

Nuclear Astrophysics in the Era of Multi-Messenger Astronomy

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Lecturer:_____ Day _____

Group members _____

_____

Things that were clear:

Things that were not clear:

Specific Questions (continue on back if needed):

Forming group (4~6 people)

Email: xtang@impcsa.ac.cn

Or give me a hardcopy after the end of the class



Outline

- Hydrogen Burning: "solar neutrino missing problem" and solar metallicity puzzle (pp Chain, CNO cycle)
- Helium Burning: Mass gap of black hole (3α reaction and $^{12}C(\alpha,\gamma)^{16}O$)
- Carbon Burning: Production of ^{20}Ne, ^{23}Na in Pop-III
- S-process: Production of ^{59}Fe
- R-process: Origin of elements from Fe to U

The first idea of instantaneous origin

The Origin of Chemical Elements 1948

R. A. ALPHER*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland
AND
H. BETHE
Cornell University, Ithaca, New York
AND
G. GAMOW
The George Washington University, Washington, D. C.
February 18, 1948

AS pointed out by one of us,[1] various nuclear species must have originated not as the result of an equilibrium corresponding to a certain temperature and density, but rather as a consequence of a continuous building-up process arrested by a rapid expansion and cooling of the primordial matter. According to this picture, we must imagine the early stage of matter as a highly compressed neutron gas (overheated neutral nuclear fluid) which started decaying into protons and electrons.

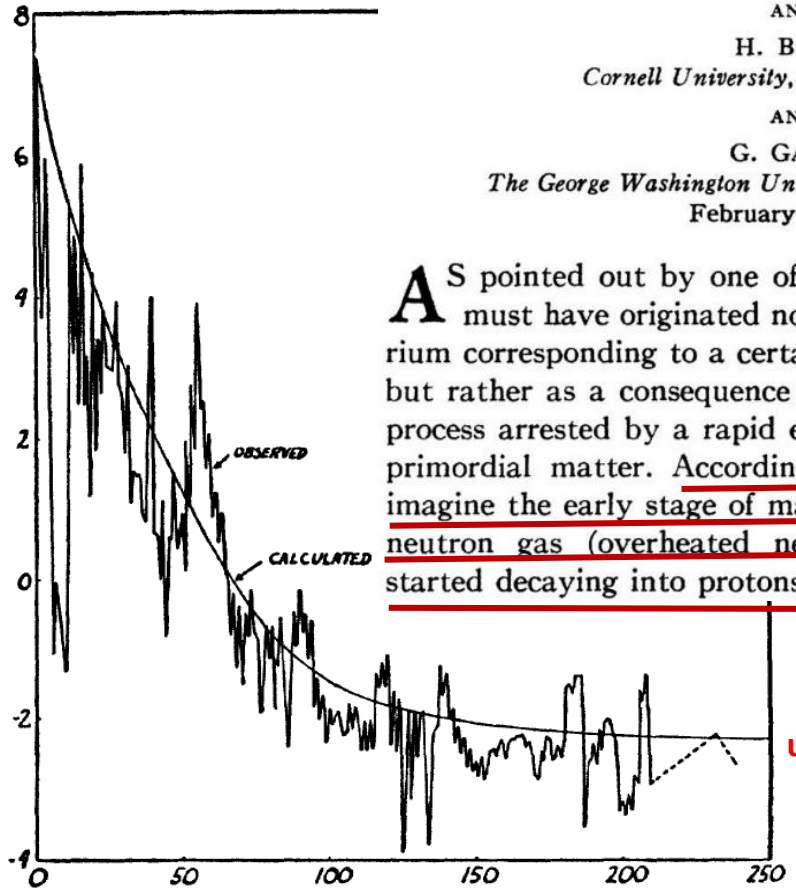
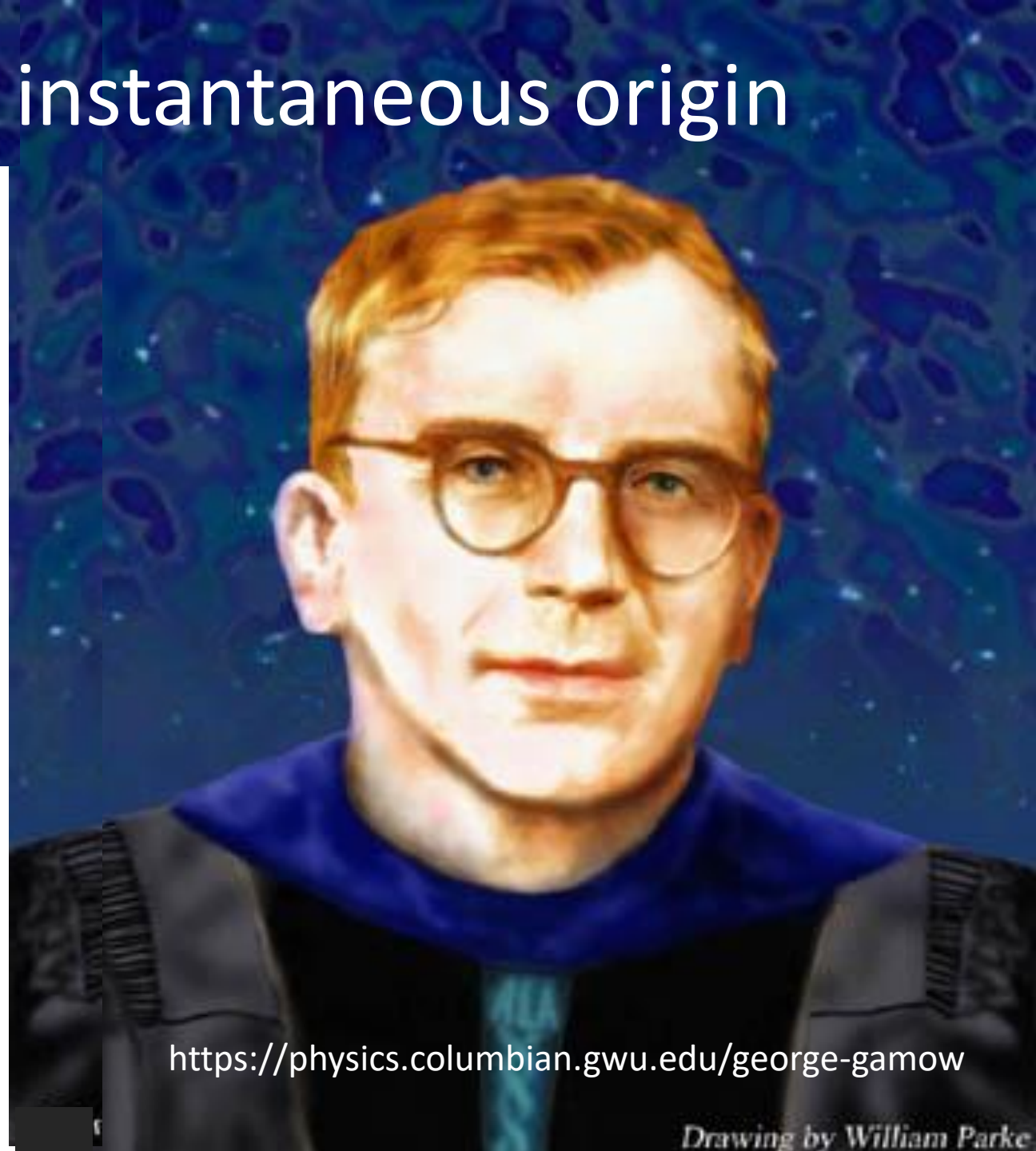
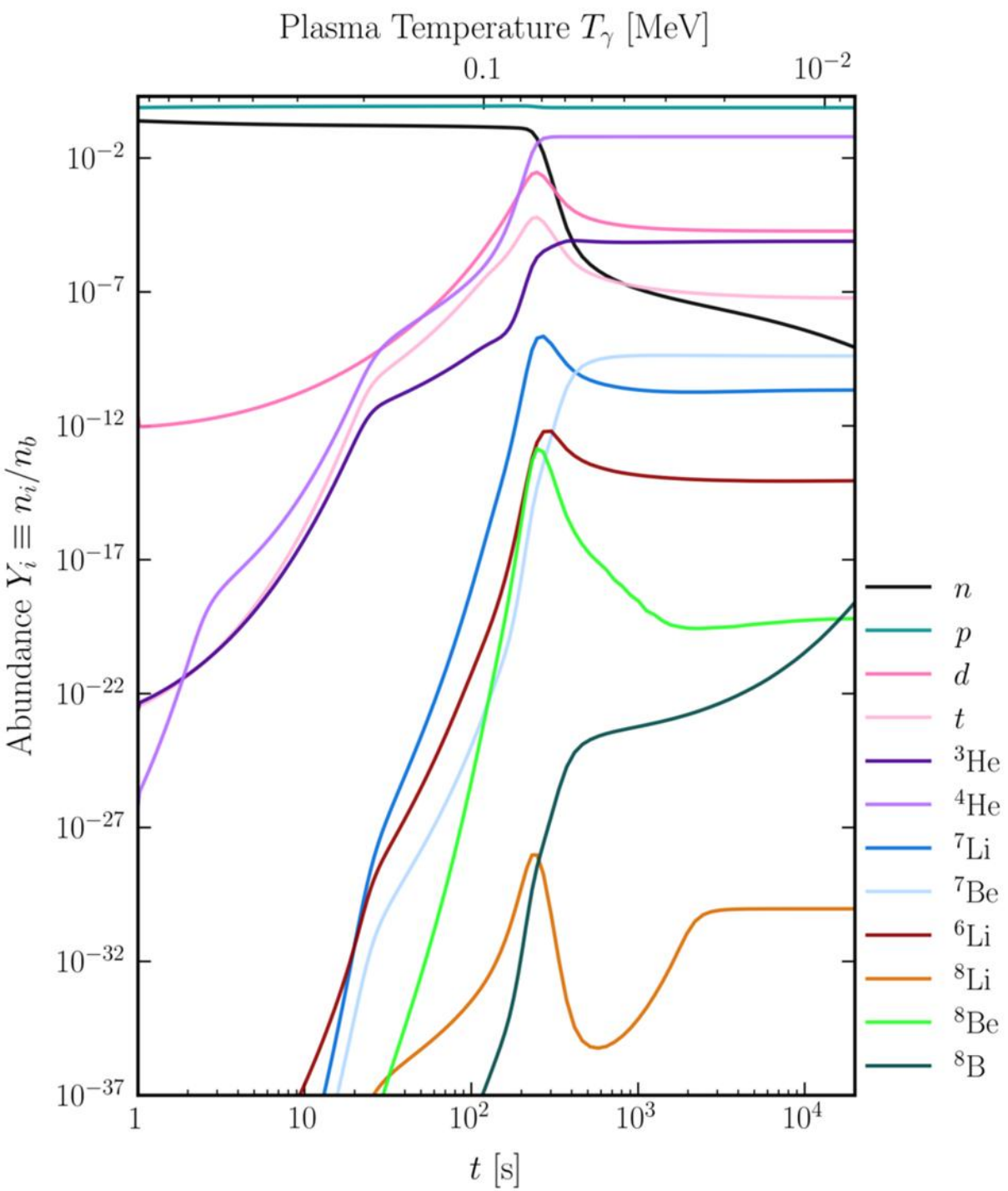


FIG. 1.
Log of relative abundance
Atomic weight

up to Uranium





Neutrons and protons in equilibrium

$$n + \nu_e \leftrightarrow p + e^-$$

$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$

$$\frac{N_n}{N_p} = \exp\left(-\frac{\Delta m c^2}{kT}\right)$$

$$\Delta m = m_n - m_p = 1.293 \text{ MeV}$$

T = 10 MeV $\quad N_n/N_p = 0.88$

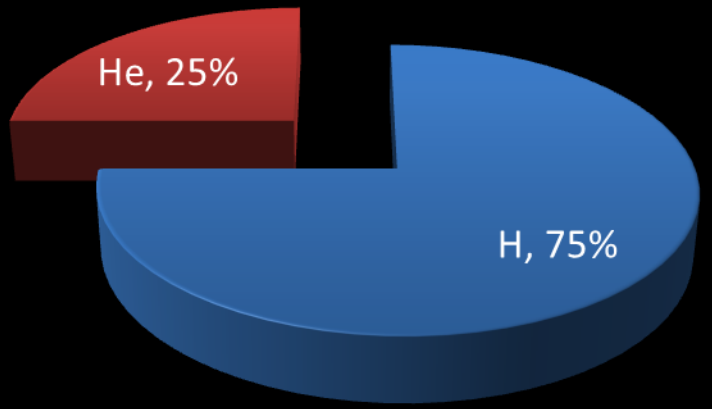
T ~0.8 MeV $\quad \frac{N_n}{N_p} = e^{-1.293/0.8}$ ~ 1/5

