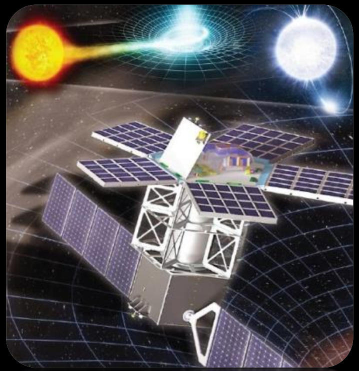
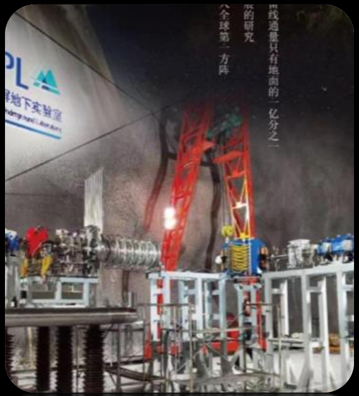
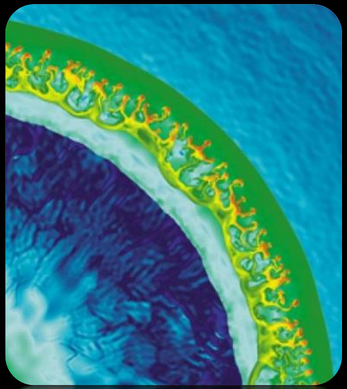
     

Forging Elements: Precise Nuclear Astrophysics Experiments in the Multi-Messenger Era

Xiao-Dong Tang

Institute of Modern Physics, CAS

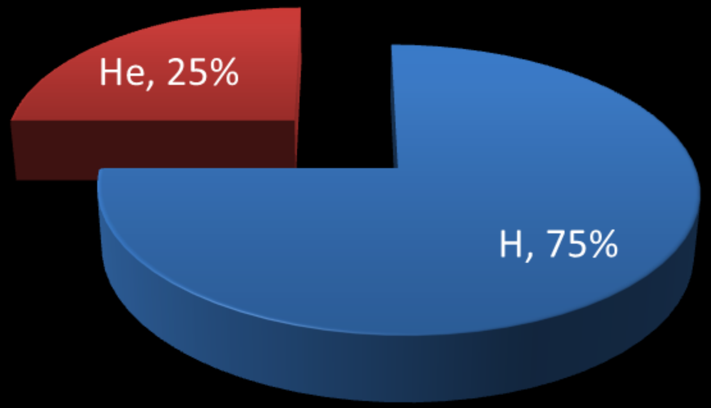
Joint Department for Nuclear Physics, Lanzhou University and IMP, CAS

Carpathian Summer School of Physics, June 22-July 3, 2025

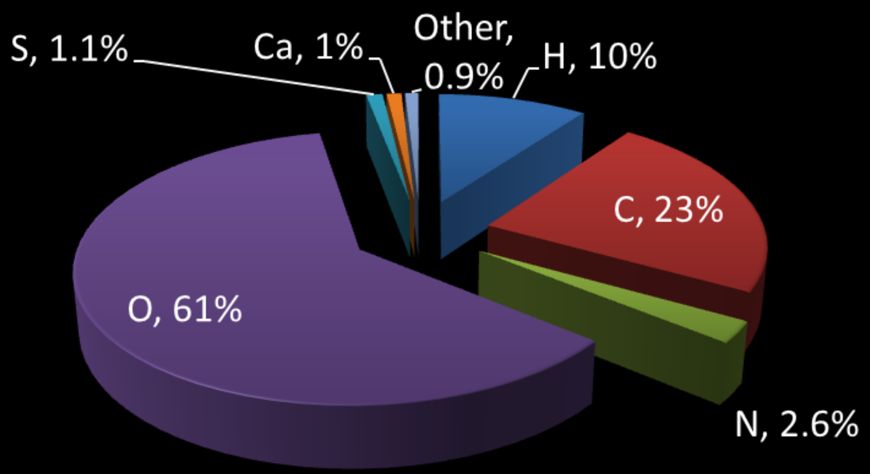
Outline

- The importance of precise nuclear astrophysics experiment in the multi-messenger era
- Status of important reaction rates and opportunies
  - $^{12}C(\alpha,\gamma)^{16}O$: nucleosynthesis of massive star, black hole mass distribution
  - $^{12}C+^{12}C$: stellar evolution(M_{up}), superburst puzzle
  - ^{59}Fe stellar decay half life: gamma ray astronomy
  - Opportunity with HIAF: Origin of elements heavier than Fe
- Outlook

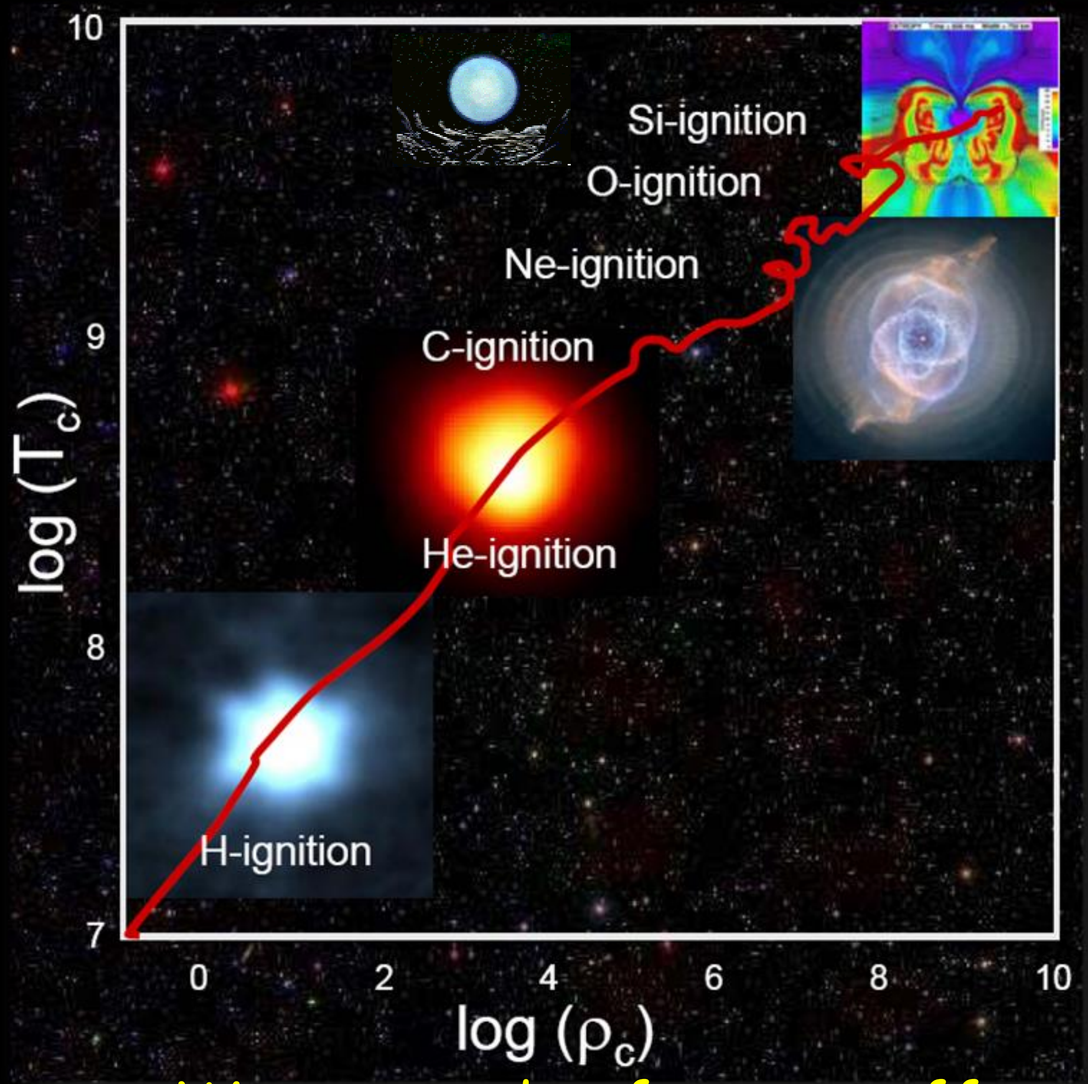
Origin of Elements



3 mins



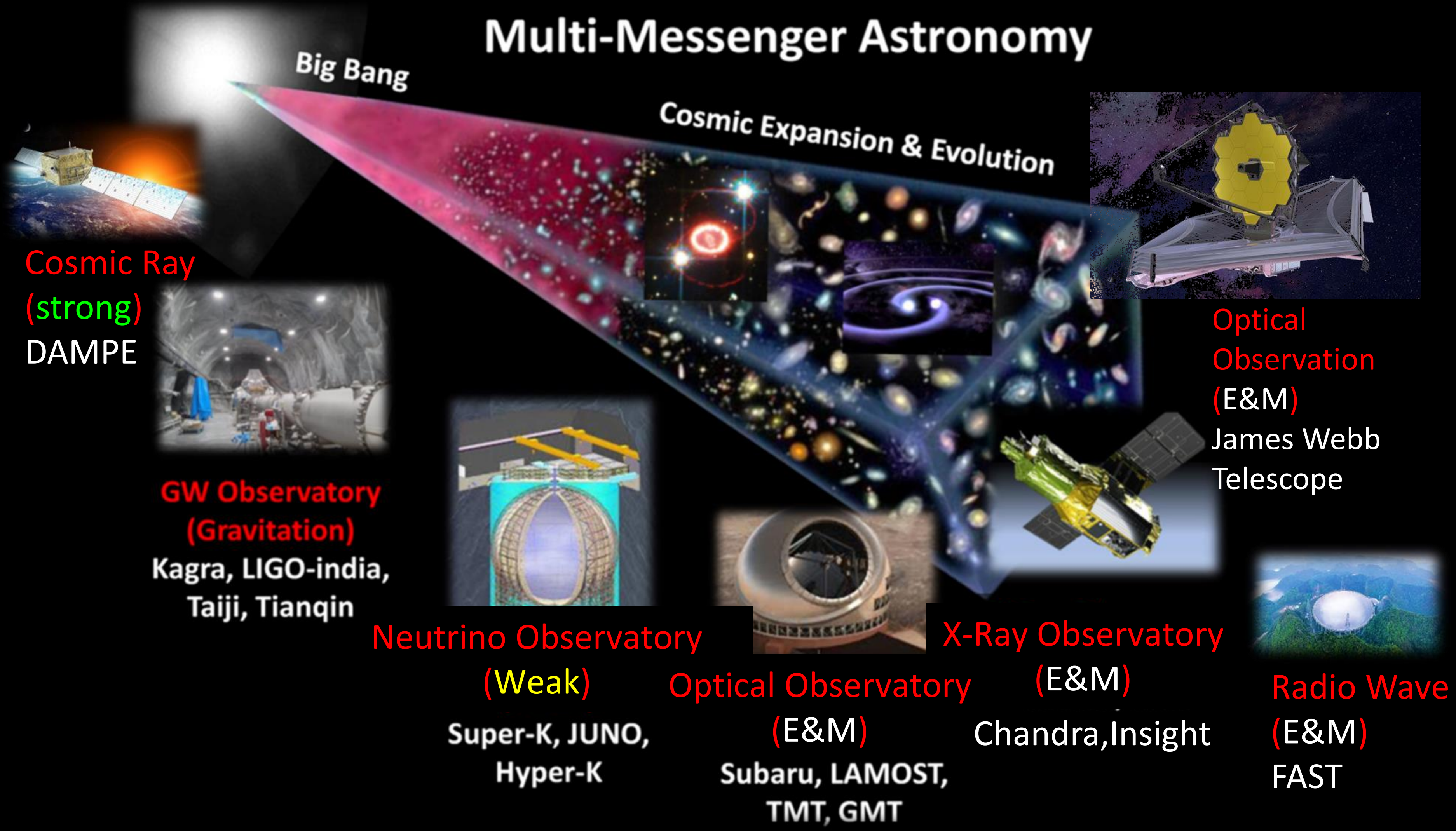
13.8 years



We are made of star-stuff.

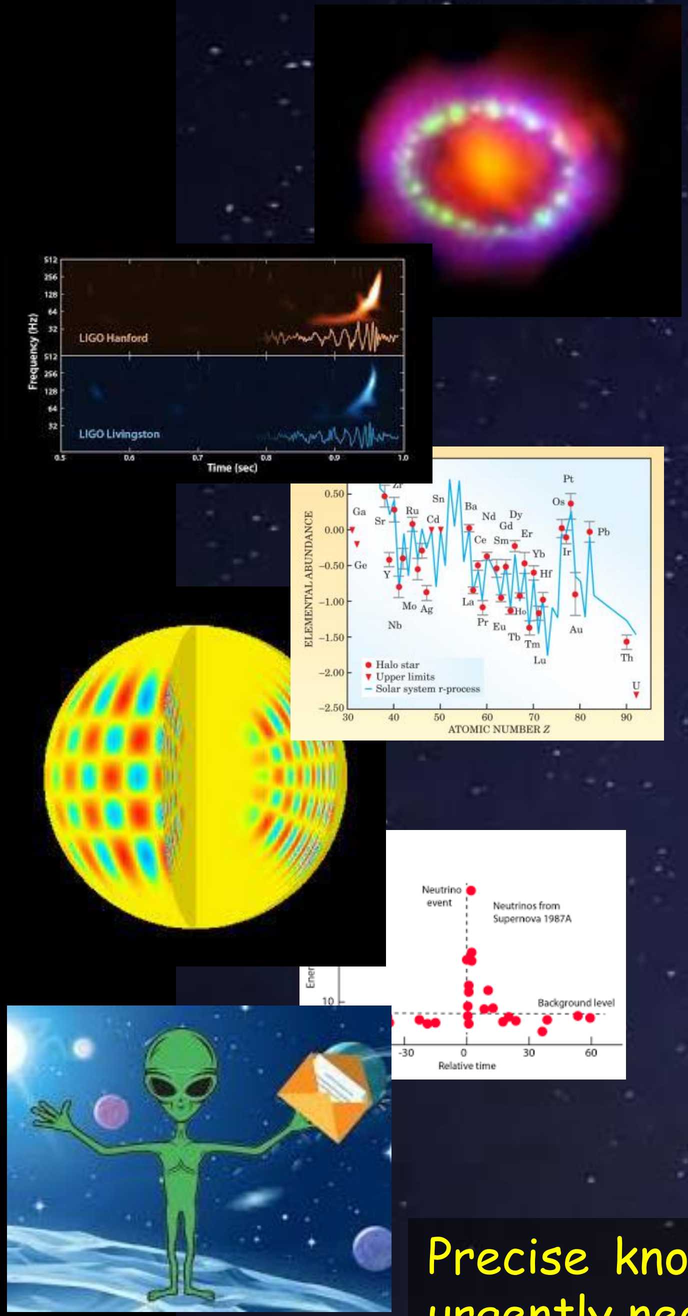
Carl Sagan

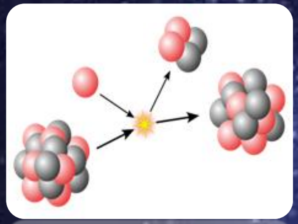
Multi-Messenger Astronomy



Multi-Messenger Astronomy probes nuclear processes via E&M, Weak, Strong, and Gravitational interactions, allowing us to see deeper into stars and further into space

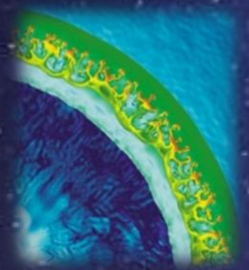
"Progress in Nuclear Astrophysics of East and Southeast Asia", AAPPS bulletin(2021) 31:18





Nuclear Experiment

Nuclear Theory



Nuclear Uncertainty

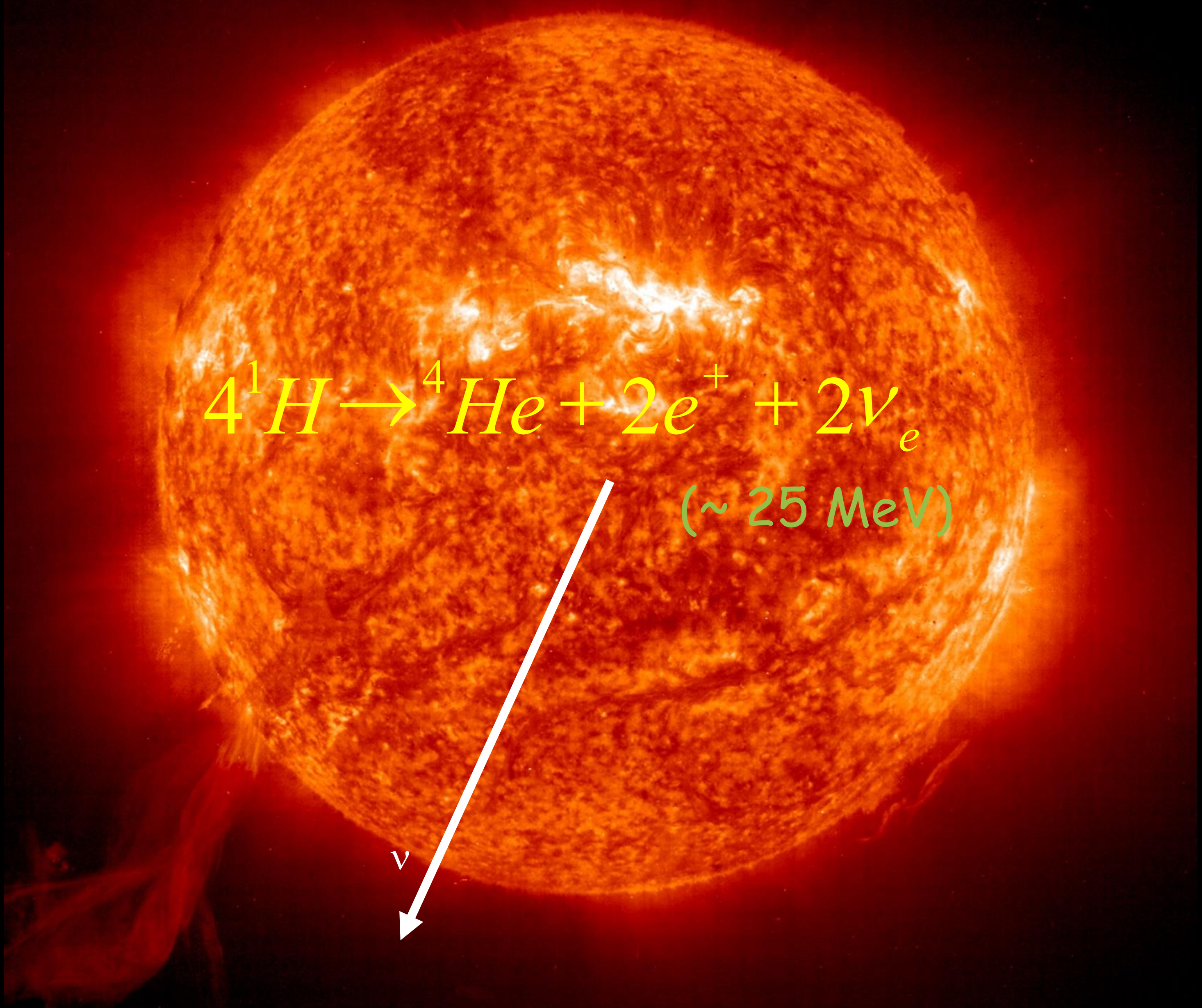
Model Uncertainty

Multi-Messenger

(Visible light, X-ray, Neutrino, Gravitational wave etc.)

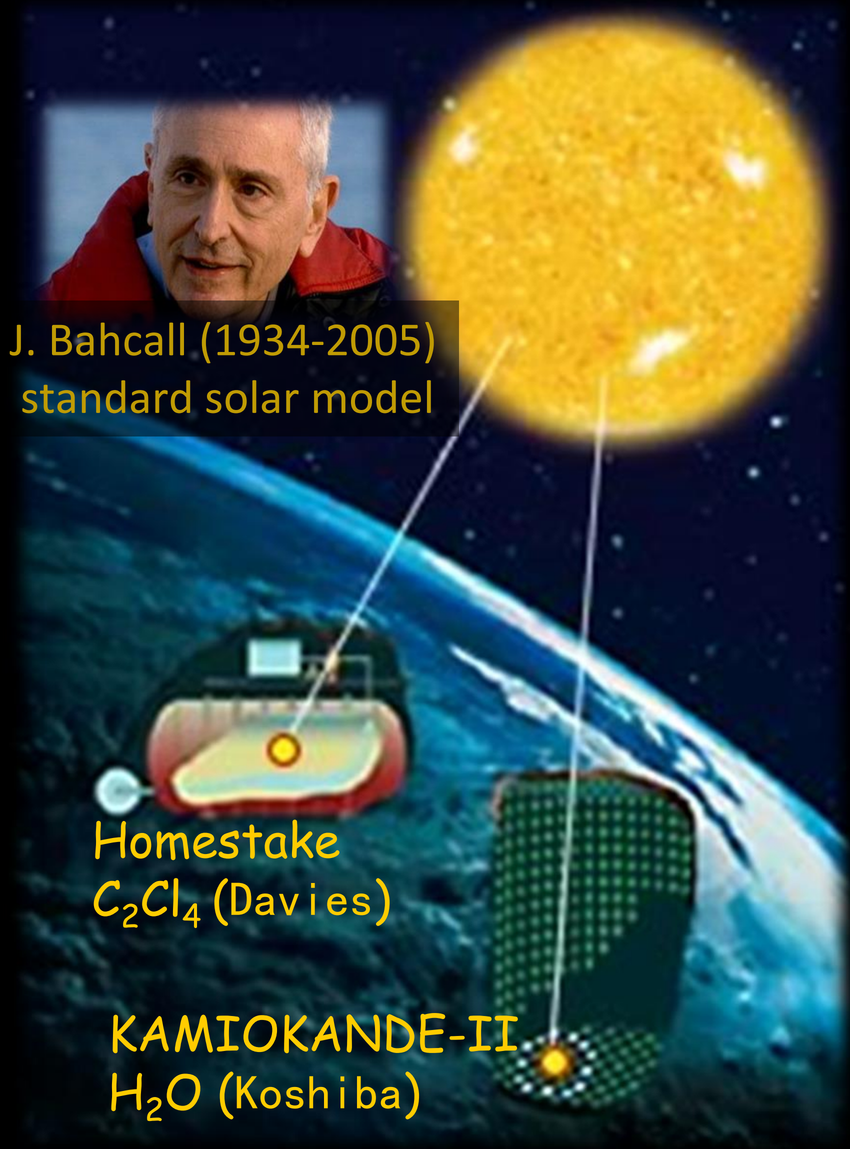
Precise knowledge of the critical nuclear physics inputs and reliable stellar models are urgently needed to decipher the encoded messages correctly.

The first success of multi-messenger astronomy



Solar Neutrino "Problem"

New discovery beyond standard model in particle physics



Experiment	Detector medium	Observation /prediction
Homestake	^{37}Cl	0.33 ± 0.03
Kamiokande	water	0.57 ± 0.07

2002 Nobel prize in physics

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

Solar Neutrino "Problem"

- Solar model
- Important cross sections: $^3He(^3He,2p)^4He$, $^3He(^4He,\gamma)^7Be$, $^7Be(p,\gamma)^8B$
- Unknown neutrino physics-neutrino oscillation???

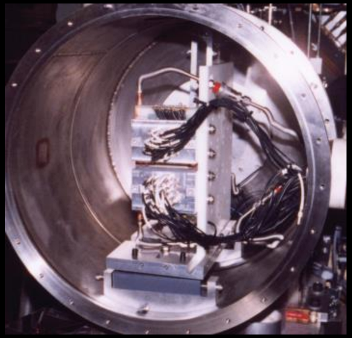
"Most likely, the solar neutrino problem has nothing to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of ^8B neutrinos to within a factor of 2 or 3…"

Howard Georgi and Michael Luke (1990)

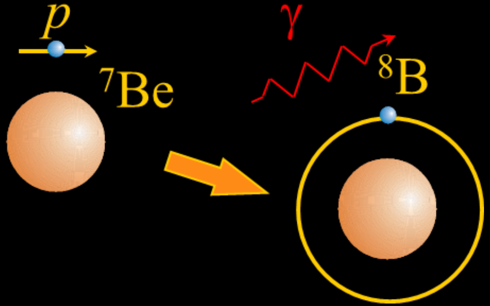
S factor of $^7Be(p,\gamma)^8B$

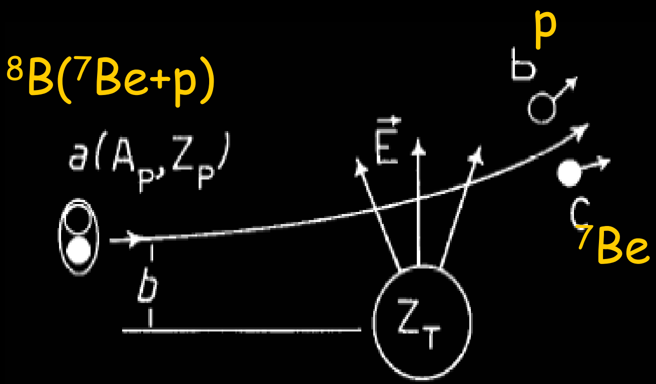
Direct measurement (<MeV/u)

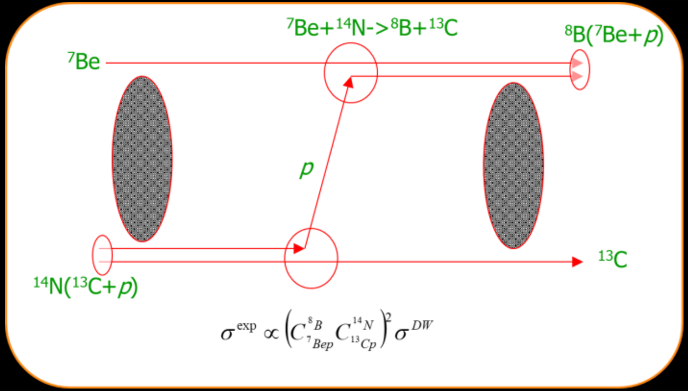
Coulomb Dissociation (~100 Mev/u)

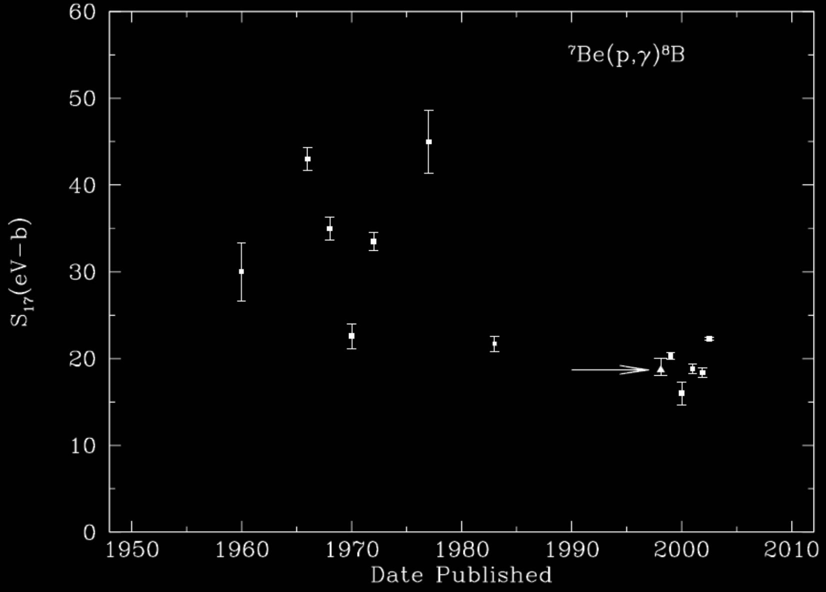


Asymptotic Normalization Coefficient (ANC) (<10MeV/u)









$S_{17}(0) = 20.5(7)$ eV b

TEXAS A&M UNIVERSITY
Physics & Astronomy

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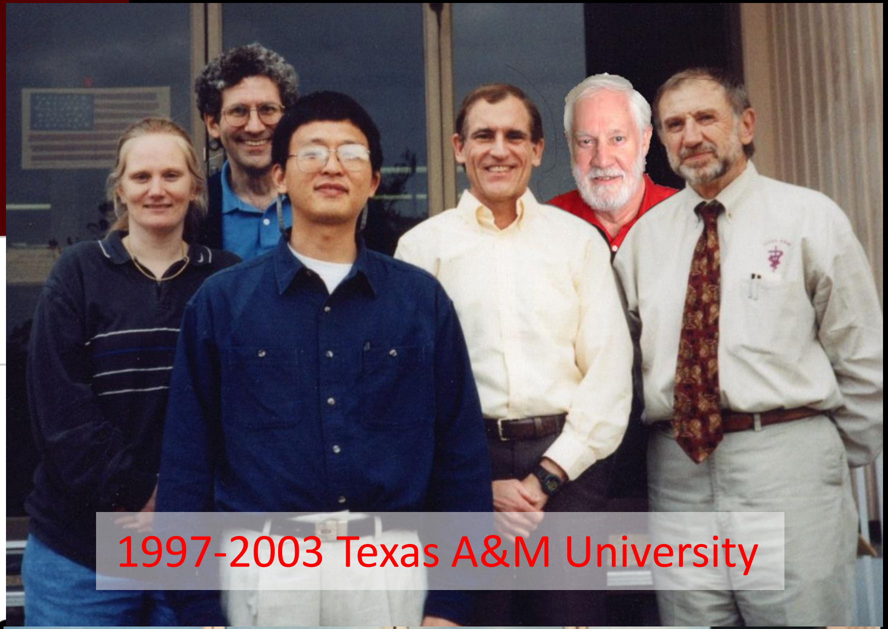
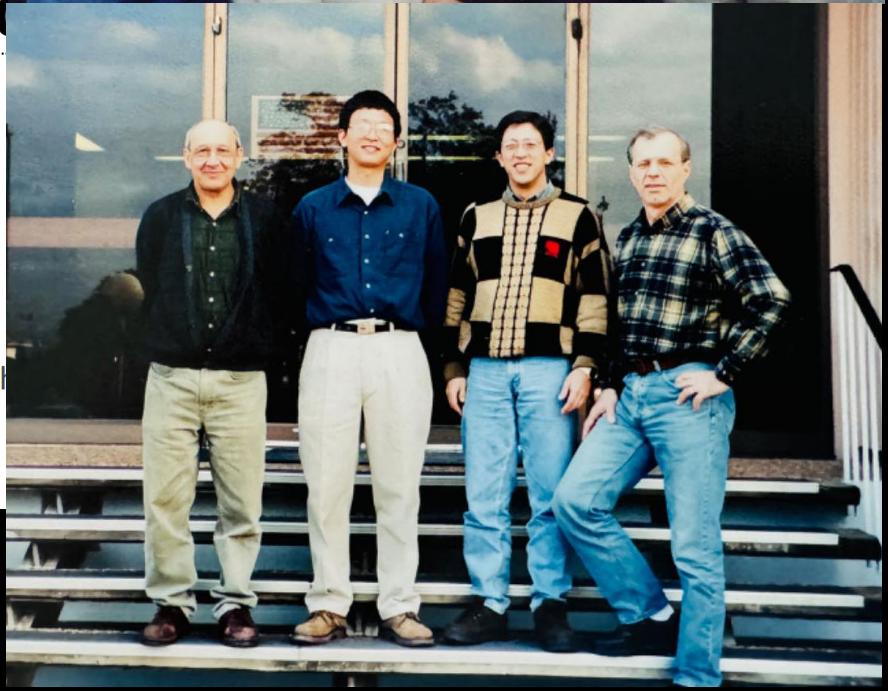
OCTOBER 16, 2001

Physicists Count Subatomic Particles Release[d] By The Sun

COLLEGE STATION —

The sun not only radiates light all over the place, but it also emits millions of tiny invisible particles called neutrinos. A team of Texas A&M University physicists has reported in the journal Physical Review C one of t[he] most precise results about the number of solar neutrinos by using an original approach starting a new sub-discipline within nuclear astrophysics.

