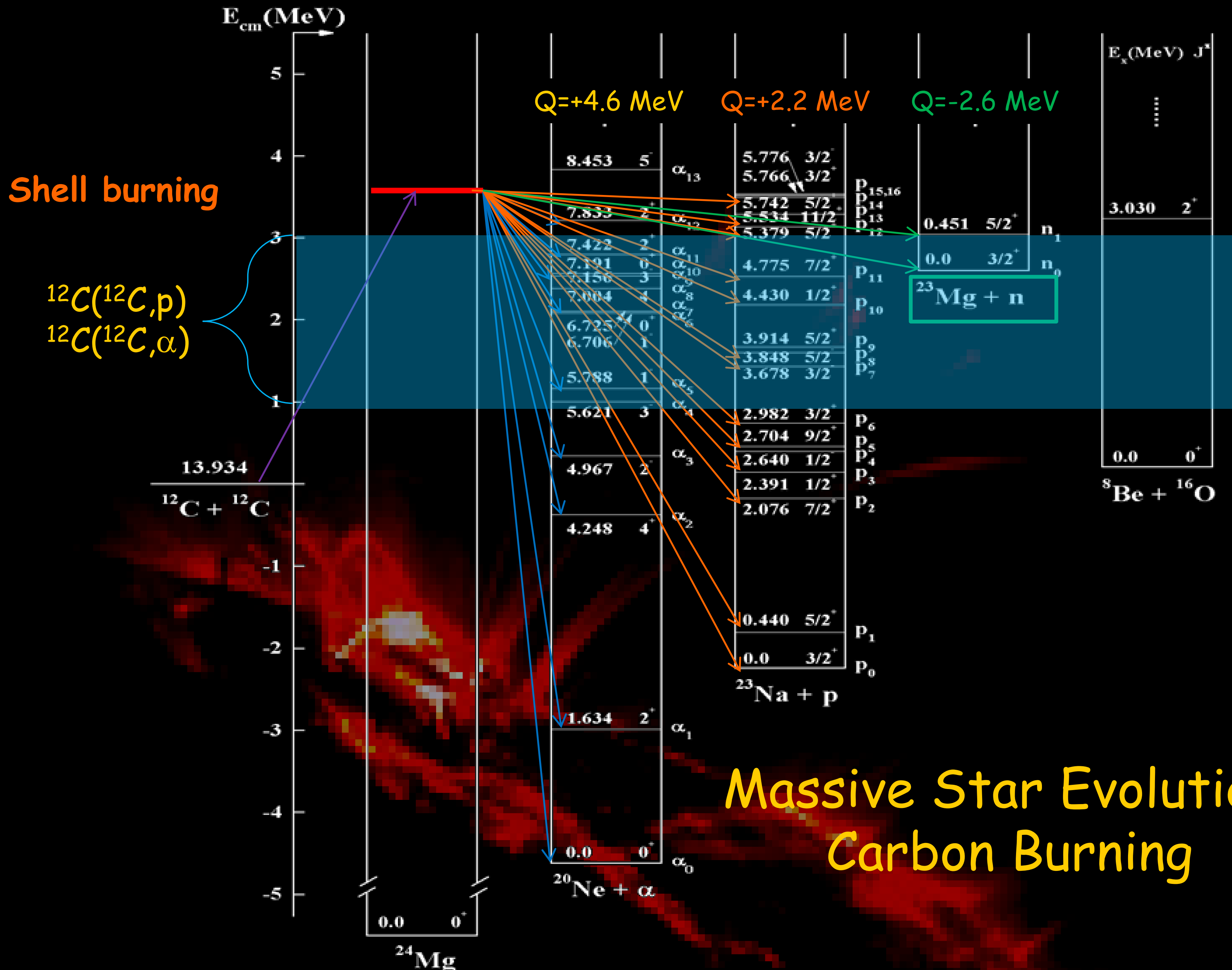
Life of a 20 solar mass star

Fuel	Primary Products	Secondary products	Approximate temperature (10^9 K)	Approximate duration
Hydrogen	^{4}He	^{14}N	0.02	10^7 yr
Helium	C,O	^{18}O, ^{22}Ne s-process	0.2	10^6 yr
Carbon	Ne,Mg	Na	0.8	10^3 yr
Neon	O,Mg	Al, P	1.5	3 yr
Oxygen	Si, S	Cl, Ar, K, Ca	2.0	0.8 yr
Silicon	Fe	Ti, V, Cr Mn, Co, Ni	3.5	1 week

Carbon burning

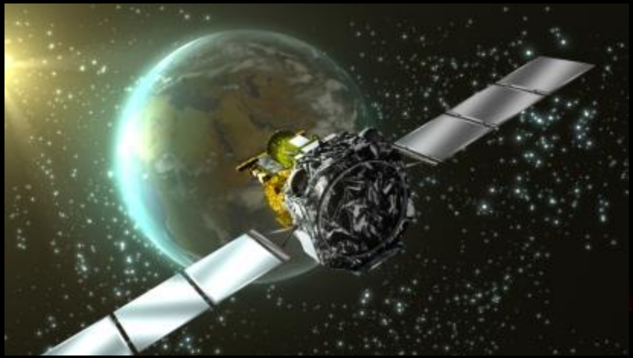


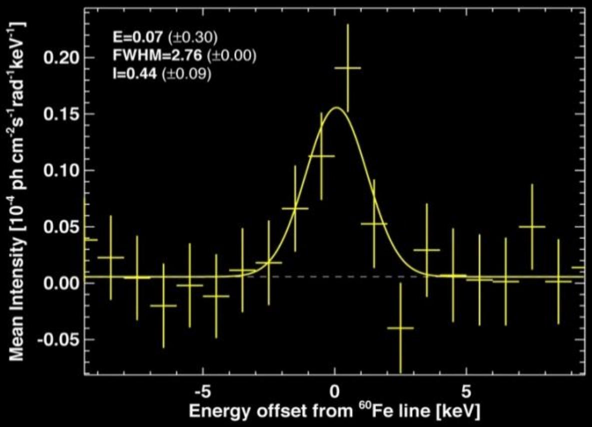
Massive Star Evolution: Carbon Burning



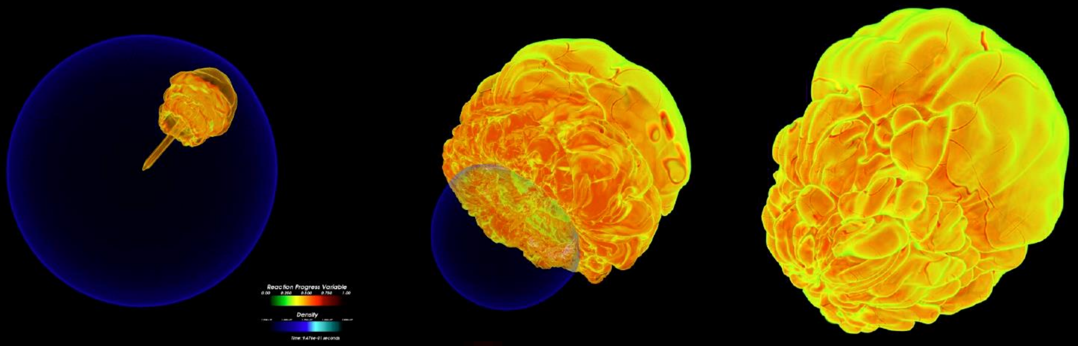
$^{12}C+^{12}C$: a reaction of paramount importance

^{60}Fe Production in supernovae

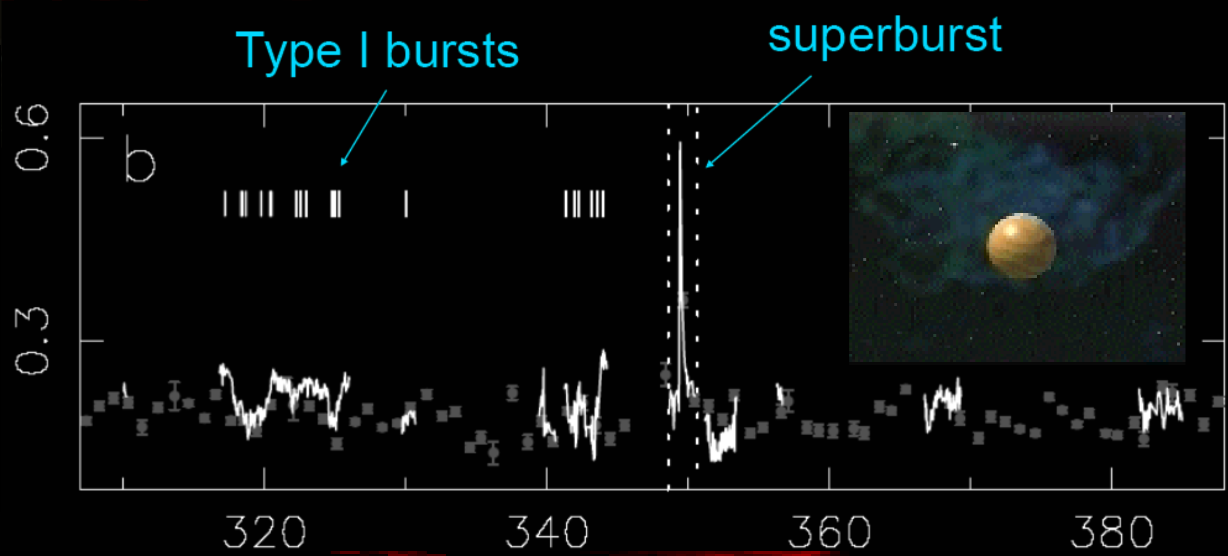


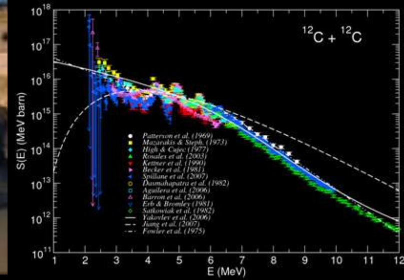


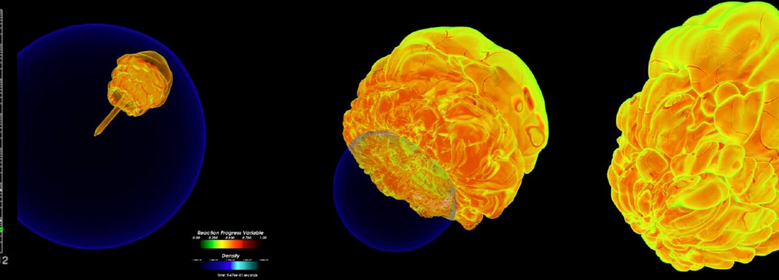
Ignition conditions in type Ia supernovae