After freezing out at T~0.8 MeV, neutron decays to proton until n+p→d+γ

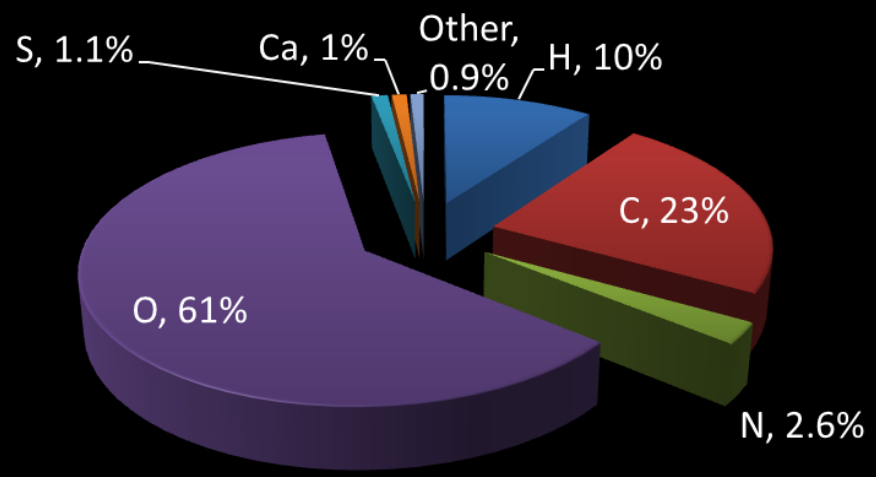
$$\frac{N_n}{N_p} \approx 0.14$$ ~ 1/7

Origin of Elements

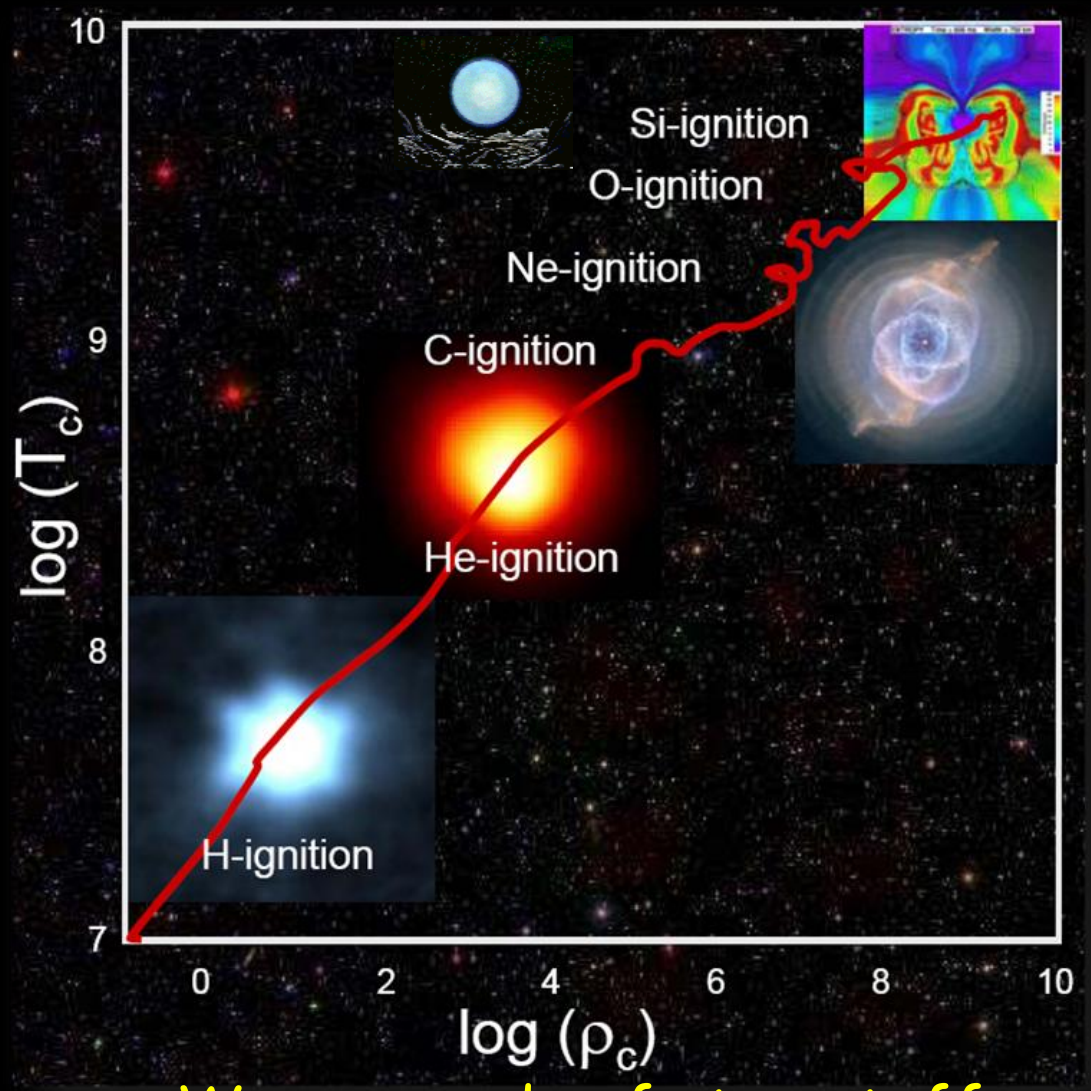
Other isotopes (^{2}H,^{3}He,^{6}Li,^{7}Li)<0.00001



3 mins



13.8 billion years



We are made of star-stuff.

Carl Sagan

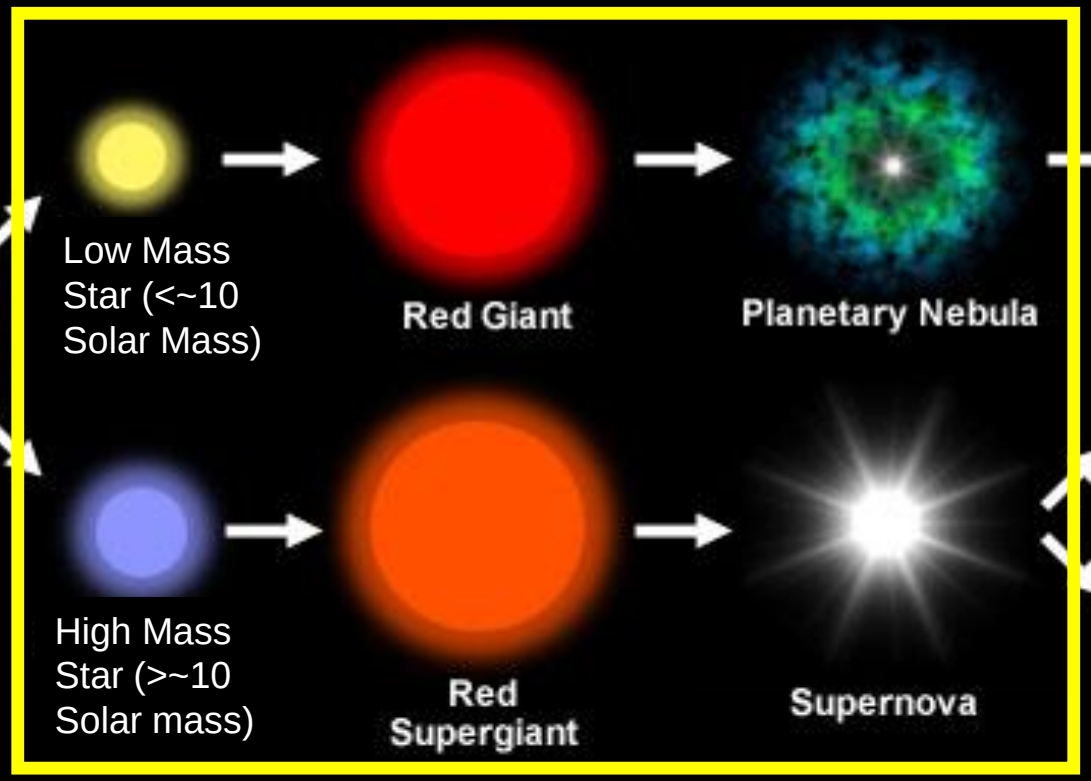
Chemical Element Enrichment

Big Bang

H,
He,
Li

Inter Stellar Matter

0.4 billion years later, first stars appear

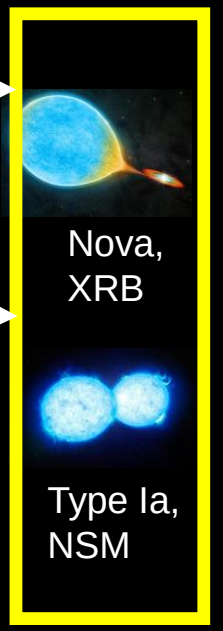


White Dwarf

Neutron Star

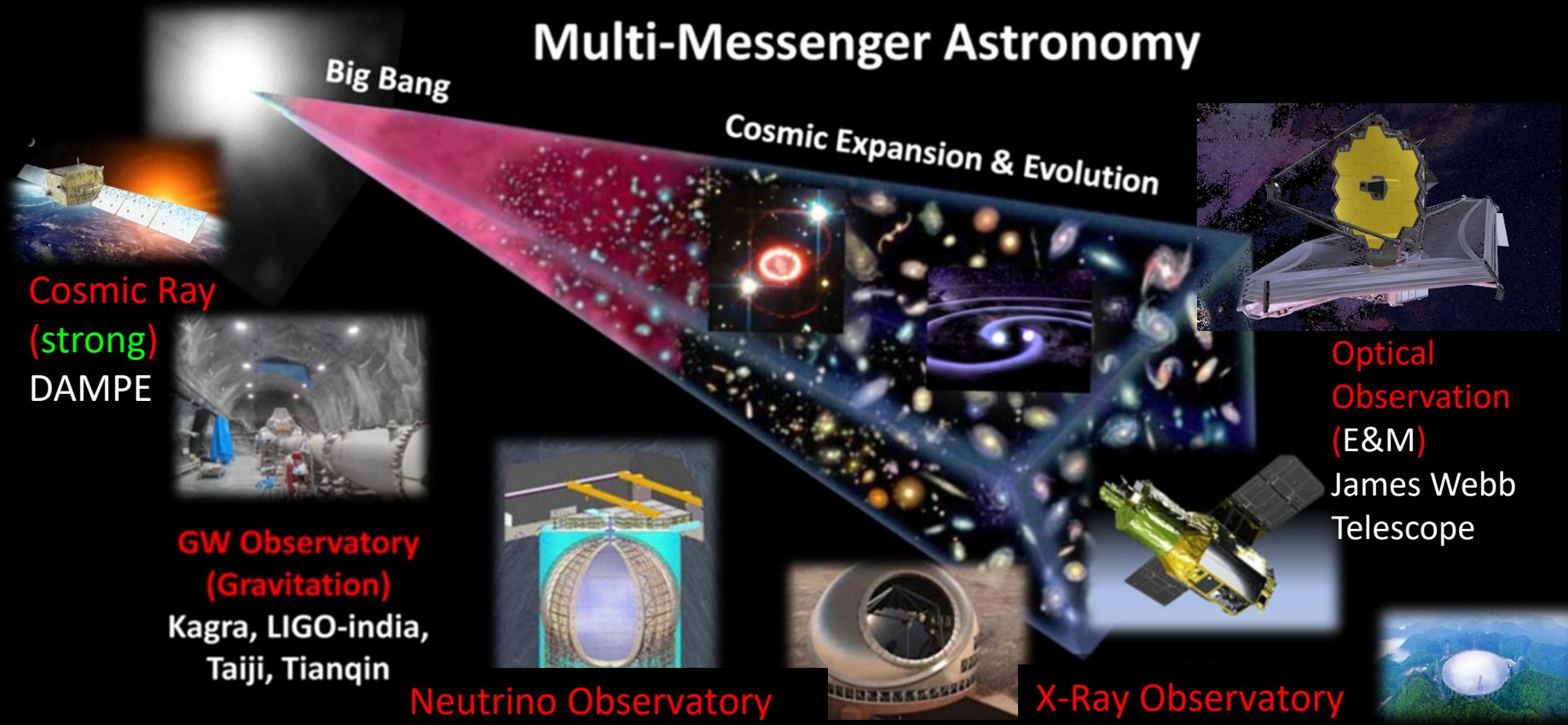
Black Hole

resurrection in binaries !