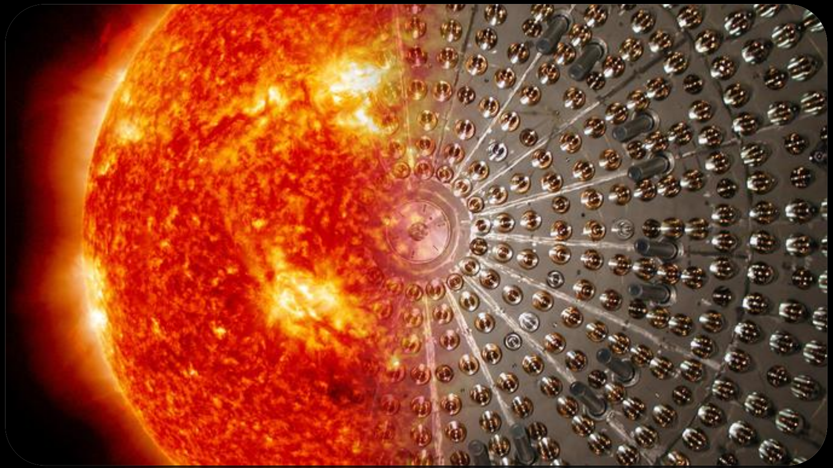




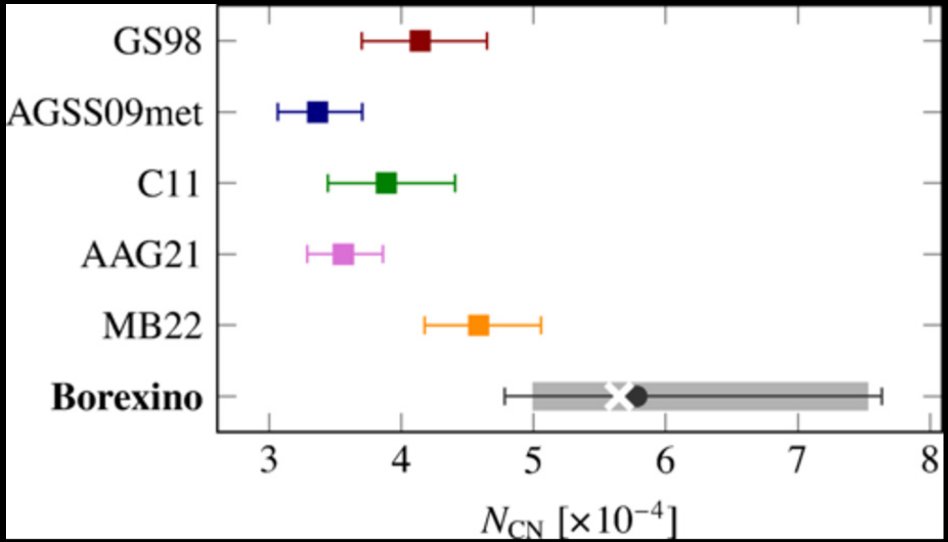
Gagliardi says. "But at the same time we have started a new sub-discipline within nuclear astrophysics, which was not our goal. **It is particularly rewarding to see other people pick up what you have been doing and emulate it**."

Solar metallicity problem

- Determination of the solar CNO neutrino source and test the predictions of the solar metallicity (abundance of elements heavier than 2) in the standard solar model.
- BOREXINO results suggest a higher metallicity than predicted by CNO predictions.



arXiv:2307.14636v1



Neutrino flux

metallicity of C+N

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} = \left[\frac{\phi(^{8}\mathrm{B})}{\phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right]^{0.729} x_{C+N}$$

$$\times \left[1 \pm 0.006(\mathrm{solar}) \pm 0.027(\mathrm{D}) \pm 0.099(\mathrm{nucl}) \pm 0.032(\theta_{12})\right]$$

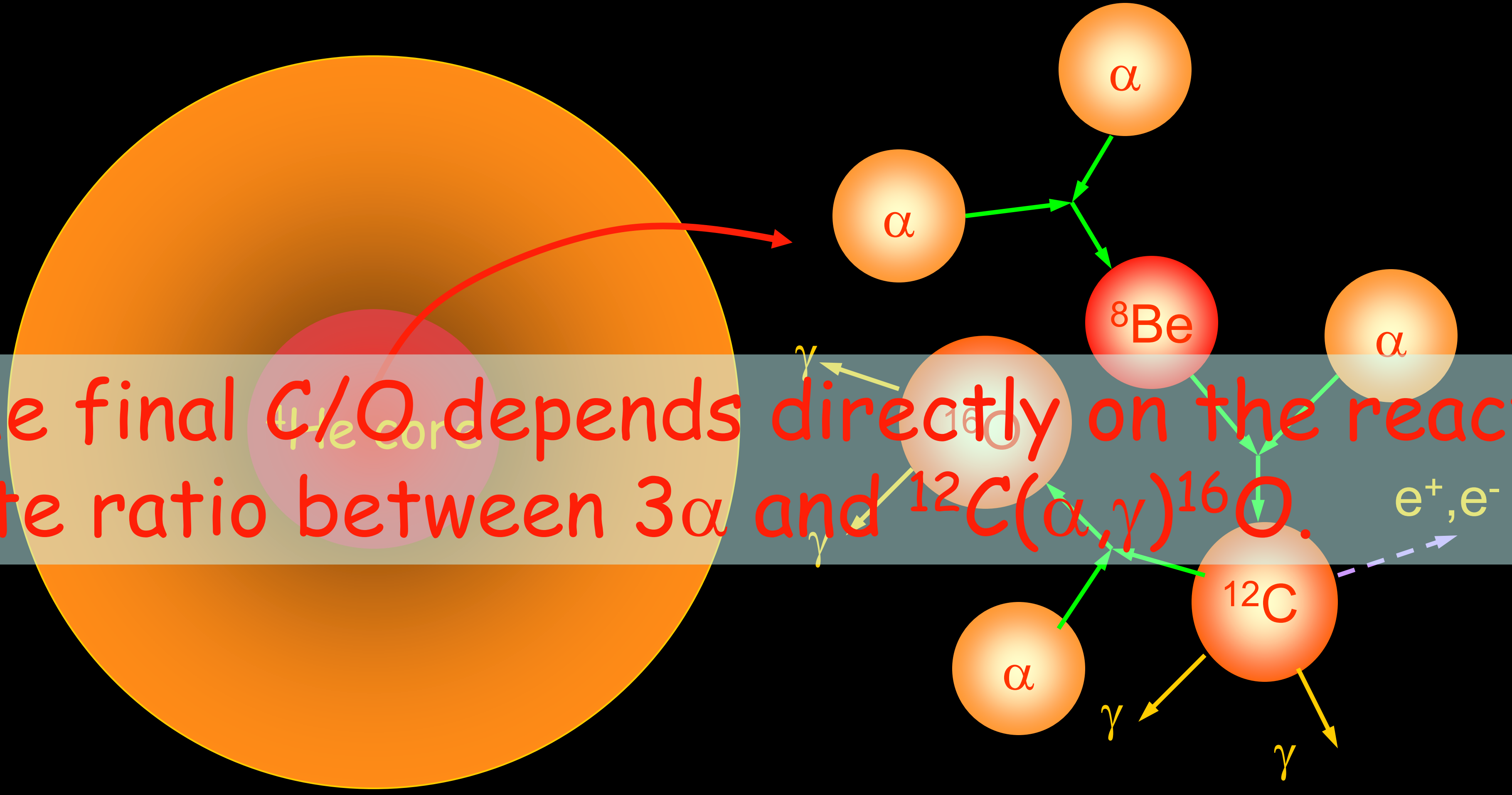
Nuclear Physics is the biggest uncertainty !

^{7}Be(p,γ)^{8}B (5.5%→3.4%)

^{14}N(p,γ)^{15}O (7.2%→8.4%)

Haxton, Roberson and Serenelli, arxiv:1208.5723v1 (2012)

Helium Burning

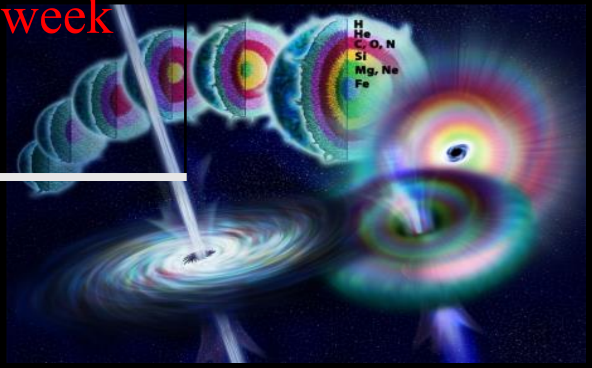


The final C/O depends directly on the reaction rate ratio between 3α and $^{12}C(\alpha,\gamma)^{16}O$.

T ~ 0.2 billion Kelvin

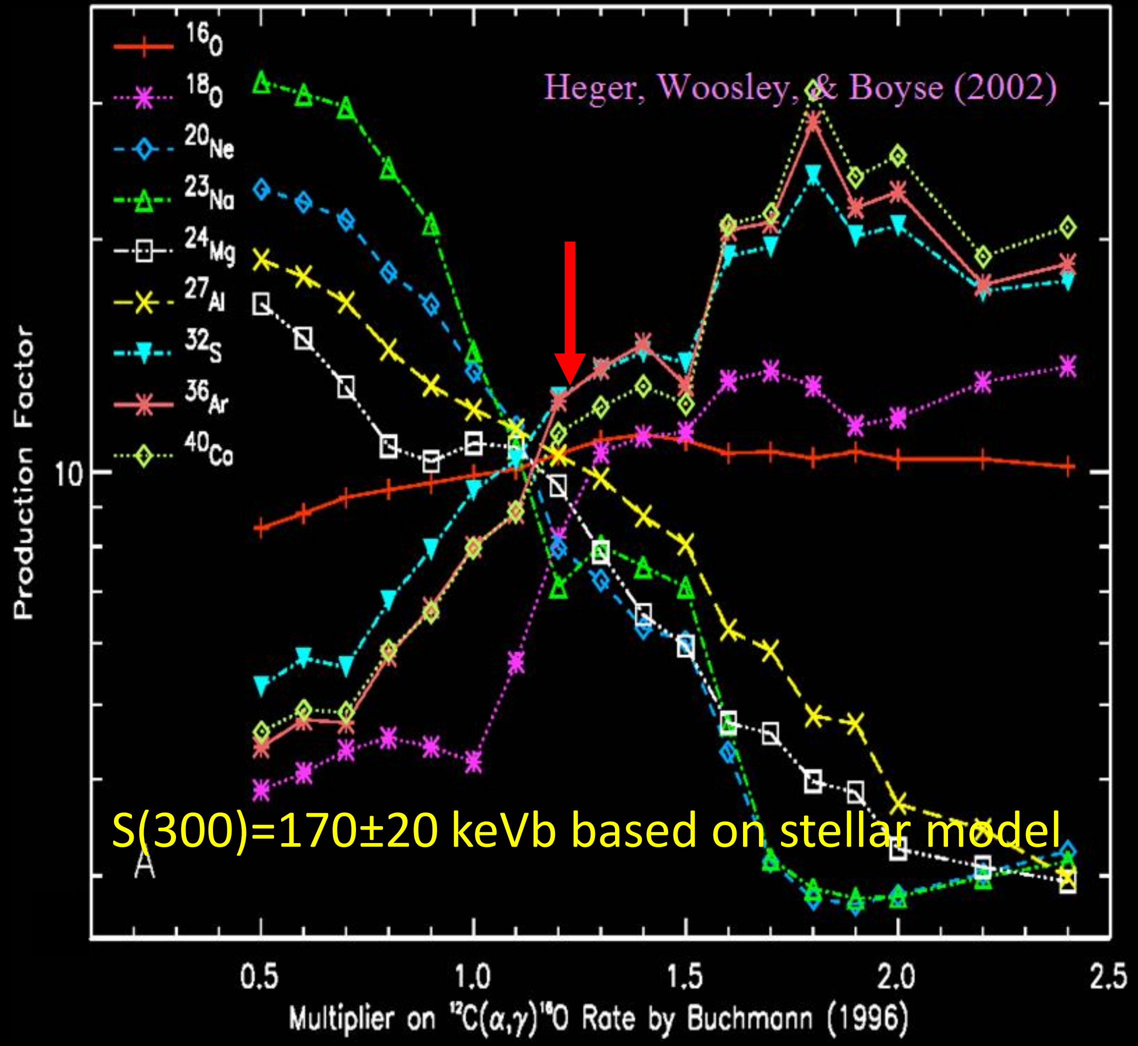
Life of massive star（~20 solar mass）

Fuel	Primary Products	Secondary products	Approximate temperature (10^9 K)	Approximate duration
Hydrogen	^{4}He	^{14}N	0.02	10 million years
Helium	C,O	^{18}O,^{22}Ne s-process	0.2	1 million years
Carbon	Ne,Mg	Na	0.8	1000 year
Neon	O,Mg	Al, P	1.5	3 year
Oxygen	Si, S	Cl, Ar, K, Ca	2.0	0.8 year
Silicon	Fe	Ti, V, Cr Mn, Co, Ni	3.5	1 week



Influences of the uncertainty in the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate in Nucleosynthesis

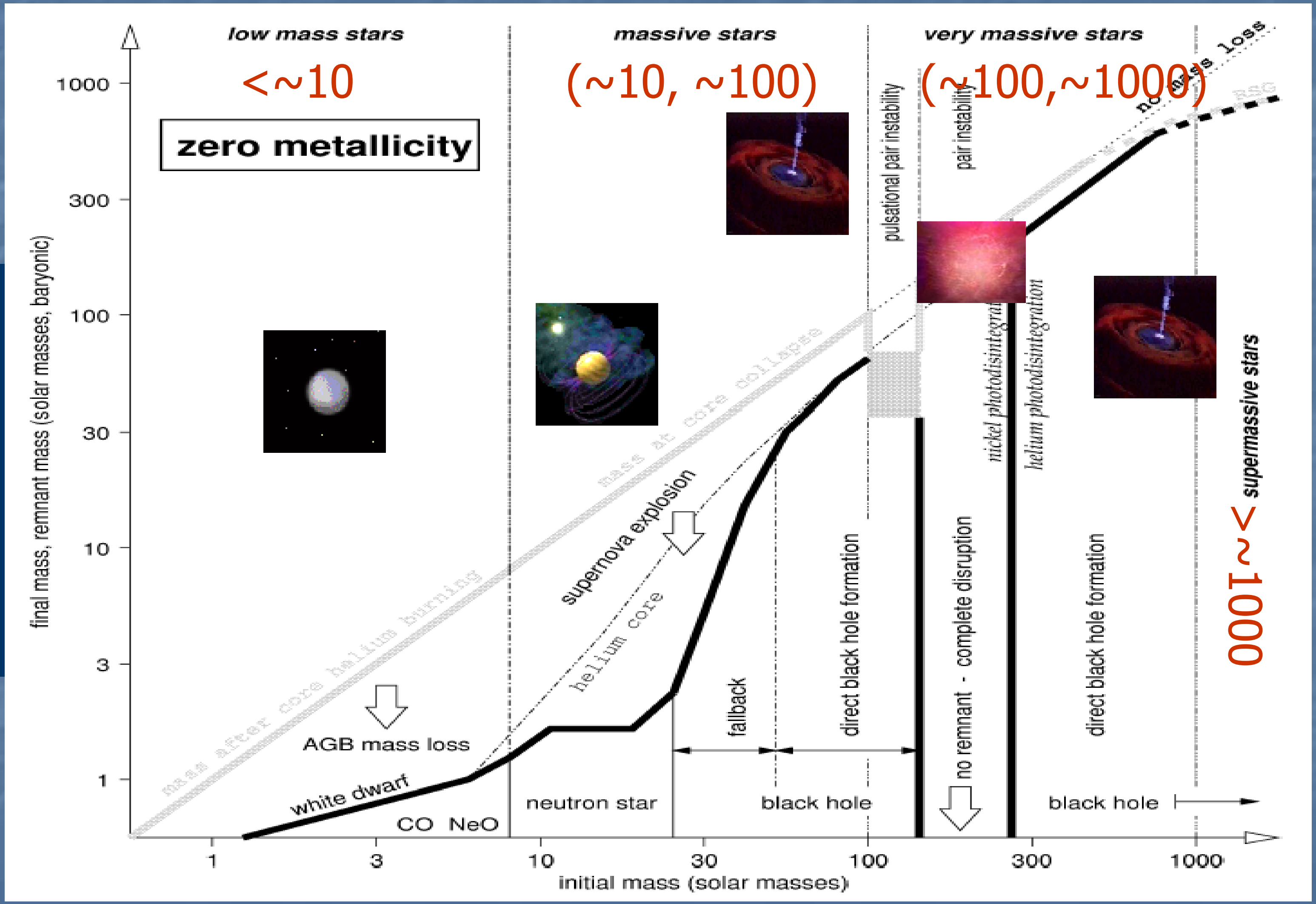
A uncertainty of ~10% is needed!



S(300)=170±20 keVb based on stellar model

Black hole mass gap

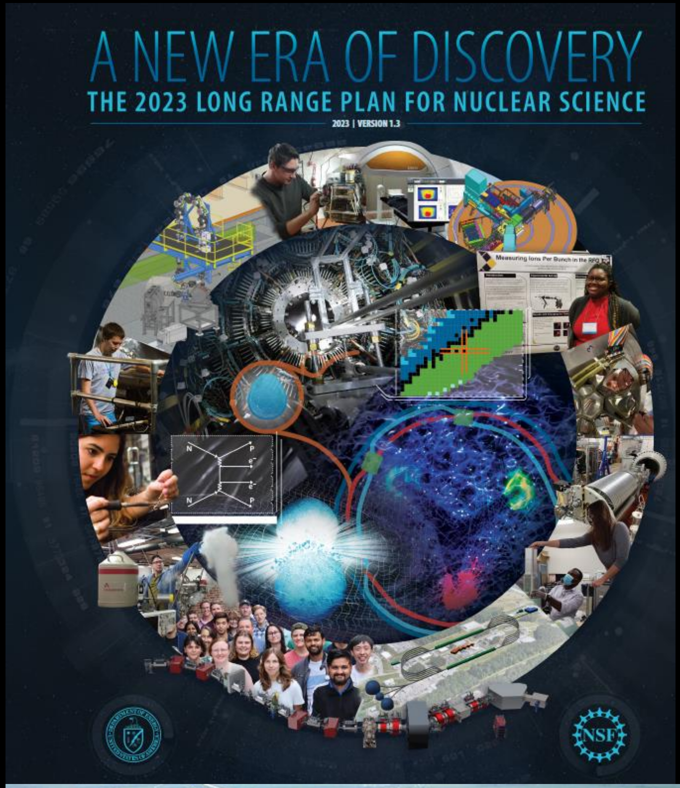
A **pair-instability supernova** is a type of supernova predicted to occur when pair production. The explosion is trigged by the $^{16}O+^{16}O$ fusion reaction.

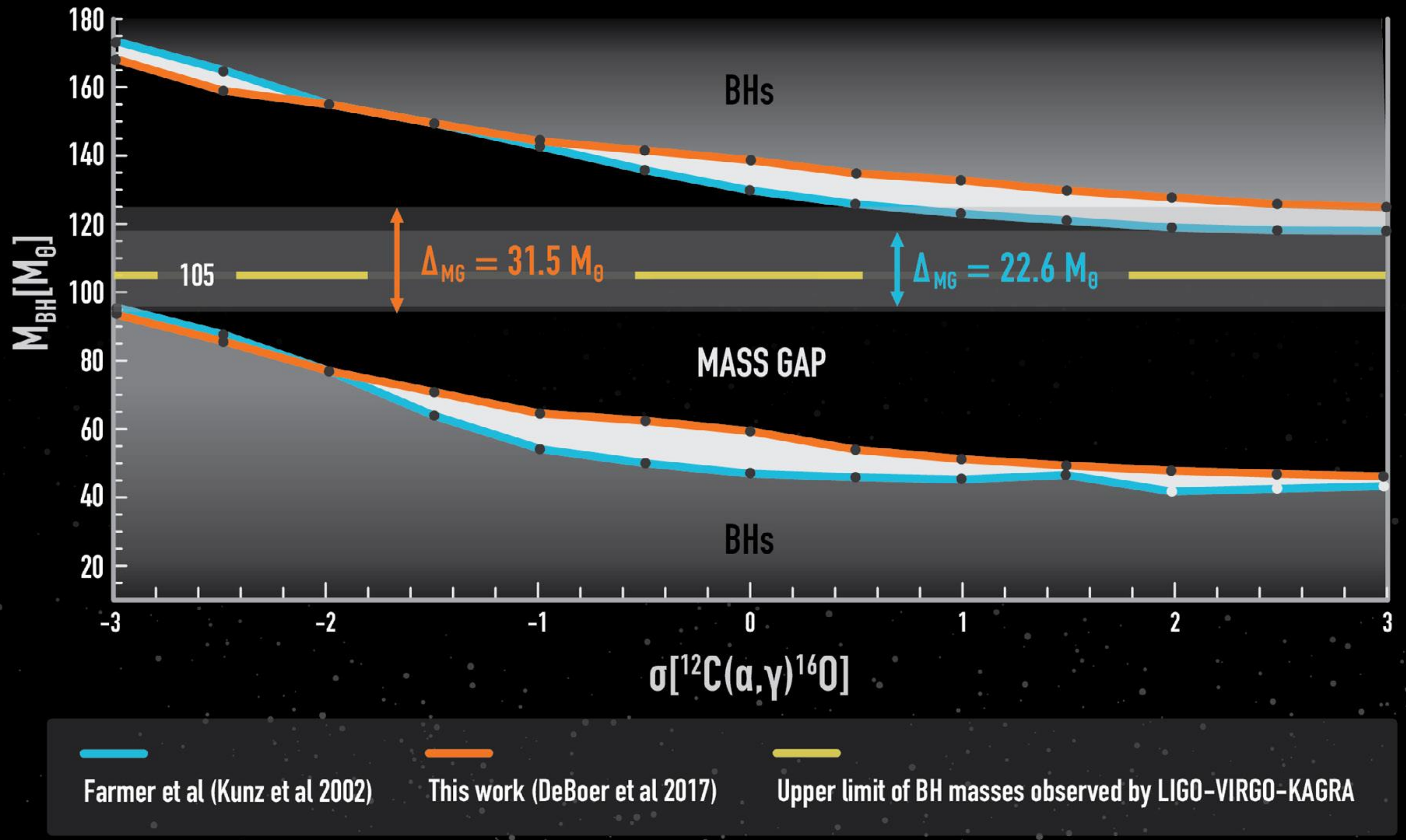


A. Heger & S. Woosley, ApJ.. 567(2002)532,
Woosley, Heger and Weaver, Rev. Mod. Phys. 74, 1015

A slide from my Ph.D. defense

Impact on Multi-Messenger Astronomy





Farmer et al., ApJ 902:L36(2020)
NSAC LONG RANGE PLAN (2023)

Holy grail for nuclear astrophysicists

Uncertainty in the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate affects not only the nucleosynthesis but also the explosion itself.

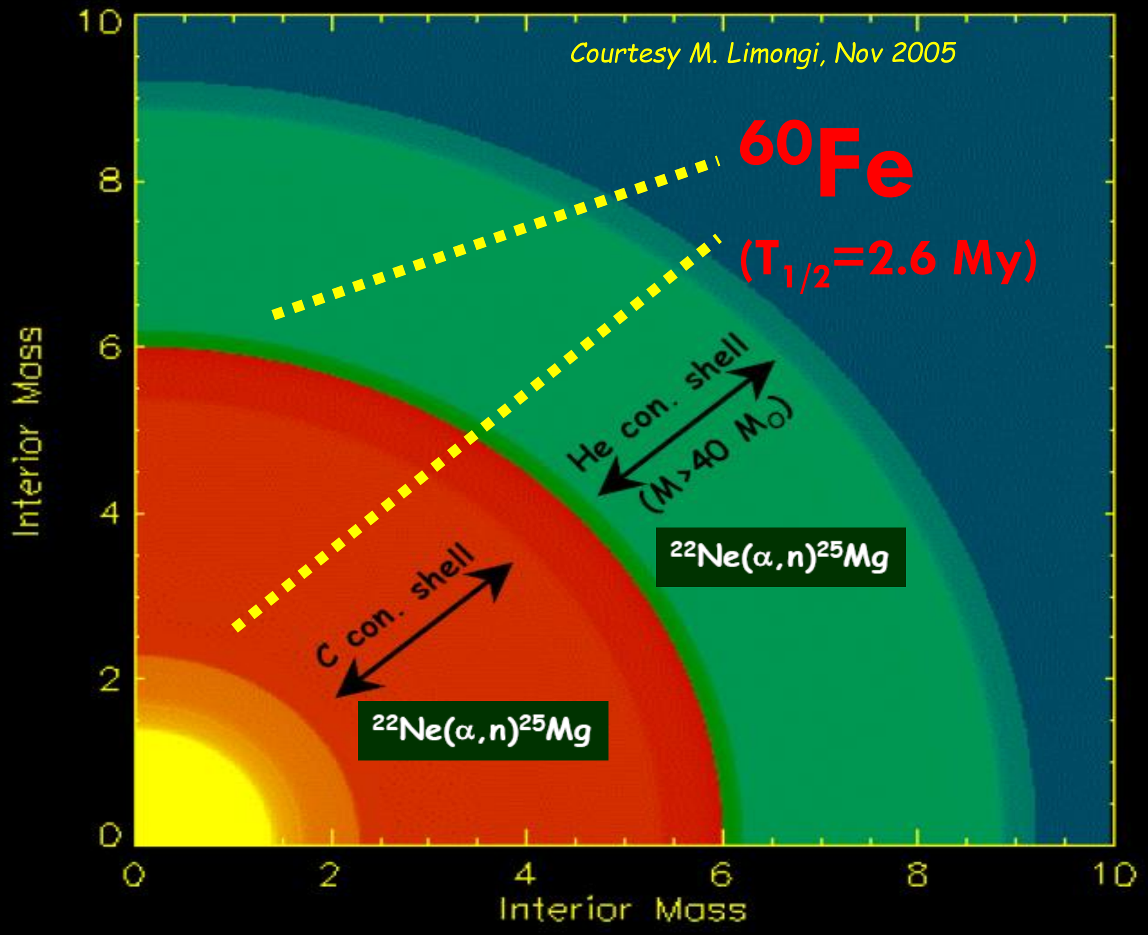
The determination of the ratio C/O produced in helium burning is a problem of paramount importance in Nuclear Astrophysics.
W. Fowler, Nobel lecture, 1983

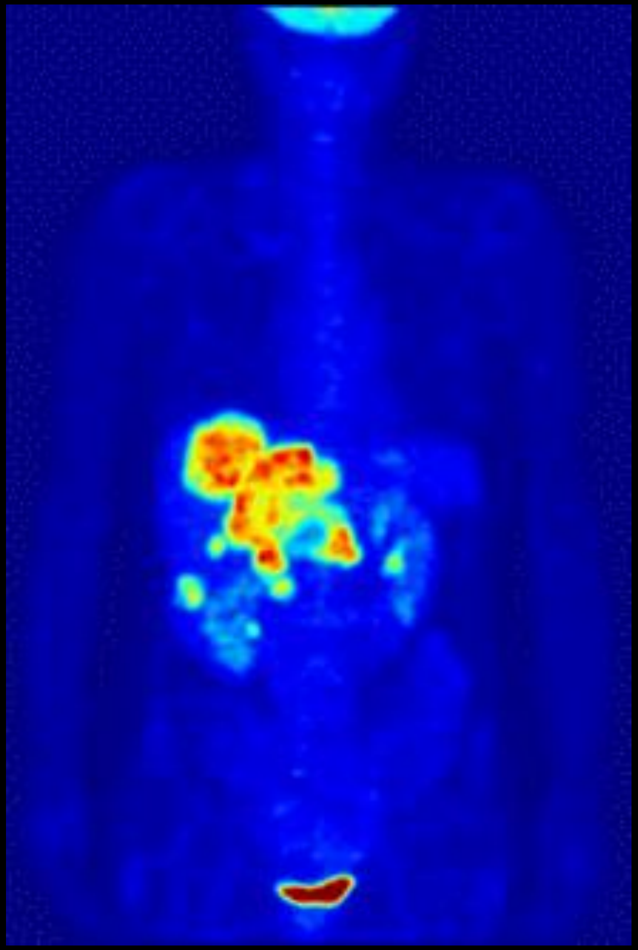
We hope that…will keenly motivate experimentalists to undertake the difficult task of accurately measuring this rate.