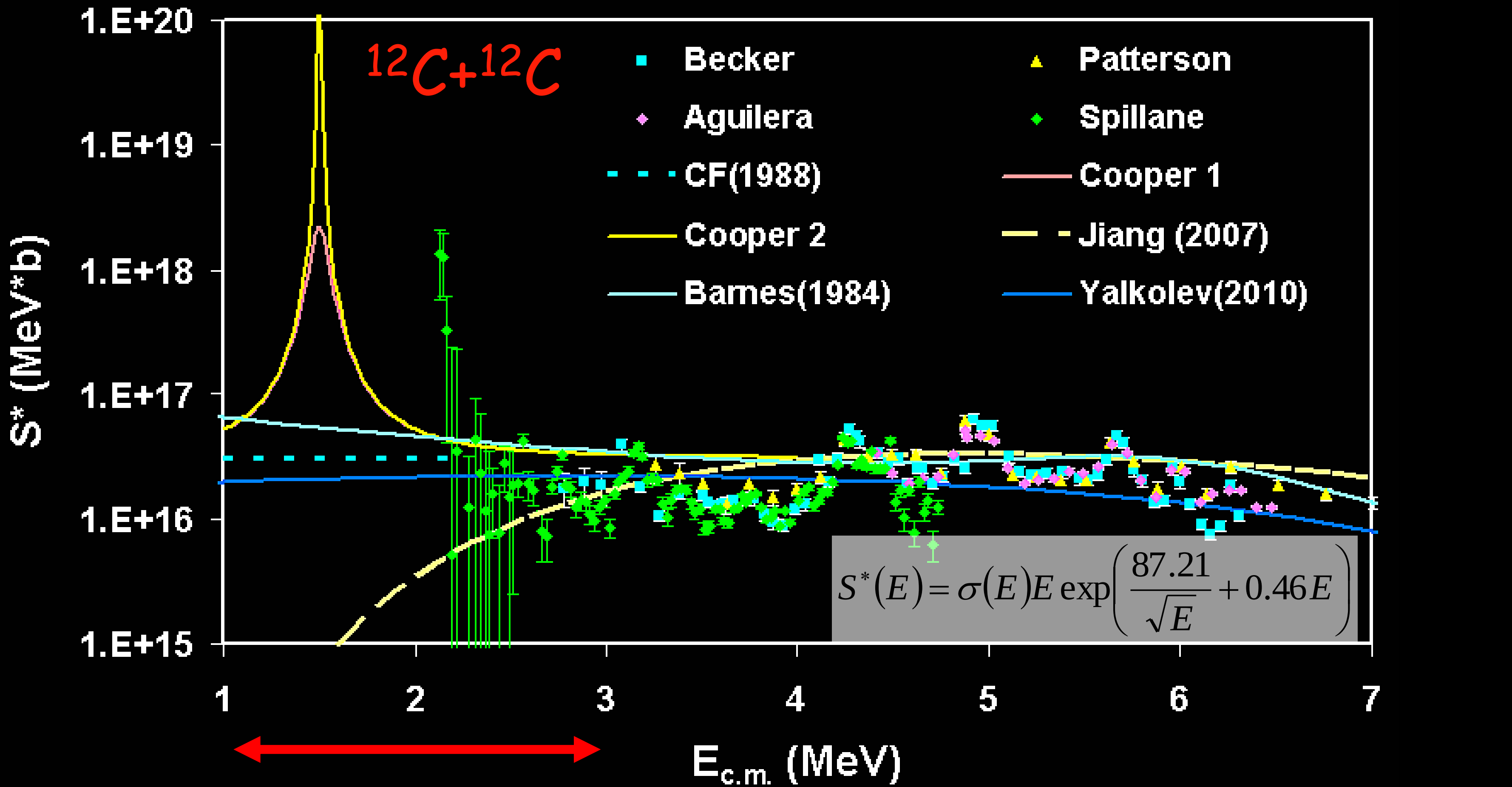


Candidate for Superburst ignition

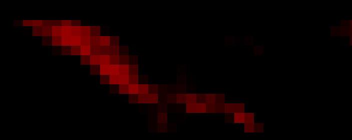








10^{-22} b 10^{-7} b

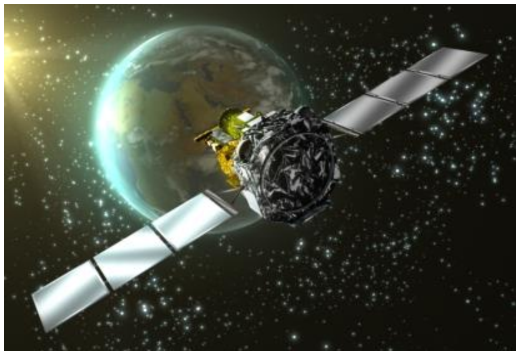


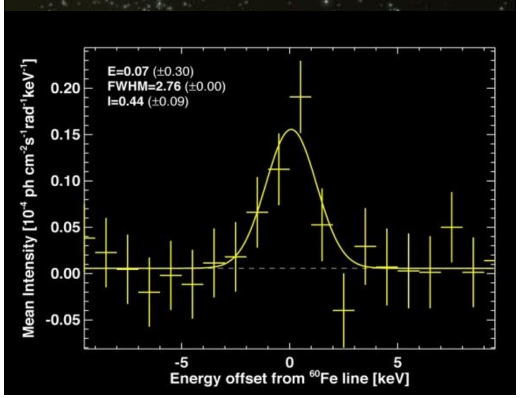
$^{12}C(^{12}C,p)^{23}Na$ (Q=2.24 MeV)

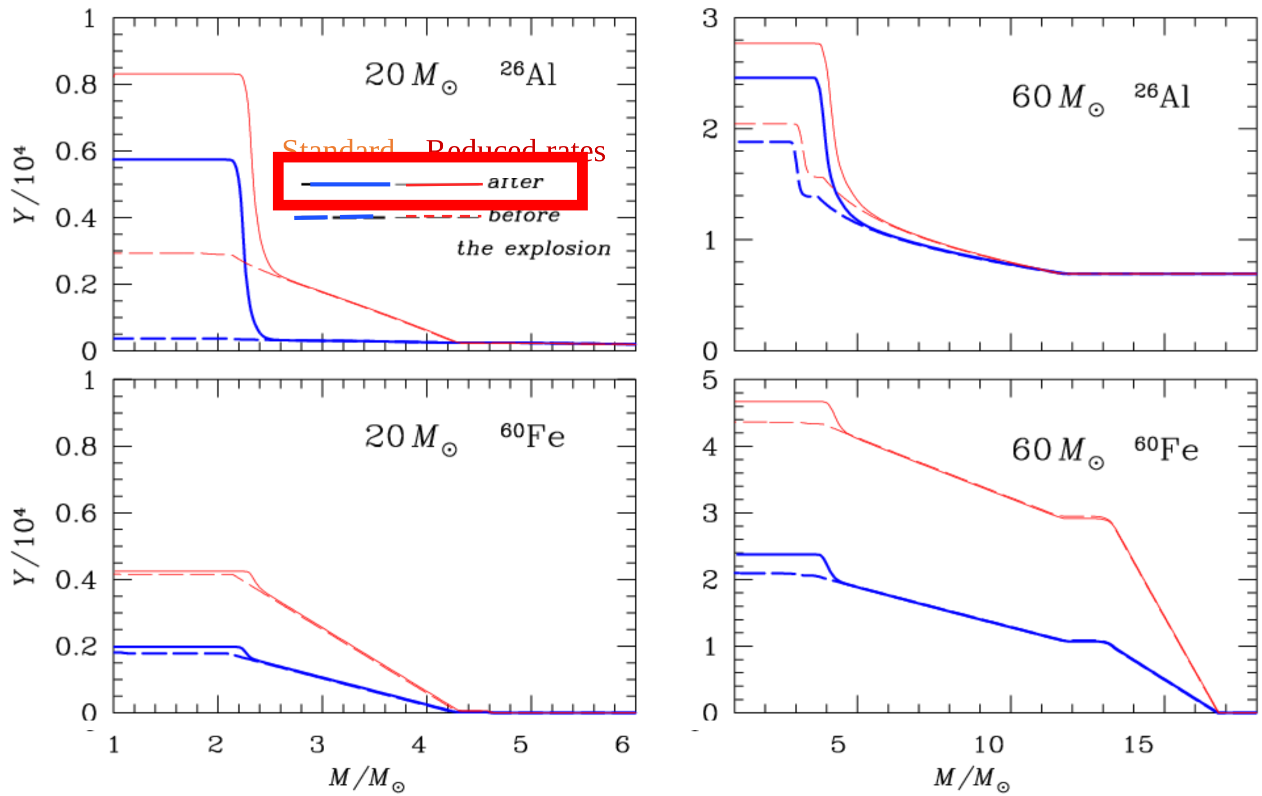
$^{12}C(^{12}C,\alpha)^{20}Ne$ (Q=4.62 MeV)

$^{12}C(^{12}C,n)^{23}Mg$ (Q=-2.62MeV)