Nucleosynthetic products（C,O,Si,Fe,…Th, U)

Multi-Messenger Astronomy



Cosmic Ray
(strong)
DAMPE

GW Observatory
(Gravitation)
Kagra, LIGO-india,
Taiji, Tianqin

Neutrino Observatory
(Weak)
Super-K, JUNO,
Hyper-K

Optical Observatory
(E&M)
Subaru, LAMOST,
TMT, GMT

X-Ray Observatory
(E&M)
Chandra,Insight

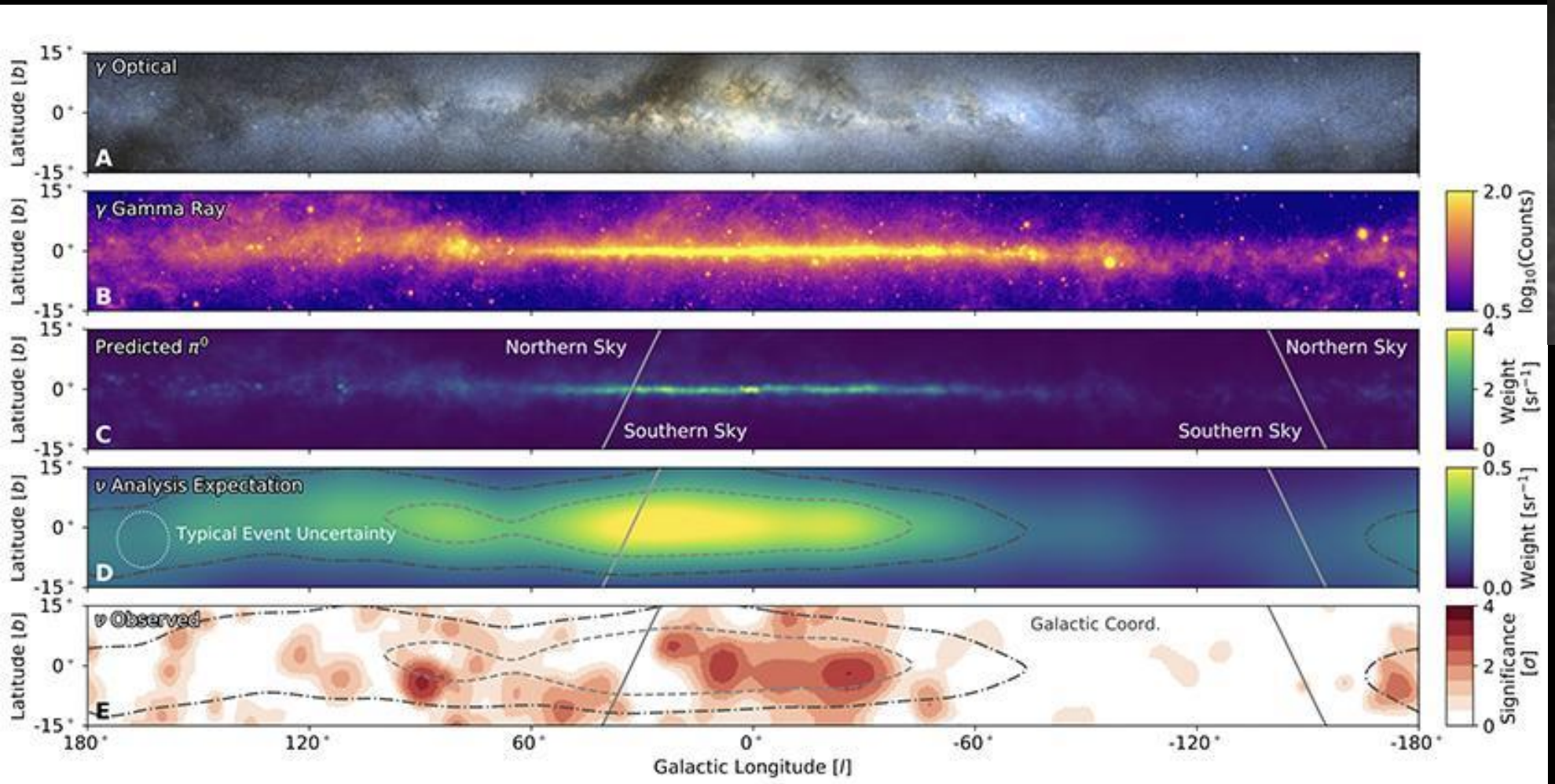
Optical
Observation
(E&M)
James Webb
Telescope

Radio Wave
(E&M)
FAST

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

Observation of high-energy neutrinos from the Galactic plane



A multi-messenger view of the Milky Way galaxy, centered on the Galactic center and viewed in galactic coordinates.

(Credit: IceCube Collaboration)

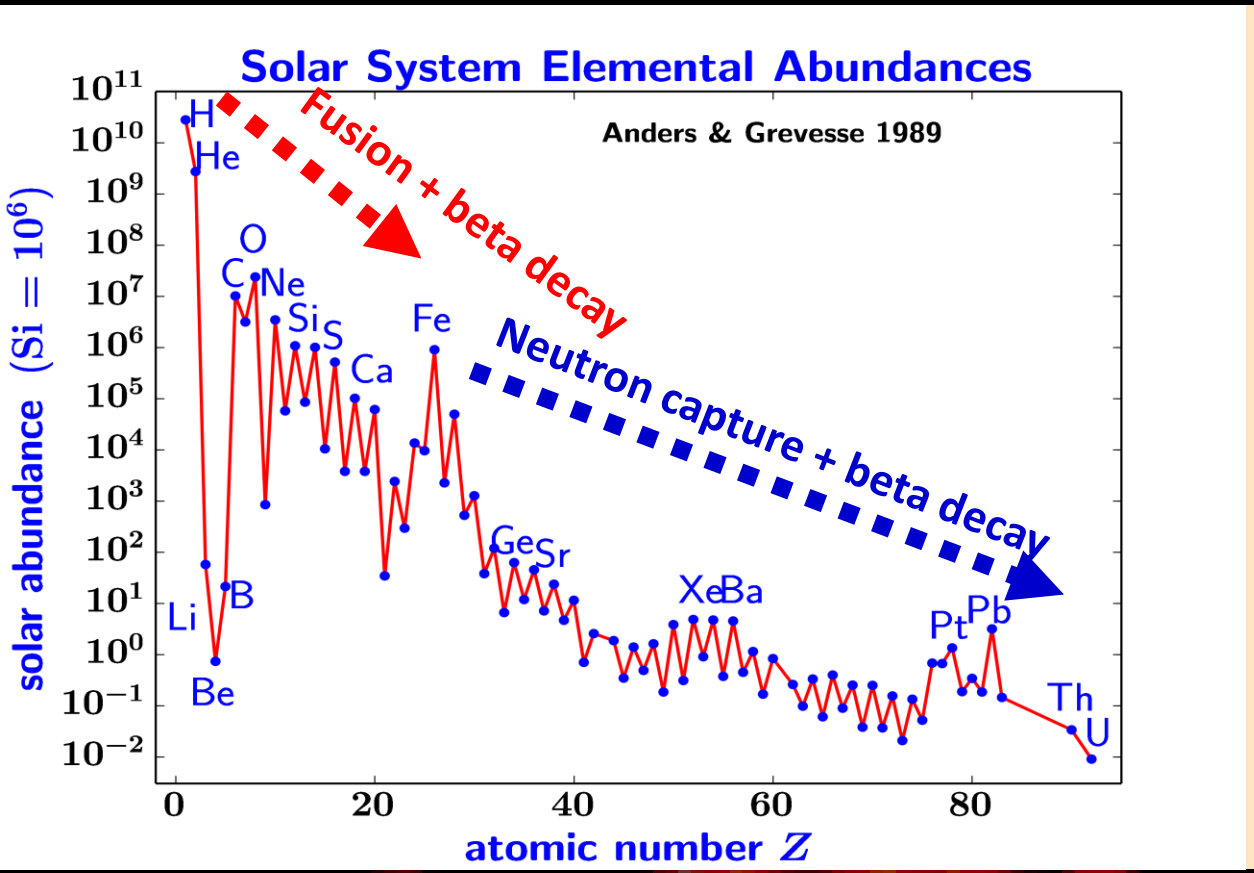
https://arxiv.org/pdf/2307.04427

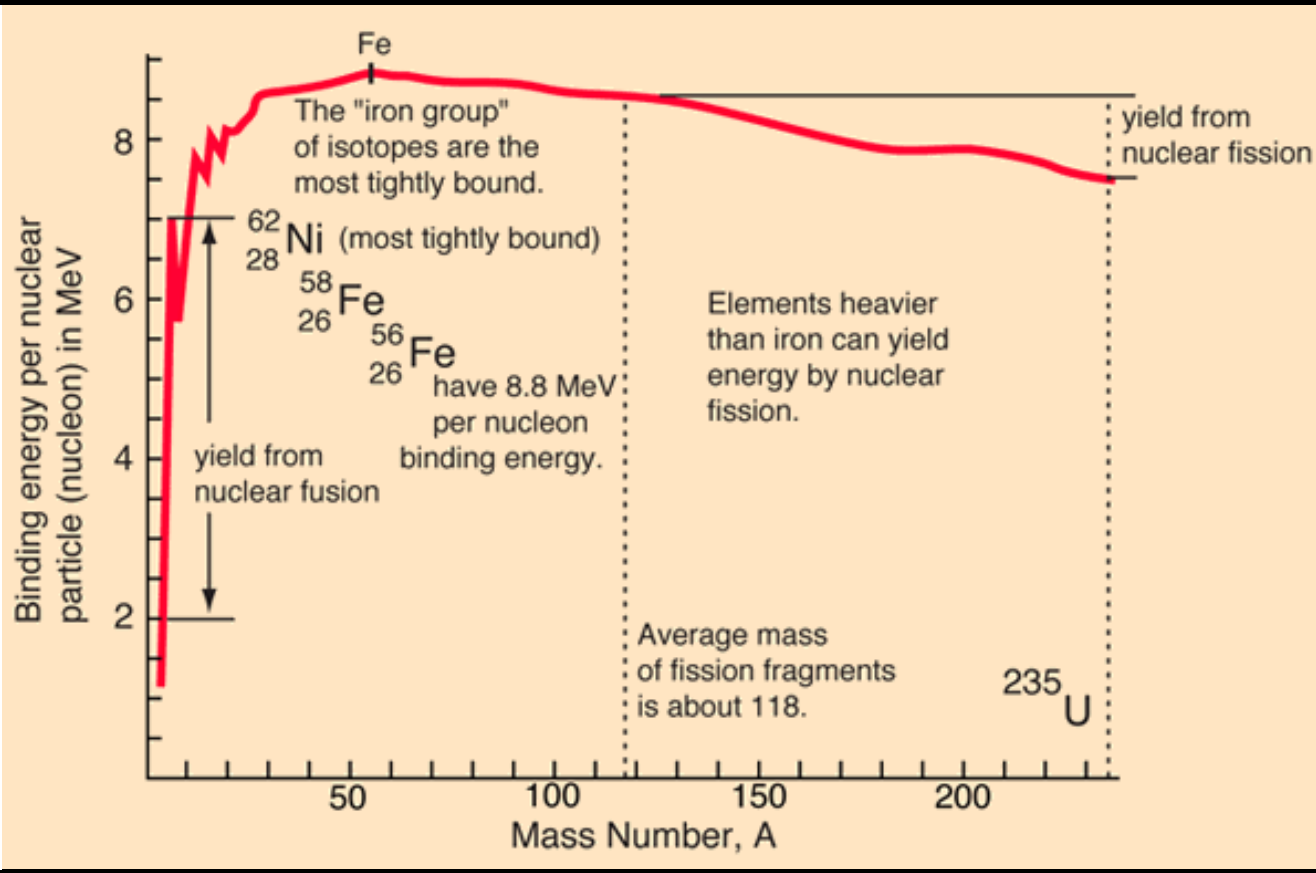


Francis Halzen

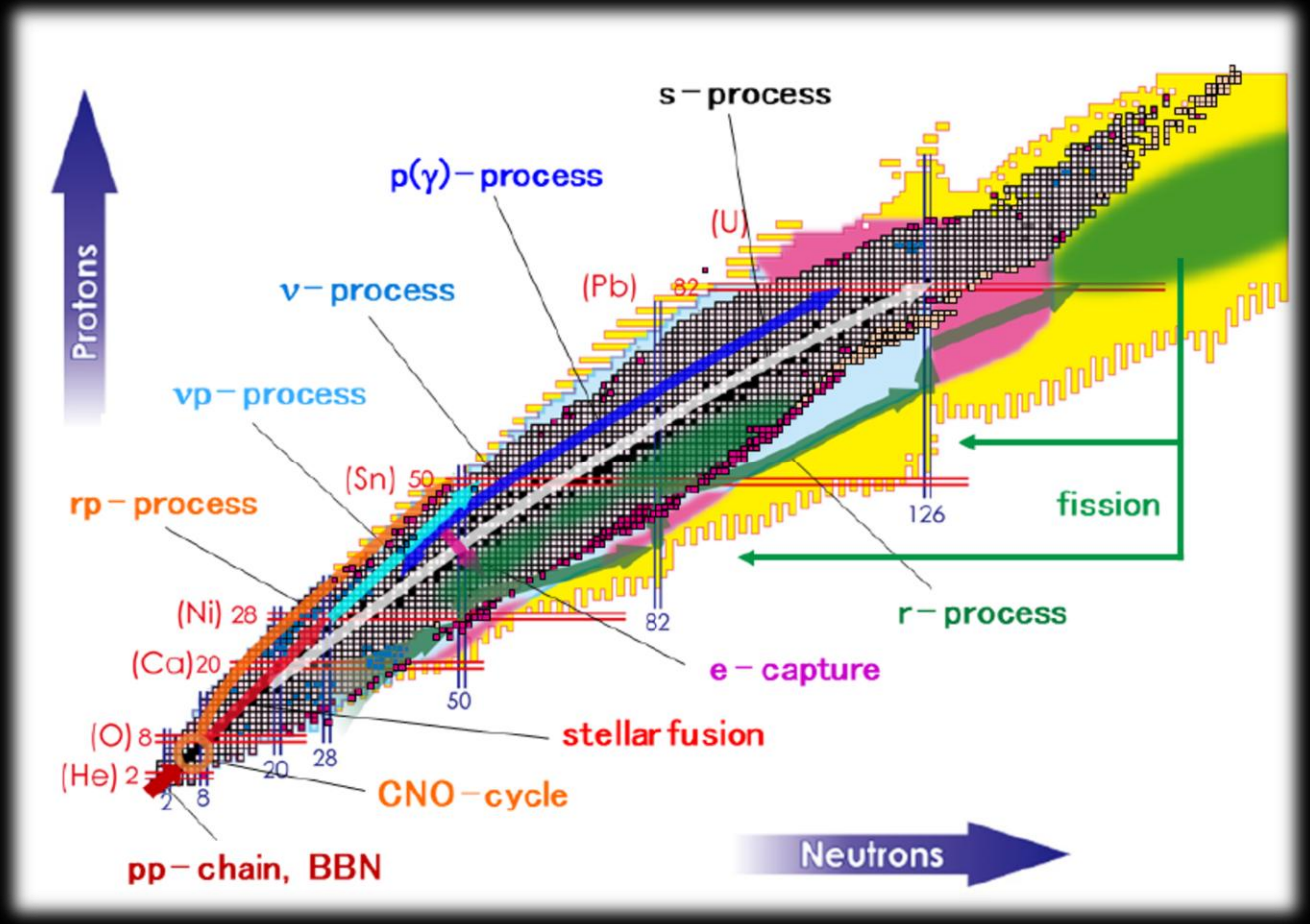
Nobel Prize in Physics 2026:"for decisive contributions to the IceCube Neutrino Observatory and the discovery of high-energy neutrinos of astrophysical origin"