Weaver & Woosley, Phys. Rep. 227 (1993) 65

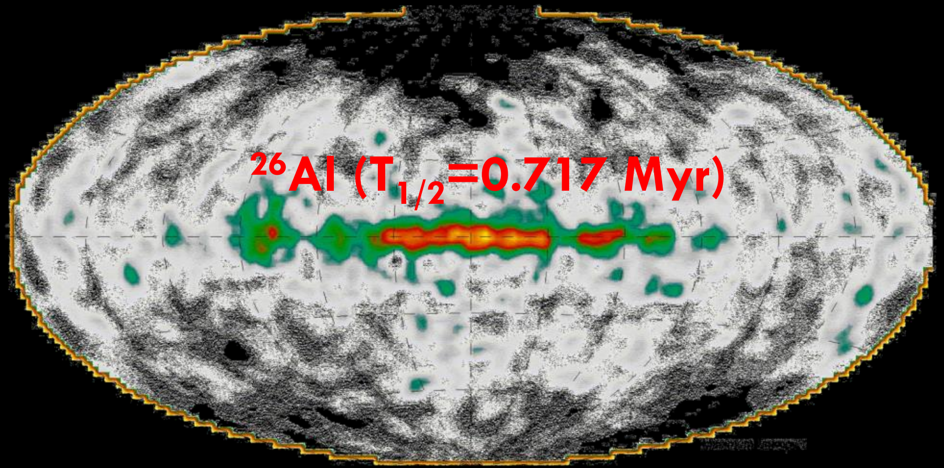
The fusion of ^{4}He and ^{12}C nuclei to ^{16}O is the most important nuclear reaction in the development of massive stars.
NuPECC Long Range Plan

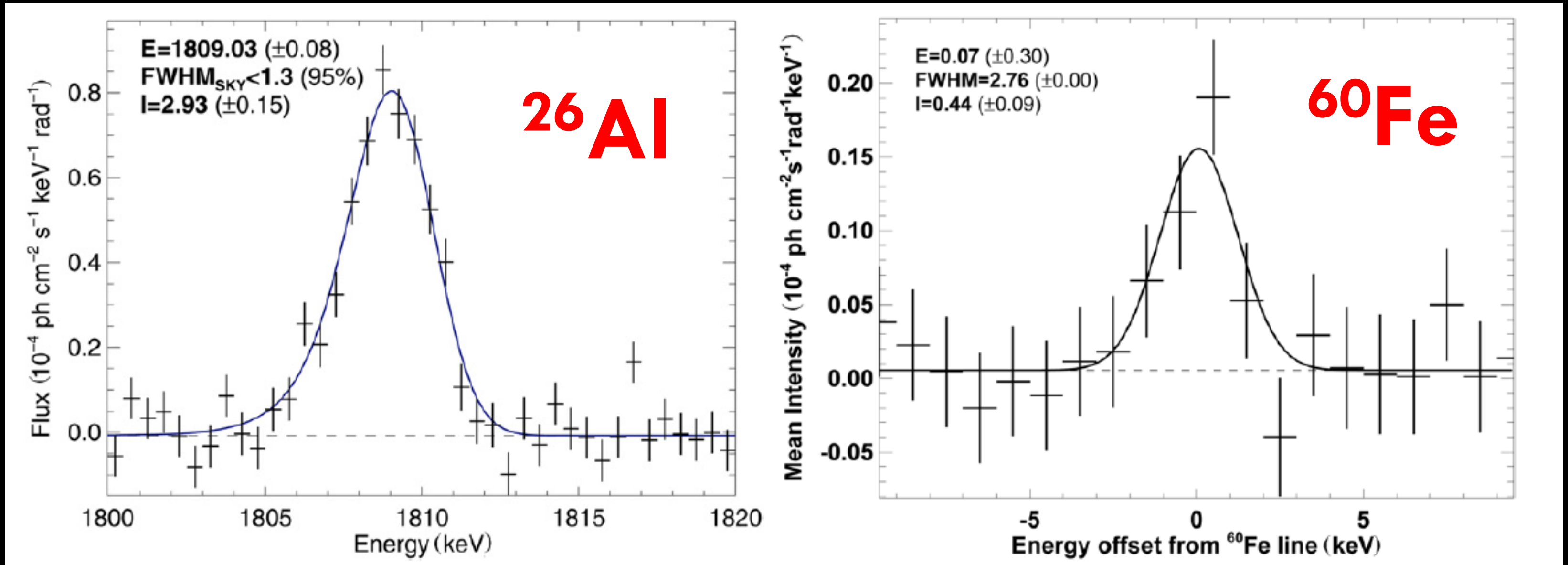
^{60}Fe from Supernova





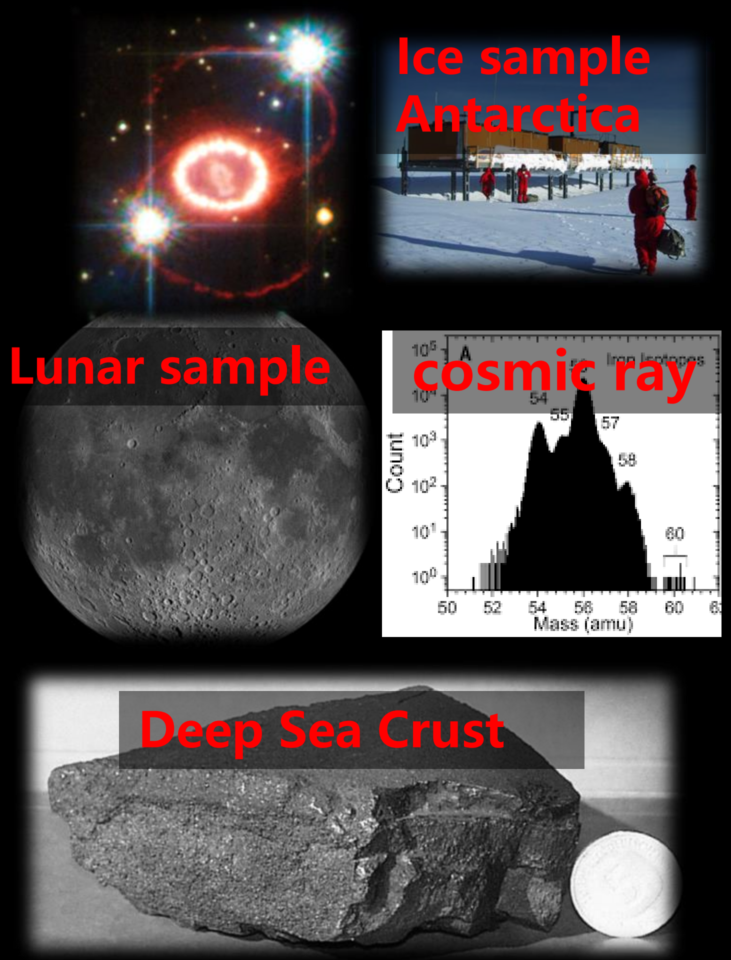
Galactic Radioactivity

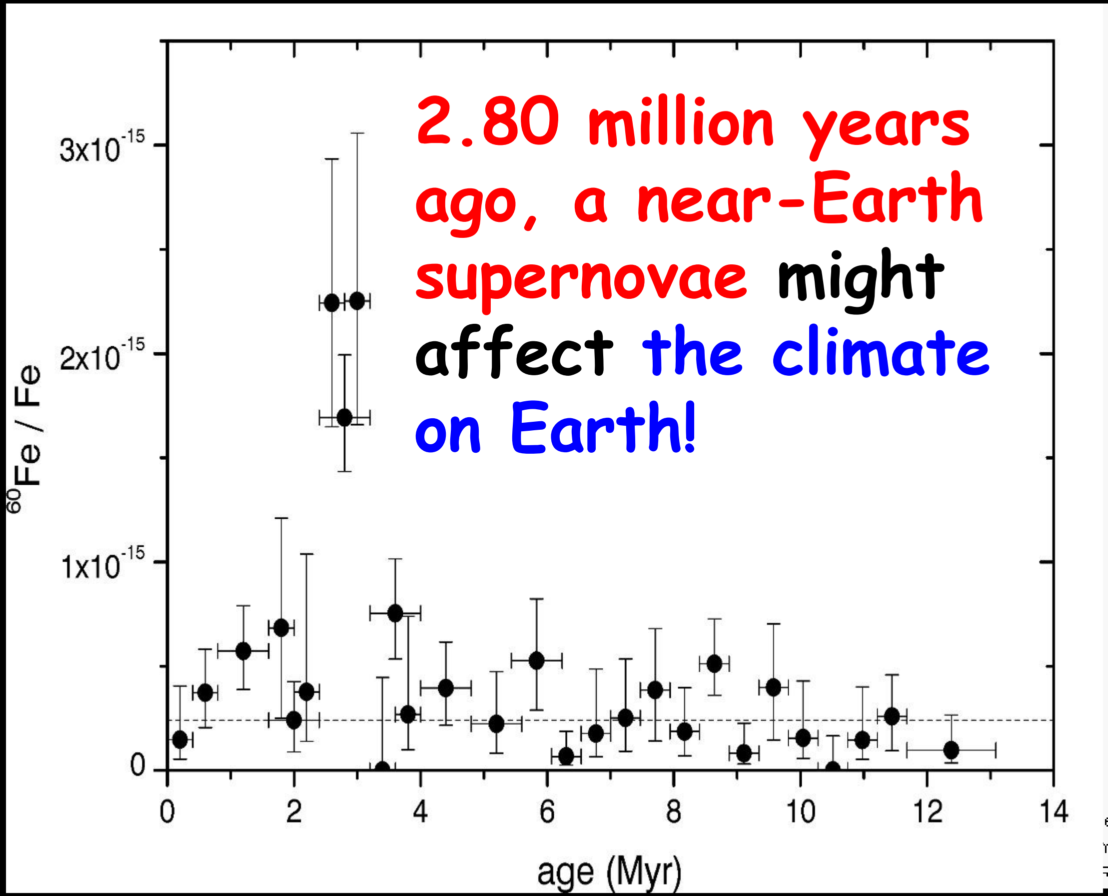


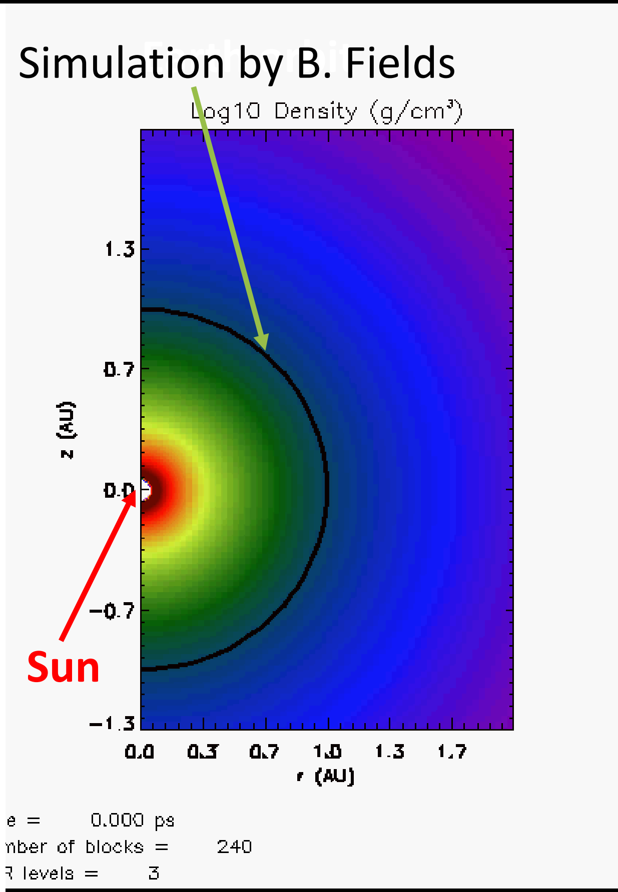


Diehl R *et al* 2006 *Astron. Astrophys.* **449** 1025–31 Wang W *et al* 2007 *Astron. Astrophys.* **469** 1005–12

^{60}Fe found on Earth!







A. Wallners doi:10.1038/nature17196

Knie, K. et al. Phys. Rev. Lett. 93, 171103 (2004); Fimiani, L. et al., Phys. Rev. Lett. 116, 151104 (2016); Breitschwerdt et al., Nature(2016); Wallner et al., Nature(2016)

First humans lived 2.8 million years ago, jawbone shows

BBC

5 March 2015 Last updated at 15:19 GMT

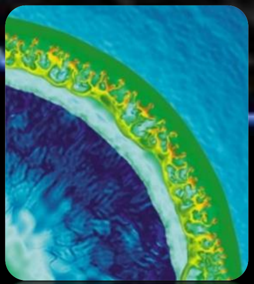
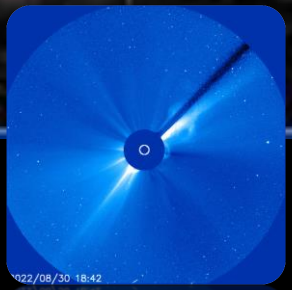
Scientists have found a jawbone that they say proves the first humans were alive much earlier than we thought.

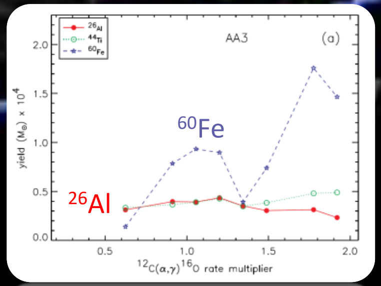
^{60}Fe/^{26}Al abundance puzzle

Prediction : ^{60}Fe/^{26}Al = 0.45
Observation: ^{60}Fe/^{26}Al = 0.15±0.04

Model Ingredients:

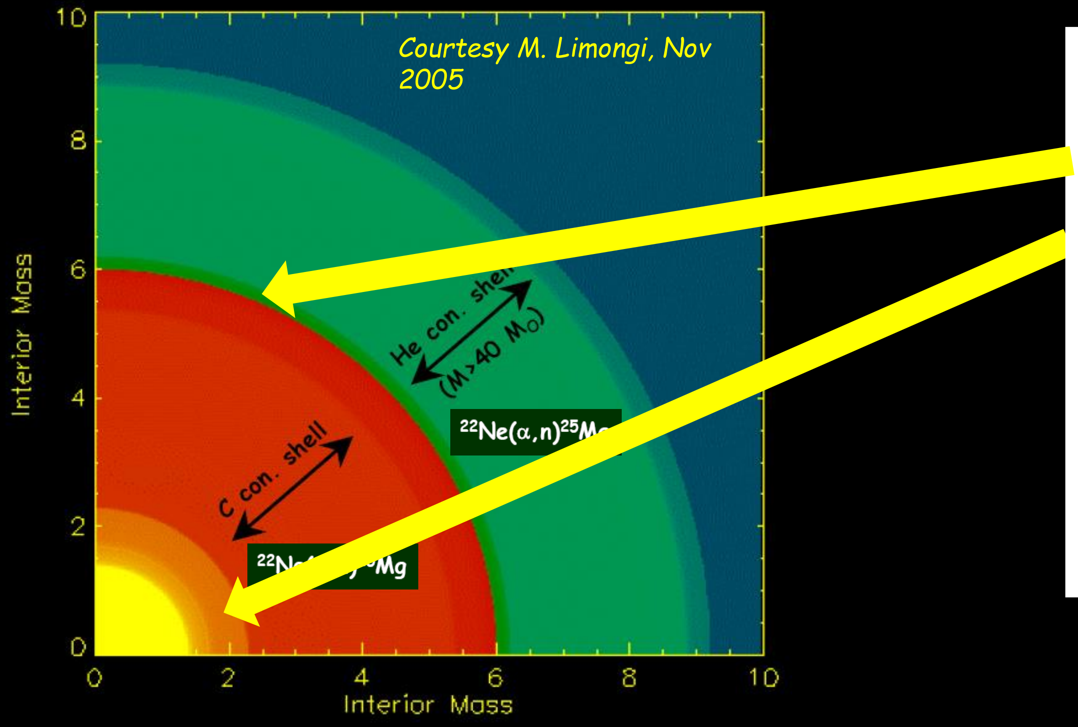
- Initial Mass Function and birth rate
- **Stellar evolution (driven by nuclear energy,** convection?**)**
- Stellar Wind Model(s) (Mass loss during evolution)
- **Nucleosynthesis Yields (depends on nuclear physics)**
- **Explodability (explode as SNe or collapse to black holes)**

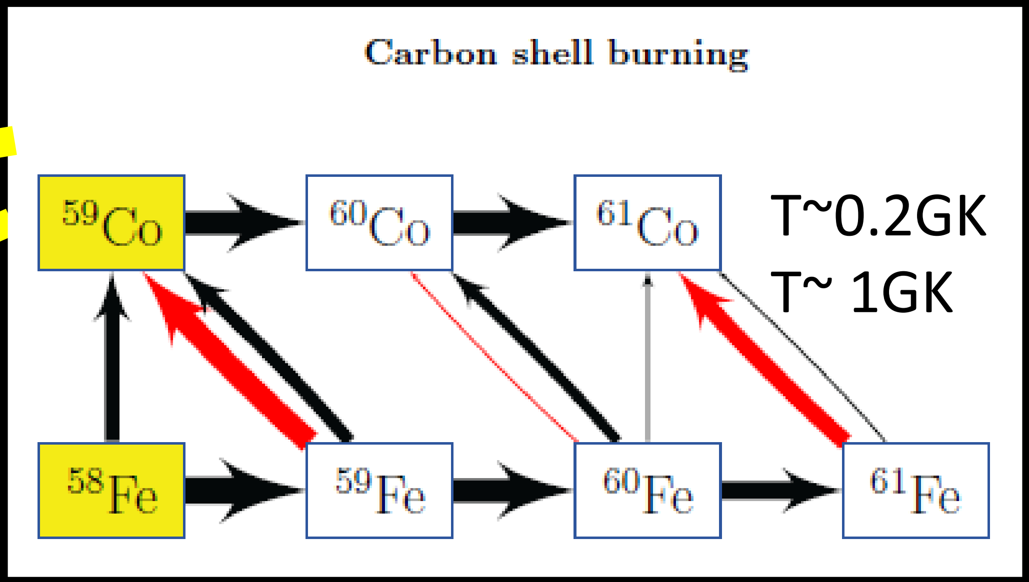






Diehl, Lugaro, Heger, Sieverding, Tang et al., PASA (2021), 38, e062

^{60}Fe nucleosynthesis





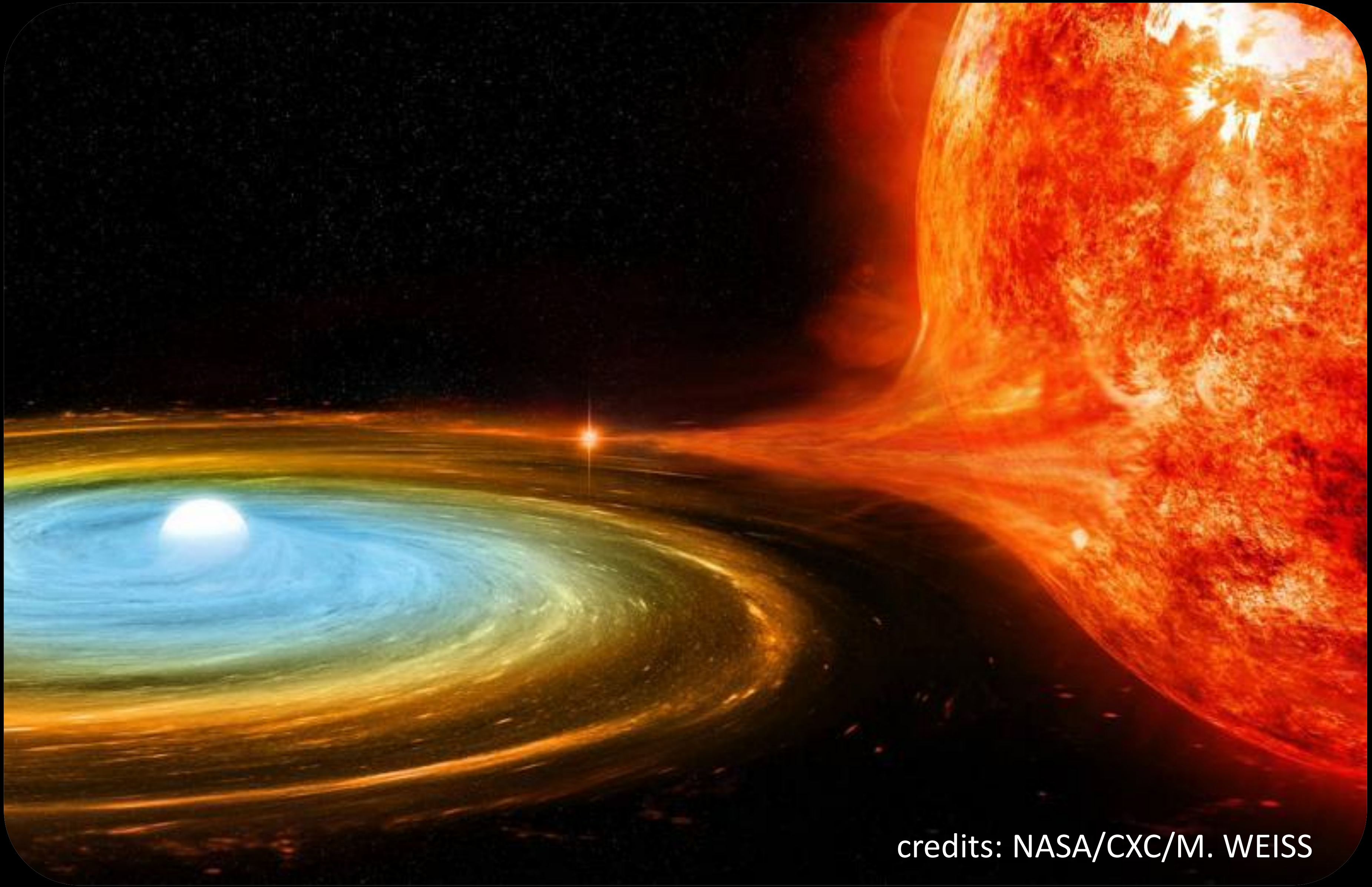
Calculation using NUNET; Flux in log scale

Important nuclear reactions or decays

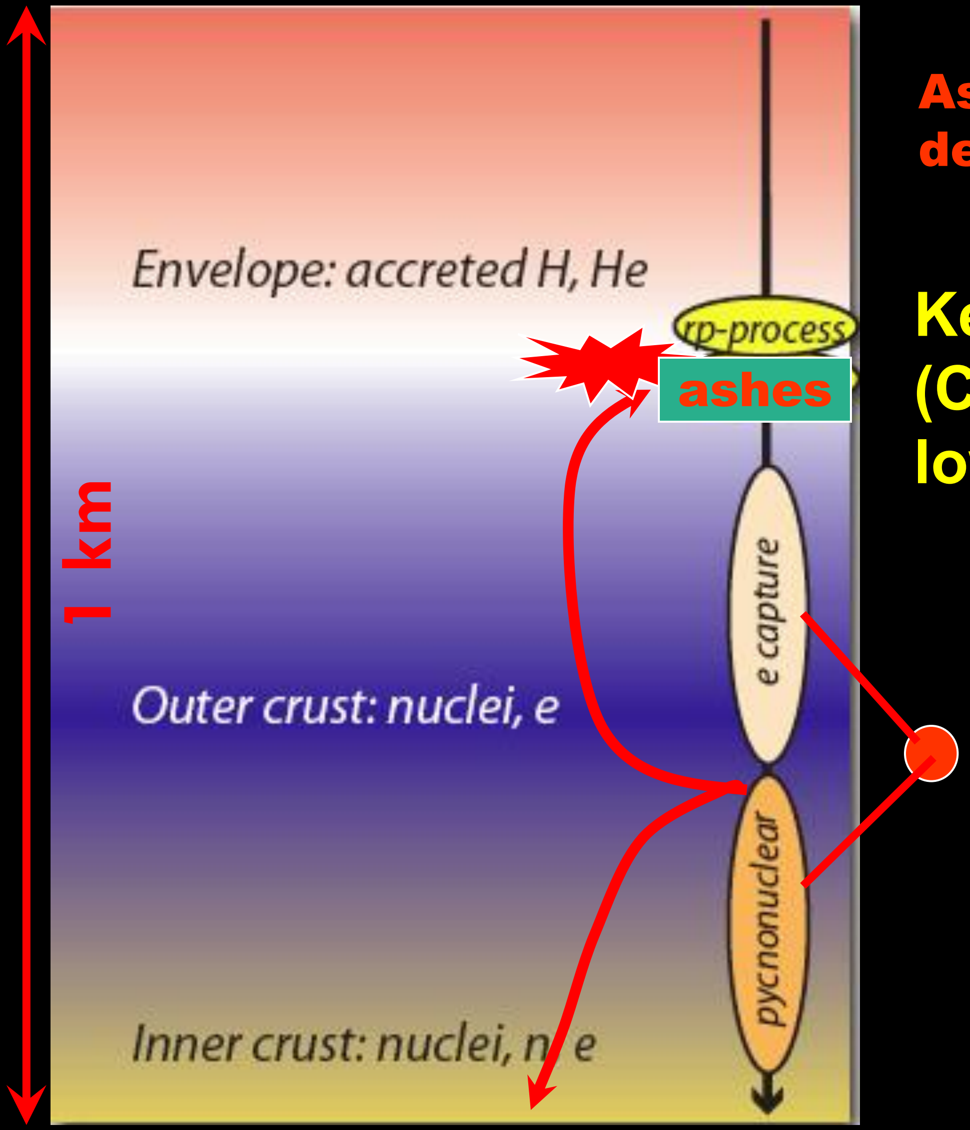
- **Neutron sources: ^{22}Ne(α,n)^{25}Mg**
- **Stellar decay rate of ^{59}Fe**
- **^{12}C(α,γ)^{16}O, ^{12}C+^{12}C, ^{59}Fe(n,γ), ^{60}Fe(n,γ)**

Diehl, Lugaro, Heger, Sieverding, Tang et al., PASA (2021), 38, e062

Type Ia X-ray burst



Superburst: ignited by Carbon burning



Picture by E. Brown (MSU)

Ashes from rp process (He burning) deposit in the outer crust.

Key problem: With the standard rate (CF88), the crust temperature is too low to ignite the carbon fuel! ☹

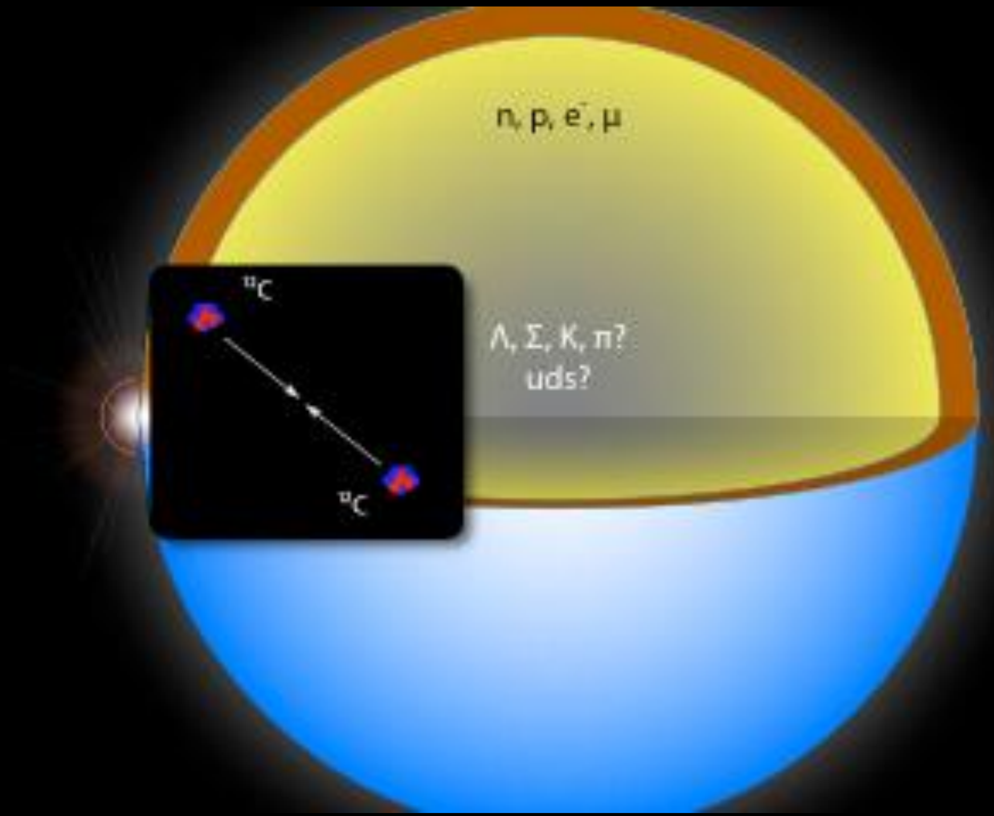
Crust processes
(EC, pycnonuclear fusion)
→crust heating and cooling
→crust conductivity

$^{24}O+^{24}O$

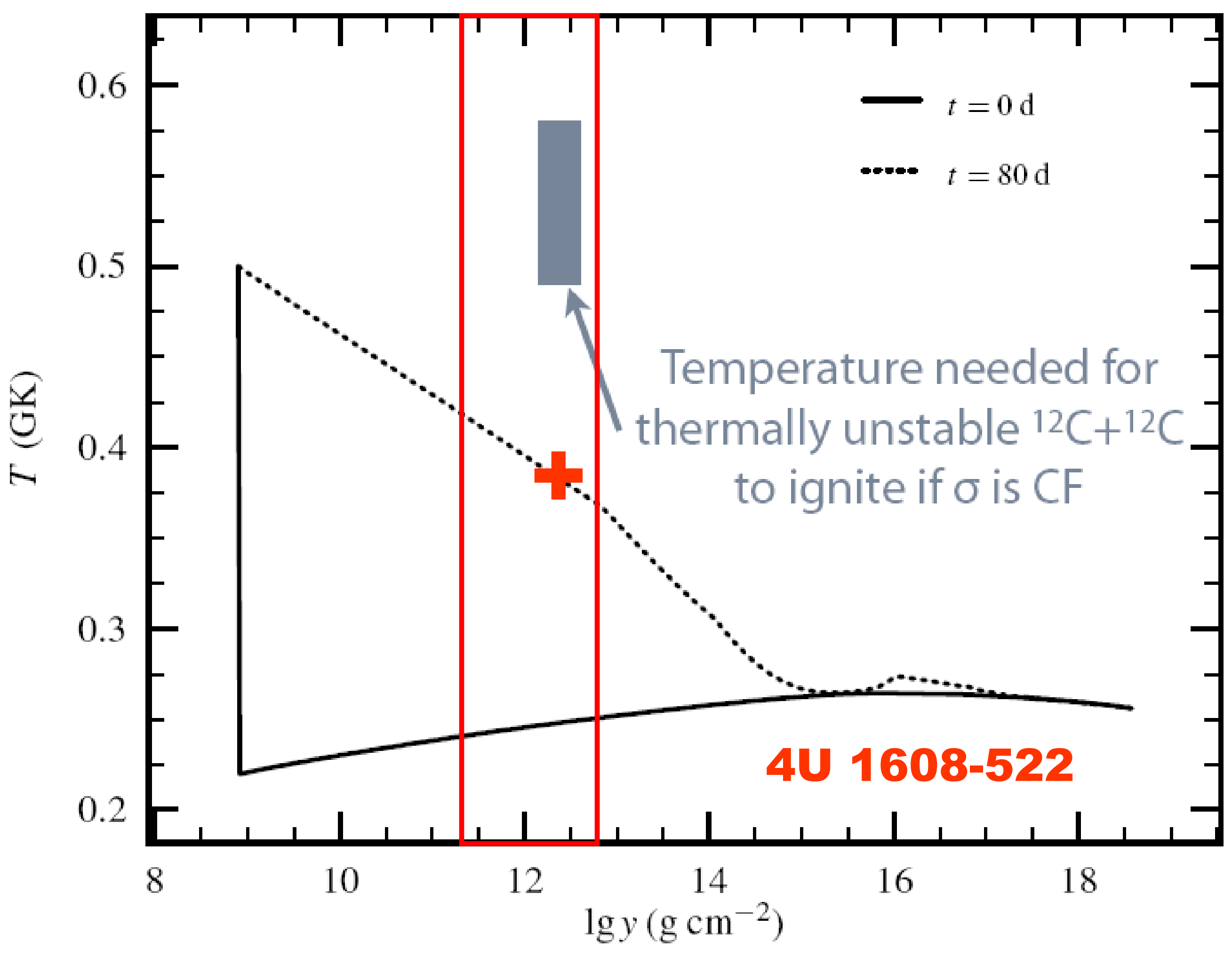
$^{34}Ne+^{34}Ne$

....