Impact to nucleosynthesis

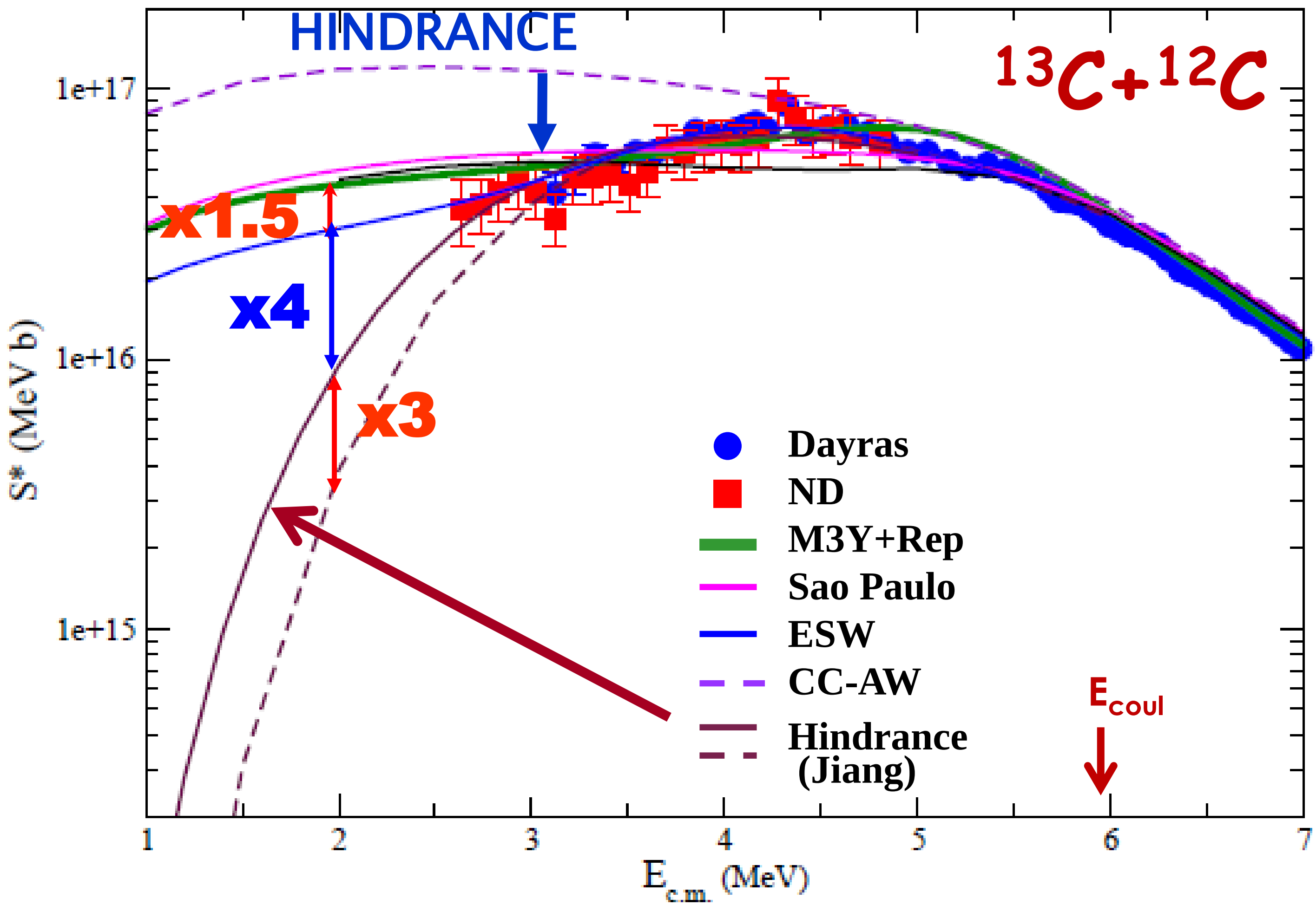






Chieffi, Limongi, ApJ 647 (2006) 483
Gasques et al. PRC 76 (2007) 035802

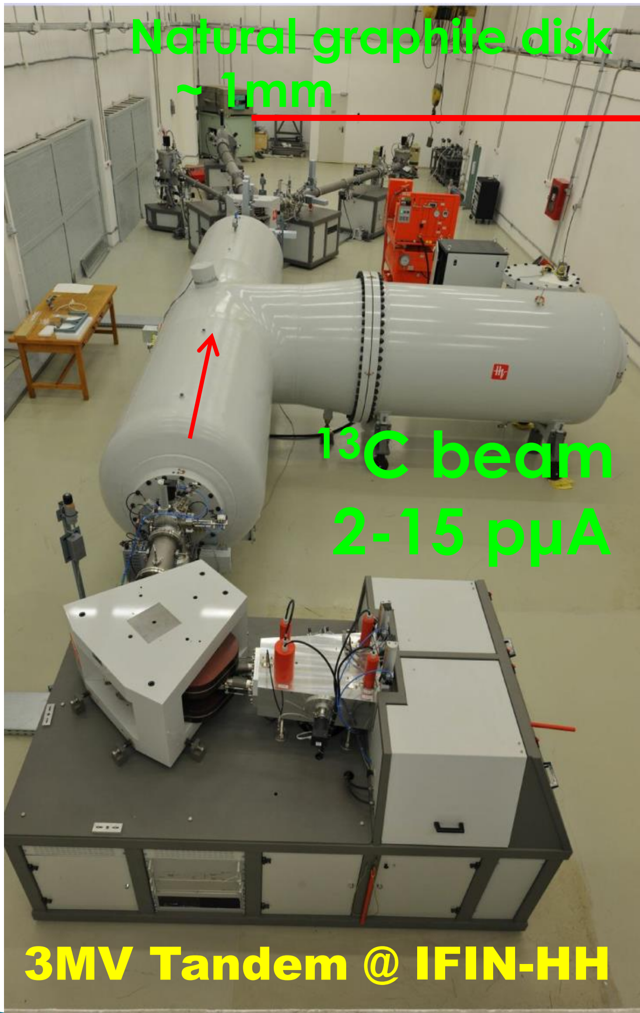
Test of extrapolating model



Courtesy of N.T. Zhang

IMP+IFIN experiments (2014,2015)