Nuclear Physics : Core of matter, Fuel of stars





Nucleosynthesis in stars



1) Big bang

2) Stellar quiescent burning

(pp-chain, stellar fusion, s-process)

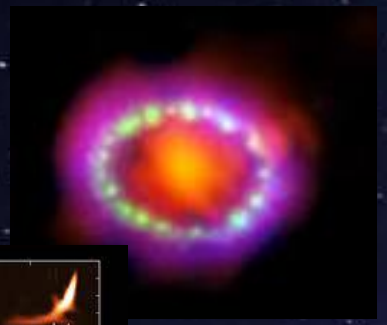
3) Stellar explosive burning

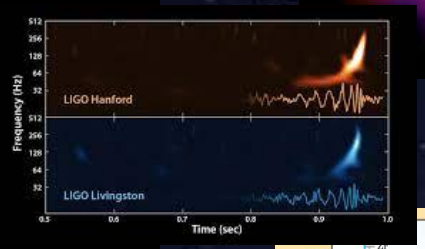
(r-, νp-, ν-, p-, rp-processes)

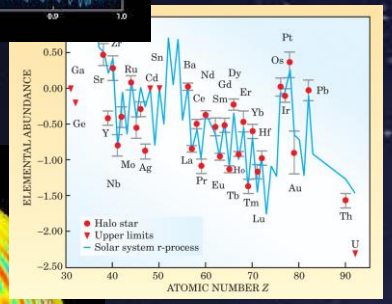
4) Cosmic Ray spallation

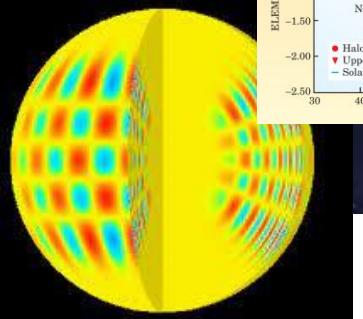
- **What is the origin of the elements in the cosmos?**
- **What are the nuclear reactions that drive the evolution of stars and stellar explosions?**

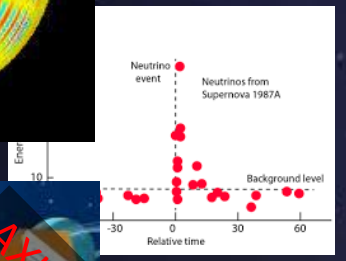
"Progress in Nuclear Astrophysics of East and Southeast Asia", AAPPS bulletin(2021) 31:18



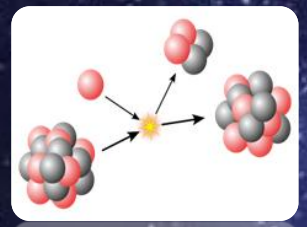






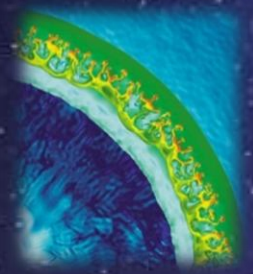






Nuclear Experiment

Nuclear Theory



Nuclear Uncertainty

Model Uncertainty



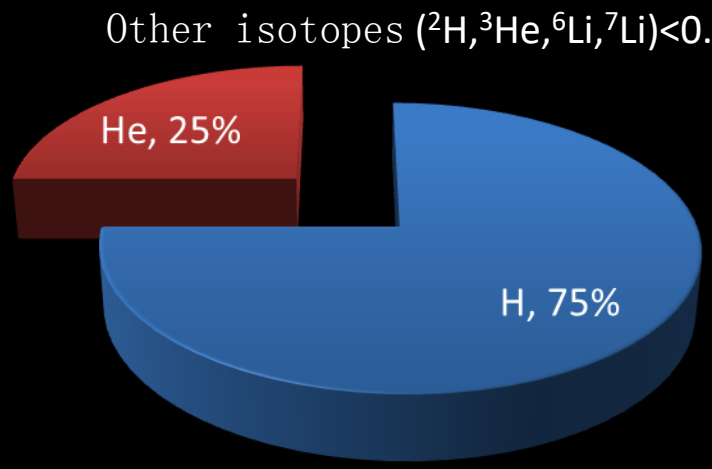
Multi-Messenger

(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.

Group Activity 1: Given Nn/Np = 1/7=2/14, predict the mass ratio of proton to ^{4}He after the Big Bang Nucleosynthesis

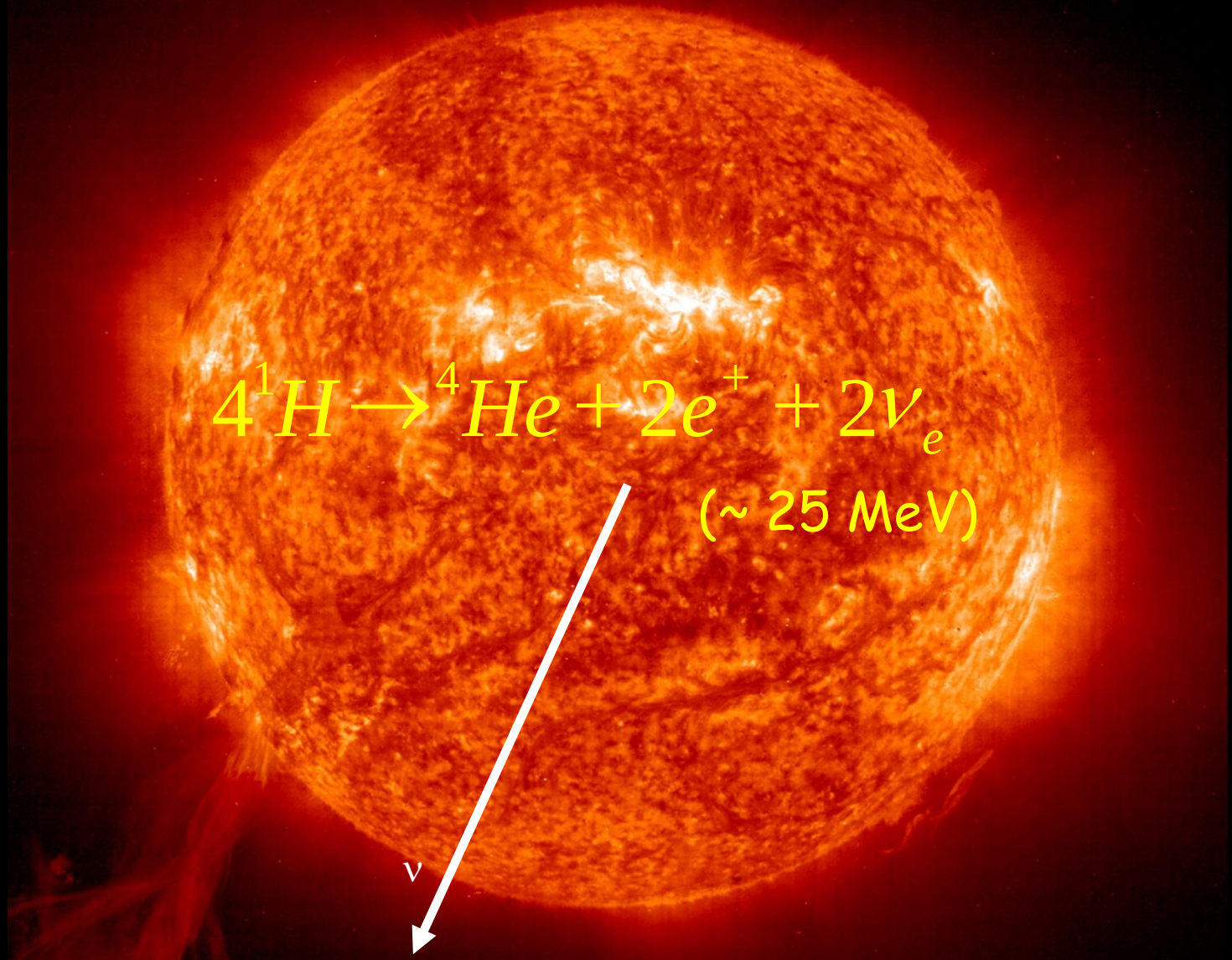




3 mins



First success of Multi-messenger astronomy



pp

$p^+ + p^+ \rightarrow {}^2H + e^+ + \nu_e$

99,77 %

0,23 %

pep

$p^+ + e^- + p^+ \rightarrow {}^2H + \nu_e$

10^{-5} %

84,92 %

$^2H + p^+ \rightarrow {}^3He + \gamma$

$^3He + p^+ \rightarrow {}^4He + e^+ + \nu_e$

hep

15,08 %

$^3He + {}^4He \rightarrow {}^7Be + \gamma$

0,1 %

99,9 %

^7Be

$^7Be + e^- \rightarrow {}^7Li + \nu_e$

$^7Be + p^+ \rightarrow {}^8B + \gamma$

^8B

$^3He + {}^3He \rightarrow {}^4He + 2p^+$

ppI

$^7Li + p^+ \rightarrow {}^4He + {}^4He$

ppII

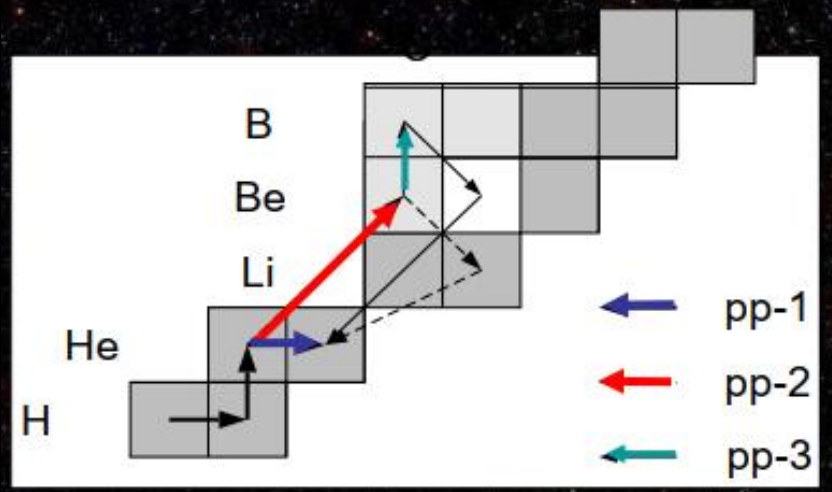
$^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

$^8Be^* \rightarrow {}^4He + {}^4He$

ppIII



Neutrino production & neutrino energy



Neutrino production reaction

$p + p \Rightarrow {}^2H + e^+ + \nu_e$	E= 0.0 to 0.4 MeV
$p + e^- + p \Rightarrow {}^2H + \nu_e$	E= 1.4 MeV
$e^- + {}^7Be \Rightarrow {}^7Li + \nu_e$	E= 0.86, 0.38 MeV
${}^8B \Rightarrow {}^8Be + e^+ + \nu_e$	E= 0.0 to 15 MeV

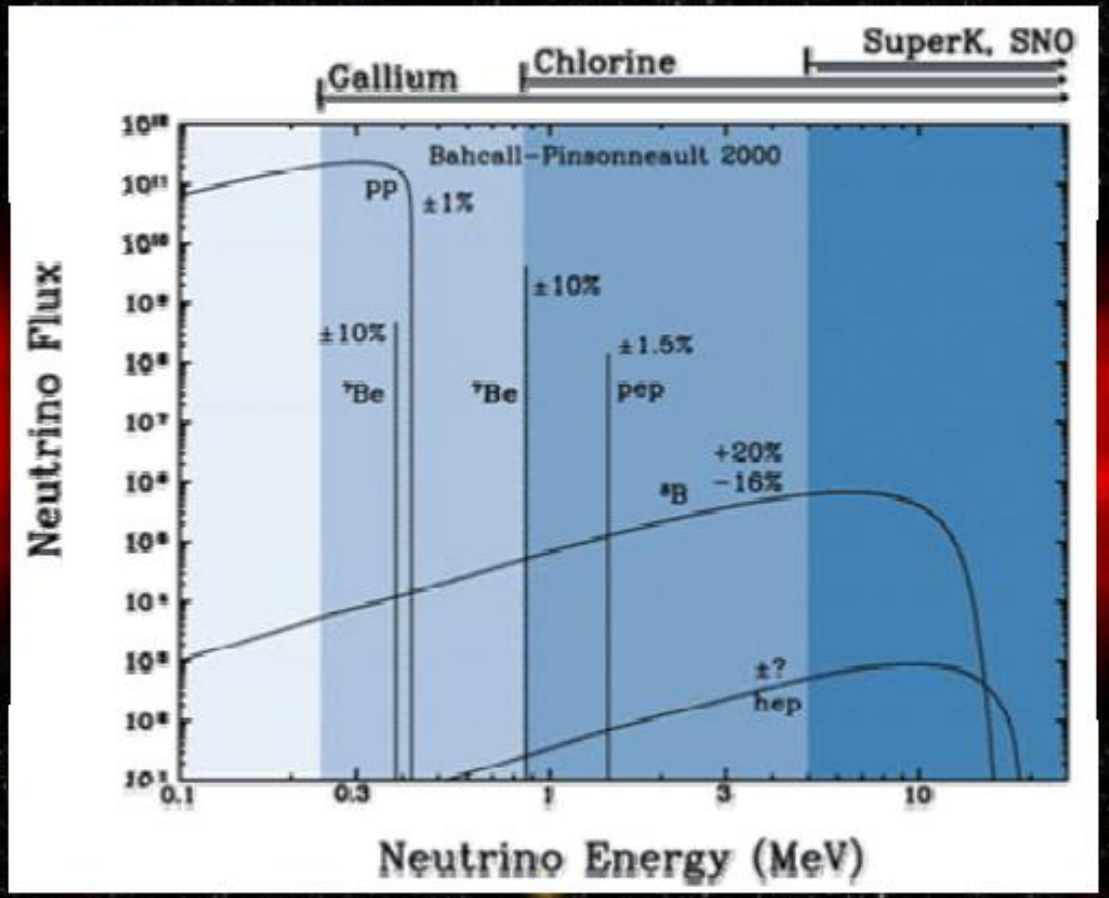
Neutrino flux in different energies depends on pp-chain branchings determined by the associated reaction rates:

- ${}^1H+{}^1H$ versus ${}^1H+e^-$ determines neutrino flux at 1.4 MeV
- ${}^3He+{}^3He$ versus ${}^3He+{}^4He$ determines neutrino flux above 0.4 MeV
- ${}^7Be+p$ versus ${}^7Be+e^-$ determines neutrino flux above 0.9 MeV

Solar Neutrino Production



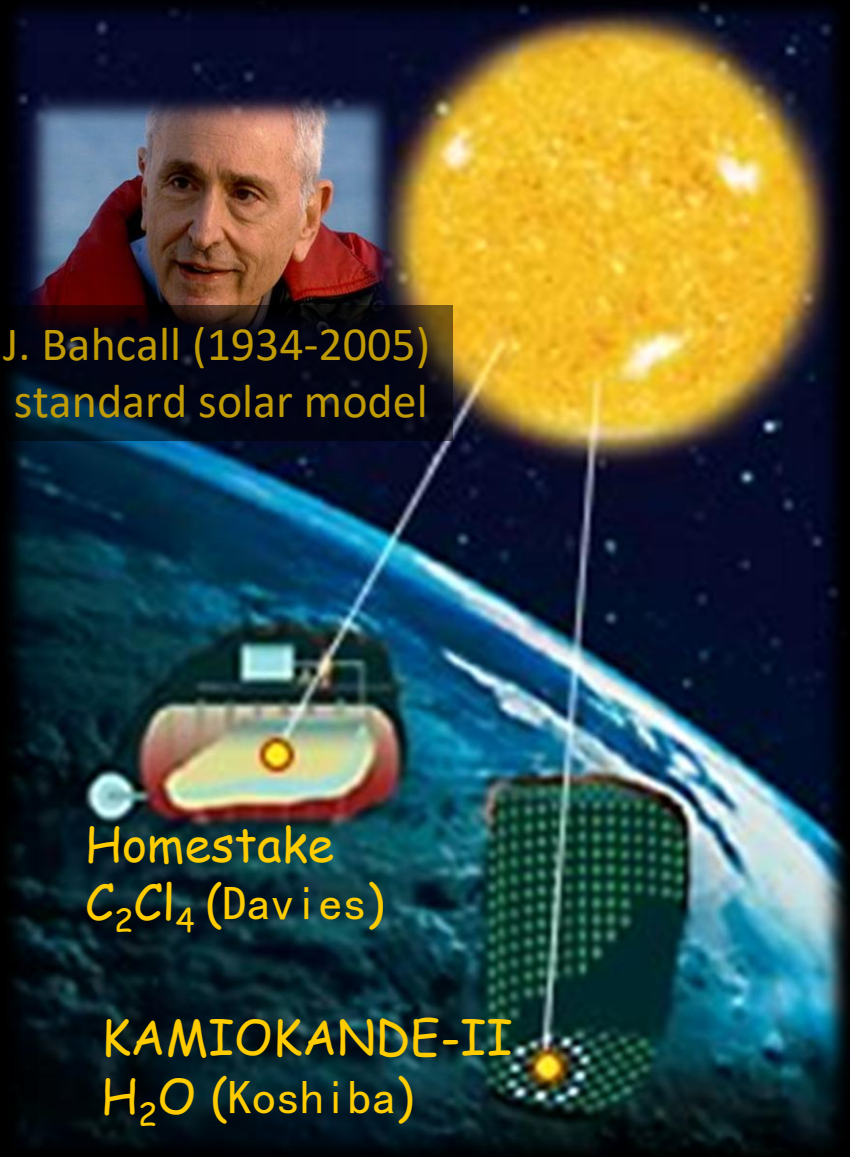
J. Bahcall (1934-2005)
standard solar model



Neutrinos as signature for probing the solar core

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: $^{3}He(^{3}He,2p)^{4}He$, $^{3}He(^{4}He,\gamma)^{7}Be$, $^{7}Be(p,\gamma)^{8}B$
- 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 ^{8}B neutrinos to within a factor of 2 or 3..."

Howard Georgi and Michael Luke (1990)

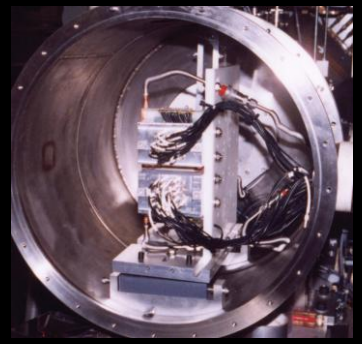
S factor of $^{7}Be(p,\gamma)^{8}B$



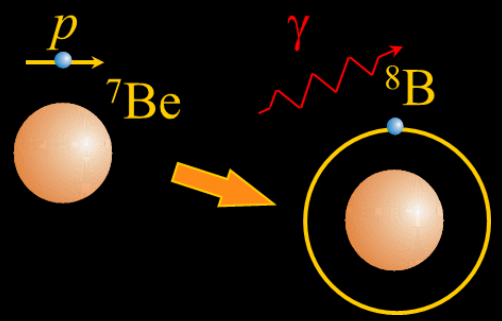
Direct measurement (<MeV/u)

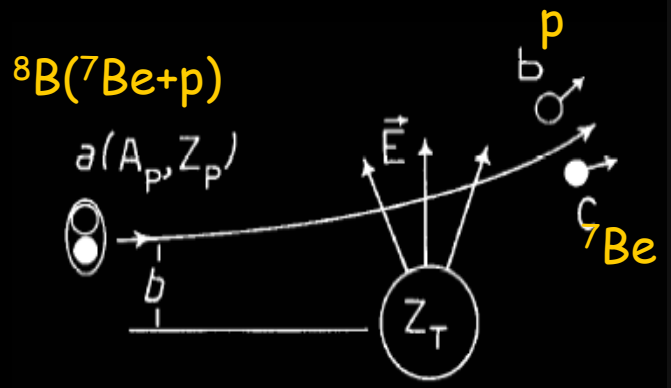


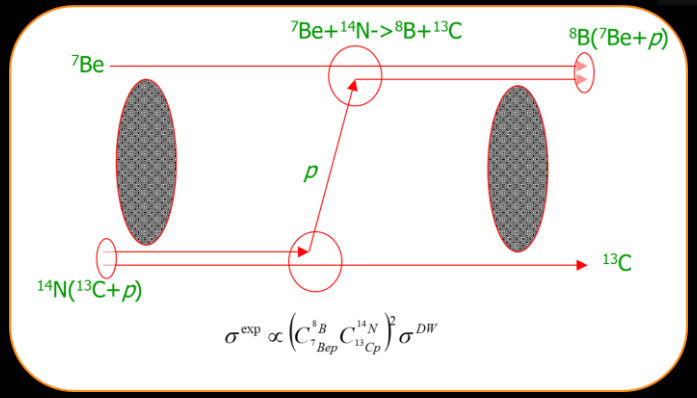
Coulomb Dissociation (~100 Mev/u)

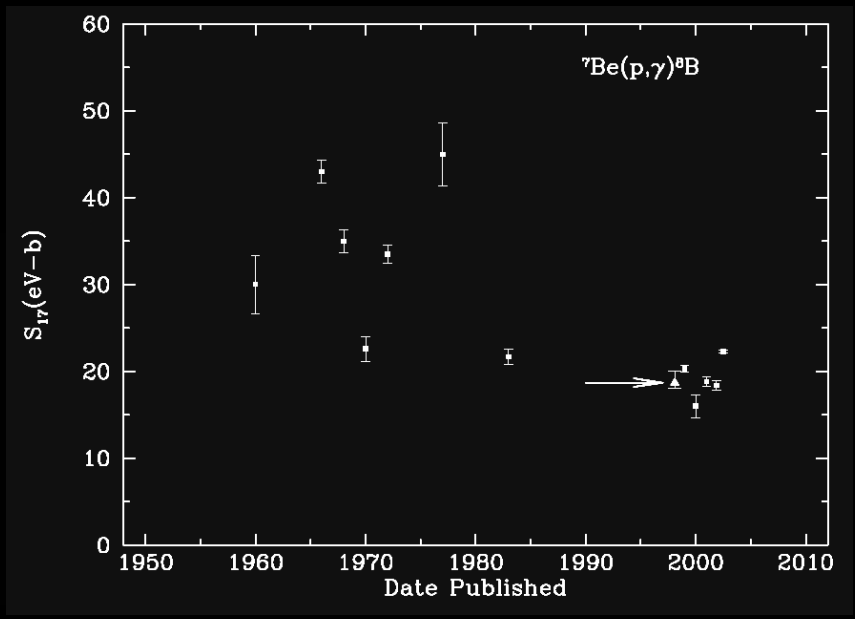


Asymptotic Normalization Coefficient (ANC) (<10MeV/u)



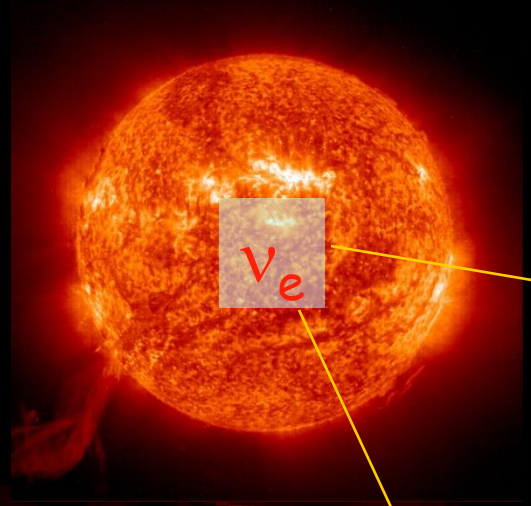






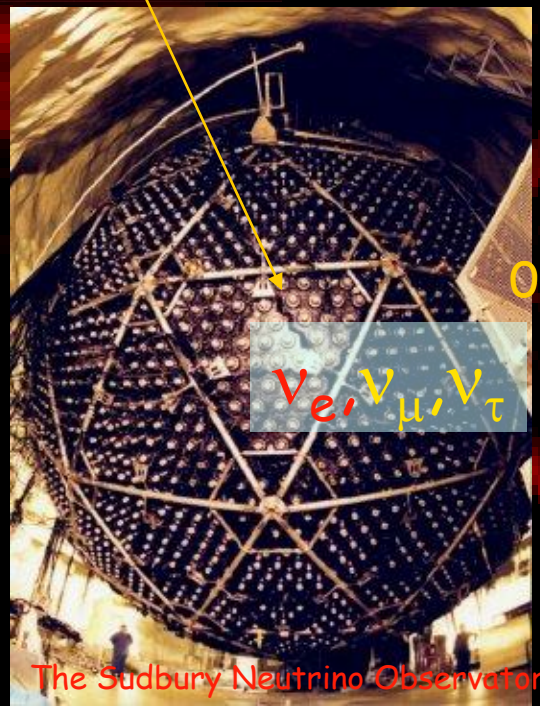
$S_{17}(0) = 20.5(7)$ eV

Neutrino Oscillation





0.57*Solar Model



0.32*Solar Model



Discovery of neutrino oscillations
Nobel Prize(2015)

^{8}B Fluxes at SNO (2001)

(10^6 cm^{-2} s^{-1})

ν_e:	1.75±0.15
$\nu_{\mu\tau}$:	3.69±1.13
ν_{total}:	5.44±0.99
ν_{SSM}:	5.05+1.01/-0.81



1964



2003

For three decades people had been pointing at this guy and saying this is the guy who wrongly calculated the flux of neutrinos from the sun, and suddenly that wasn't so. It was like a person who had been sentenced for some heinous crime, and then a DNA test is made and it's found that he isn't guilty. That's exactly the way I felt.