Superburst Puzzle: the crust is too cold to ignite the carbon burning!
How to ignite the carbon?



Picture by Ed Brown (MSU)



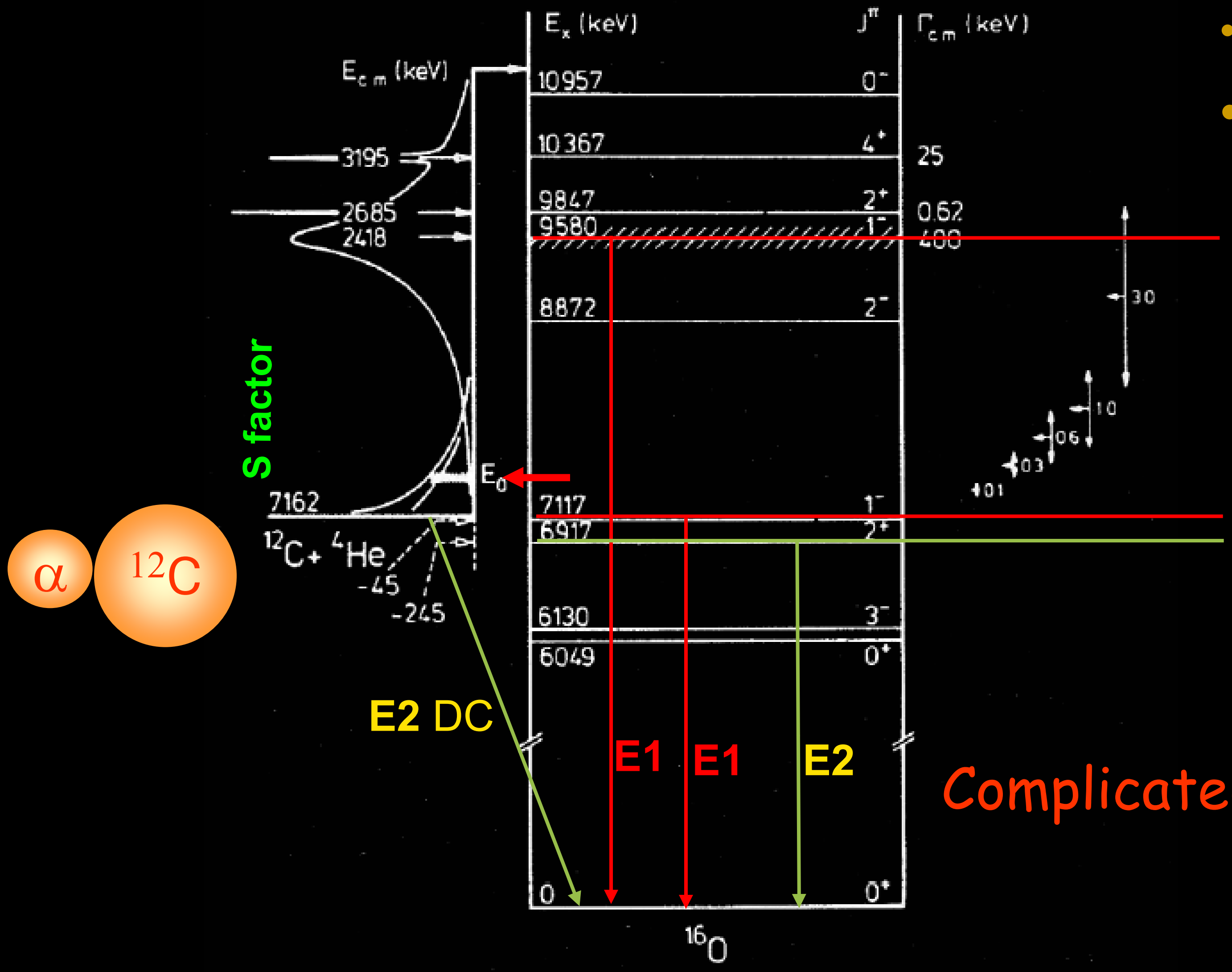
Keek et al. (2007), Astron. & Astrophys. 479: 177
Cooper, Steiner and Brown, ApJ (2009)

How to get precise reaction rates?

- $^{12}C(\alpha,\gamma)^{16}O$
- $^{12}C+^{12}C$

Level Scheme of ^{16}O

- **3 resonances**
- **1 direct capture**

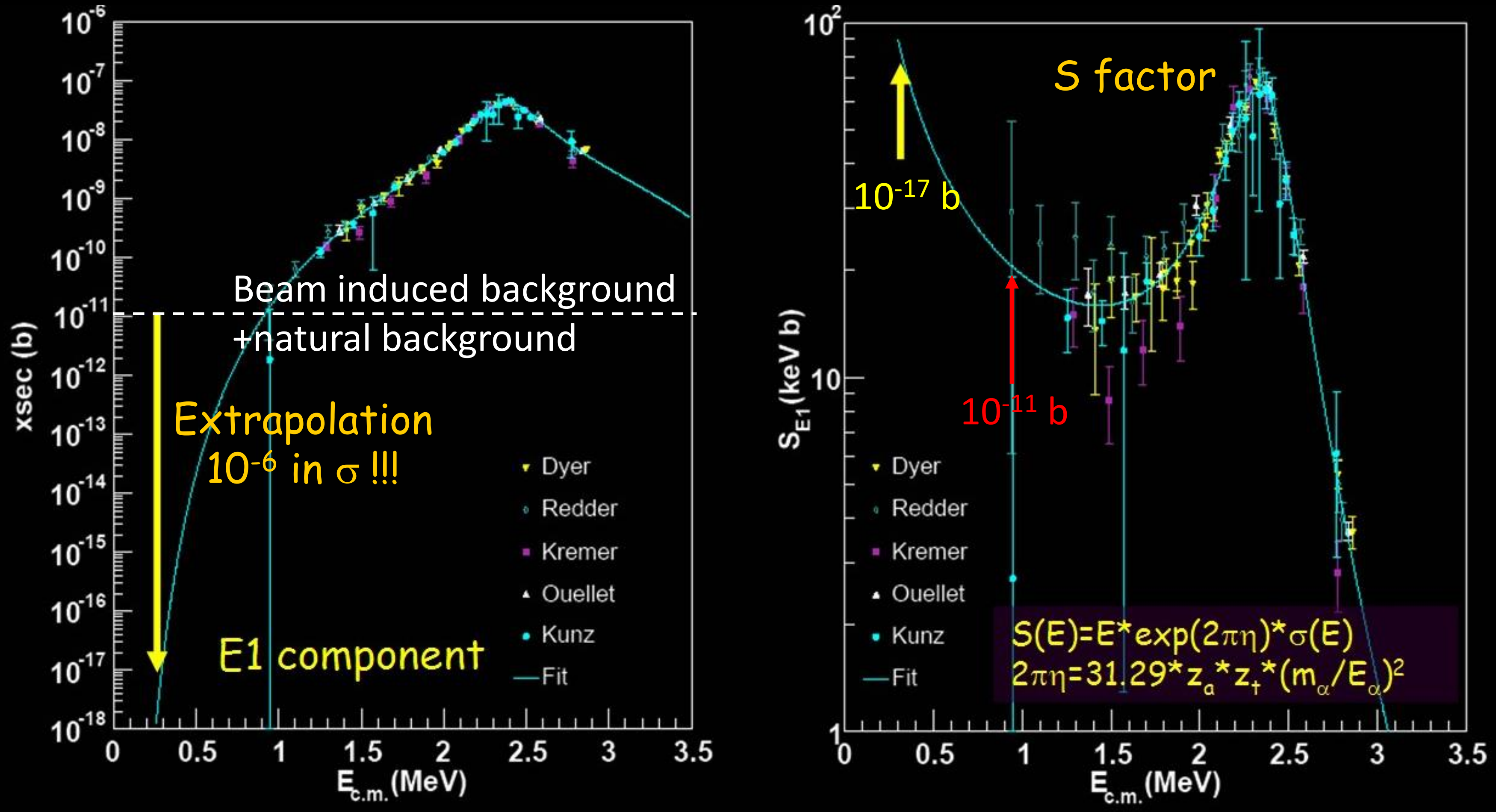


Complicated reaction mechanism

A fundamental challenges for nuclear astrophysics :
Measure reaction rate at extremely low energies

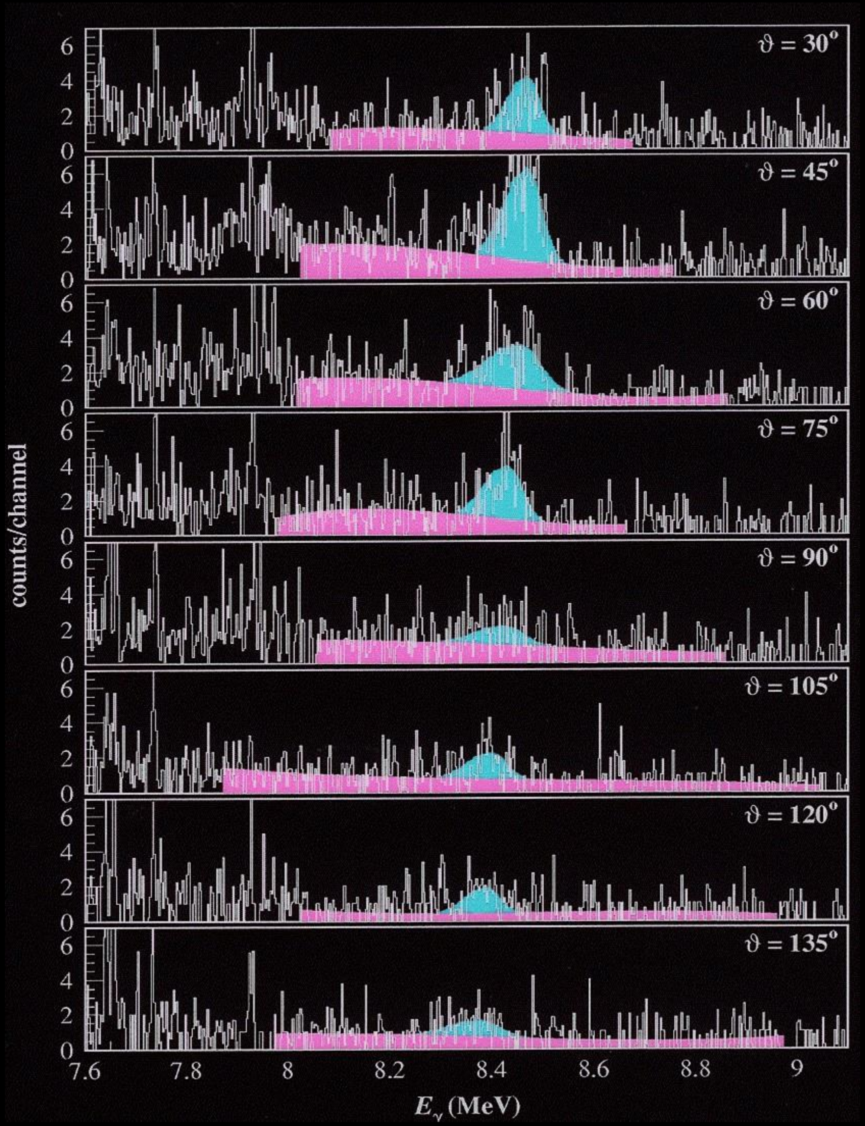
NSAC Long Range Plan (2023)

$^{12}C(\alpha,\gamma)^{16}O$

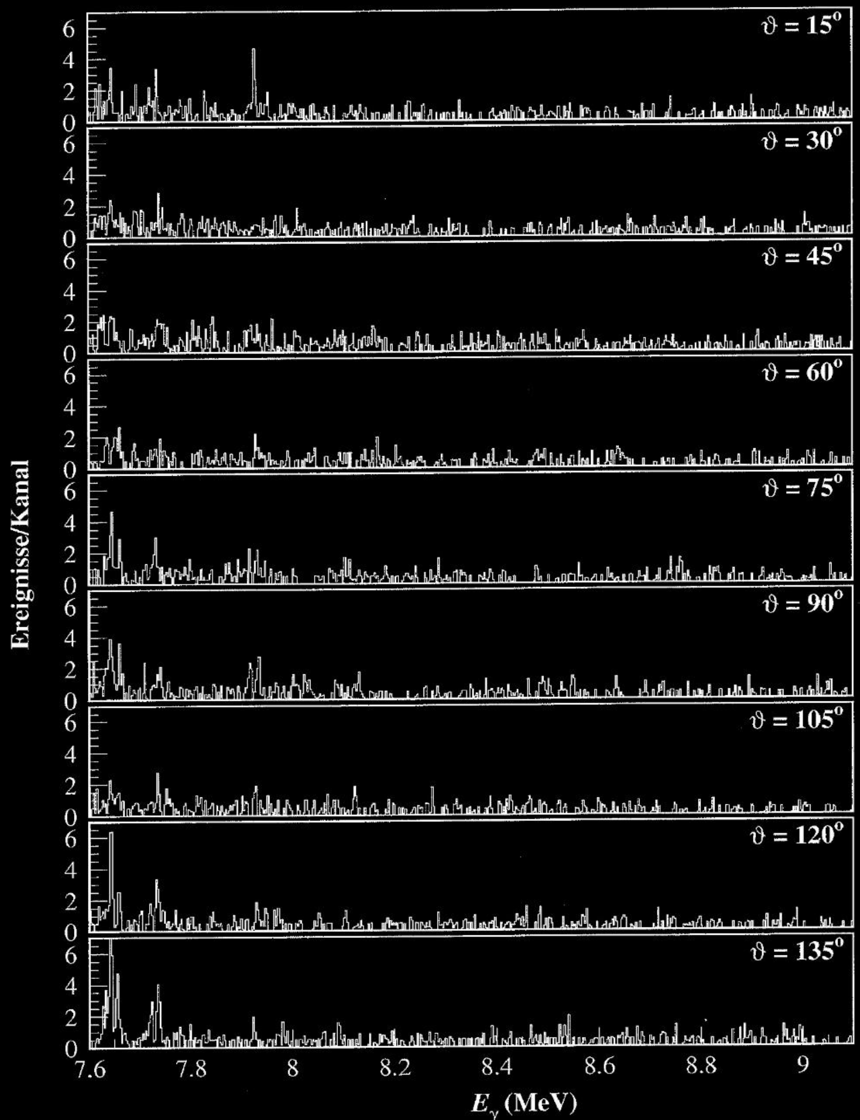


1 barn=10^{-24} cm^2

Difficulties in direct measurement: $^{12}C(\alpha,\gamma)^{16}O$ (1974-)

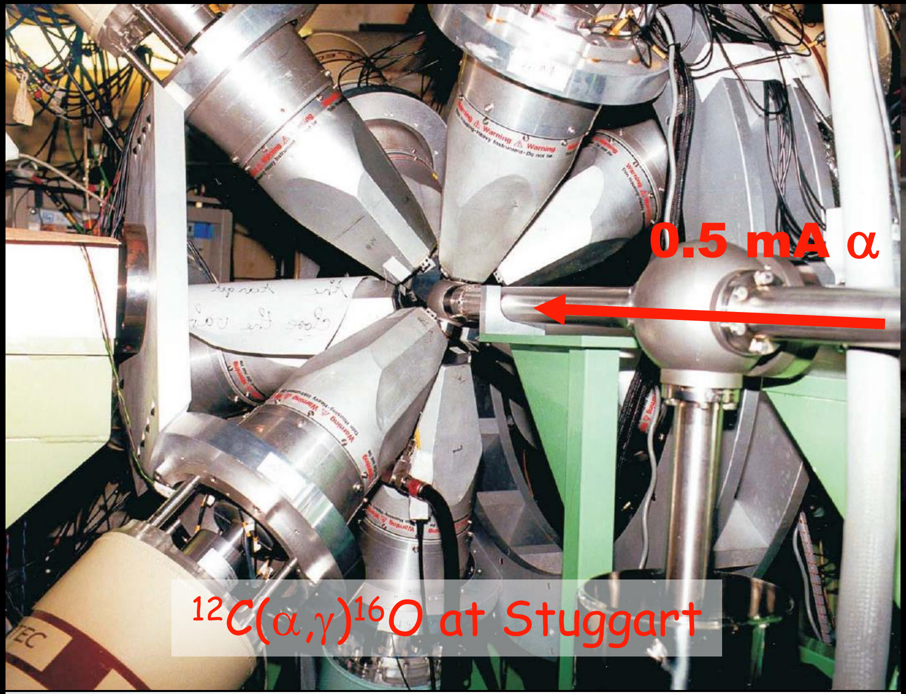


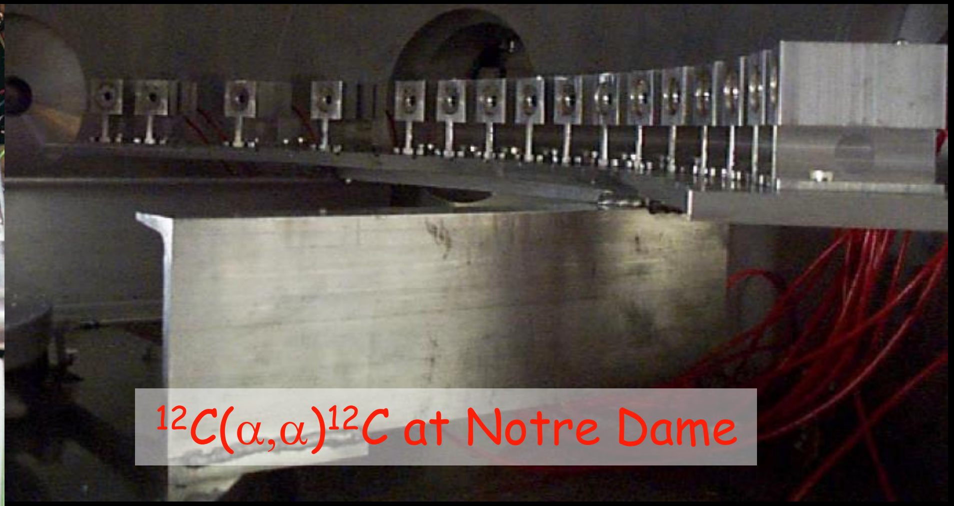
E_{cm}=1.254 MeV

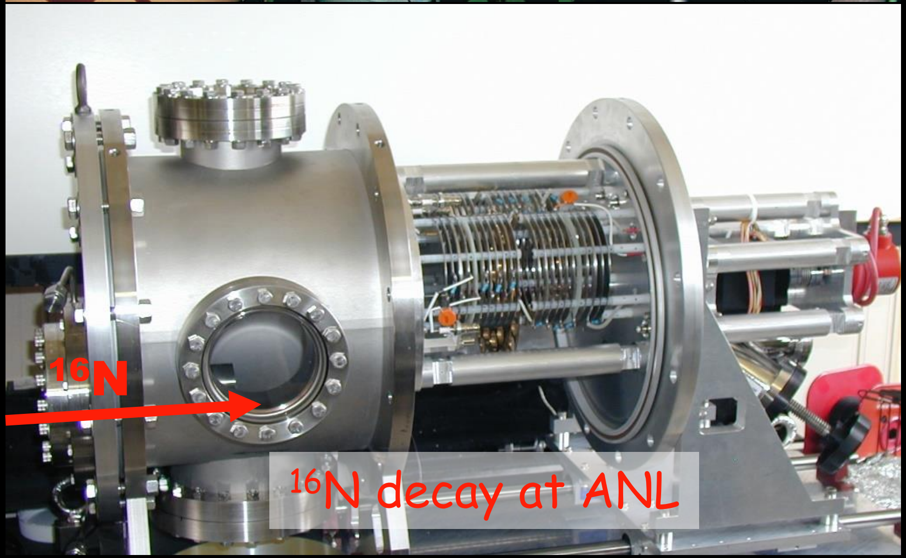


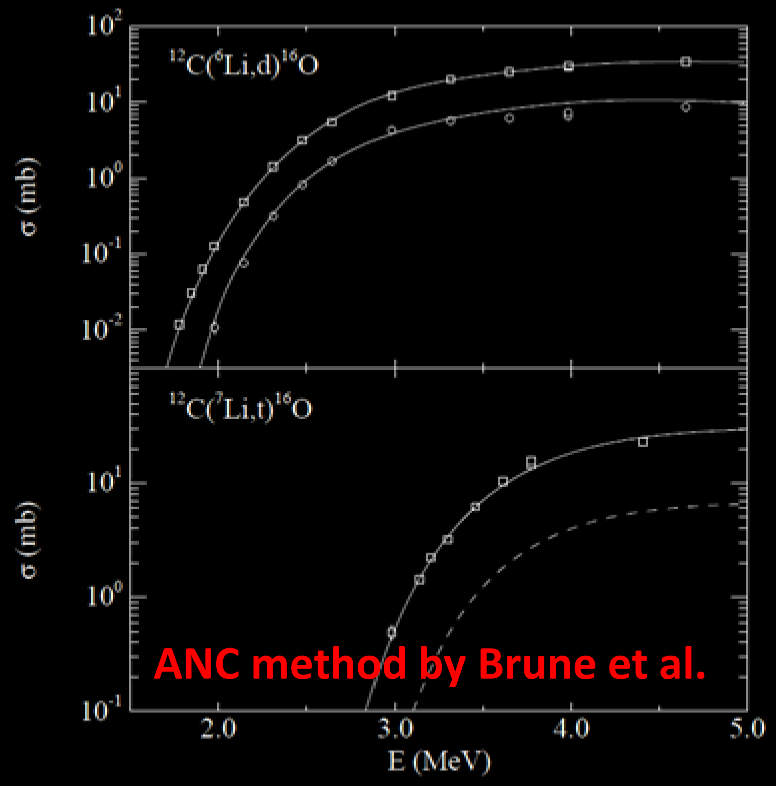
E_{cm}=0.945 MeV

Kunz et al. PRL 86(2001)3244

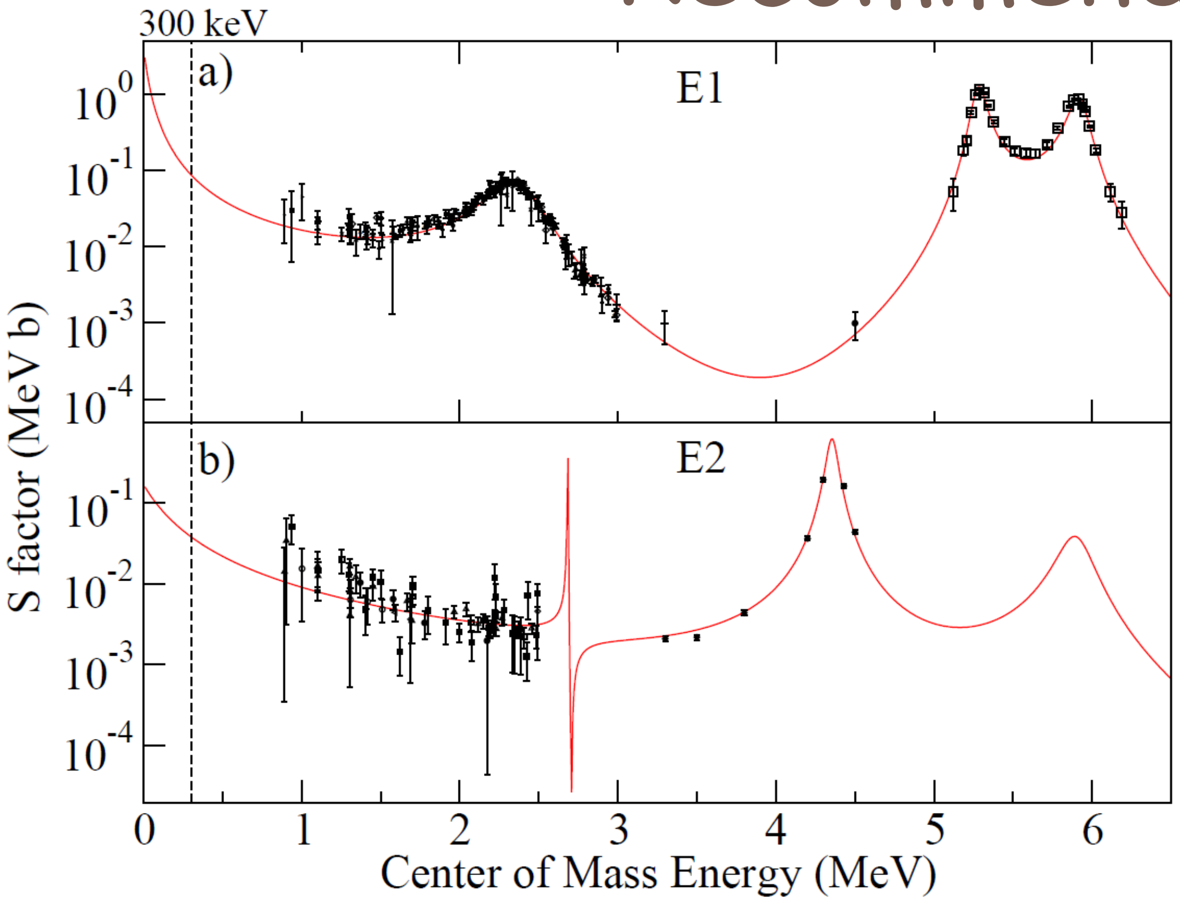

0.5 mA α
$^{12}C(\alpha,\gamma)^{16}O$ at Stuggart

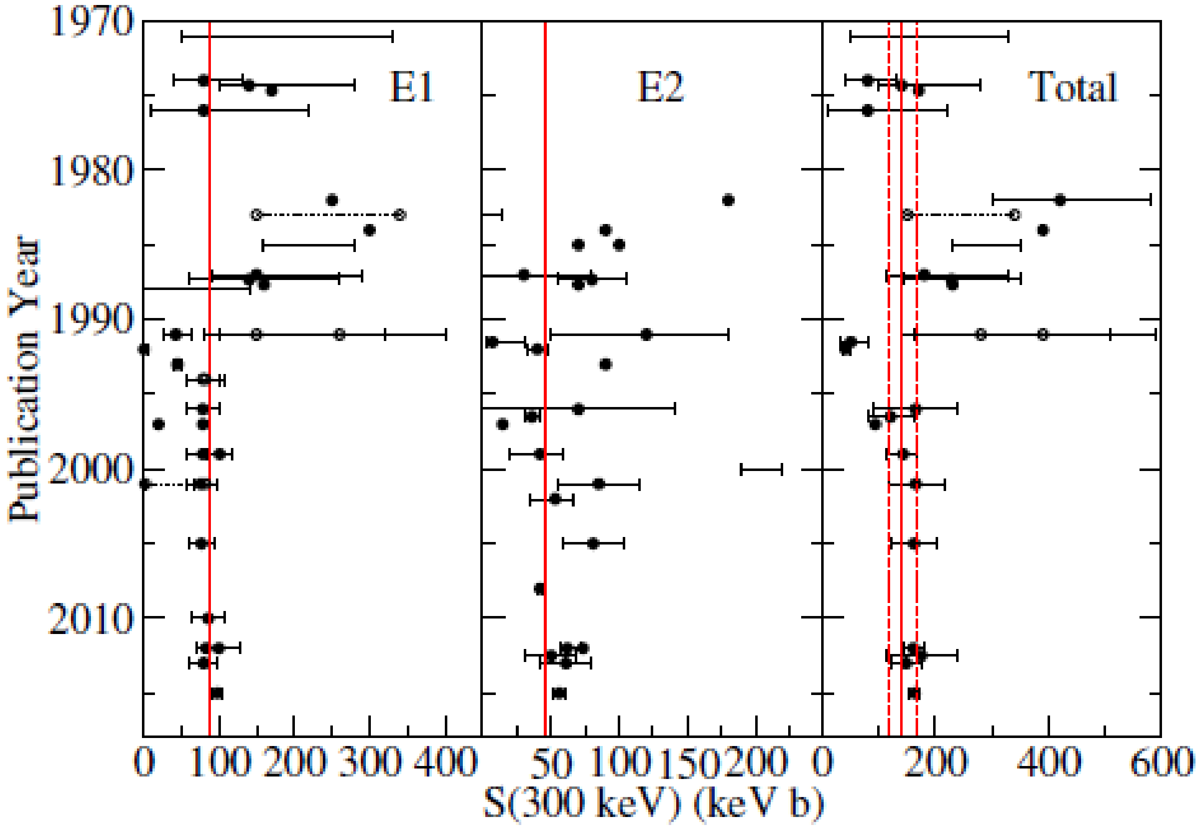

$^{12}C(\alpha,\alpha)^{12}C$ at Notre Dame


^{16}N
^{16}N decay at ANL


$^{12}C(^{6}Li,d)^{16}O$
$^{12}C(^{7}Li,t)^{16}O$
σ (mb)
σ (mb)
E (MeV)
2.0
3.0
4.0
5.0
ANC method by Brune et al.