Online irradiation



$^{12}C(^{13}C, p)\,^{24}Na$

^{24}Na: $T_{1/2}$=15 hr

1369-2754 keV γ rays

Offline activity measurement

Underground, μBq lab

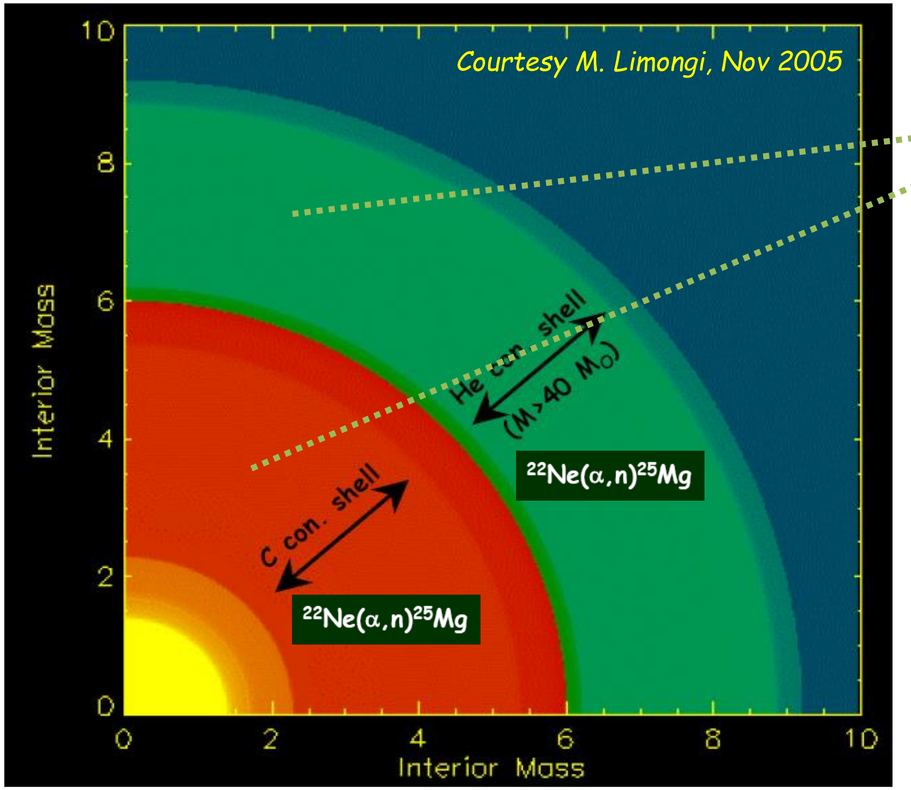
IFIN-HH GamaSpec


Slanic-Prahova salt mine

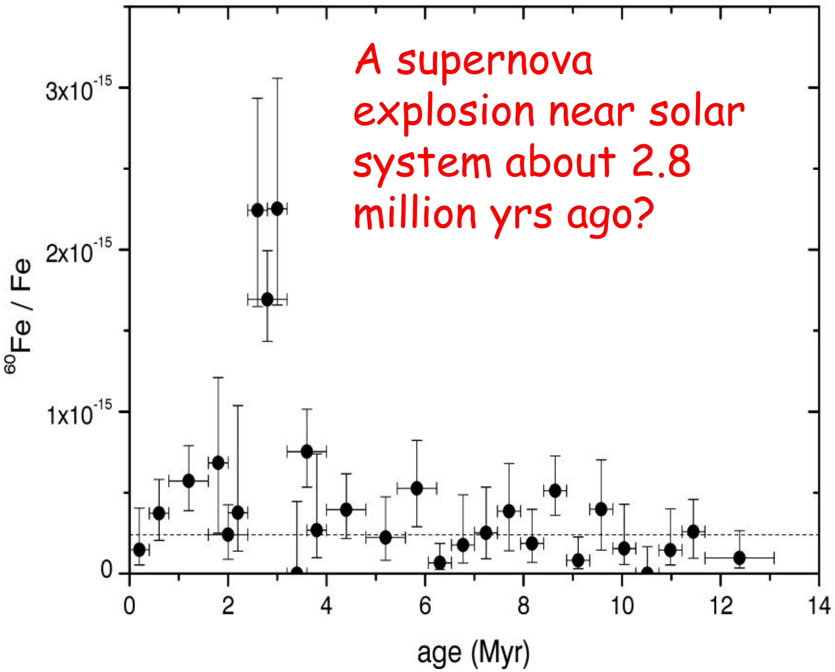
Basement

Courtesy of N.T. Zhang

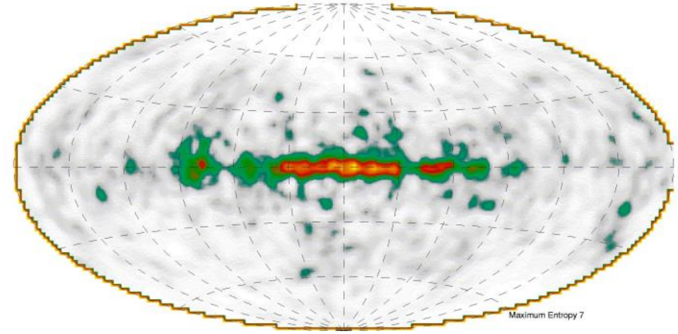
Cosmic gamma emitter



^{60}Fe

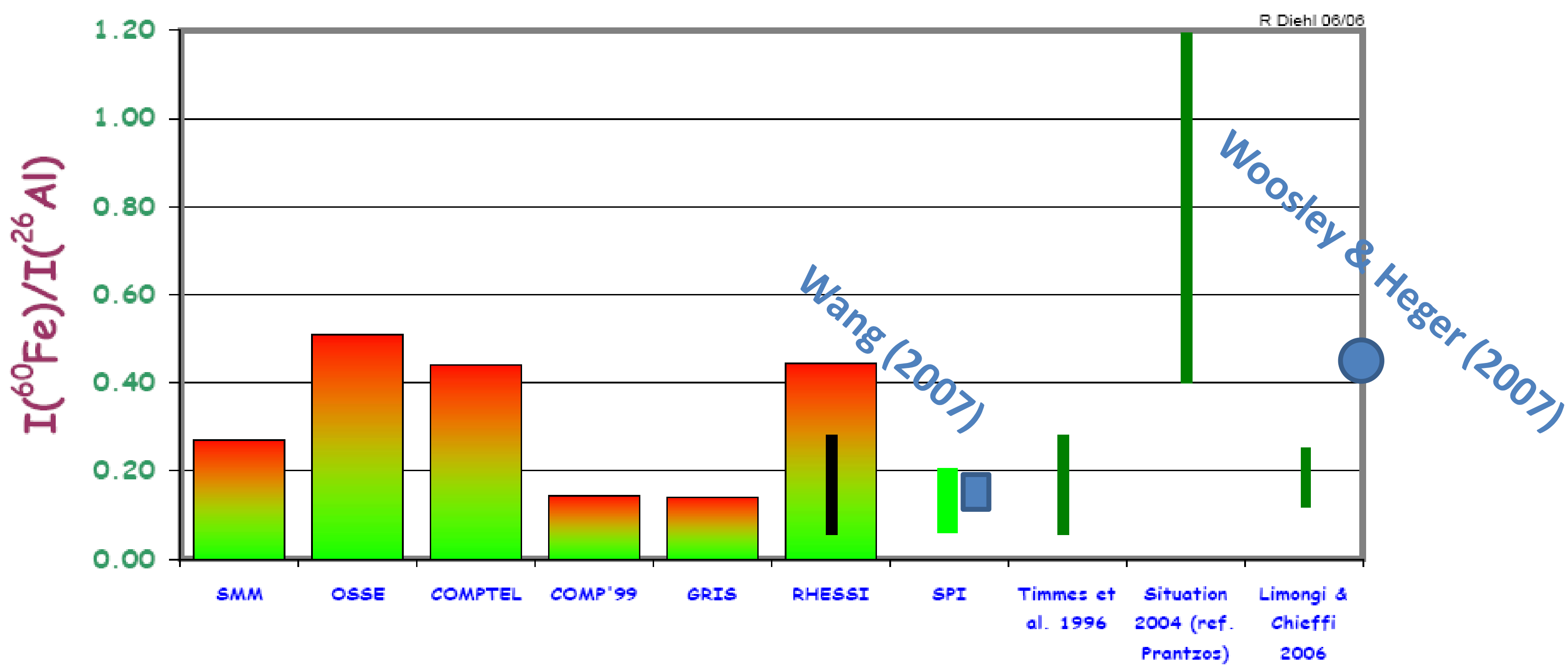


Milky Way:

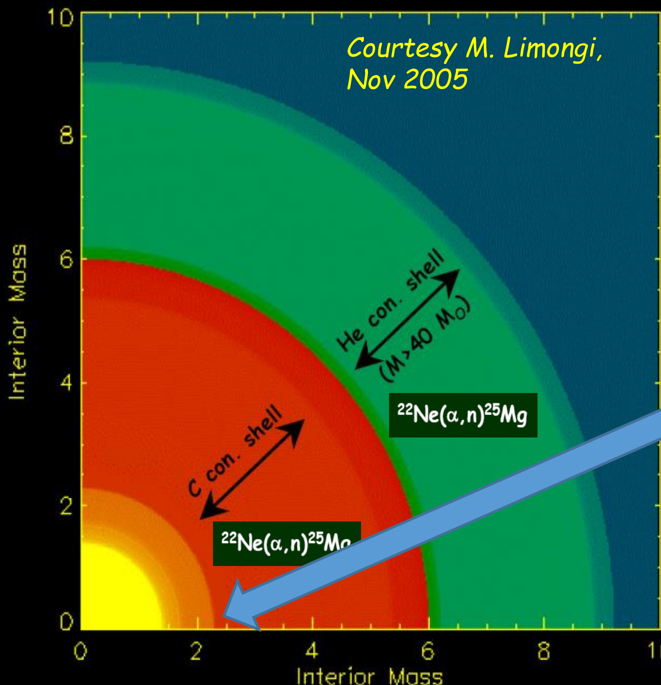


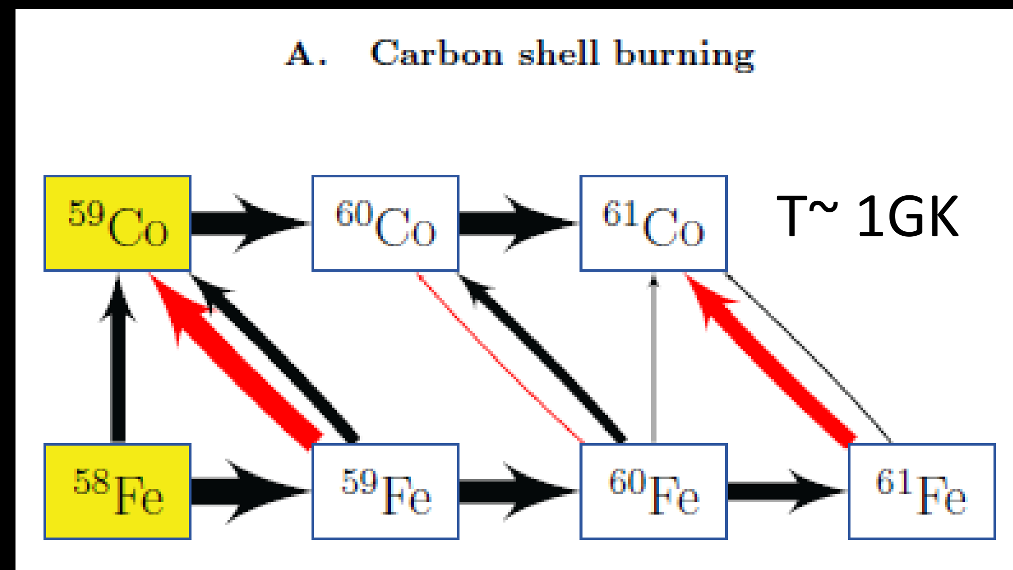
$^{60}Fe/^{26}Al = 0.15 \pm 0.04$ (Wang et al. 2007)