John Bahcall (1934-2005), Dancing with neutrinos

Cross section

cross section depends sensitively on:

- **type of interaction (strong>electromagnetic>weak)**
- **properties of the nuclei involved**
- **reaction mechanism**

and can vary by orders of magnitude, depending on the interaction

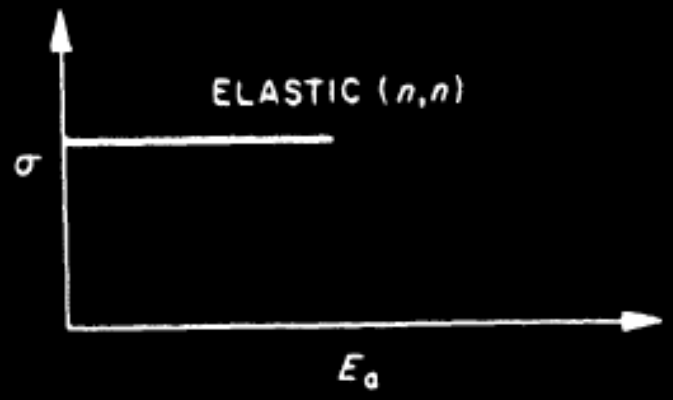
examples:

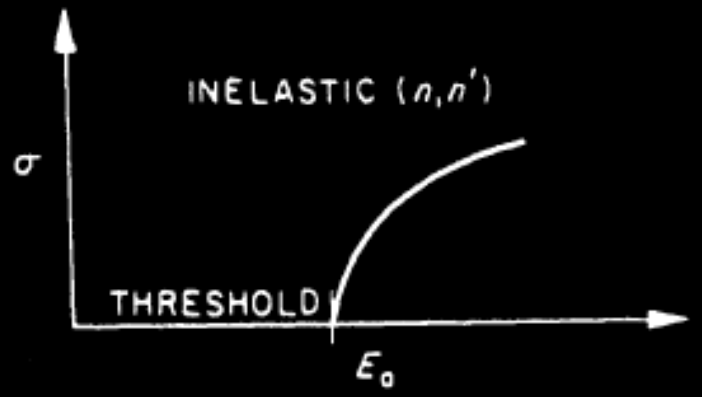
Reaction	Force	σ (barn)	E_{proj} (MeV)
$^{15}N(p,\alpha)^{12}C$	strong	0.5	2.0
$^{3}He(\alpha,\gamma)^{7}Be$	electromagnetic	10^{-6}	2.0
$p(p,e^{+}\nu)d$	weak	10^{-20}	2.0

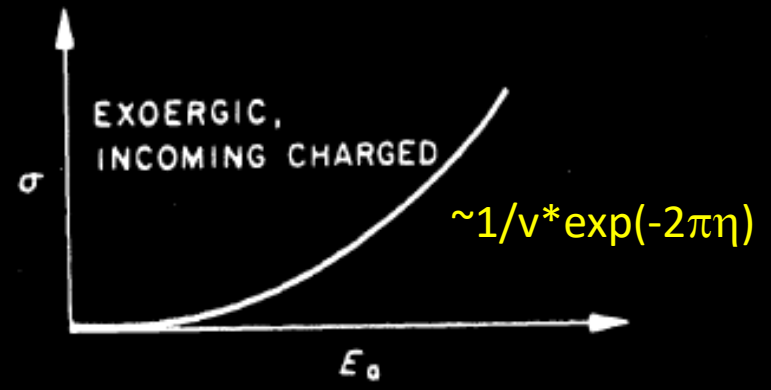
Courtesy of M. Aliota

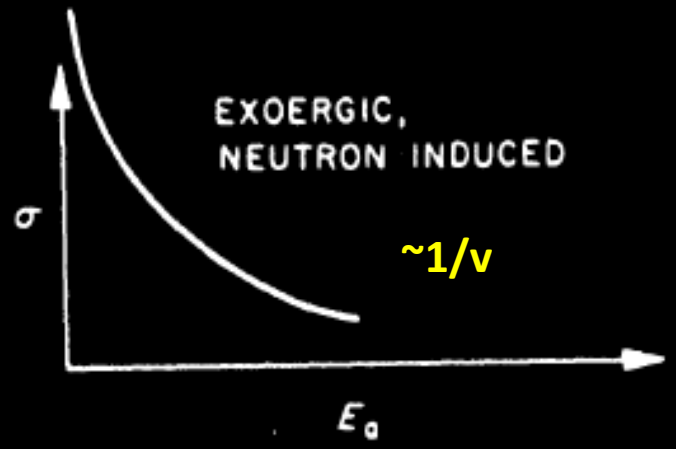
1 barn = 10^{-24} cm^2 = 100 fm^2

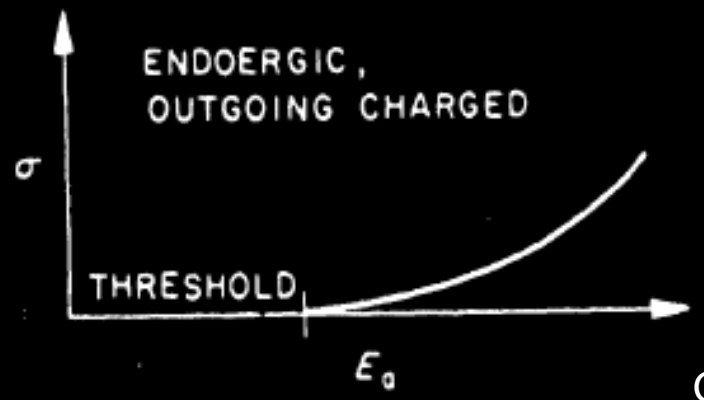
Behavior of cross section near threshold









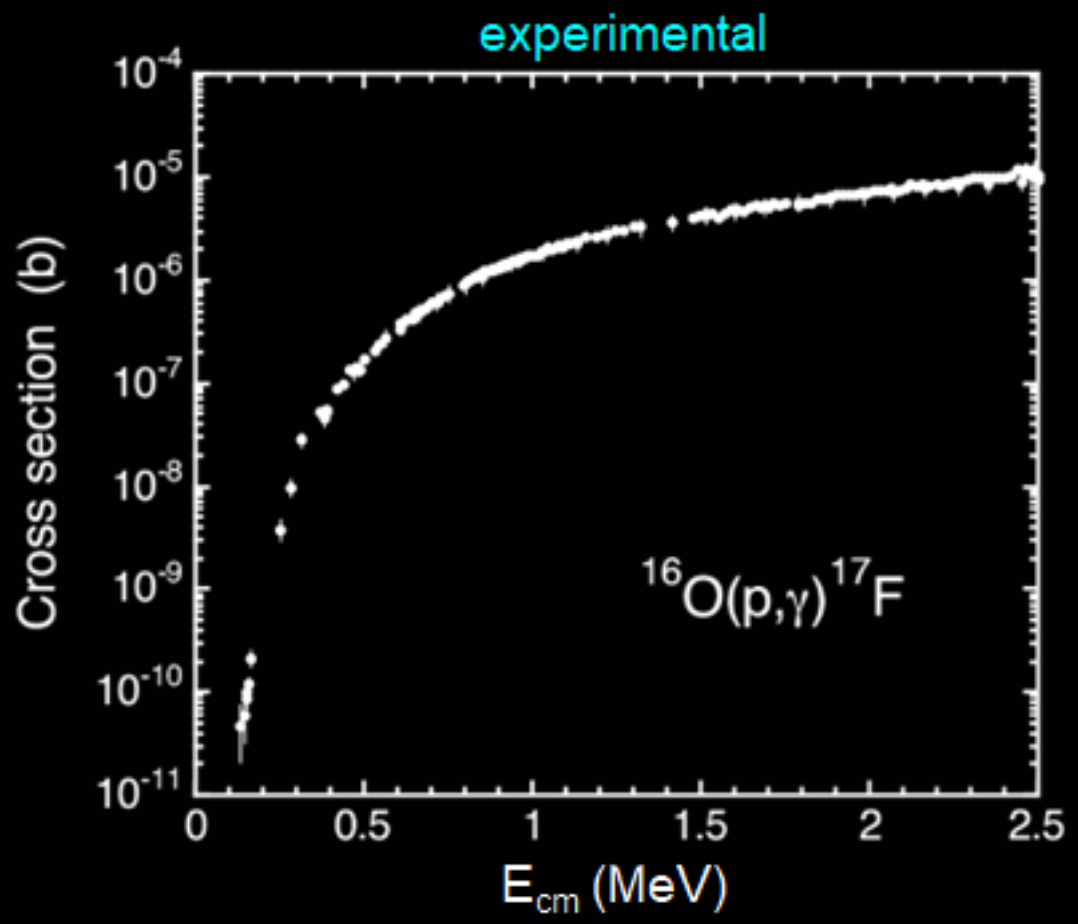


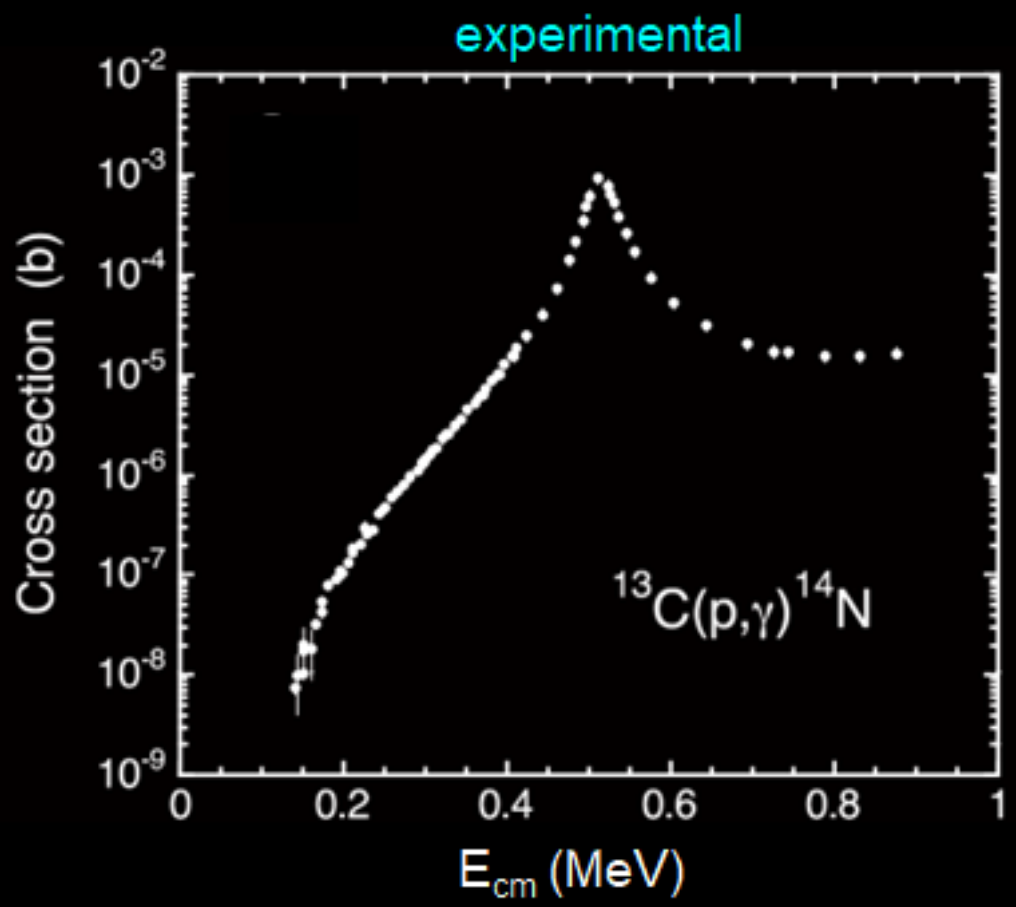
$$2\pi\eta = 0.989534 Z_0 Z_1 \sqrt{\frac{1}{E}\frac{M_0 M_1}{M_0 + M_1}}$$

η is the Sommerfeld parameter
E is the energy in MeV
M_i is in the unit of amu

G.R. Satchler, Introduction to nuclear reactions
E. Segre, Nuclei and particles

Cross section (Charged particle induced Reaction)





Experimental and theoretical nuclear astrophysics: the quest for the origin of the elements*

William A. Fowler

W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

Ad astra per aspera et per ludum

TABLE I.

DEFINITION OF THE S FACTOR (BETHE, 1967)
AS A FUNCTION OF REACTION ENERGY (E)

$\sigma(E) = \pi\lambda\!\!\!^{-2} \times P \times$ INTRINSIC NUCLEAR FACTOR

$\pi\lambda\!\!\!^{-2} \propto E^{-1}$ $\quad\quad$ $\lambda\!\!\!^{-}$ = DE BROGLIE WAVELENGTH/2π

$P(E)$ = GAMOW PENETRATION FACTOR

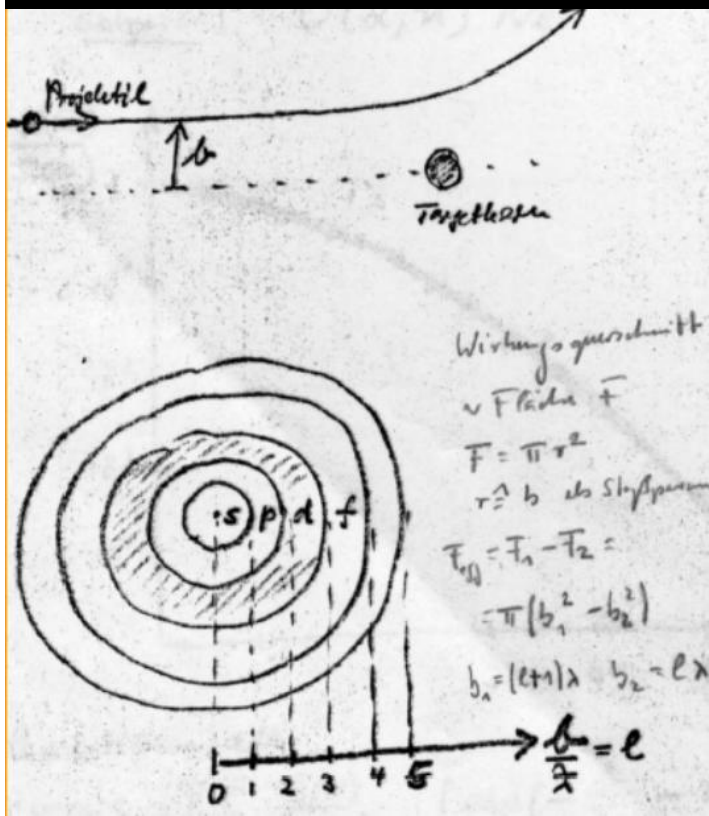
$\propto \exp(-E_G^{1/2}/E^{1/2})$ $\quad\quad$ $E_G \approx Z_0^2 Z_1^2 A$ MeV

$S(E) \equiv E\sigma(E) \exp(+E_G^{1/2}/E^{1/2})$

S(E) {
- PERMITS MORE PRECISE EXTRAPOLATION FROM
- LOWEST ENERGY MEASUREMENTS IN LABORATORY
- TO VERY LOW EFFECTIVE STELLAR ENERGIES
}

s-wave !