Recommended S factor





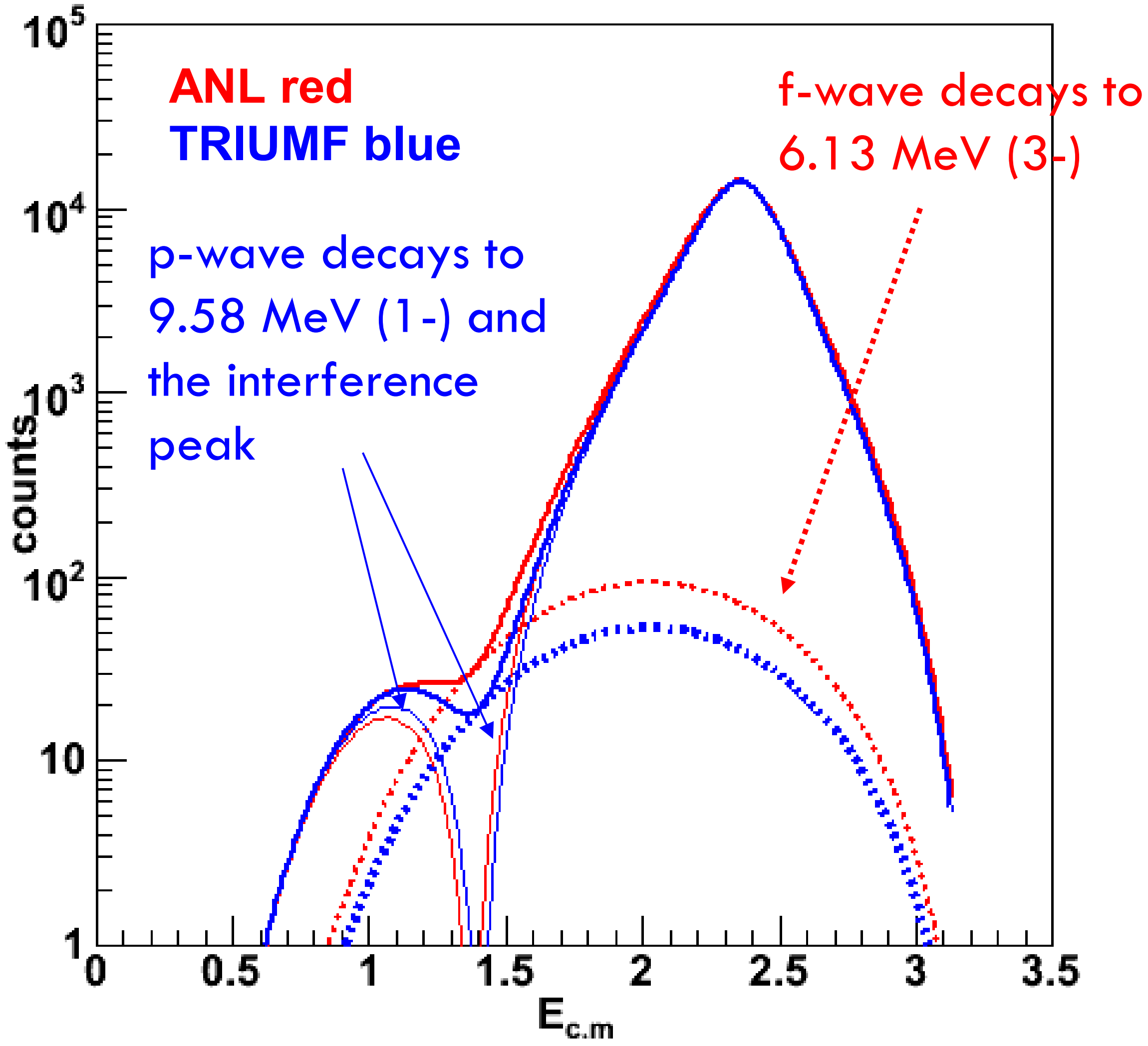
S(E1)=86.3 keVb; S(E2)=45.3 keVb; S(cascade)=7 keVb

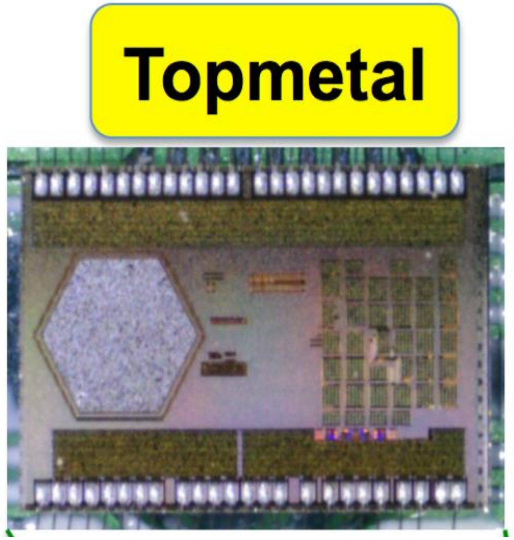
Total S factor = $140 \pm 21_{(MC)}\ ^{+18}_{-11(model)}$ keV b.

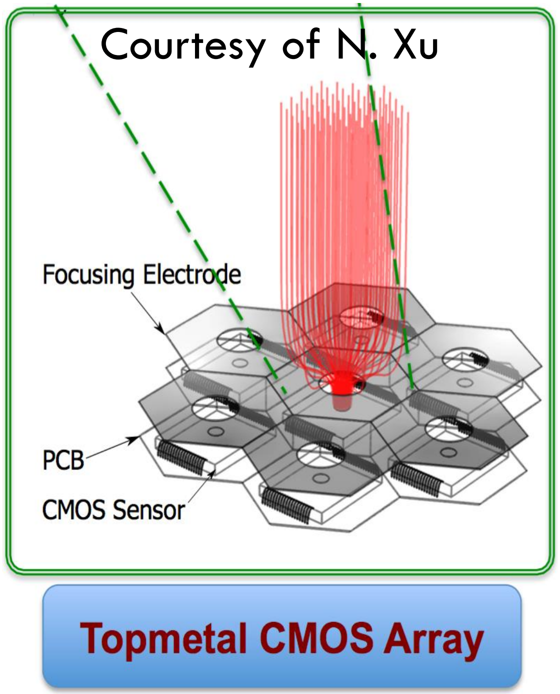
ANC plays the key role to fix the strengths of the subthreshold states and direct capture

deBoer et al., RMP(2017)

Another ^{16}N decay experiment is needed to resolve the tension!

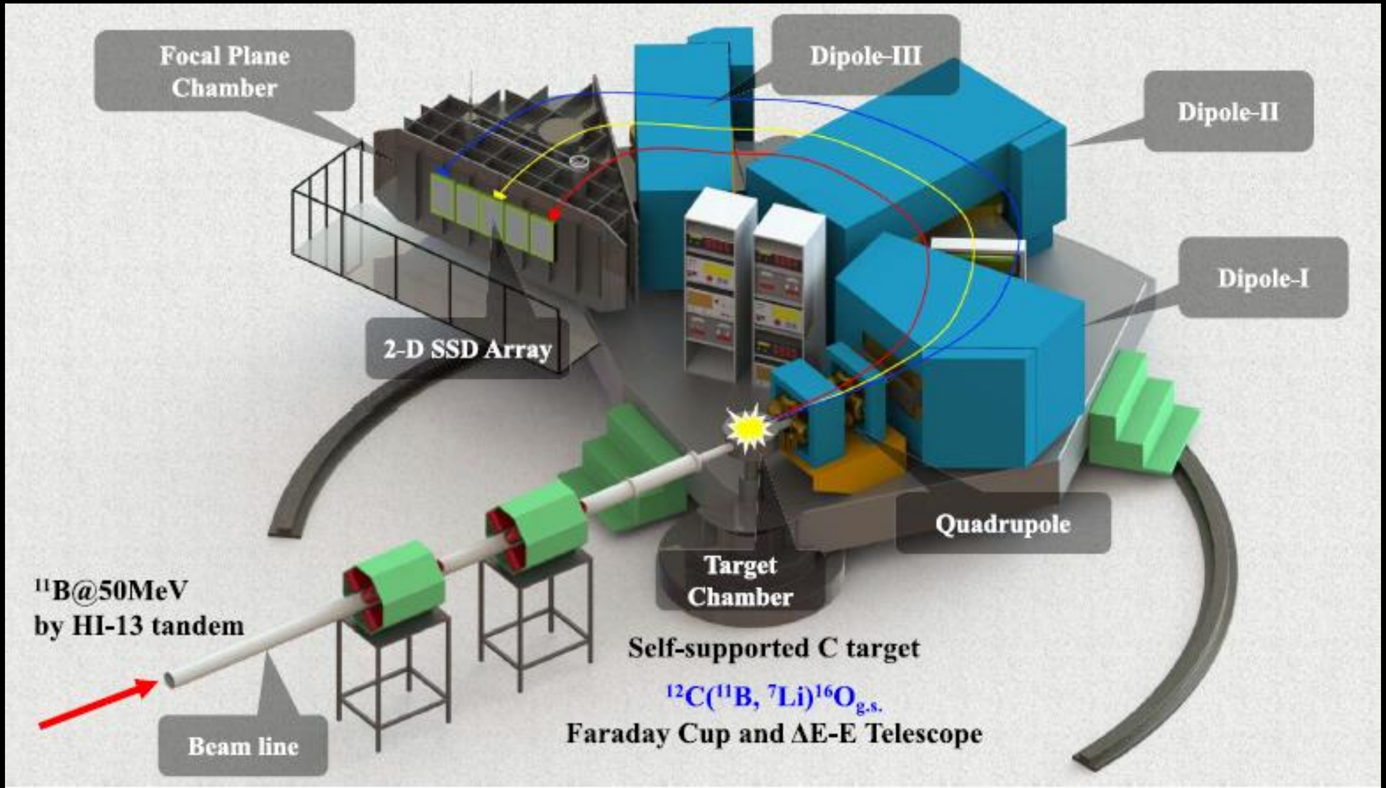


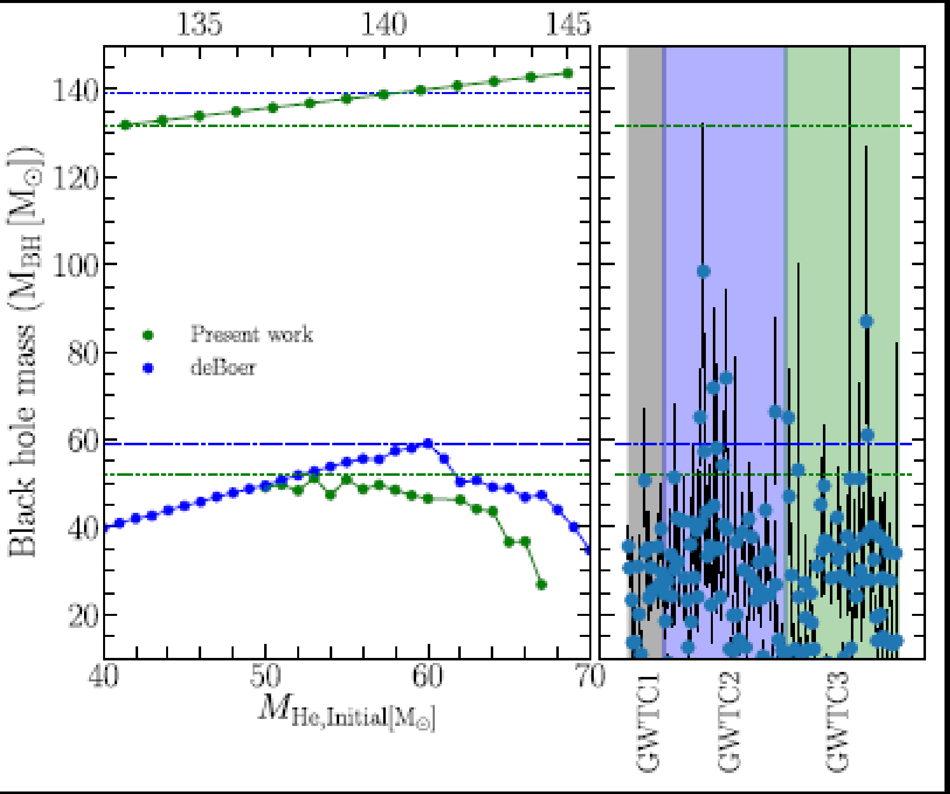




Azuma et al., PRC(1994); Tang et al., PRL(2007), PRC(2010)

New measurement of ANC of ^{16}O(g.s.) leads to larger S(E2)

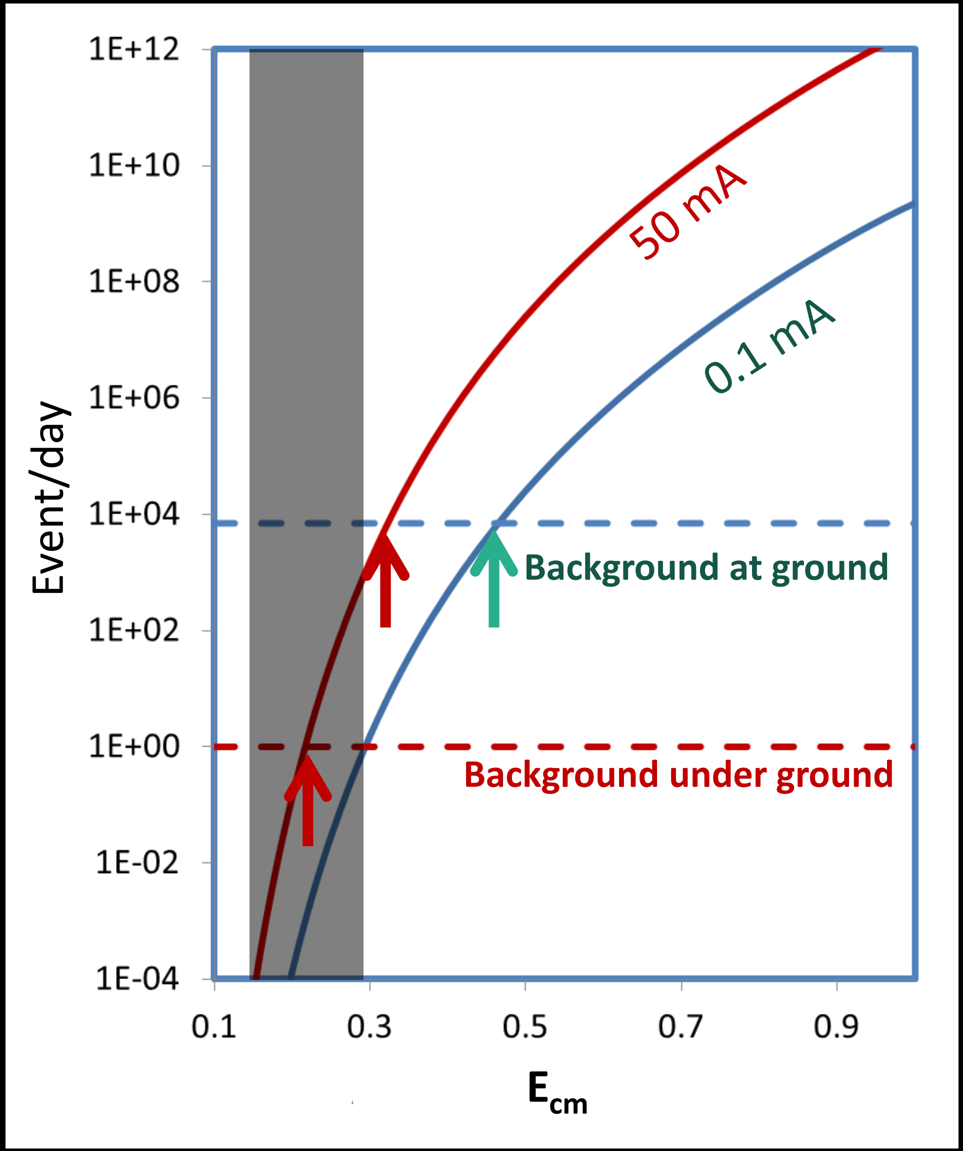


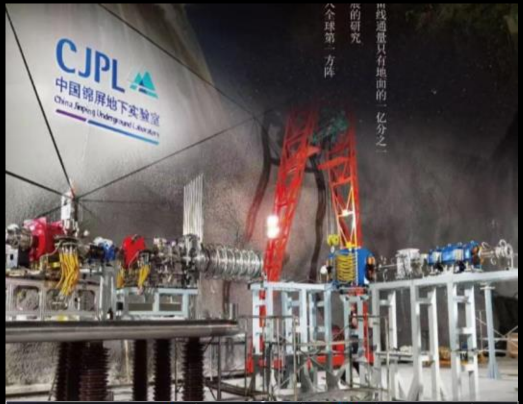


- S(E2) increases from 45 keVb to 70±7 keVb → Total S factor = 162 keVb (err TBD)
- The updated $^{12}C(\alpha, \gamma)^{16}O$ reaction rate decreases the lower and upper edges of the black hole mass gap about 12% and 5%, respectively.

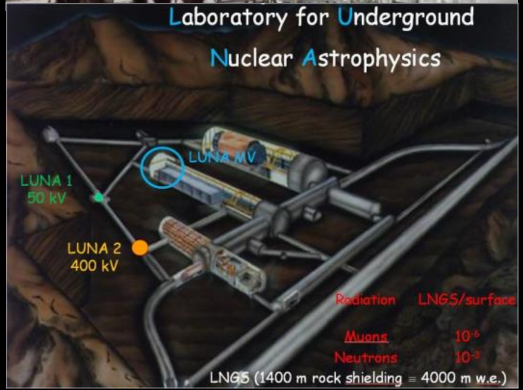
Shen … DeBoer… Tang… et al, PRL(2022), ApJ(2023)

Challenging the tiny cross-sections

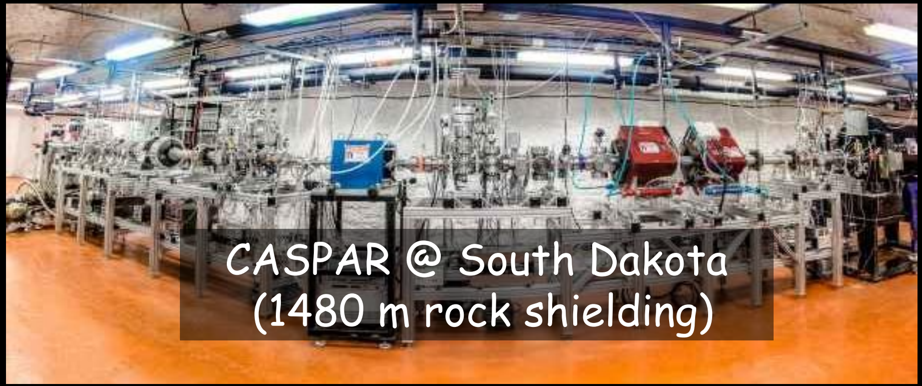




JUNA@China
Jinping
Underground
Laboratory
(2400 m rock shielding)

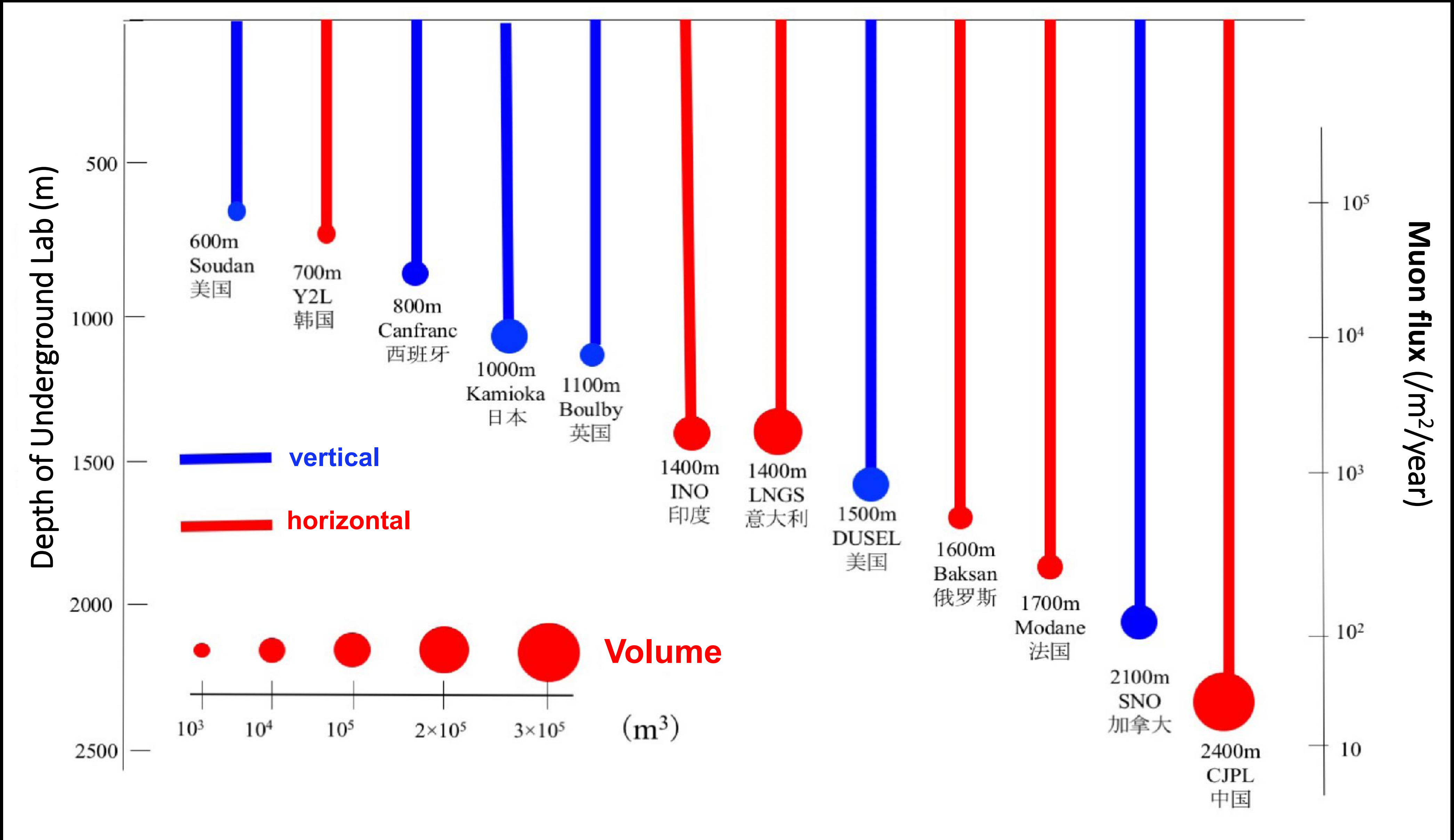


LUNA @
Gran Sasso
Italy
1400m rock shielding

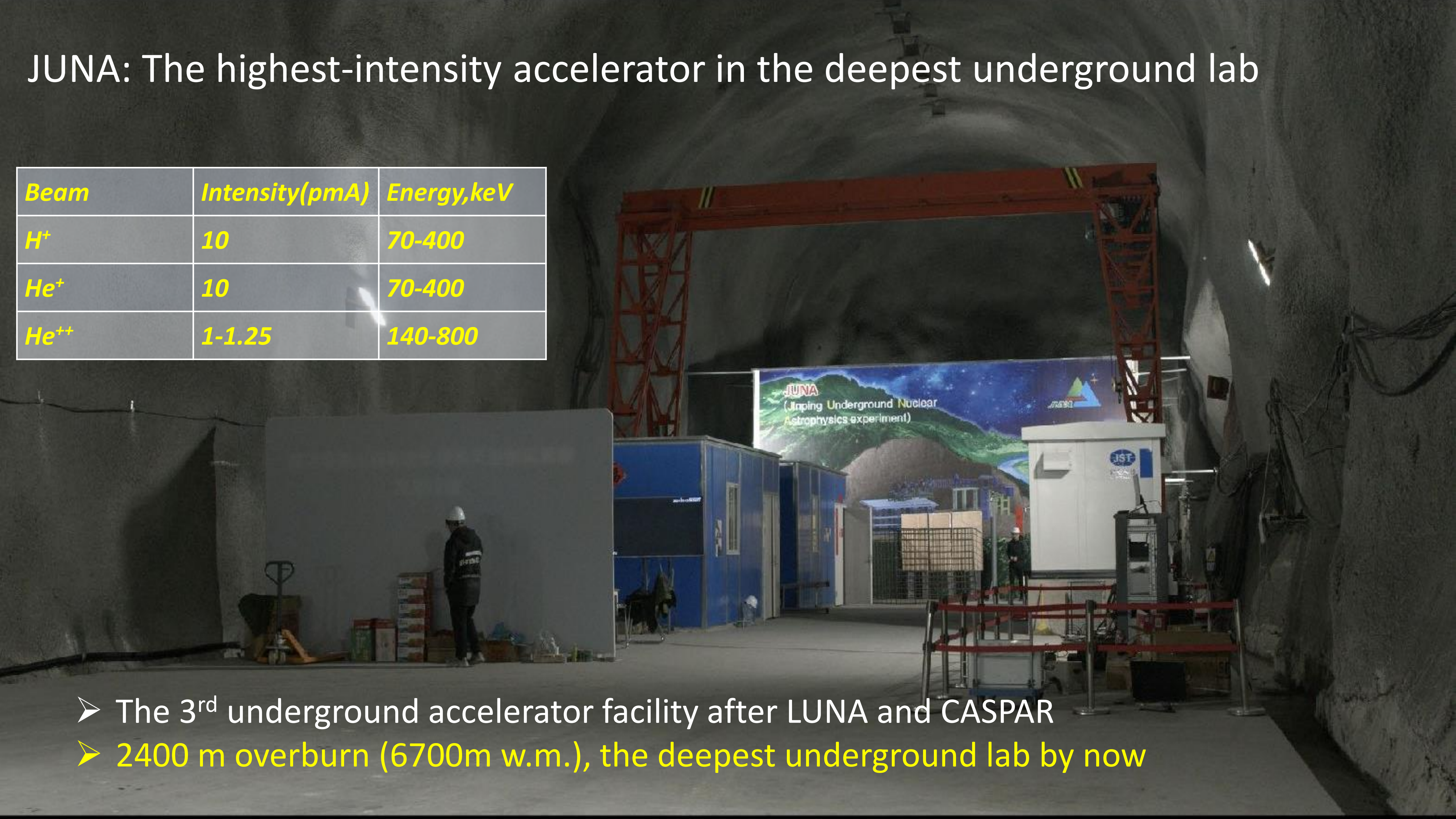


CASPAR @ South Dakota
(1480 m rock shielding)

Comparison of underground laboratories



JUNA: The highest-intensity accelerator in the deepest underground lab



Beam	*Intensity(pmA)*	*Energy,keV*
H^+	*10*	*70-400*
He^+	*10*	*70-400*
He^{++}	*1-1.25*	*140-800*

- The 3rd underground accelerator facility after LUNA and CASPAR
- 2400 m overburn (6700m w.m.), the deepest underground lab by now

Jinping Underground Nuclear Astrophysics(JUNA) projects (2015-2021)

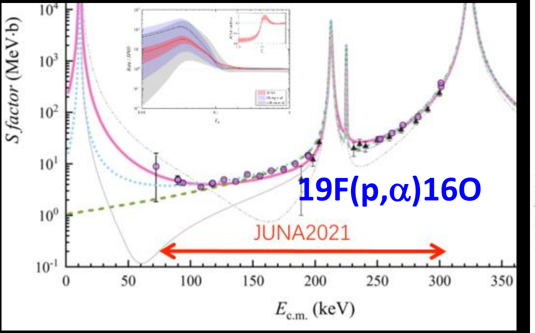
CIAE， W.P. Liu
12C(α,γ)16O

BNU, J.J. He
19F(p,α)16O
19F(p,γ)20Ne

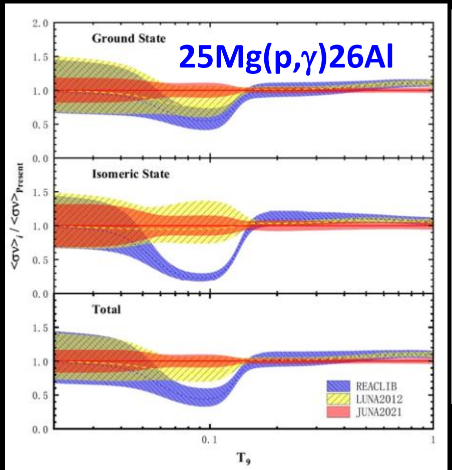
CIAE, Z.H. Li
25Mg(p,γ)26Al

IMP, X.D. Tang
13C(α,n)16O

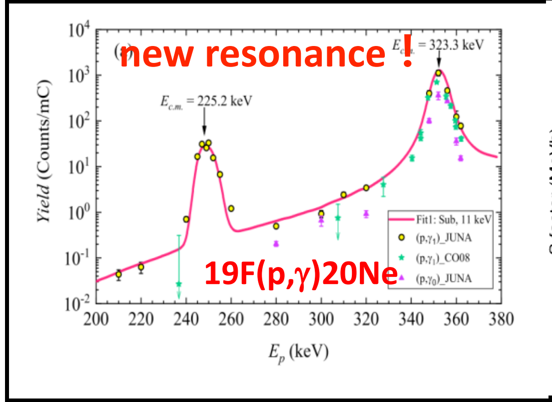
CIAE, G. Lian
Accelerator and Infrastructure