$^{60}Fe/^{26}Al$ Flux Ratio: Observations versus Theory

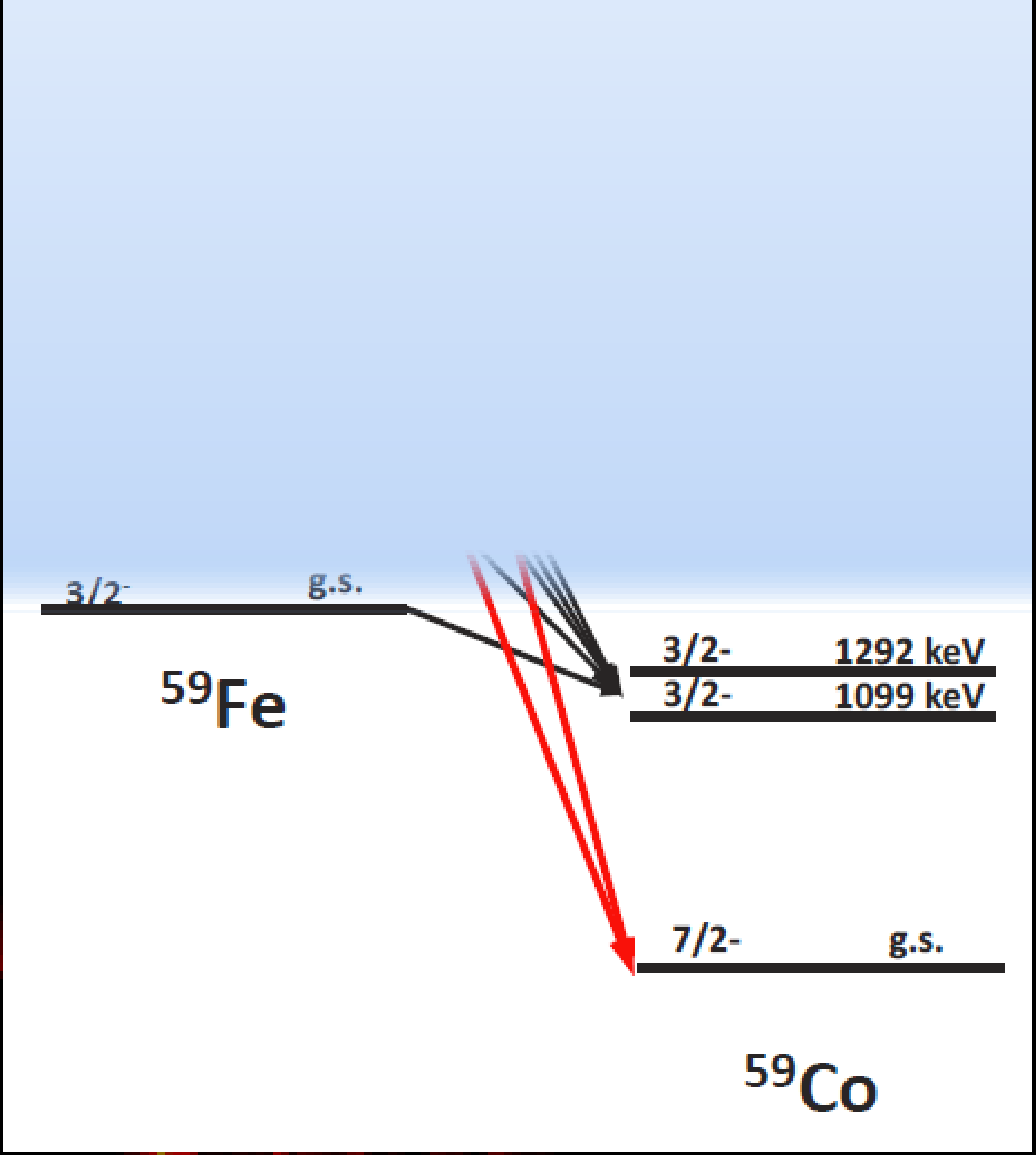


^{59}Fe decay in carbon shell burning

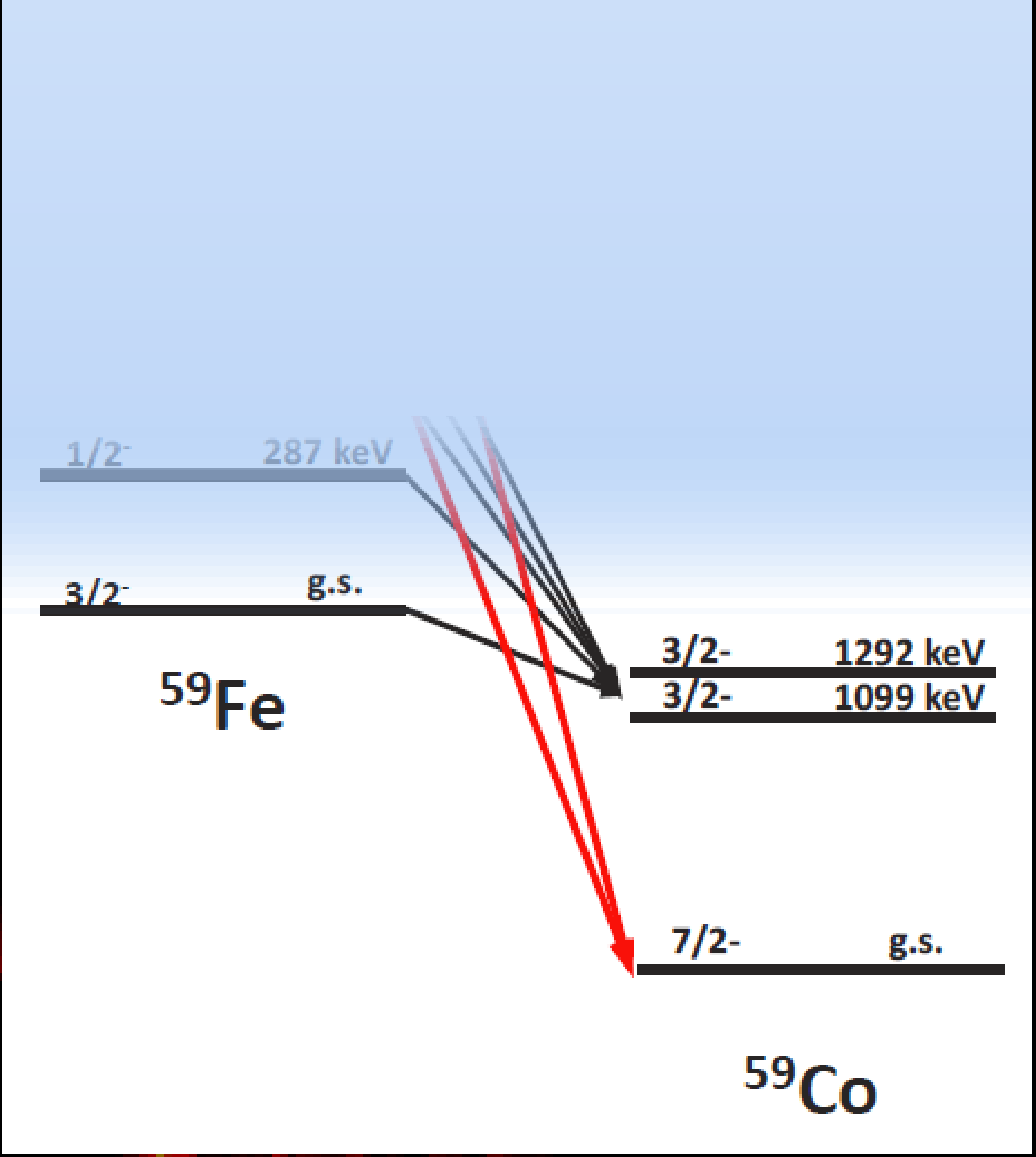




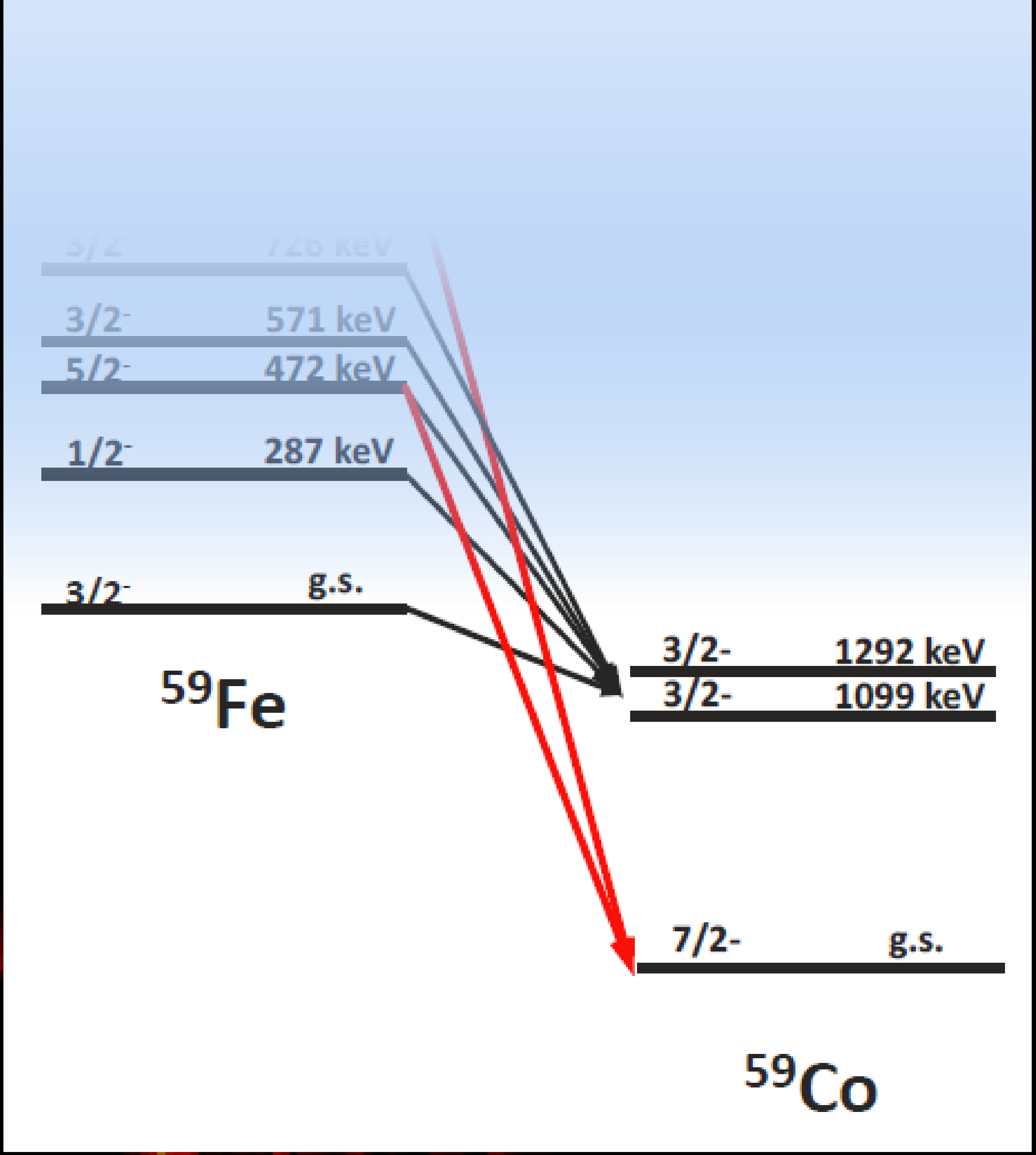
Flux in log scale



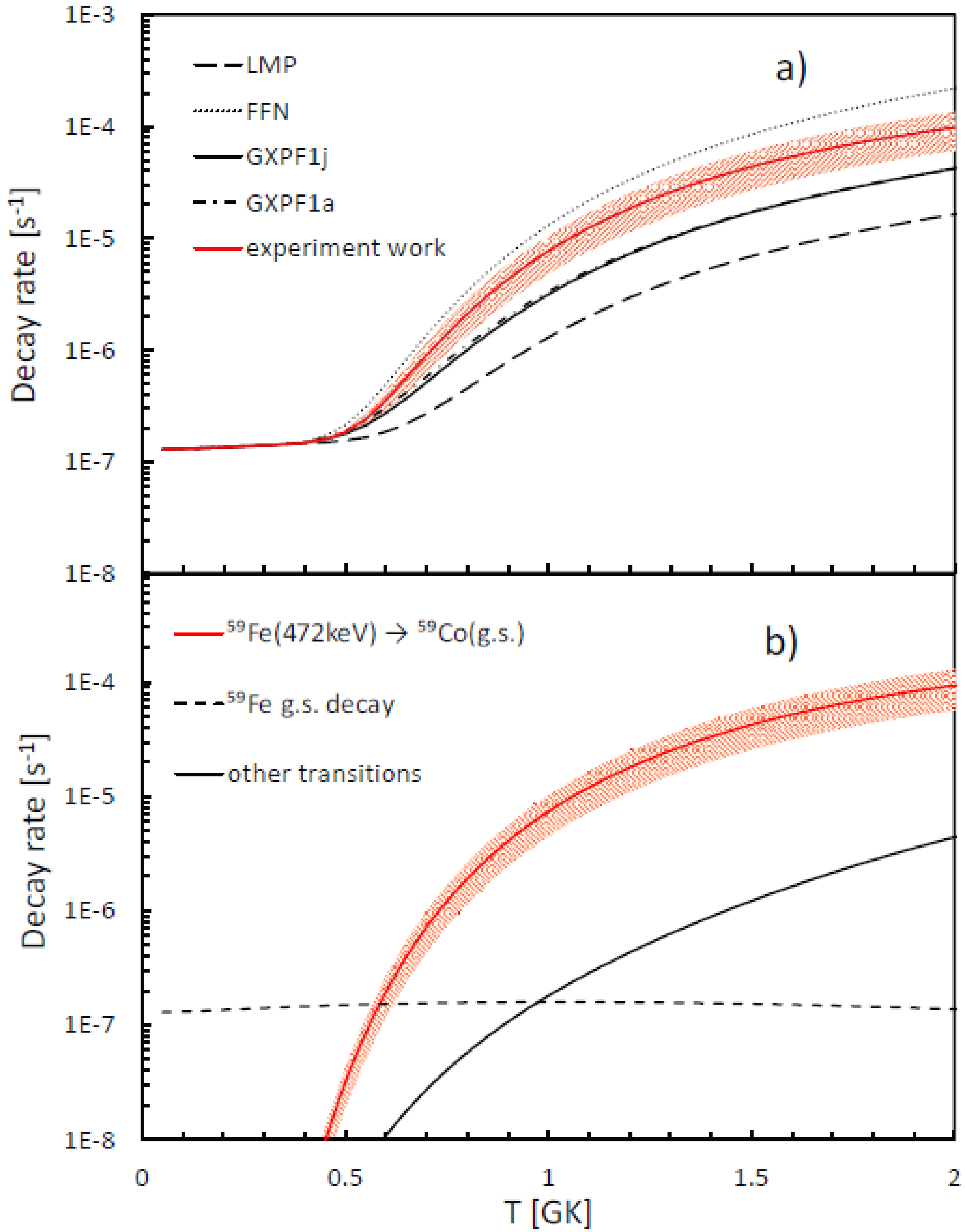
Laboratory

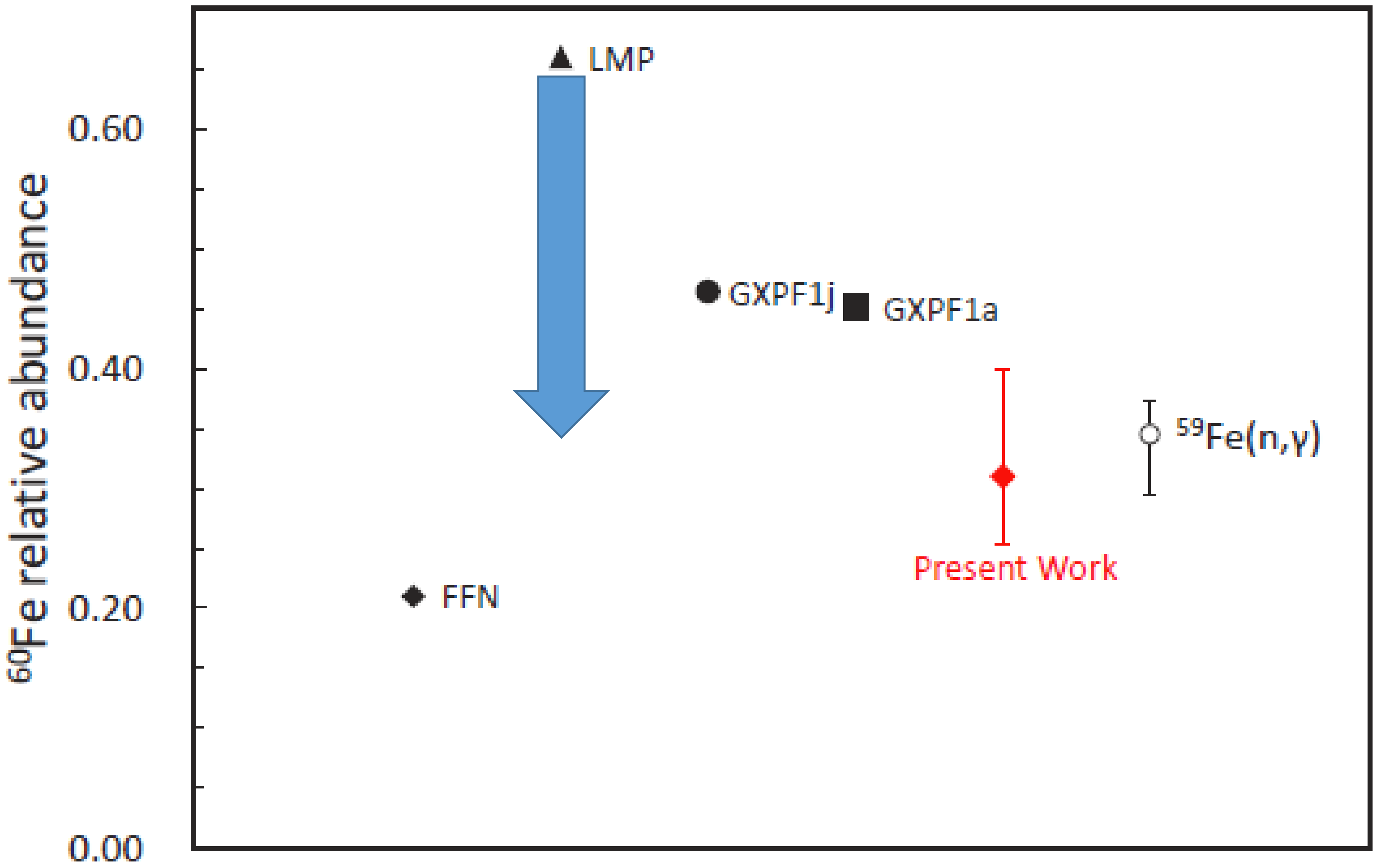


Star (low temperature)



Star (higher temperature)


a)
LMP
FFN