Large Z,A, lower penetration factor



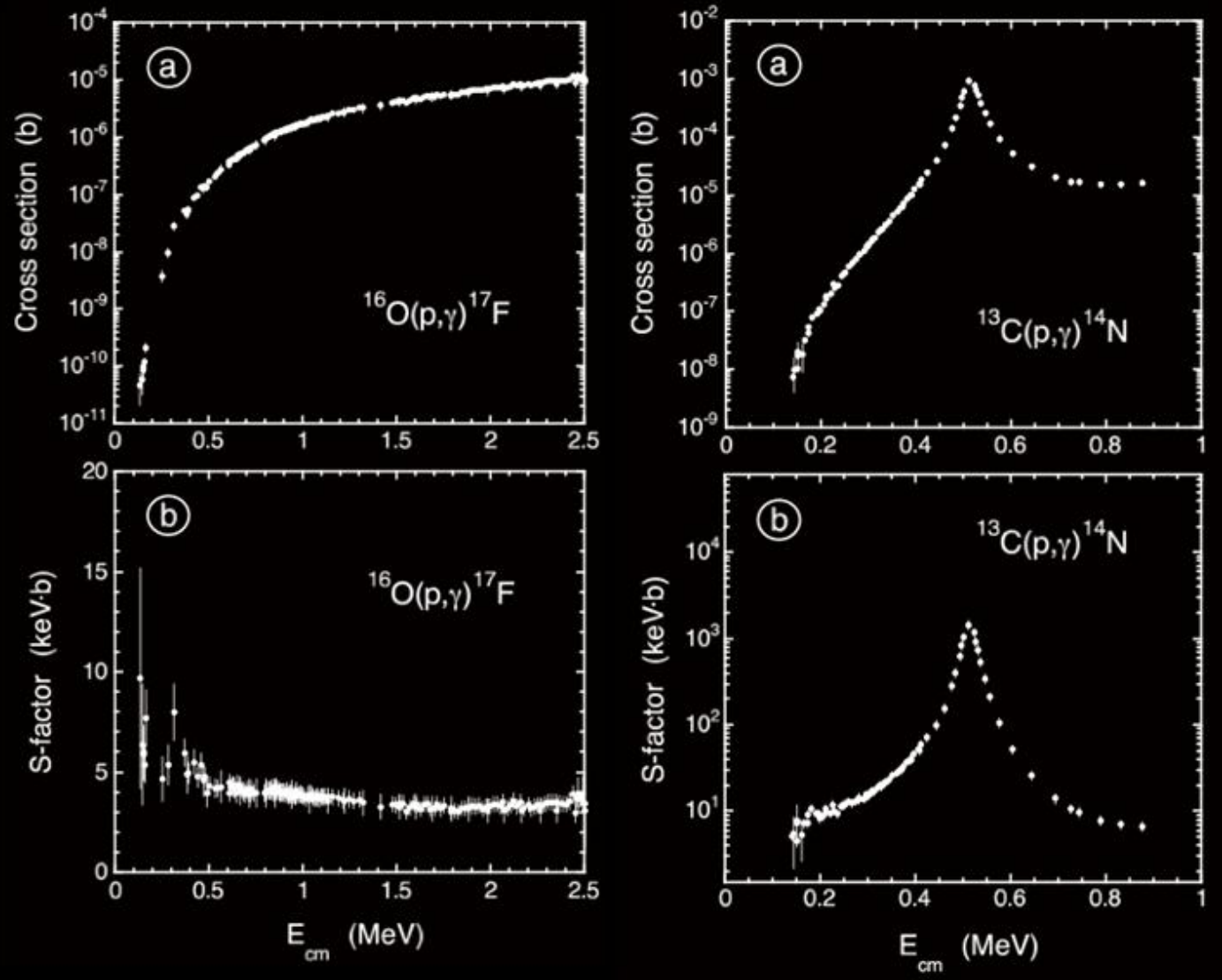
S factor: complication of nuclear structure

$$\sigma(E) \equiv \frac{1}{E} e^{-2\pi\eta} S(E)$$

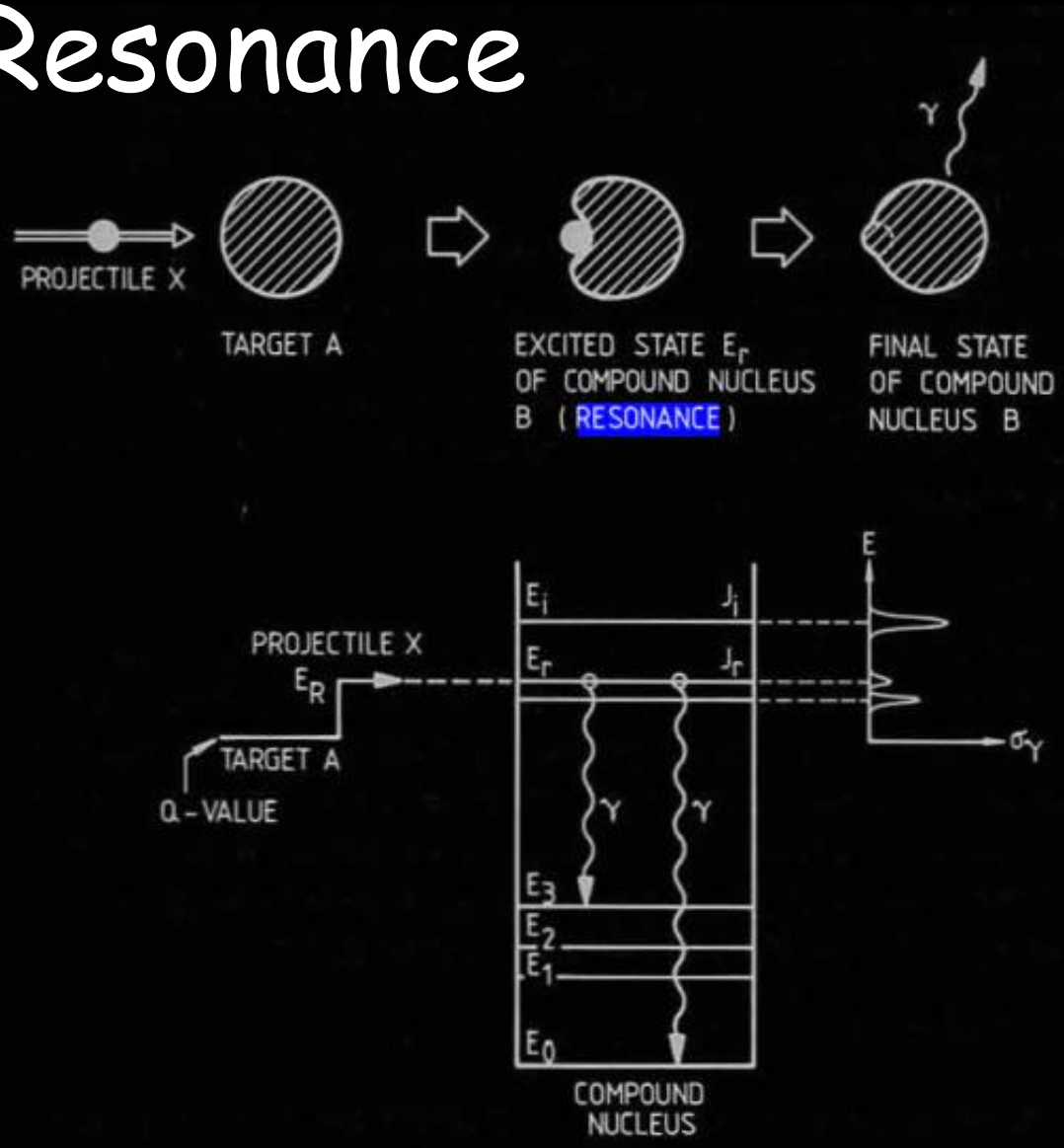
"astrophysical S-factor"

$$\eta = 0.157489 \cdot Z_p Z_t \sqrt{\frac{M_p M_t}{M_p + M_t} \frac{1}{E}}$$

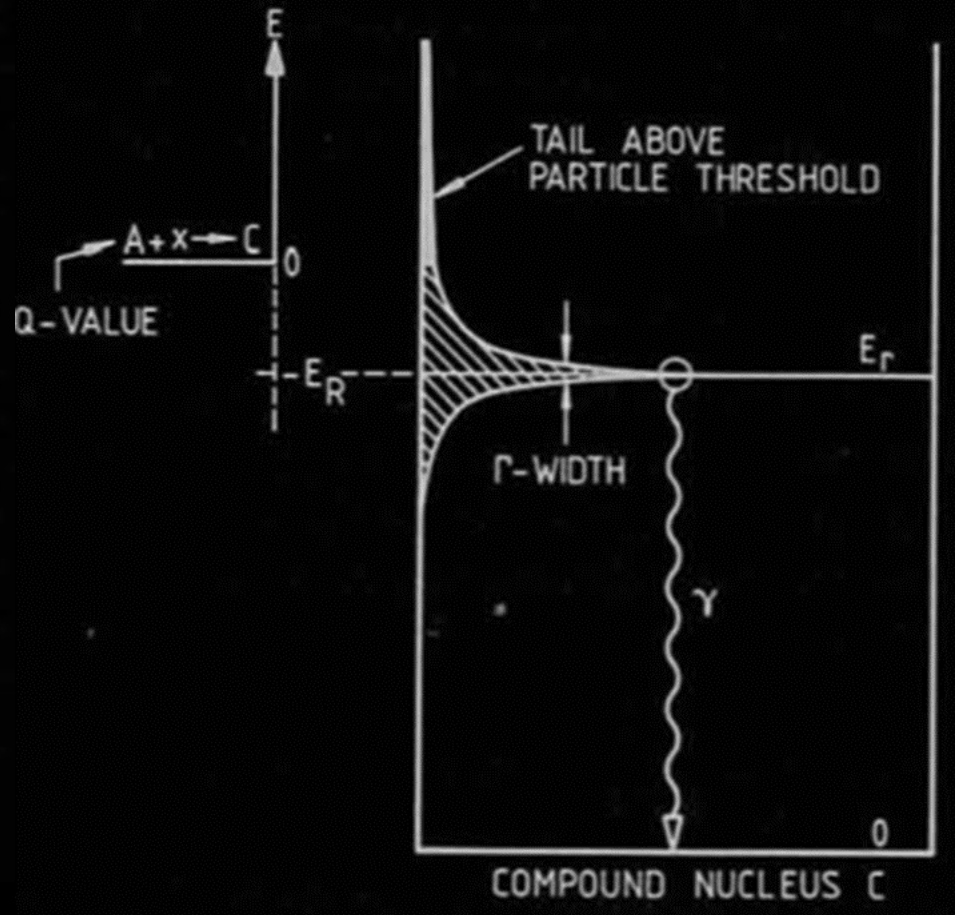
where M_i, E and r are in units of u, MeV and fm, respectively.