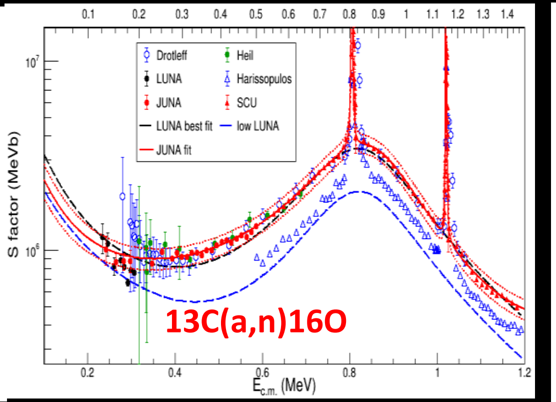
Zhang et al., PRL(2021)



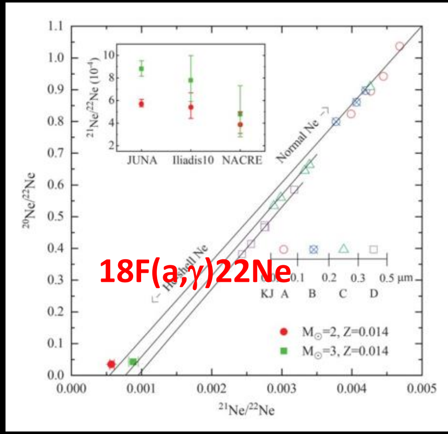
Su et al., Science Bulletin(2022)



Zhang et al,
Nature (2022)

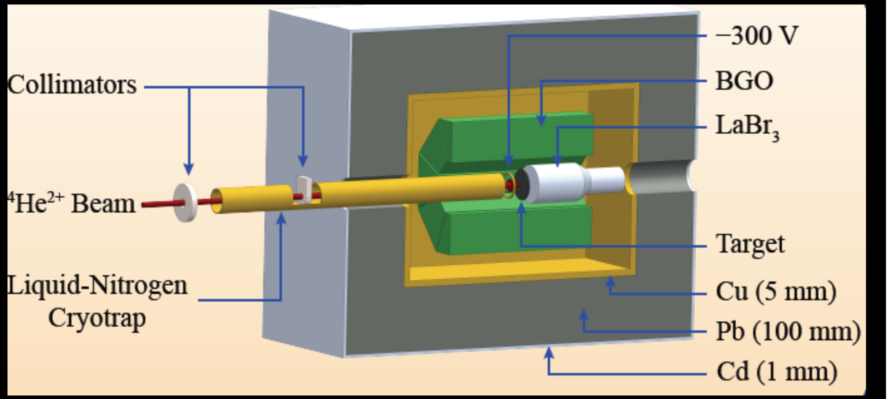


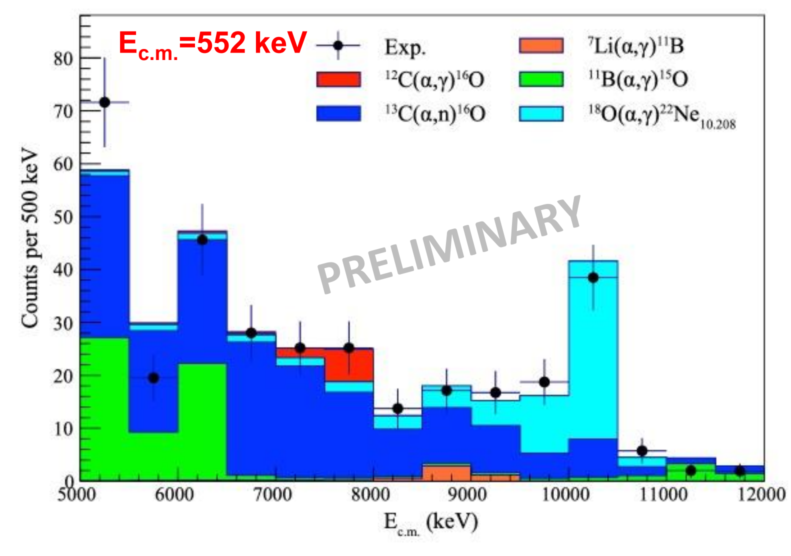
B.S. Gao et al,
PRL (2022)

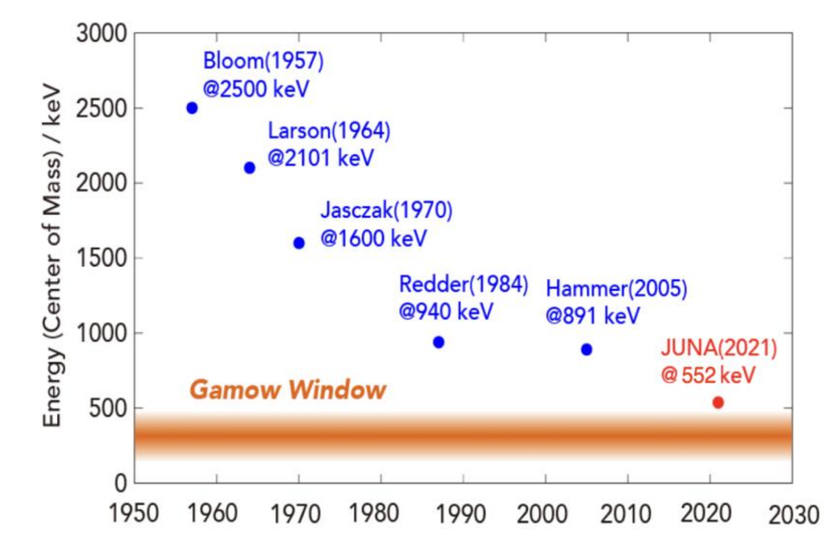


Wang et al,
PRL (2023)

$^{12}C(\alpha,\gamma)^{16}O$： better sensitivity





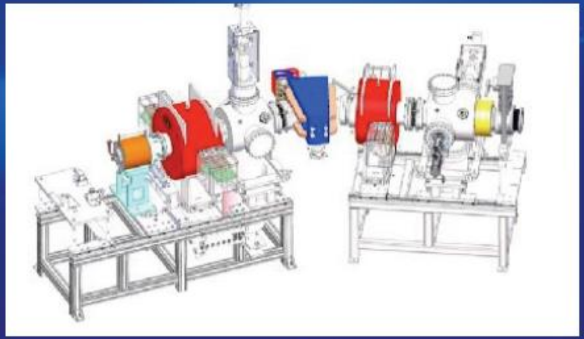


- FCVA implantation CTi thick targets with enriched ^{12}C sample
- BGO+LaBr$_3$ (Lanthanum bromide) veto
- Background is dominated by $^{18}O(\alpha,\gamma)^{22}Ne$ contaminations
- Sensitivity: 10^{-11}b→ 10^{-12} b @$E_{c.m.}$ = 552 keV

Green lights for JUNA Run-2

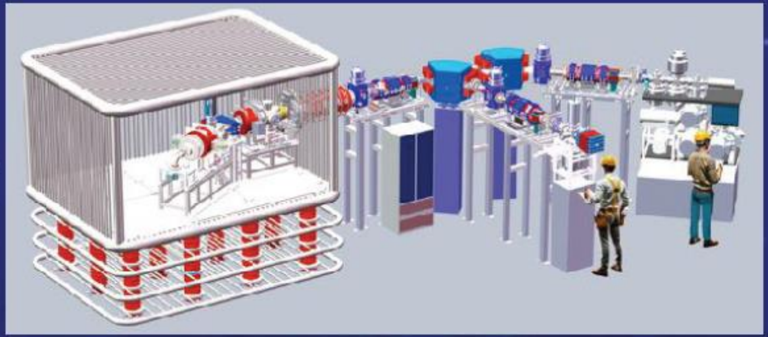
Courtesy of W.P. Liu

- CJPL IAC highly recommend JUNA and gave green lights for next 5 years and support JUNA using A1 space
- High density radiation hard target and gas target, higher efficiency neutron and gamma detectors
- Run 2 proposal evaluated and approved from July 2025 to February 2026

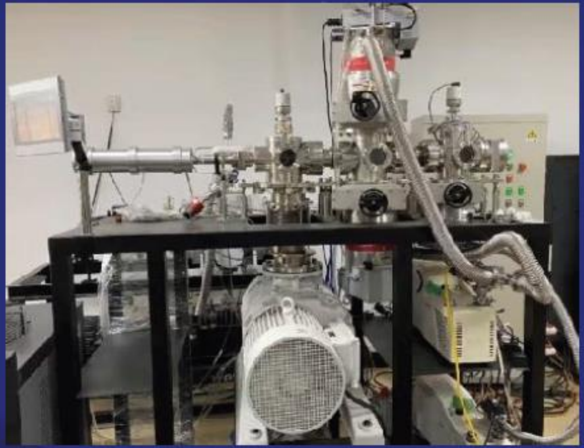


Improved ion source

Run-2 kickoff meeting April 24, 2024, CIAE

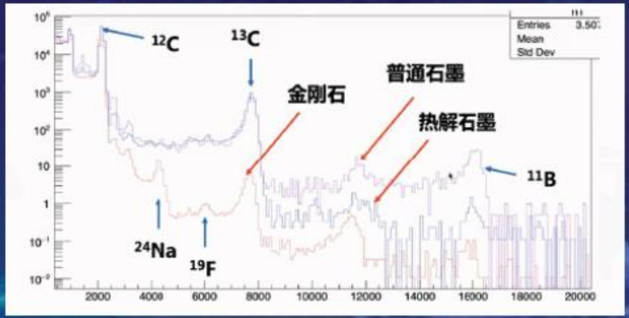


floor plan for JUNA Run-2



Gas jet target

Run-2 plan approved May 15, 2025, BNU



test result for diamond target

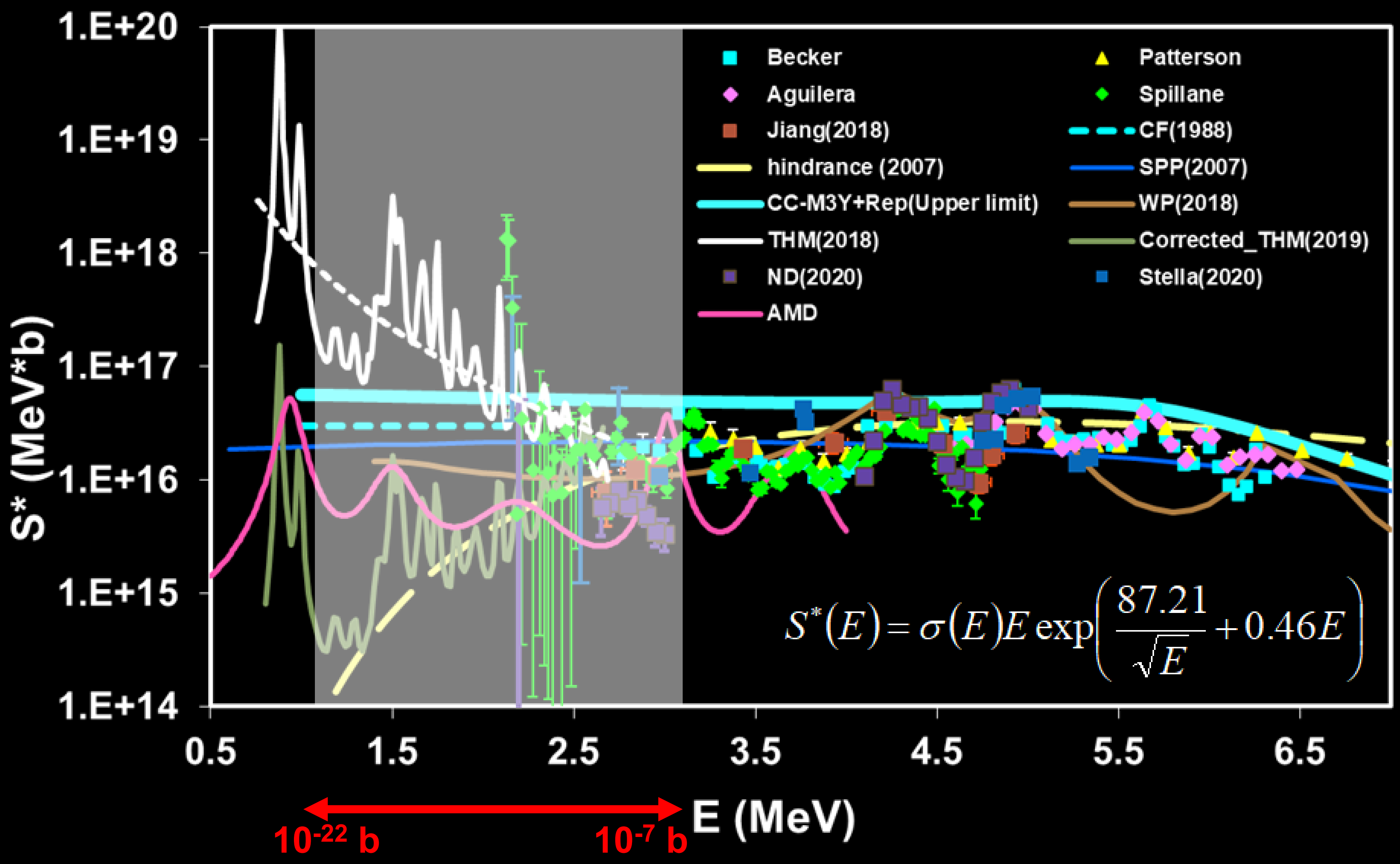
Enlarged BGO array

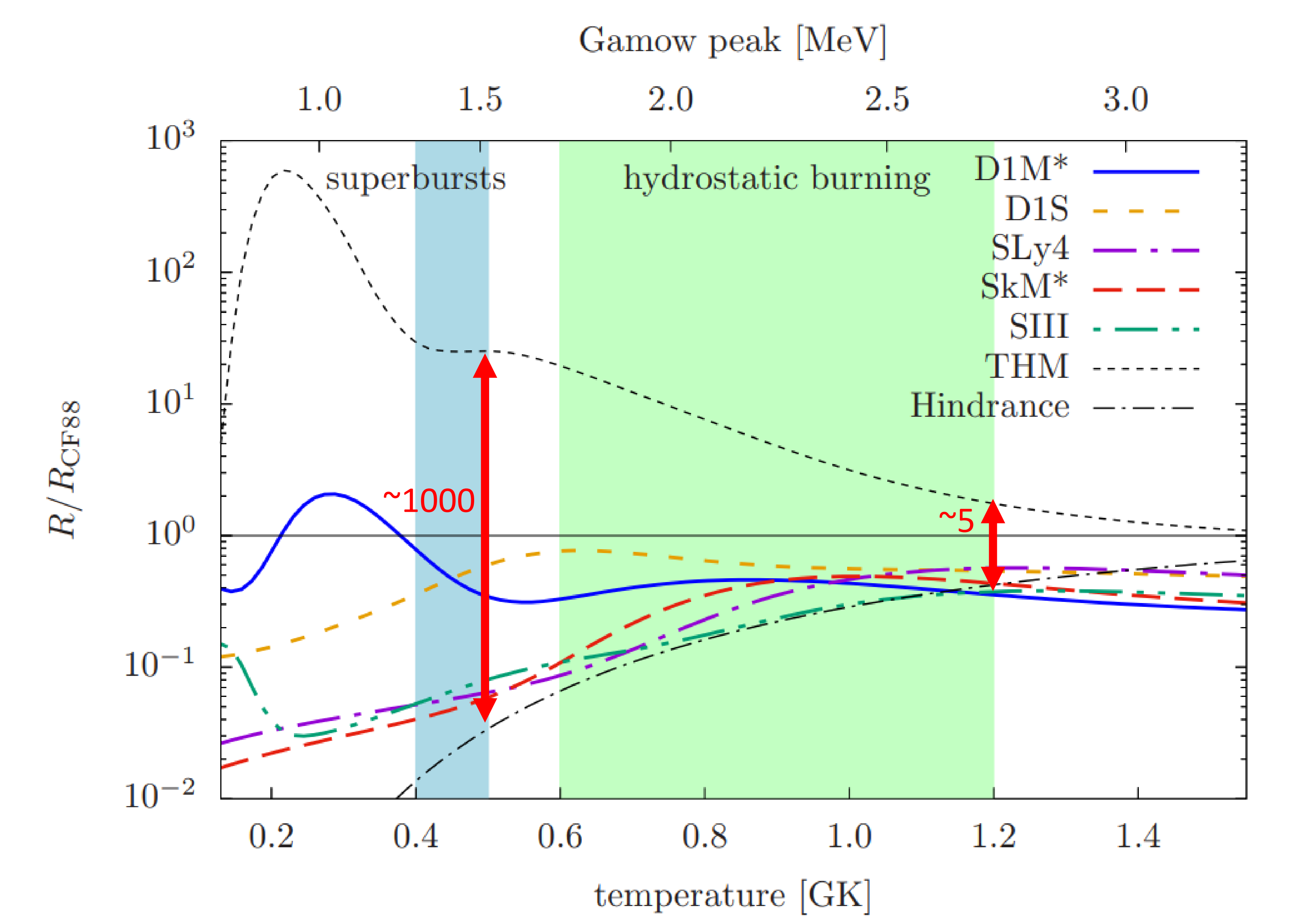
Sept., 2024
CJPL-II A1 ready

October, 2024
Accelerator in A1

May, 2025
Accelerator ready for beam

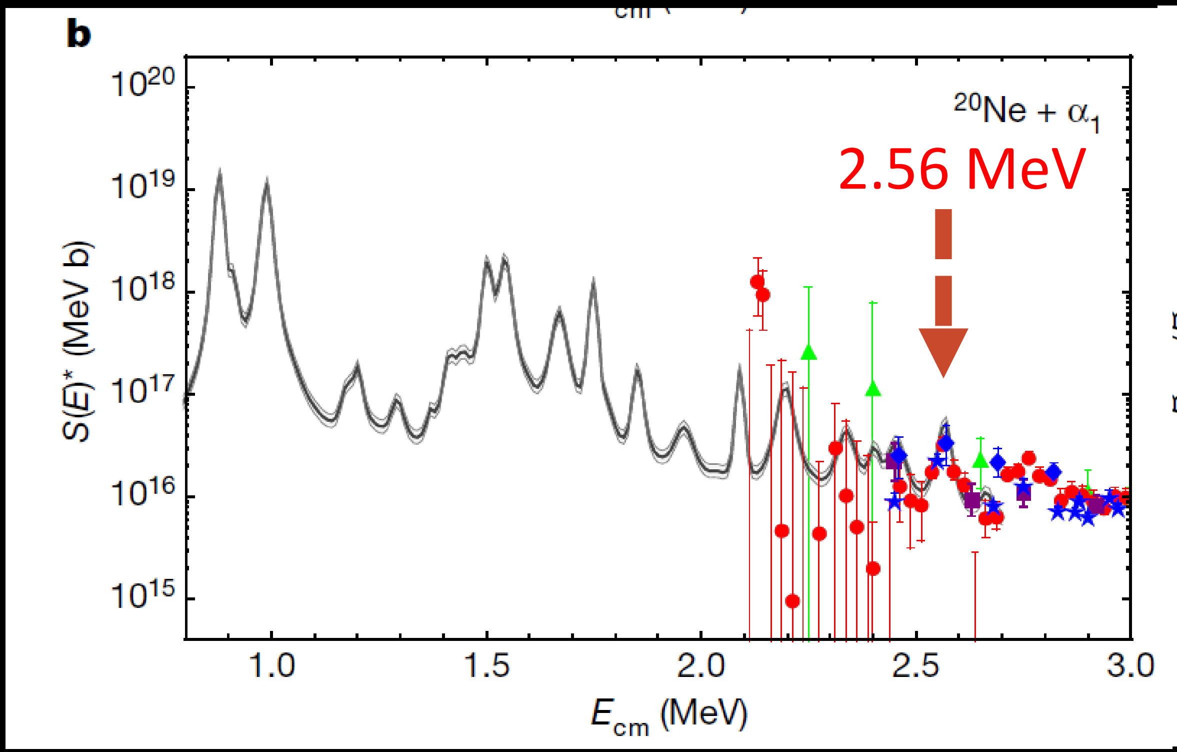
$^{12}C+^{12}C$ Fusion Reaction (1960-)

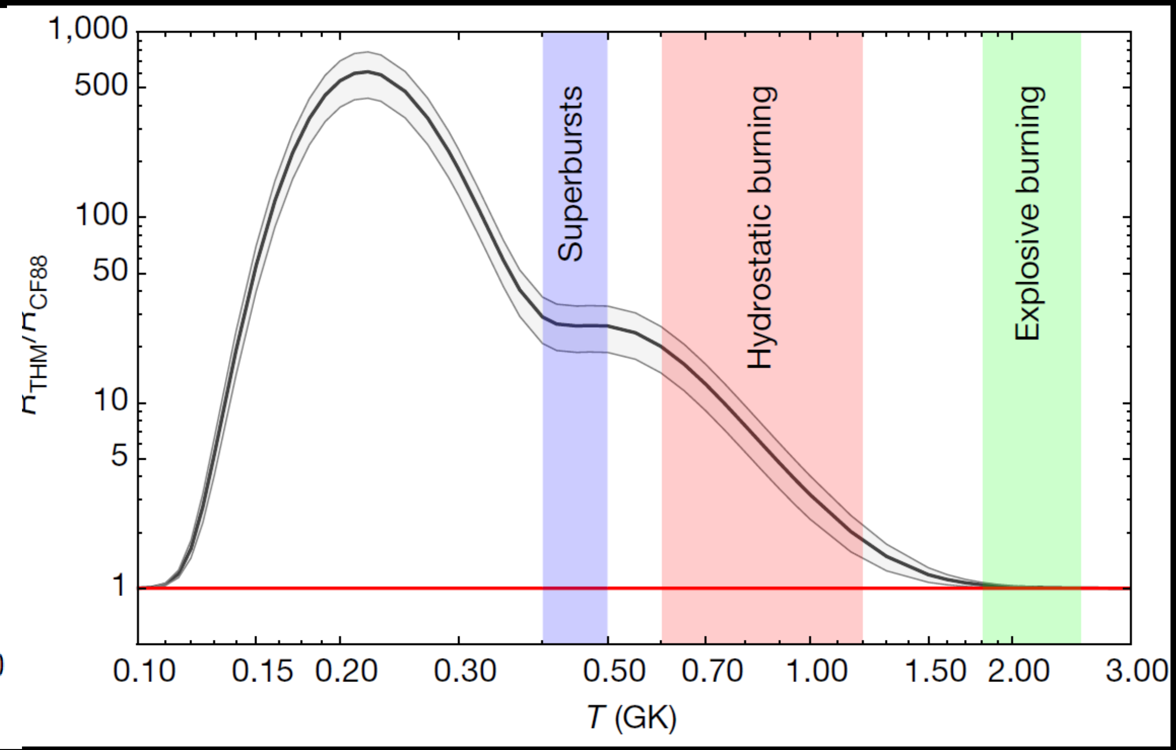




Taniguchi & Kimura, Phys. Lett. B 849 (2024) 138434

THM: Carbon burning can trigger superbursts

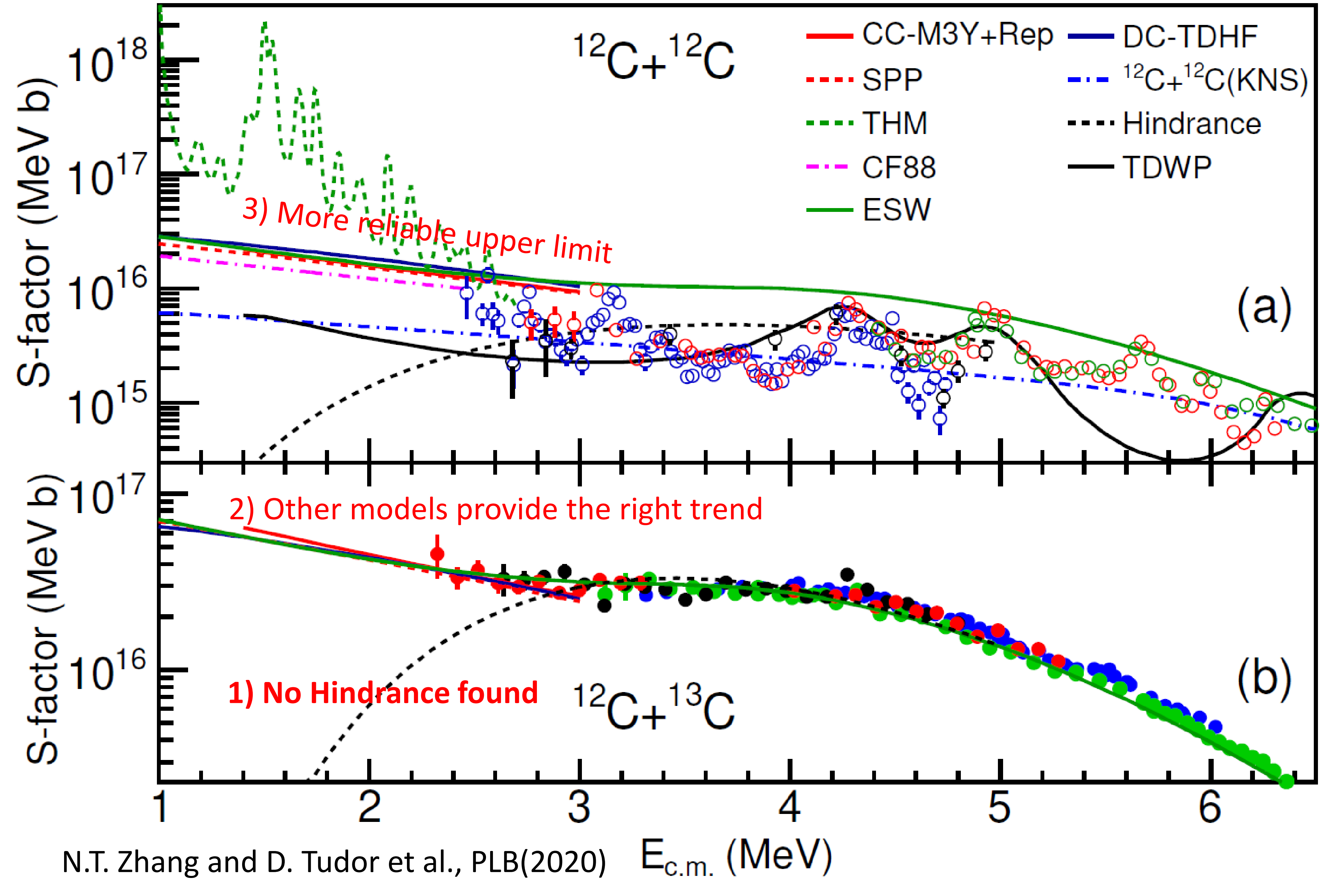




- Increase in the $^{12}C + ^{12}C$ fusion rate from resonances at astrophysical energies
- This change matches the observationally inferred ignition depths and can be translated into an ignition temperature below 0.5 GK, compatible with the calculated crust temperature

Tumino et al., Nature (2018)

Test of hindrance and upper limit of $^{12}C+^{12}C$ based on systematics

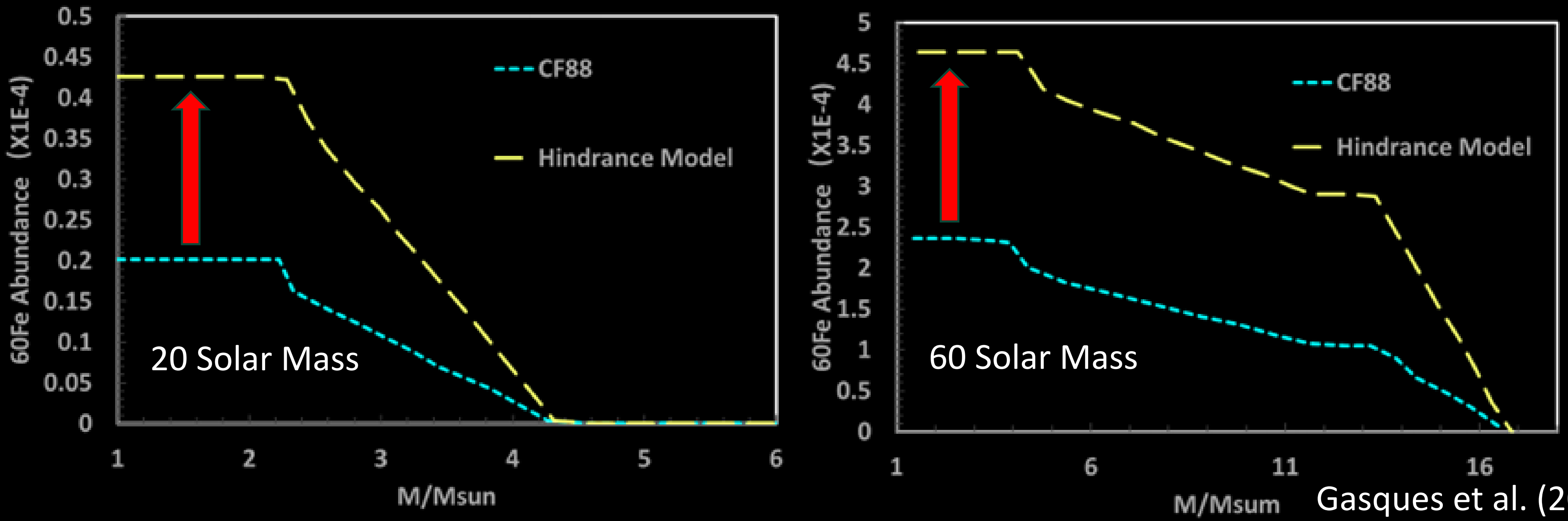


N.T.Zhang(IMP)