GXPF1j
GXPF1a
experiment work
Decay rate [s-1]
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
b)
59Fe(472keV) → 59Co(g.s.)
59Fe g.s. decay
other transitions
Decay rate [s-1]
1E-4
1E-5
1E-6
1E-7
1E-8
0
0.5
1
1.5
2
T [GK]



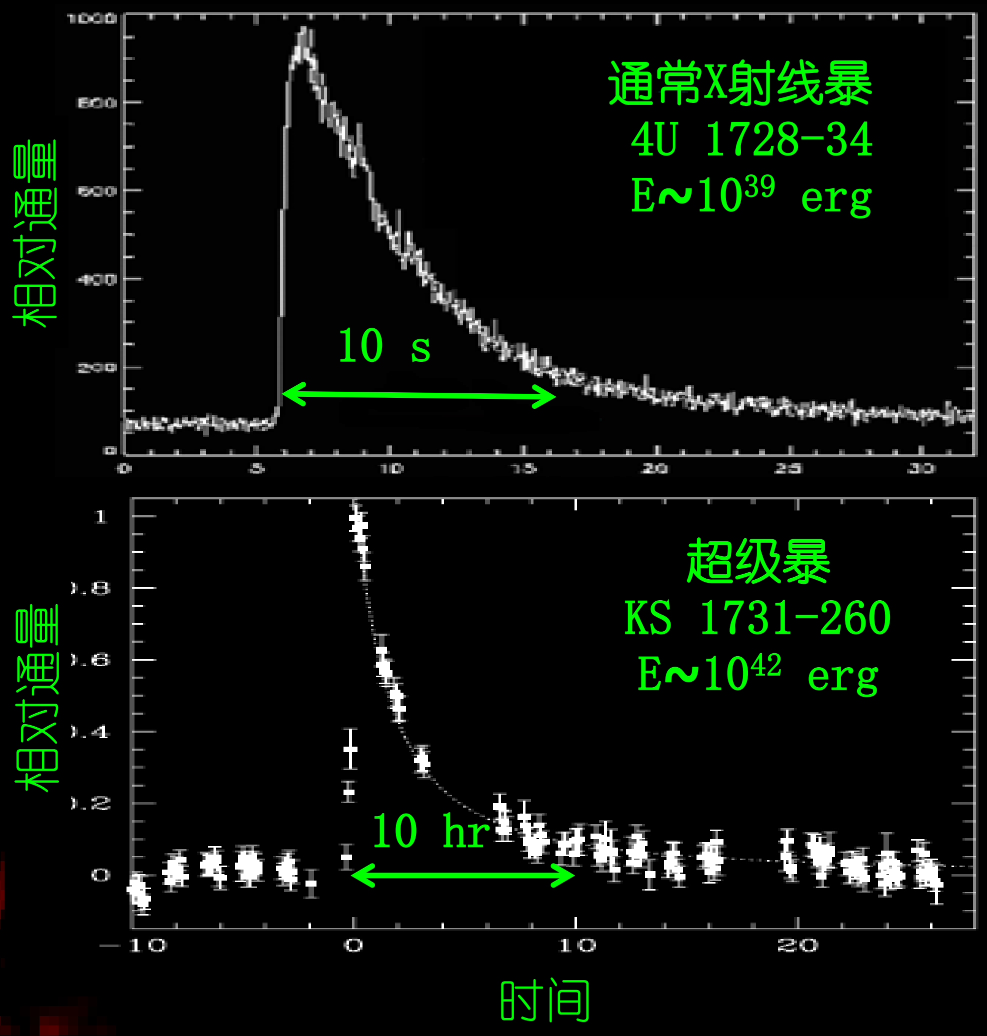
K. A. Li, Y.H. Lam, C. Qi, X.D. Tang, N.T. Zhang, to be published in PRC

High Intensity heavy ion Accelerator Facility in Lanzhou (HIRFL)