D. Tudor (IFIN-HH)

L. Trache (IFIN-HH)

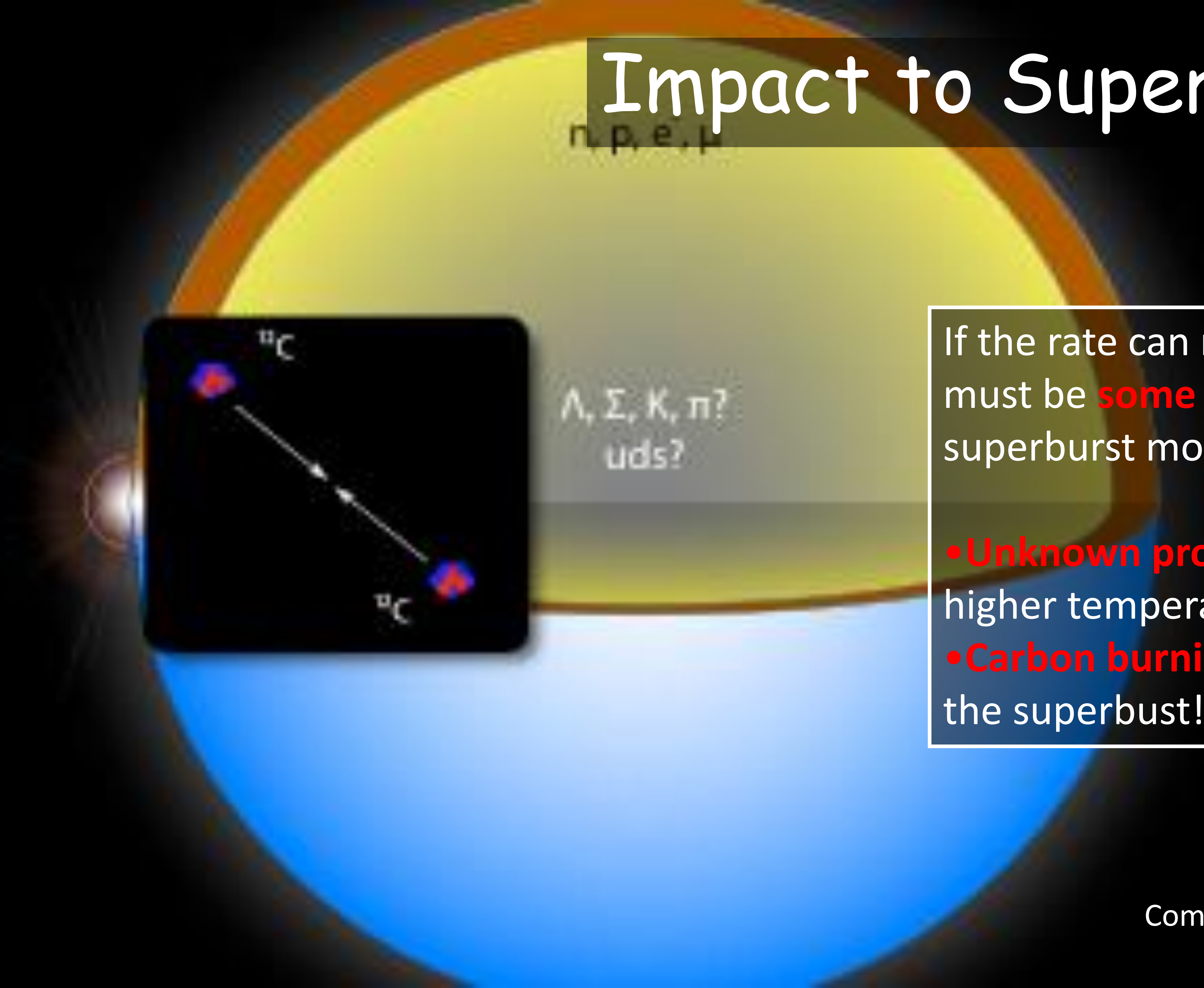
Impact on ^{60}Fe in massive stars



Gasques et al. (2007)

- Enhanced ^{60}Fe production provided by the hindrance fusion rates would further enhance the already overpredicted ^{60}Fe abundance in the galaxy
- Enlarge the discrepancy: [Perdition: 0.45 vs. Observation: 0.15± 0.04]
- But our result rules out such a scenario

Impact to Superburst model

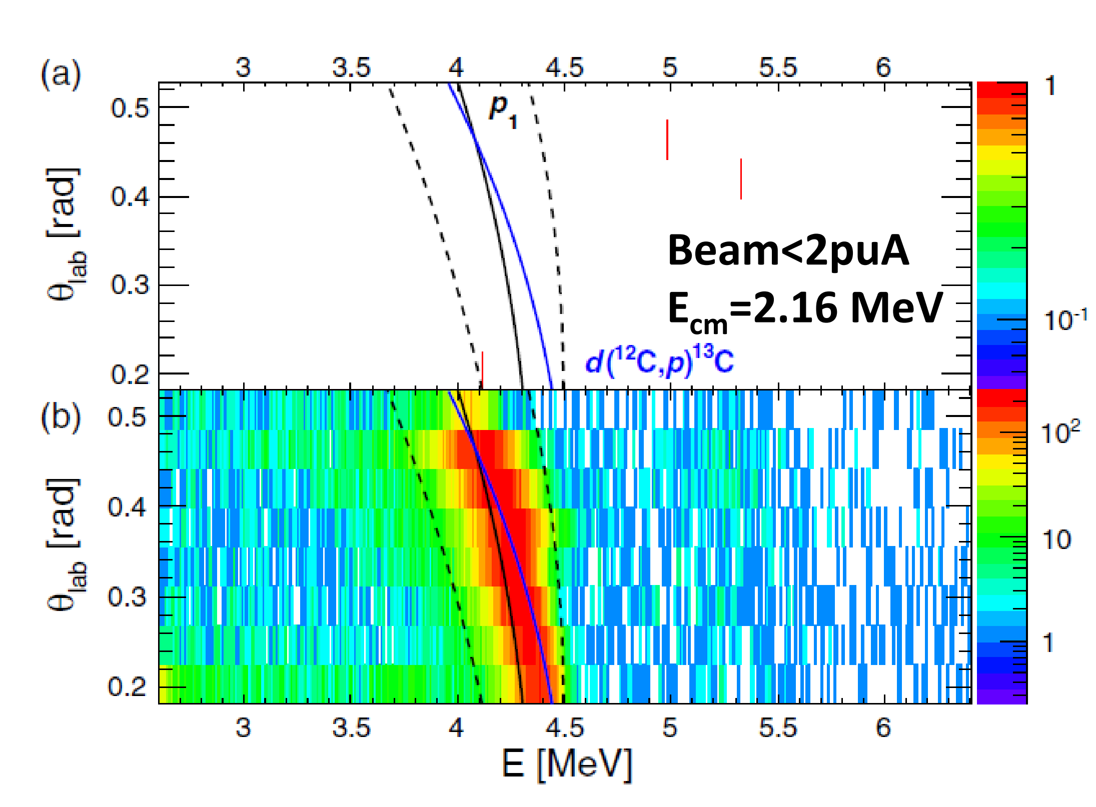


If the rate can not be as that high, there must be **some physics missing** in the superburst model.

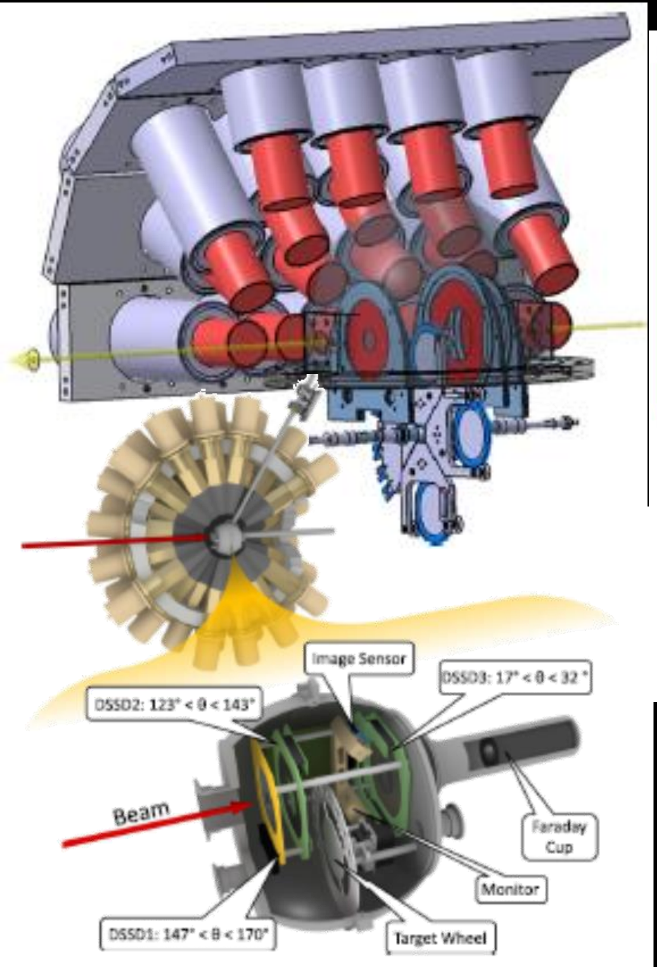
- **Unknown process to heat** up the crust to higher temperature.
- **Carbon burning is not the one triggered** the superbust!

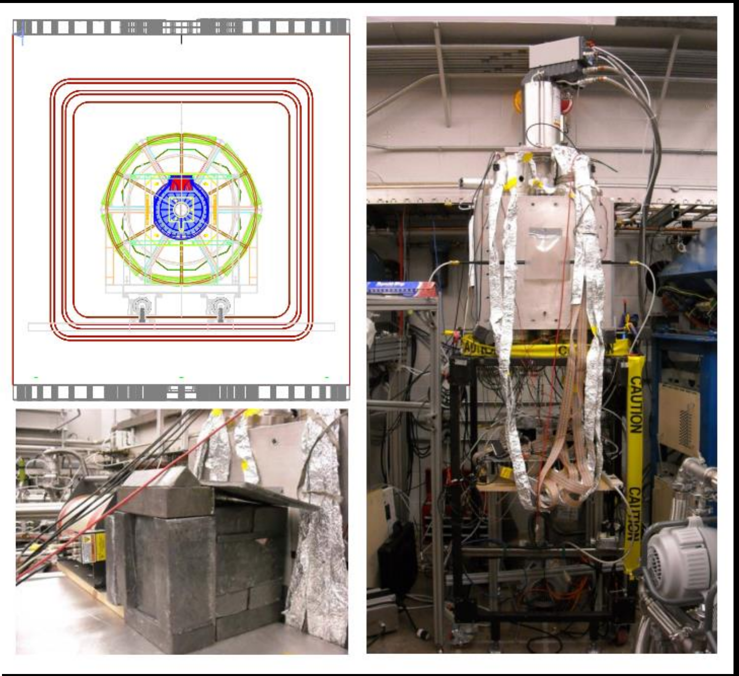
Communication with Ed. Brown(MSU)

Particle-γ coincidence at lower stellar energies



Fruet+ PRL(2020)





Beam<15puA

Jiang et al. (2012), Jiang et al. (2018)
Heine et al. (2018), Tan et al. (2021),
Fruet et al. (2021)

- Particle-γ coincidence technique pushed the measurement down to sub-nb level
- Only detect p_1 and α_1 channels

Carbon fusion project at LUNA-MV

Massive lead shield and radon flushing → push sensitivity to better than 100 reactions/day

$^{12}C+^{12}C$ - γ measurements

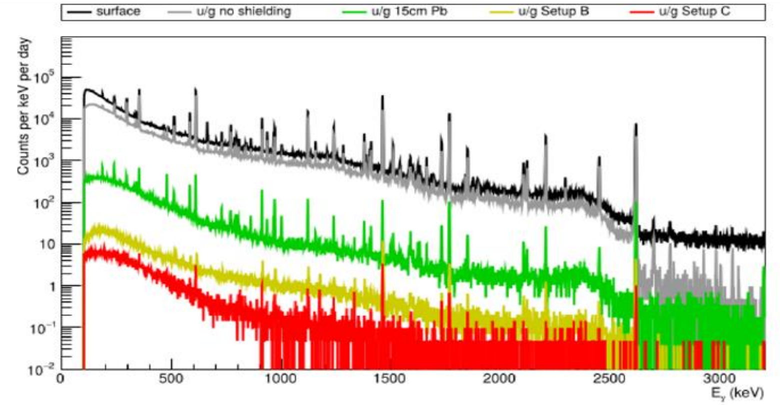


Figure 9a: *Environmental background in HPGe detectors in different shielding configurations.*

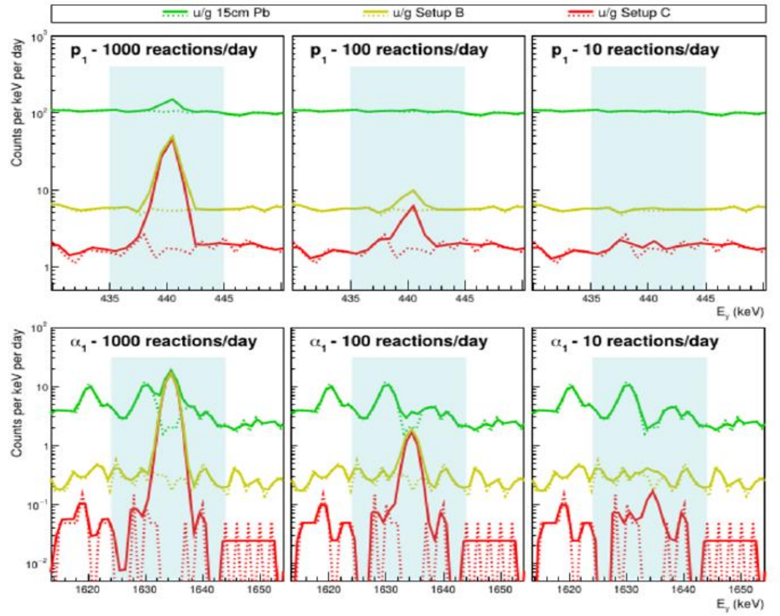
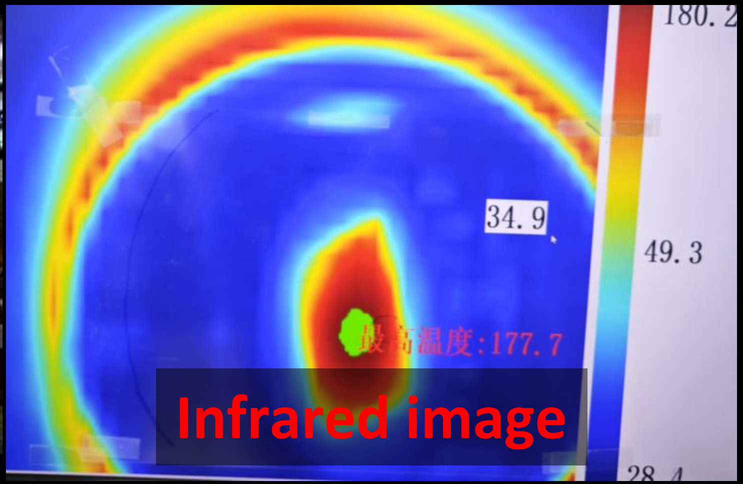
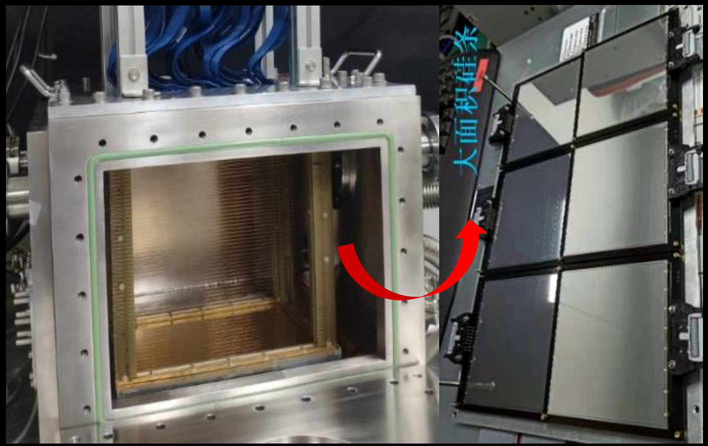
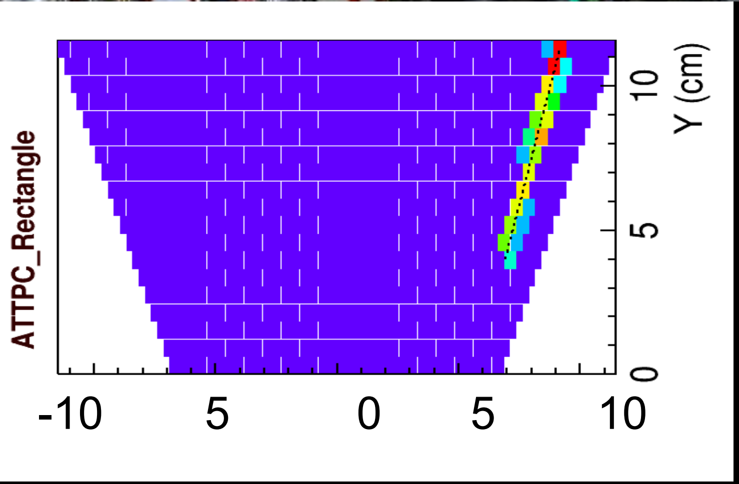


Figure 9b: *Visualization of a hypothetical reaction yield (solid) on top of the background levels of shielded setups from Fig. 9a (dotted).*

High Intensity+Time Projection Chamber

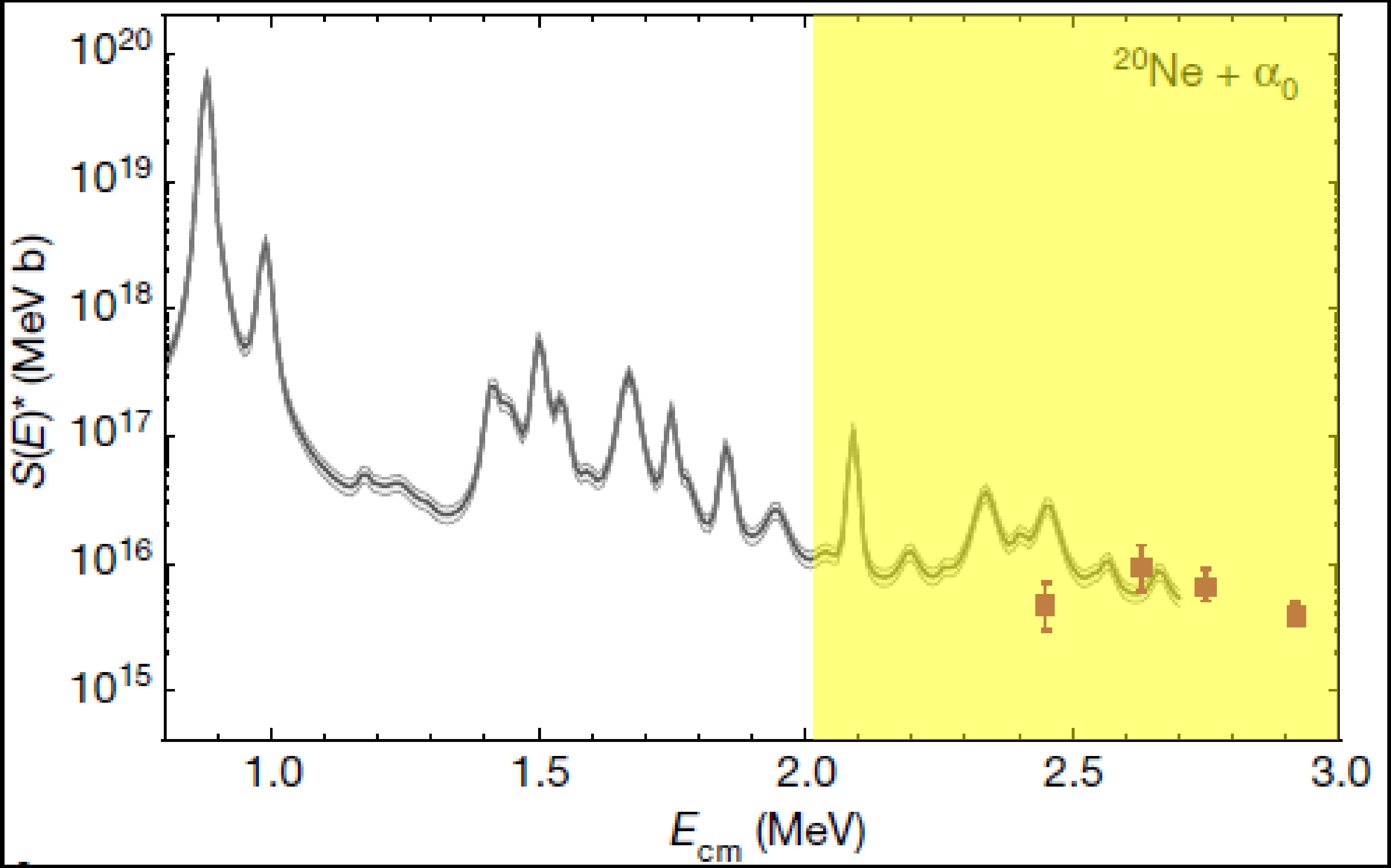






- LINAC: High Intensity beam up to 200 puA
- Time Projection Chamber: Ultra sensitive tracking detector
- Complementary to LUNA-MV and other experiments

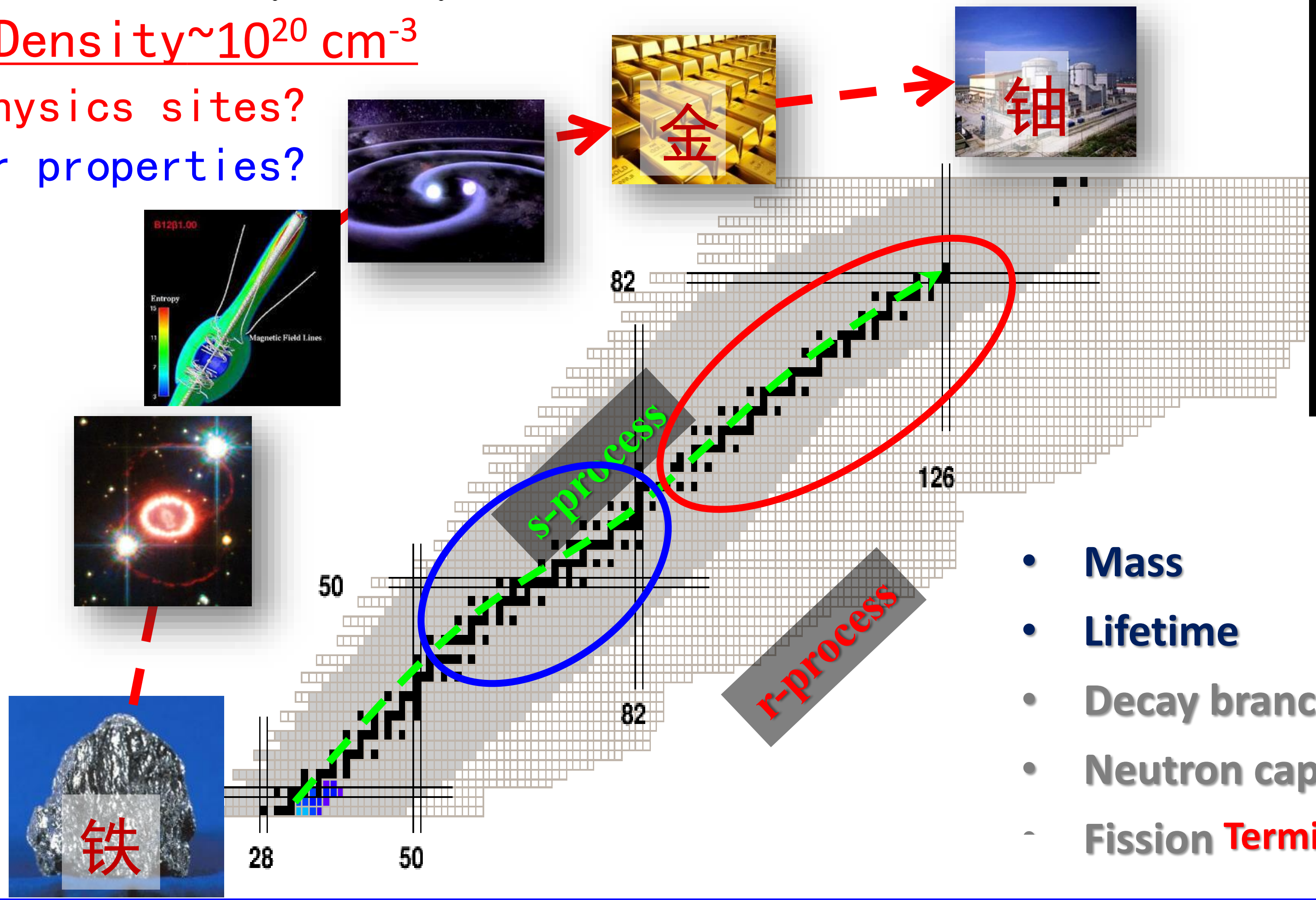
Comparisons with THM (indirect measurement)

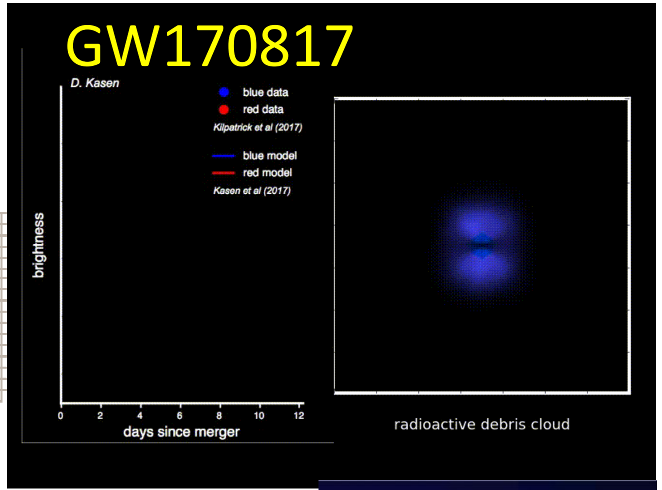


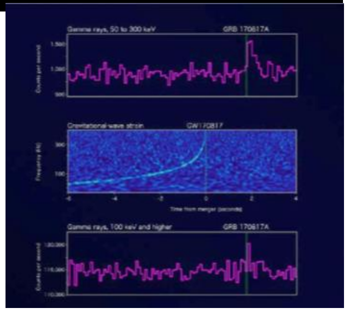
The origin of heavy elements from iron to uranium (rapid neutron capture process)

Neutron Density~10^{20} cm^{-3}

- Astrophysics sites?
- Nuclear properties?







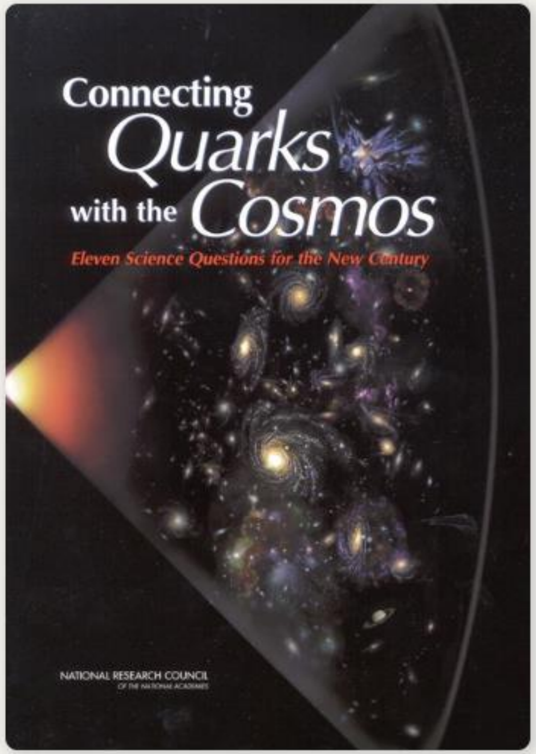
- **Mass**
- **Lifetime**
- Decay branching
- Neutron capture reaction
- Fission **Termination point of r-process**

Experiment+Theory+Observation

Improving the predictive power of stellar models by eliminating nuclear uncertainties

NATIONAL ACADEMIES *Sciences Engineering Medicine*

Consensus Study Report



Connecting Quarks with the Cosmos

Eleven Science Questions for the New Century

(2003)

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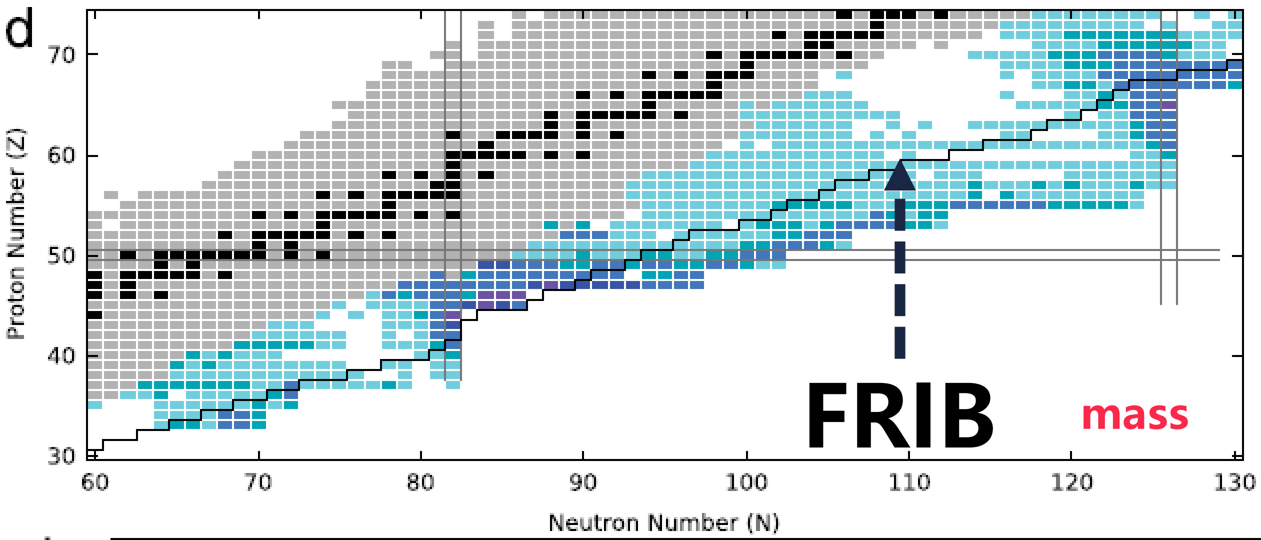
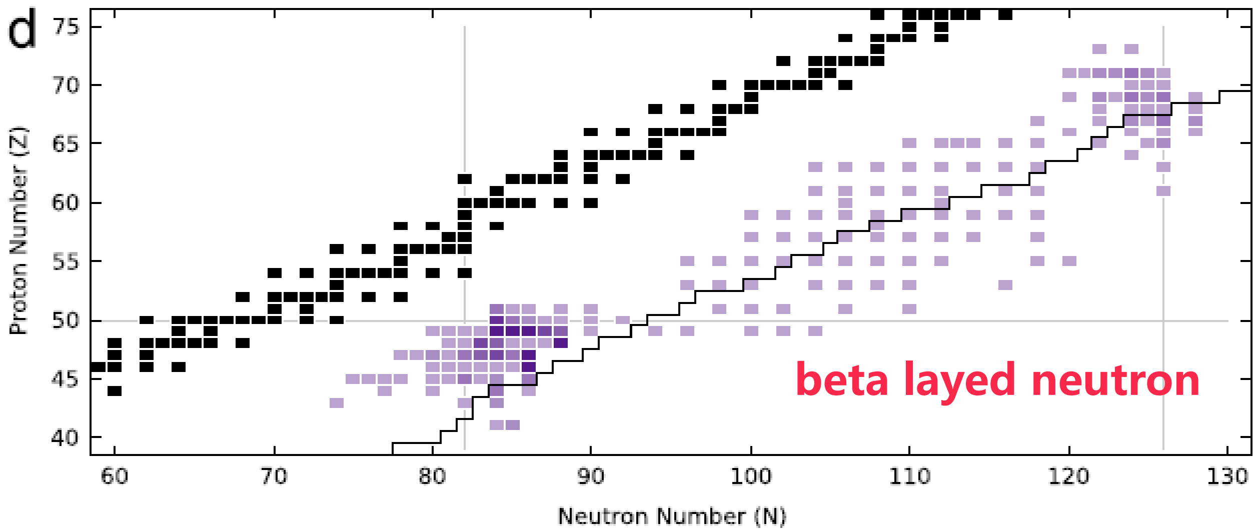
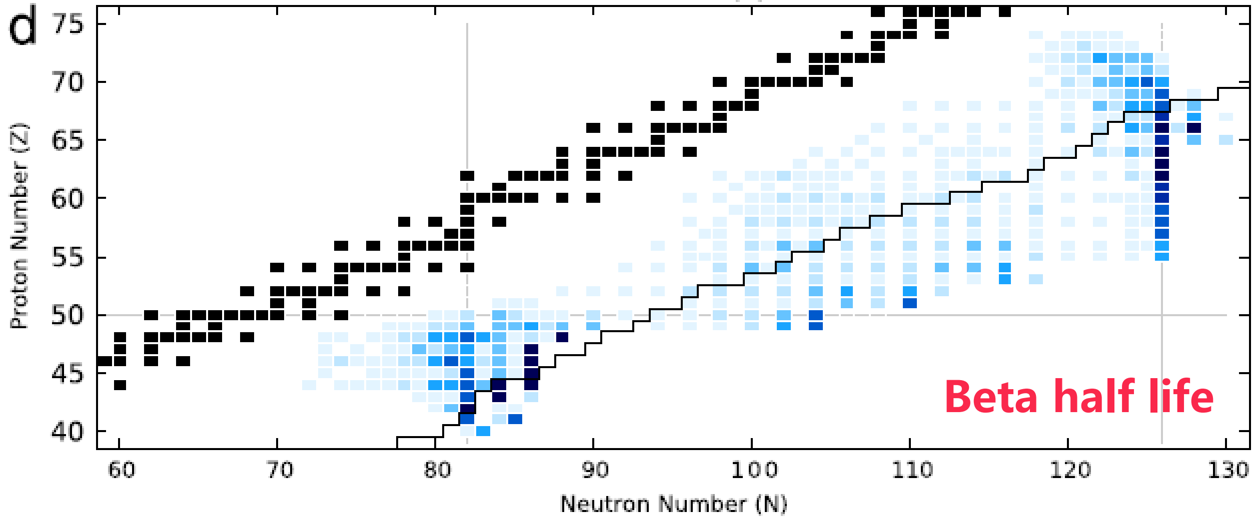
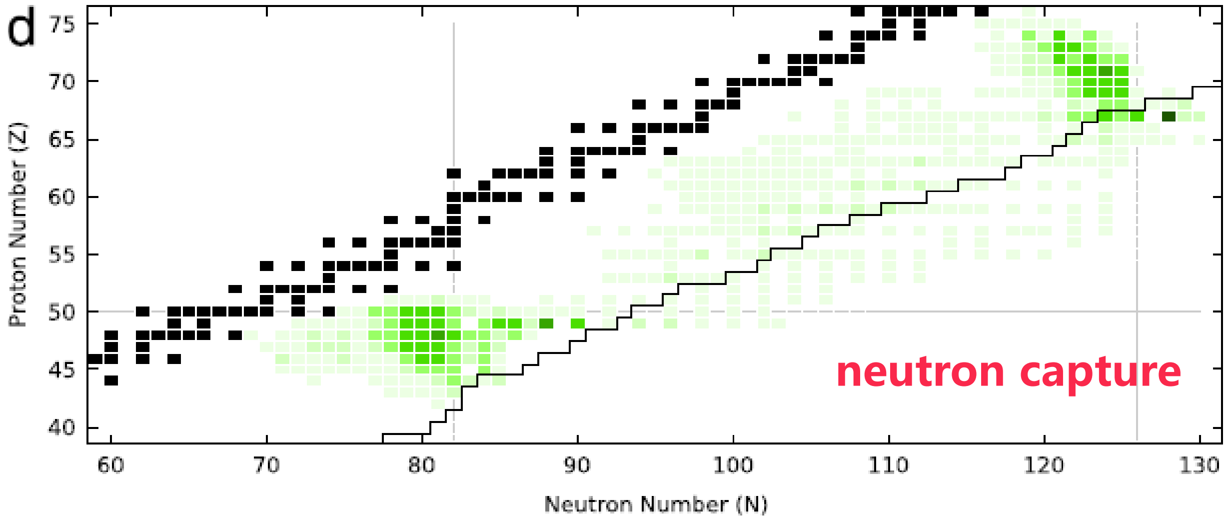
Advances made by physicists in understanding matter, space, and tim

Important nuclear physics inputs



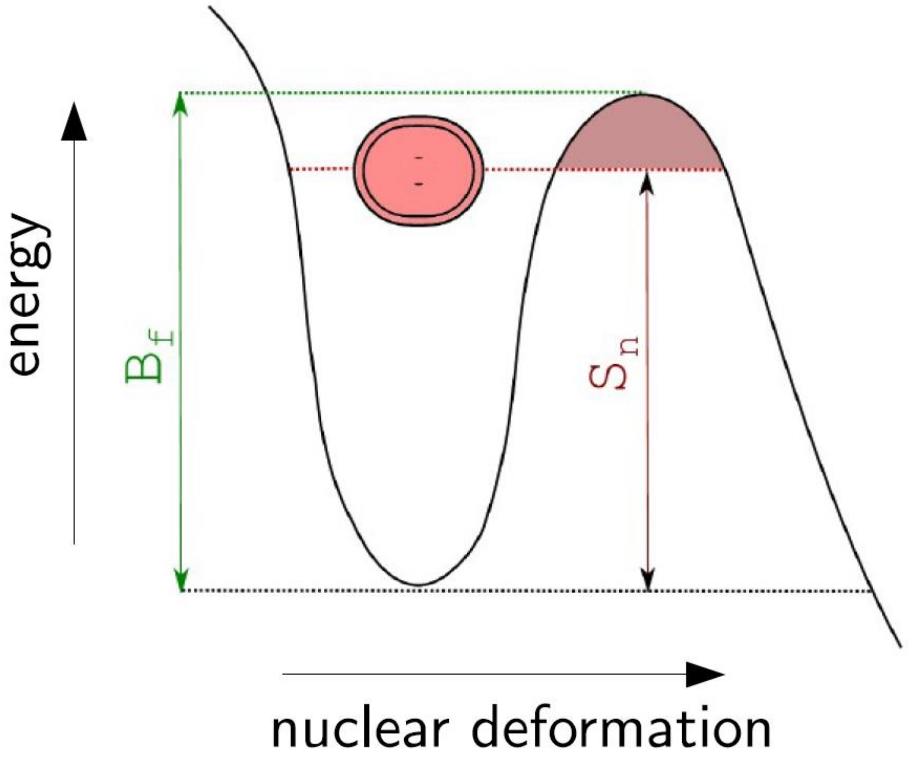


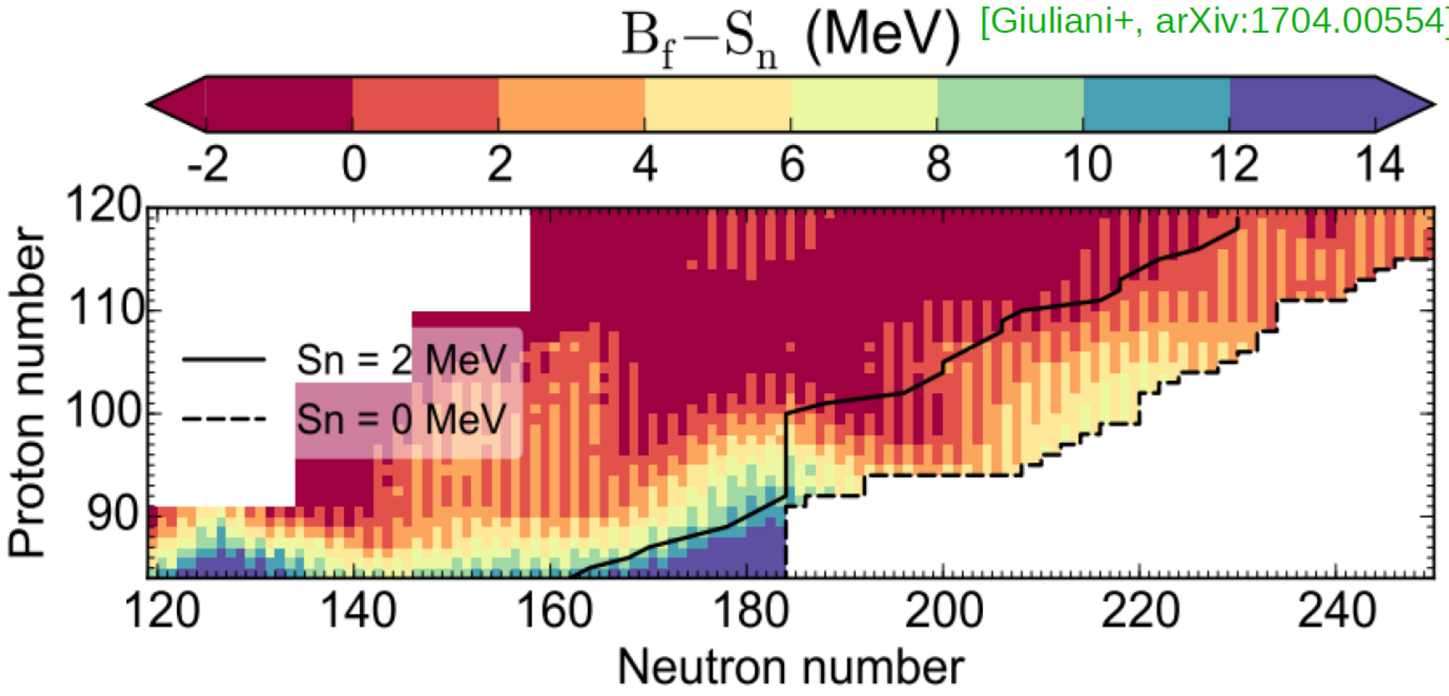




M.R. Mumpower, R. Surmana, G.C. McLaughlin, A. Aprahamian, PPNP 86 (2016) 86–126

Important nuclear physics inputs

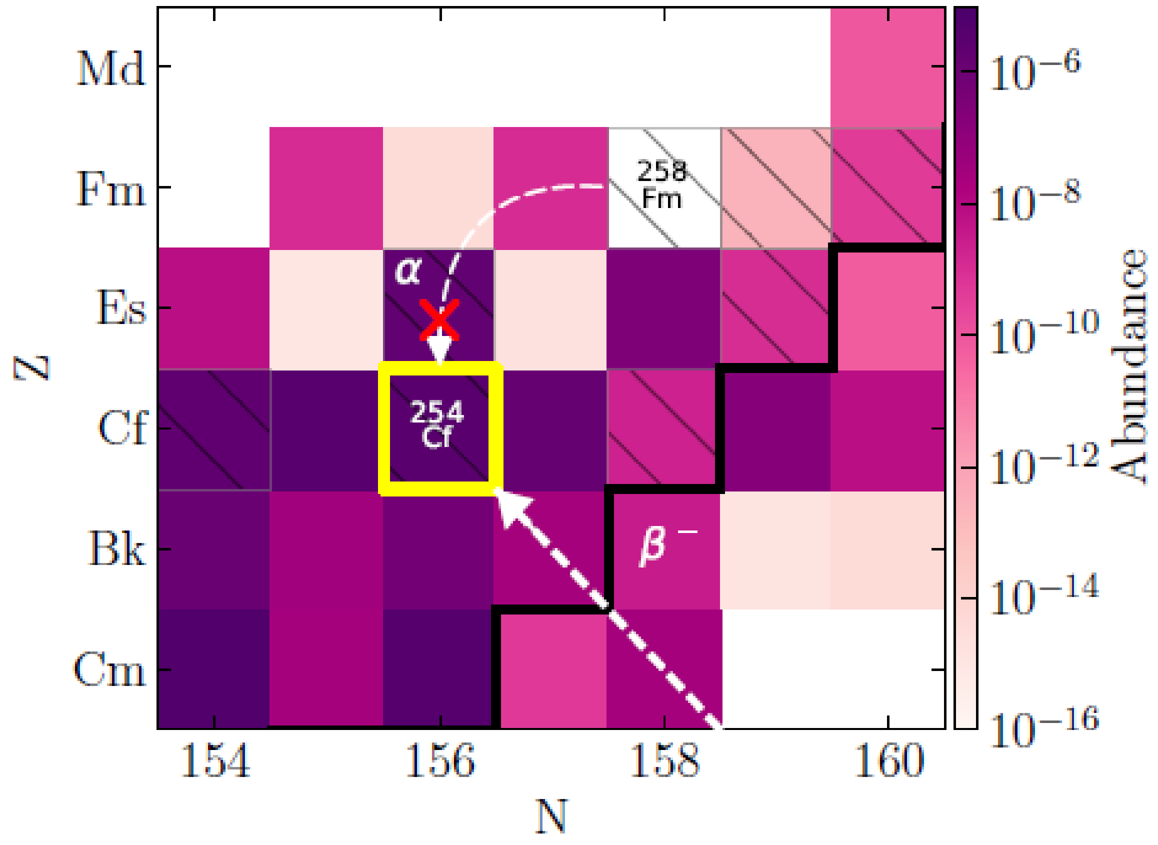




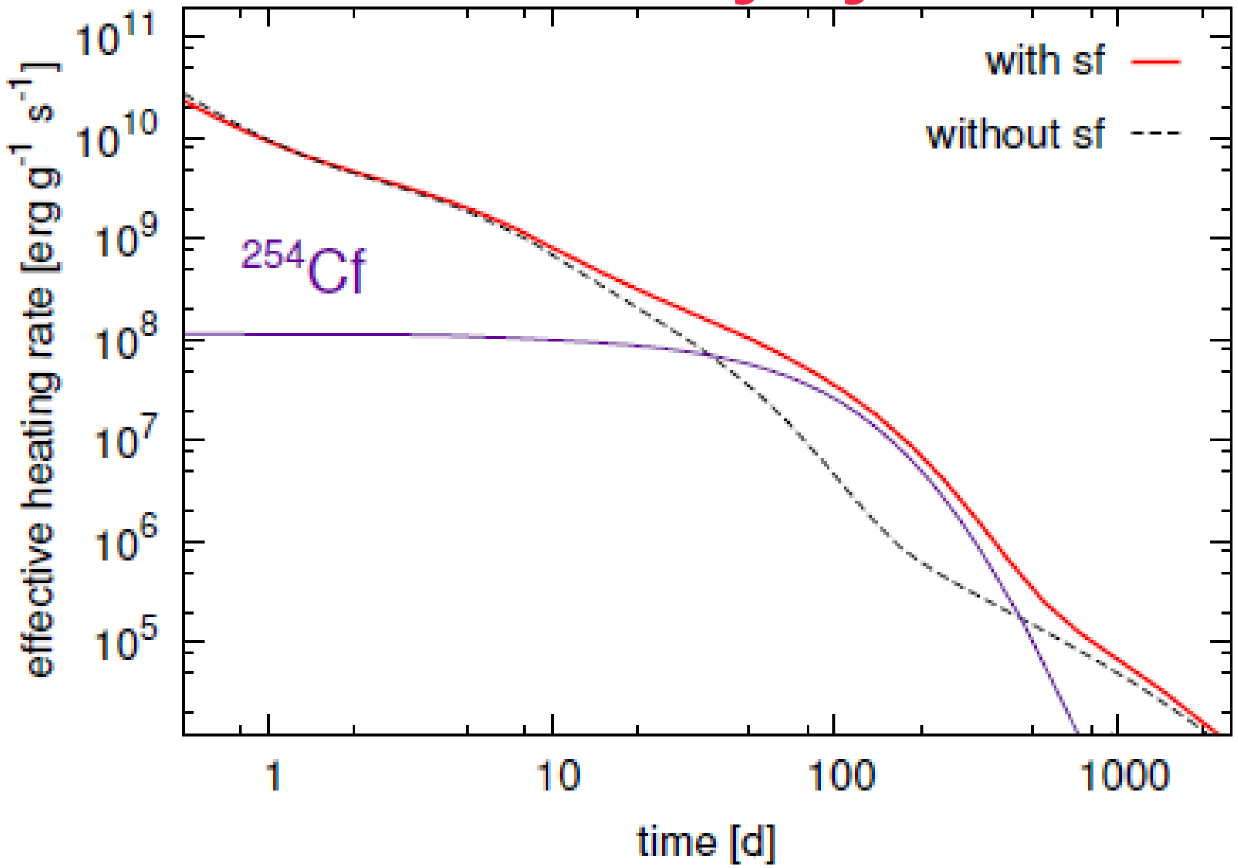
[Giuliani+, arXiv:1704.00554]

Meng-Ru Wu, NUSYS lecture

Important Nuclear Physics inputs



Neutron star merger light curve



Fission properties of A=254 isotopes are important for the understanding of the light curve of neutron star mergers.

Zhu et al., arXiv:1806.09724v1

High Intensity heavy ion Accelerator facility (HIAF: 2018. 12–2025. 12)

0.8 AGeV, 3×10^{10}ppp $^{238}U^{35+}$
1.75AGeV, 7.5×10^{10}ppp ^{78}Kr19+
2.6~3.0AGeV, 1.0×10^{11}ppp $^{16}O^{6+}$

China Initiated Accelerator Dirven sub-critical System (CiADS, 2021. 7–2027. 12)

Design Particle	proton
Energy	500 MeV
CW Beam current	5 mA
Beam power	2.5 MW
Operation mode	CW&Pulse
Beam loss	＜1 W/m
Reactor power	7.5 MWt
Cryogenic	2 /4 K

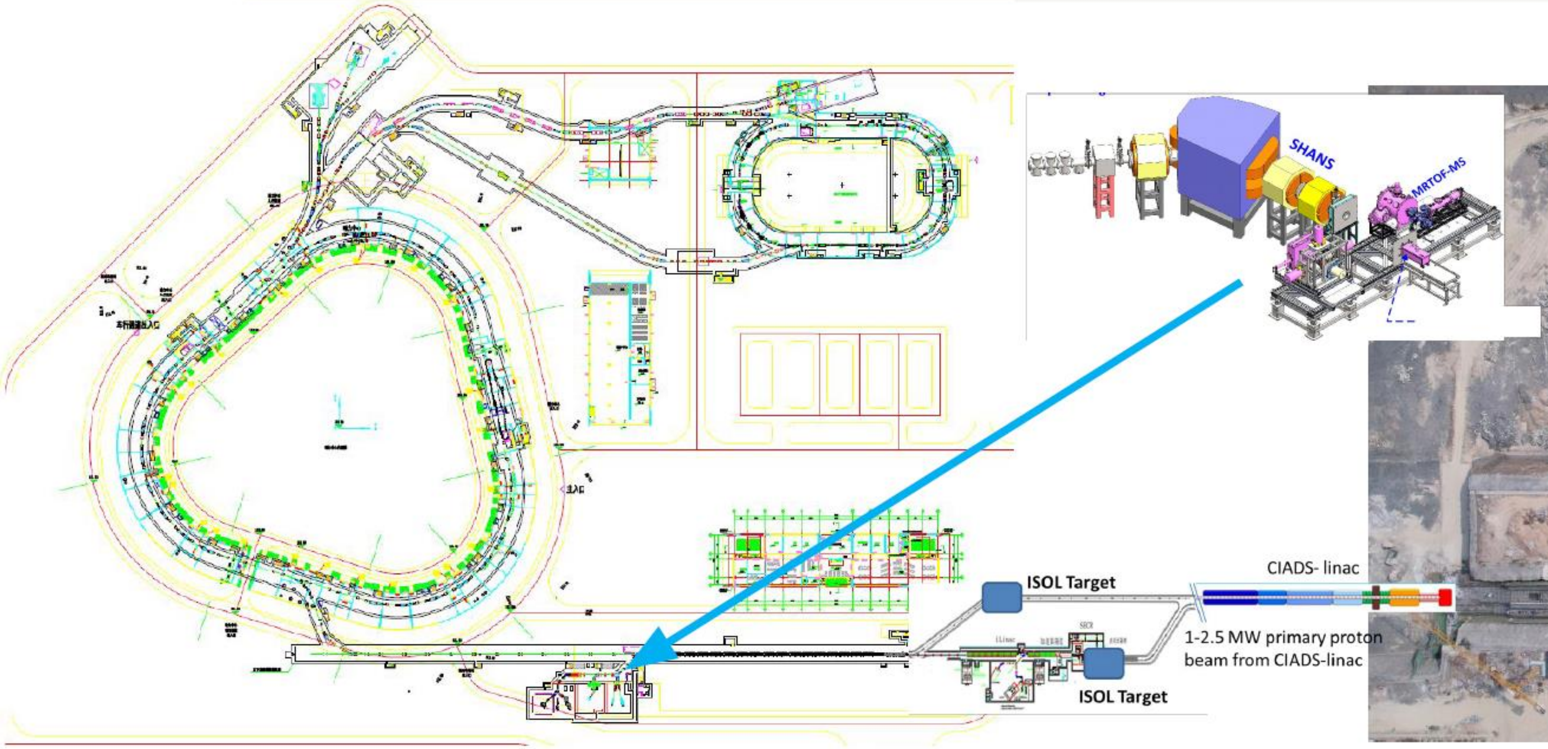
iLinac: Superconducting linac
Length:100 m
Energy: 17~22 MeV/u($U^{35+\sim46+}$)

March 23, 2025

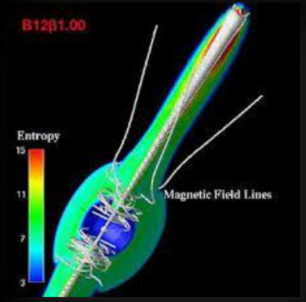
RIB produced by ISOL + In Flight based on HIAF+CiADS

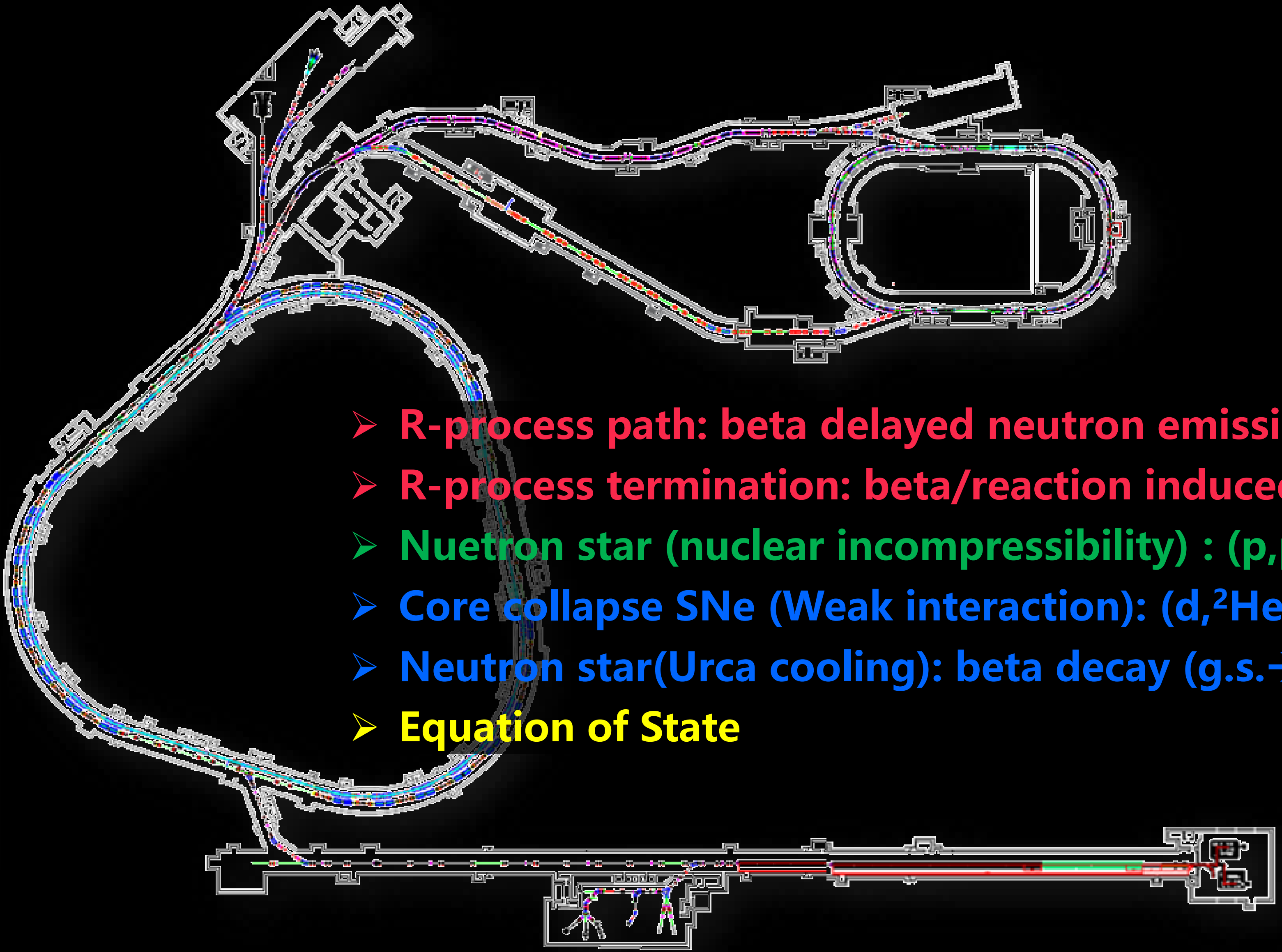
- Integrating CiADS & HIAF
- 2.5~10MW ISOL target
- Extracting Gas or low boil T isotopes, ex. He, Ar, Kr, Xe…
- Inject to iLinac of HIAF is post-acc, 5~100 MeV/u
- Using HIAF Low Energy cave for SHE

Courtesy of Wenlong Zhan (IMP, CAS)



Opportunities with HIAF





- R-process path: beta delayed neutron emission
- R-process termination: beta/reaction induced fission
- Nuetron star (nuclear incompressibility) : (p,p’) , (a,a’)
- Core collapse SNe (Weak interaction): (d,^{2}He), (p,n)
- Neutron star(Urca cooling): beta decay (g.s.→g.s.)
- Equation of State

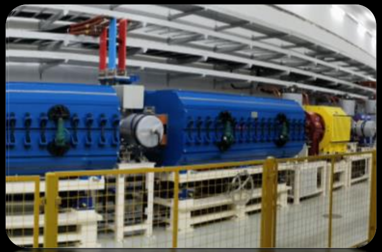
Look forward to collaborating with IFIN-HH

Conclusions

- Precise nuclear astrophysics experiments play a key role in the multi-messenger era
  $^{12}C(\alpha,\gamma)^{16}O$: impact on nucleosynthesis and black mass gap
  $^{12}C+^{12}C$: superburst ignition problem

- The studies of $^{12}C(\alpha,\gamma)^{16}O$ and $^{12}C+^{12}C$ are not yet satisfied. More demands are coming from the new multi-messenger observations

- To achieve the best understanding, we need both direct and indirect methods, joint efforts of various facilities, and interdisciplinary collaborations among nuclear physics, astrophysics and astronomy


Collaborators at ND, RCNP, TAMU, IFIN-HH, USTC and CIAE

CARbon FUSion Experiment (CARFUSE) @LEAF, IMP