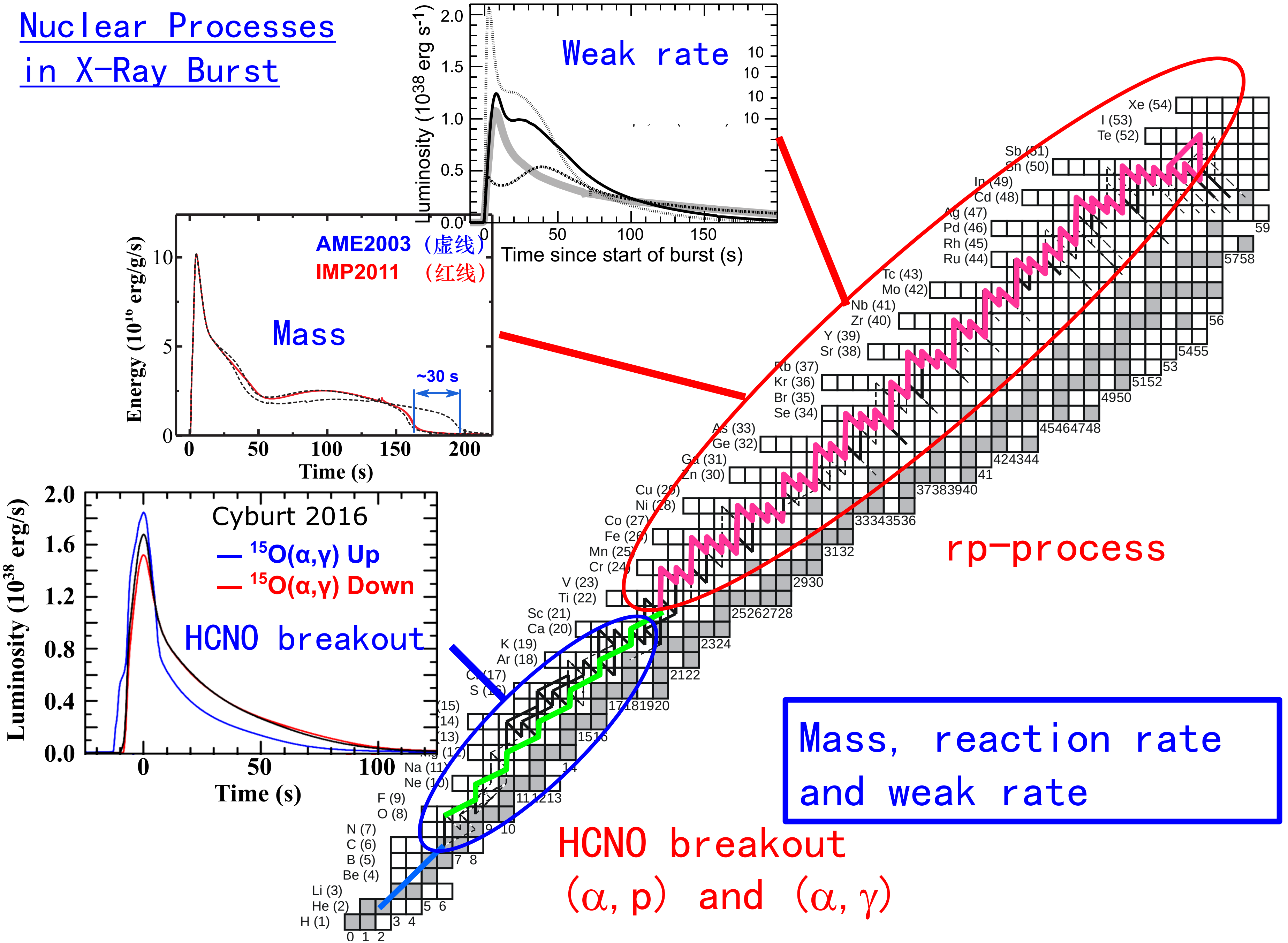
Currently ongoing activities

X-Ray burst


Companion star
Neutron star


通常X射线暴
4U 1728-34
E~10^39 erg
10 s
相对通量
超级暴
KS 1731-260
E~10^42 erg
10 hr
相对通量
时间

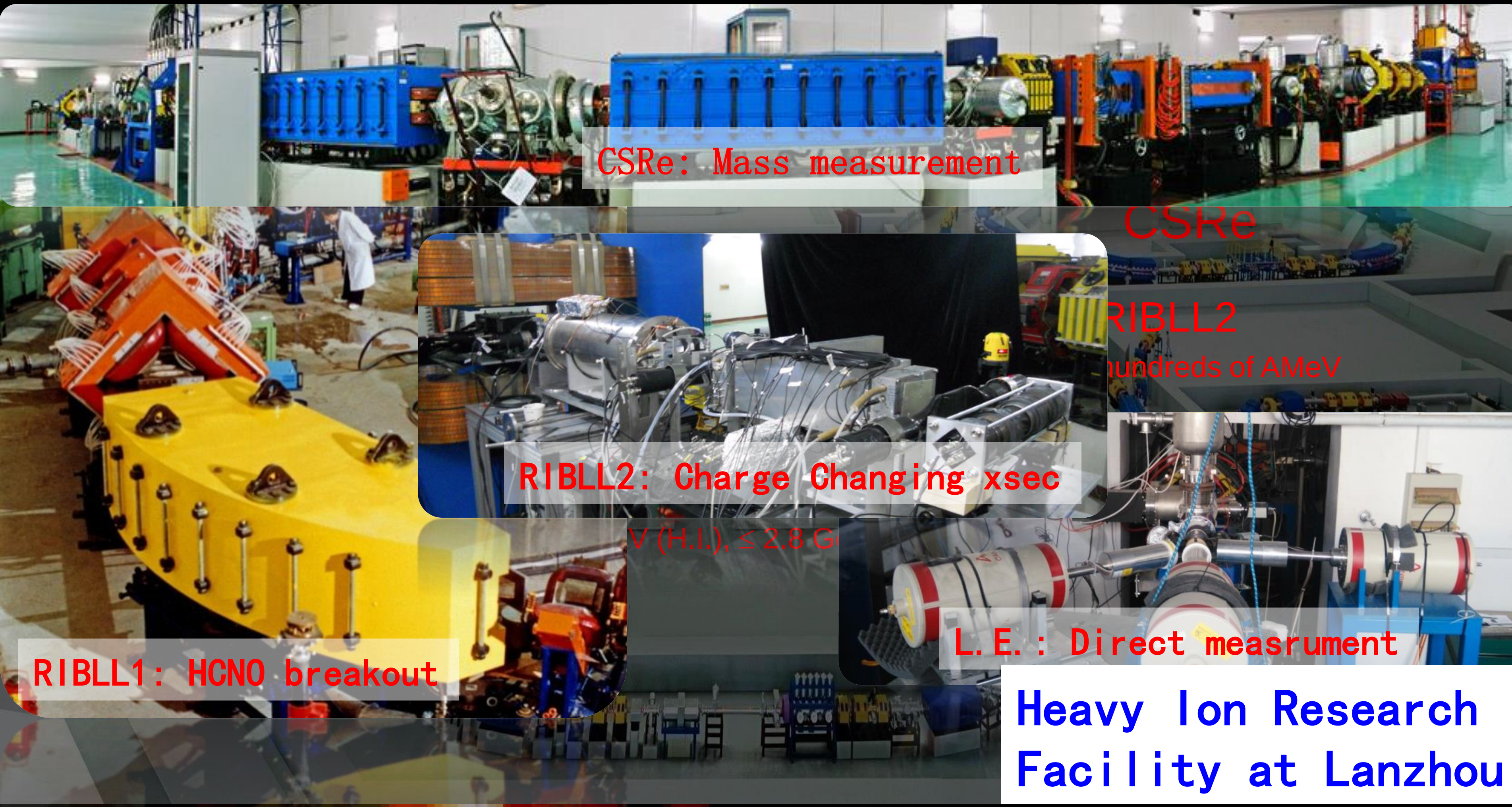
Nuclear Processes in X-Ray Burst



Nuclear Astrophysics at HIRFL

Heavy Ion Research Facility at Lanzhou

Nuclear Astrophysics at HIRFL

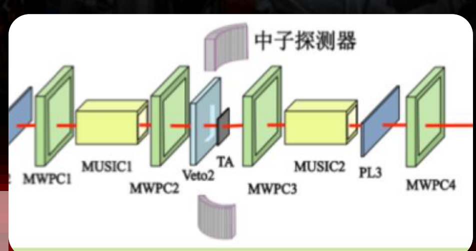


Providing ion beams from H to U in the range of keV/u to GeV/u

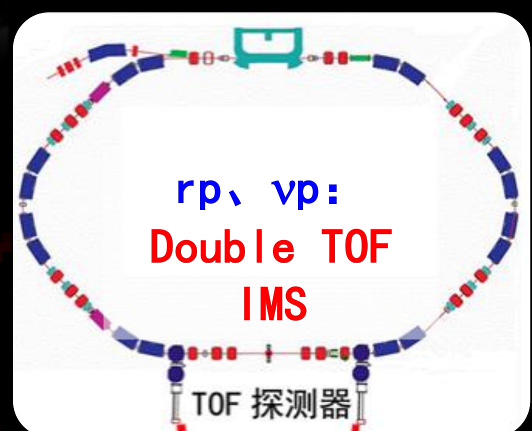
New experimental initiatives

2016-2021
6 million USD awarded

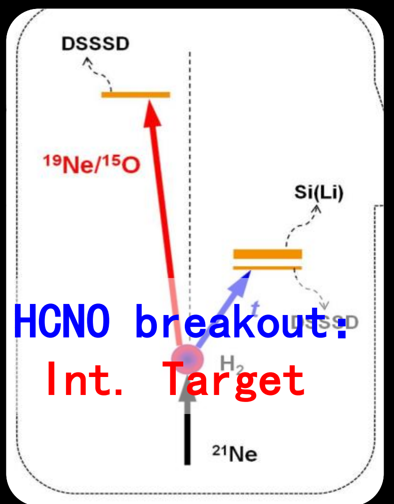
Reaction



Weakrate



Mass

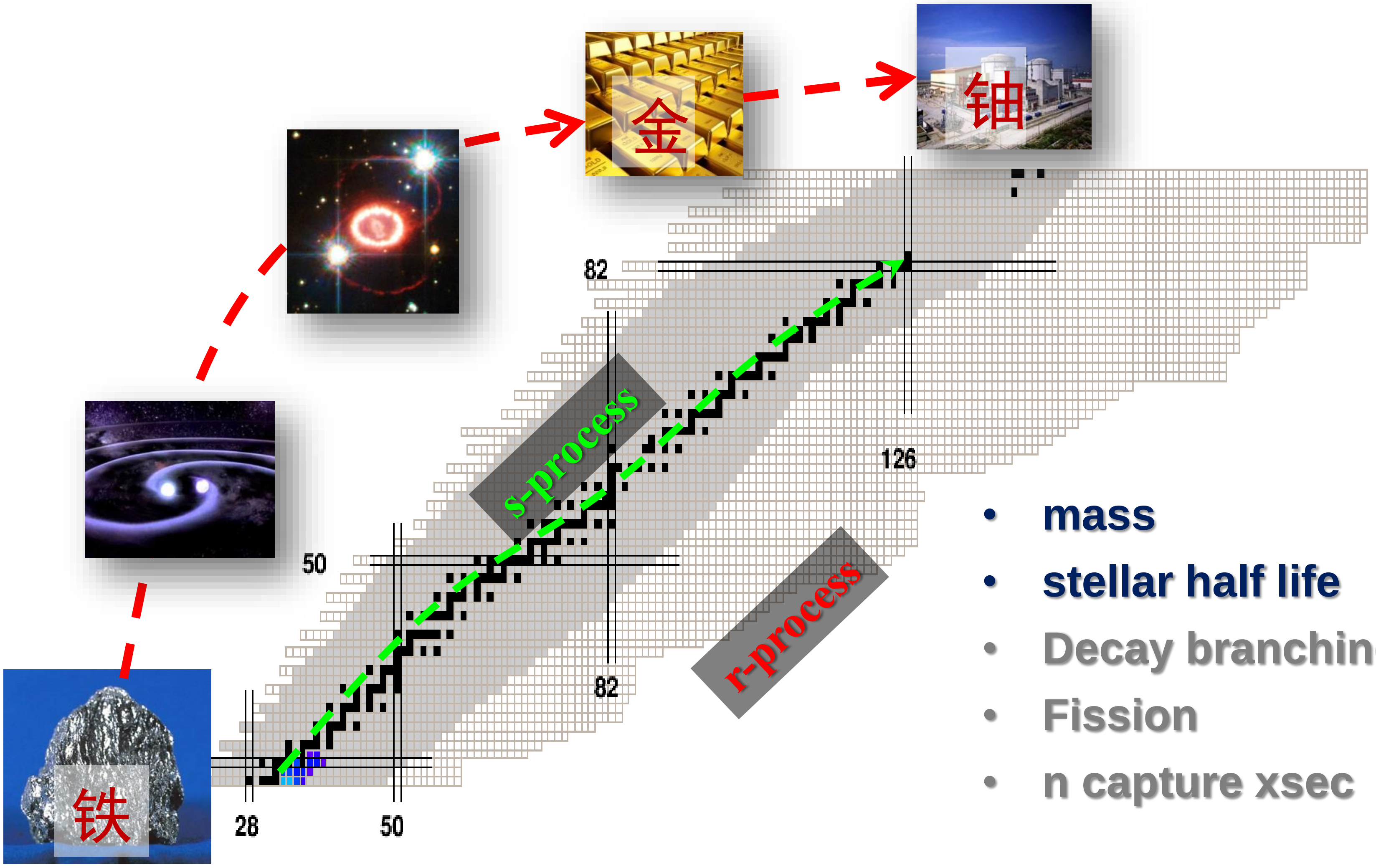


Reaction

High Intensity Accelerator Facility (HIAF)

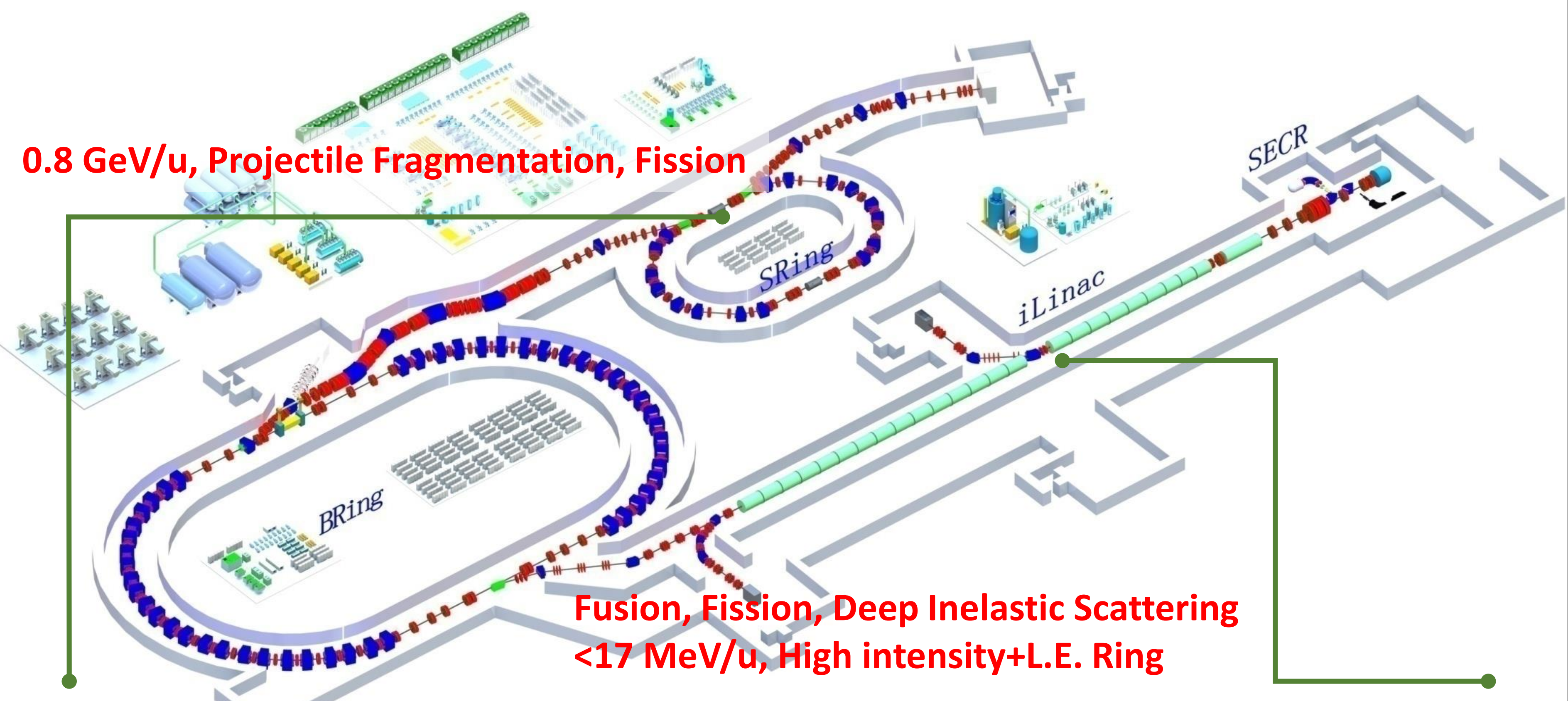
A recently funded new Chinese project funded

How were the heavy elements from iron to uranium made?



- mass
- stellar half life
- Decay branching
- Fission
- n capture xsec

Nuclear Astrophysics with High Intensity Accelerator Facility



- Mass
- Decay
- Internal target experiment
- Reactions with deaccelerated RI beams

Recoil Separator

Nuclear Reaction
(Direct reaction, Fusion, Fission, DIS)

Separator

Gas Catcher

Mass Ring
MRTOF

Laser+decay
Spectroscopy

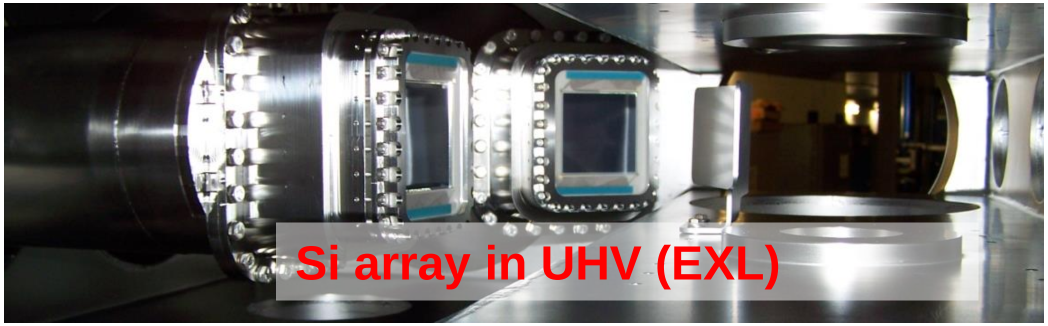
Internal target experiment

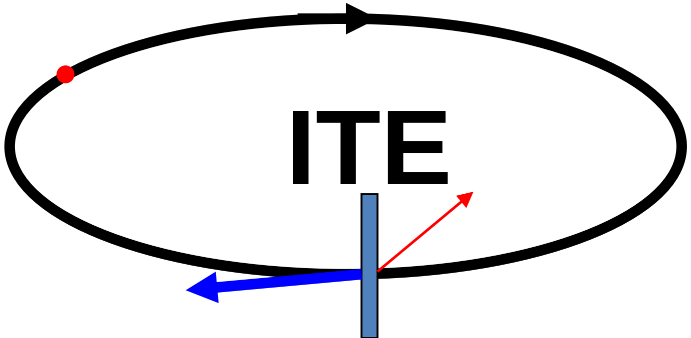
- Boost beam current (10^8 particles, 10^6 Hz → max effective intensity : 10^{14} pps)
- Free of beam induced background
- Ultra-thin target (10^{13} atoms/cm^2)

  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





^{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

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), (3He,t), (d, 2He), …
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***

TSR@HIAF

- In-flight beta-decay of light exotic nuclei
- Laser spectroscopy of rare isotopes with the TSR
- Capture reactions for the astrophysical process
- Nuclear astrophysics through transfer reactions

Summary and Outlook

- Nuclear reactions plays important role in the stars
- Chinese community is growing
- Welcome to China!