Resonance



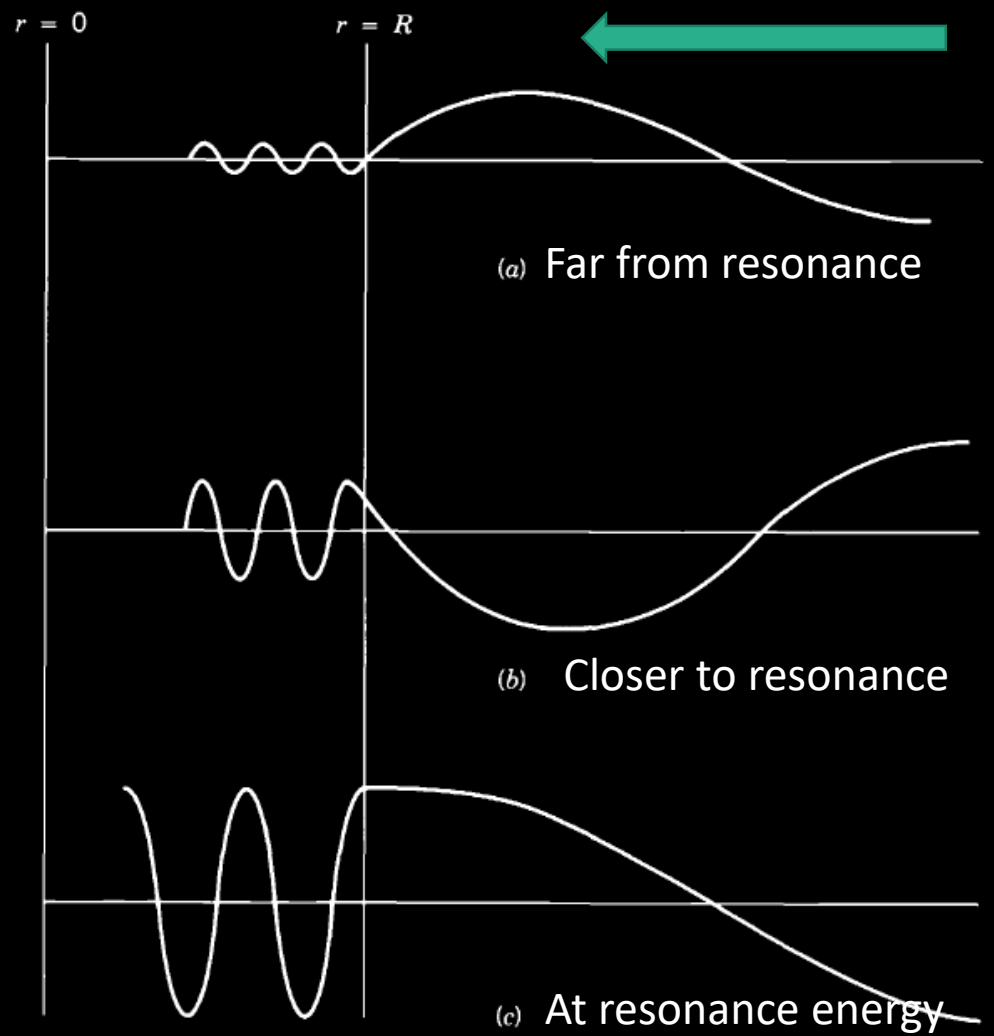
Resonance above the threshold



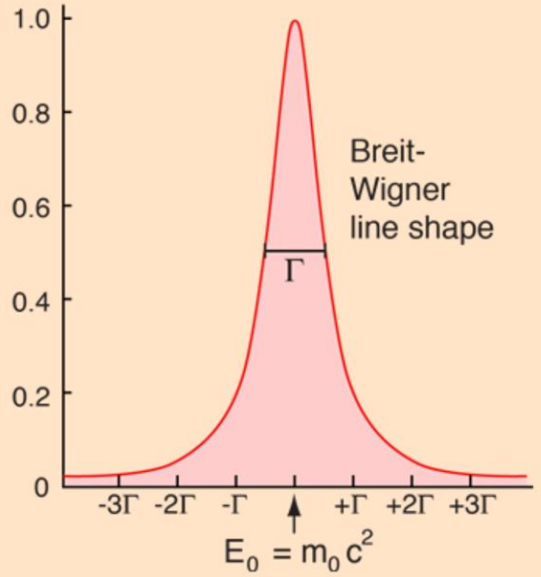
Sub-threshold Resonance

Resonance

$\Gamma\tau = \hbar$



Particle lifetimes from the uncertainty principle



The Breit-Wigner distribution is similar to a gaussian near the peak, but the tails of the curve are flatter.

The uncertainty principle provides a tool for characterizing the very short-lived products produced in high energy collisions in accelerators. The uncertainty principle in the form

$$\Delta E \Delta t > \frac{\hbar}{2}$$

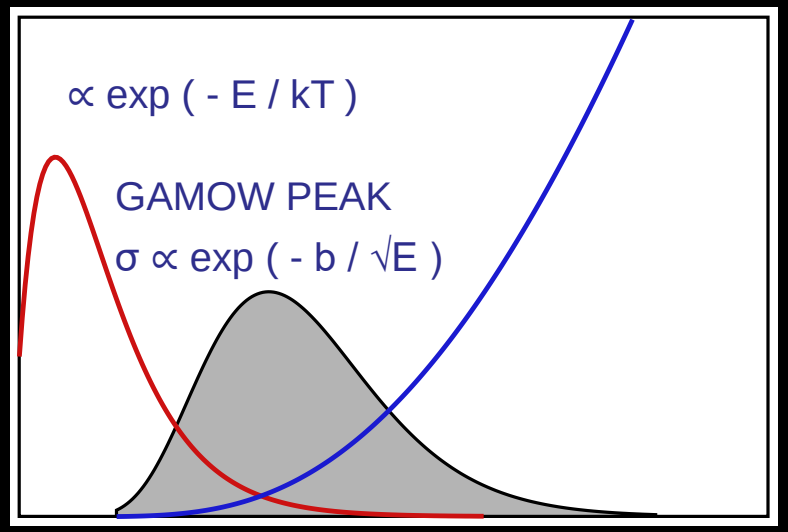
suggests that for particles with extremely short lifetimes, there will be a significant uncertainty in the measured energy. The measurment of the mass energy of an unstable particle a large number of times gives a distribution of energies called a Lorentzian or a Breit-Wigner distribution.

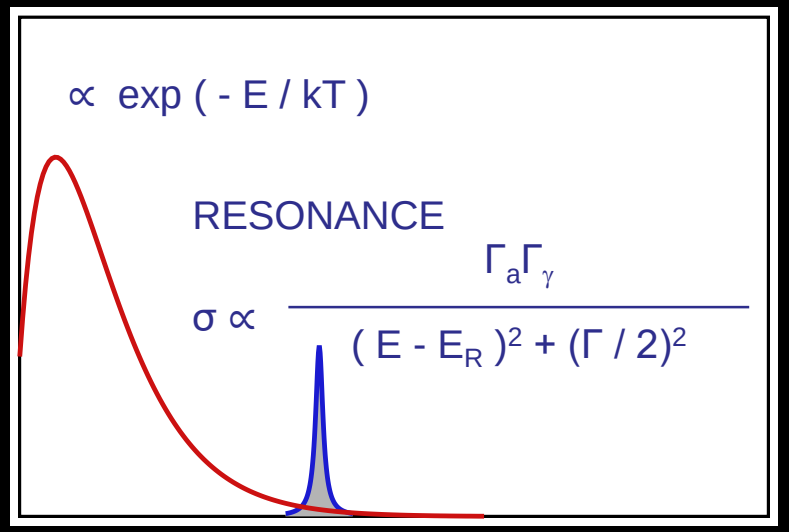
If the width of this distribution at half-maximum is labeled Γ , then the uncertainty in energy ΔE could be reasonably expressed as

$$\Delta E = \frac{\Gamma}{2} = \frac{\hbar}{2\tau}$$

where the particle lifetime τ is taken as the uncertainty in time τ = Δt.

Gamow-Range & Reaction Rate





$$\omega\gamma = \omega \frac{\Gamma_a \Gamma_\gamma}{\Gamma}$$

Nonresonant Reaction Contributions

$$N_A \langle\sigma v\rangle \propto T^{-3/2} \int \sigma E \exp (- E / kT) \, dE$$

Resonant Reaction Rate

$$N_A \langle\sigma v\rangle \propto T^{-3/2} \omega\gamma \exp (- E_R / kT)$$

σ: cross section

ωγ: res. strength

E_R: res. energy

The Gamow Range of Stellar Burning

The **Gamow window** or the range of relevant cross section for "non-resonant" processes is calculated:



Homework: Gamow window for 14N(p,g)15O@T_6=15.6
12C(a,g)16O at T_9=0.2, 12C+12C at T_9=1.0

Check derivation in book

$$E_0 = \left(\frac{bkT}{2}\right)^{3/2} = 0.122 \cdot \left(Z_1^2 Z_2^2 A\right)^{1/3} T_9^{2/3} \text{ MeV}$$

$$\Delta E = \frac{4}{\sqrt{3}} \sqrt{E_0 kT} = 0.2368 \cdot \left(Z_1^2 Z_2^2 A\right)^{1/6} T_9^{5/6} \text{ MeV}$$

with A "reduced mass number" and T_9 the temperature in GK T_9=T/1E9 K

Reaction rate from S-factor

If S-factor ~ constant over the Gamow range
the rate is calculated in terms of the S-factor

$$S(E)=S(E_0)$$

$$N_A \langle \sigma v \rangle = 7.83 \cdot 10^9 \left(\frac{Z_1 Z_2}{\mu T_9} \right)^{1/3} S(E_0)[\text{MeV barn}]\ \mathrm{e}^{-4.2487 \left(\frac{Z_1^2 Z_2^2 \mu}{T_9} \right)^{1/3}}$$

Otherwise energy dependence needs to be approximated!

Change in Abundance

$$A + a \Rightarrow B$$

A reaction is a random process with a reaction probability (reaction rate) and follows the laws of radioactive decay:

Depletion of isotope A

$$\frac{dn_A}{dt} = -n_A\lambda = -n_A Y_a \rho N_A \langle \sigma v \rangle$$

$$\lambda$$

Formation of isotope B

$$\frac{dn_B}{dt} = +n_A\lambda$$

consequently:

$$n_A(t) = n_{0A}\, e^{-\lambda t}$$

$$n_B(t) = n_{0A}(1 - e^{-\lambda t})$$

Mass fraction (X_i) and Abundance (Y_i):

X(p)=0.71

Y(p)=Xp/A=0.72

(A=1 for p)

X(4He)=0.27

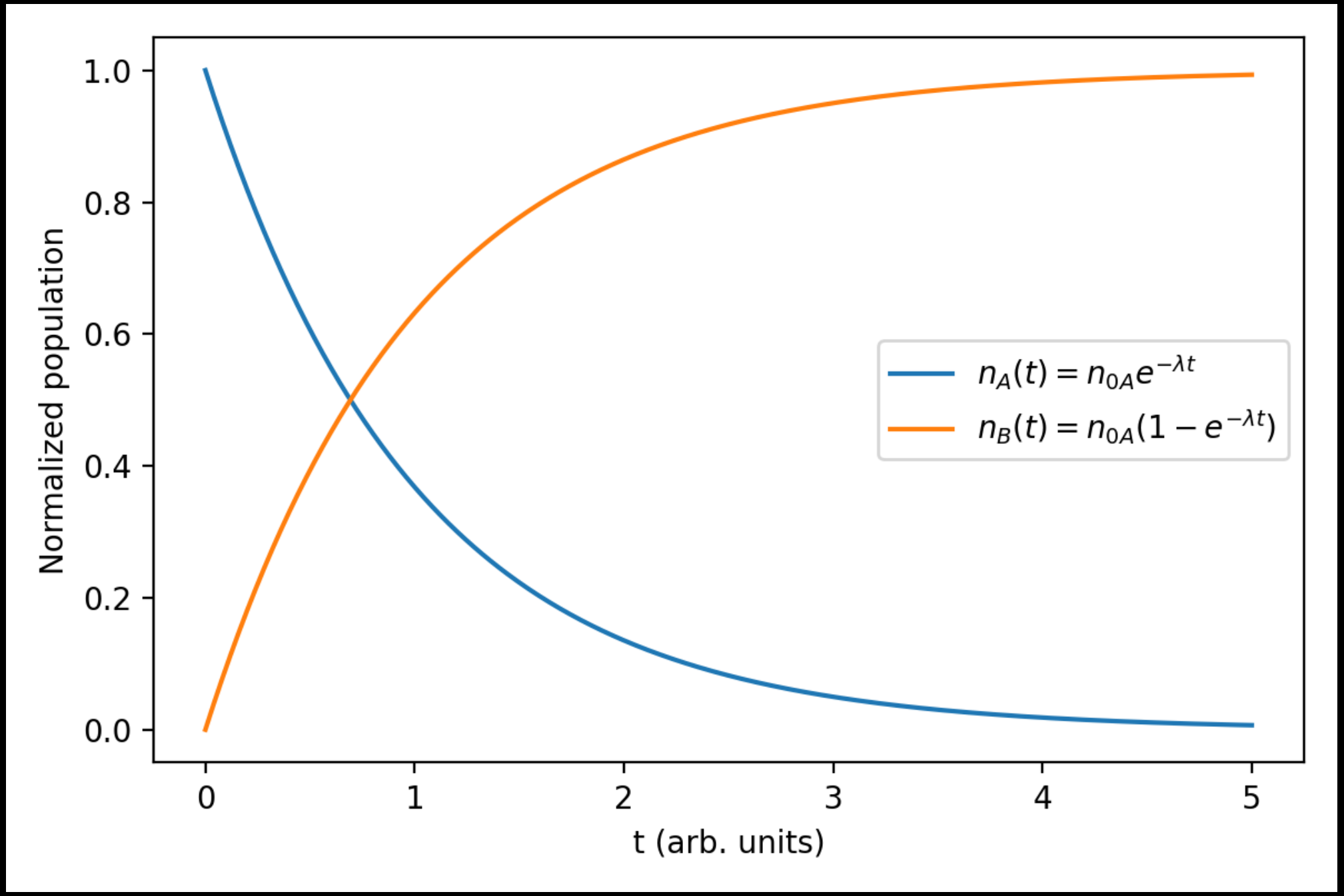
Y(4He)=0.27/A~0.06

(A=4 for 4He)

$$n_A = \rho N_A Y_A, \qquad Y_A = \frac{X_A}{A_A} = \frac{n_A}{\rho N_A}$$

n_A: number density

ρ: g/cm^3


1.0
0.8
0.6
0.4
0.2
0.0
Normalized population
0
1
2
3
4
5
t (arb. units)
$n_A(t) = n_{0A}e^{-\lambda t}$
$n_B(t) = n_{0A}(1 - e^{-\lambda t})$

CNO cycle: Why ^{14}N Piles Up

① Each nucleus is destroyed at the rate λ

$$dn_A/dt = -\, n_A\, \lambda\,, \quad \lambda = Y_p\, \rho\, N_A\, \langle \sigma v \rangle$$

② Steady state: the same flow through every link

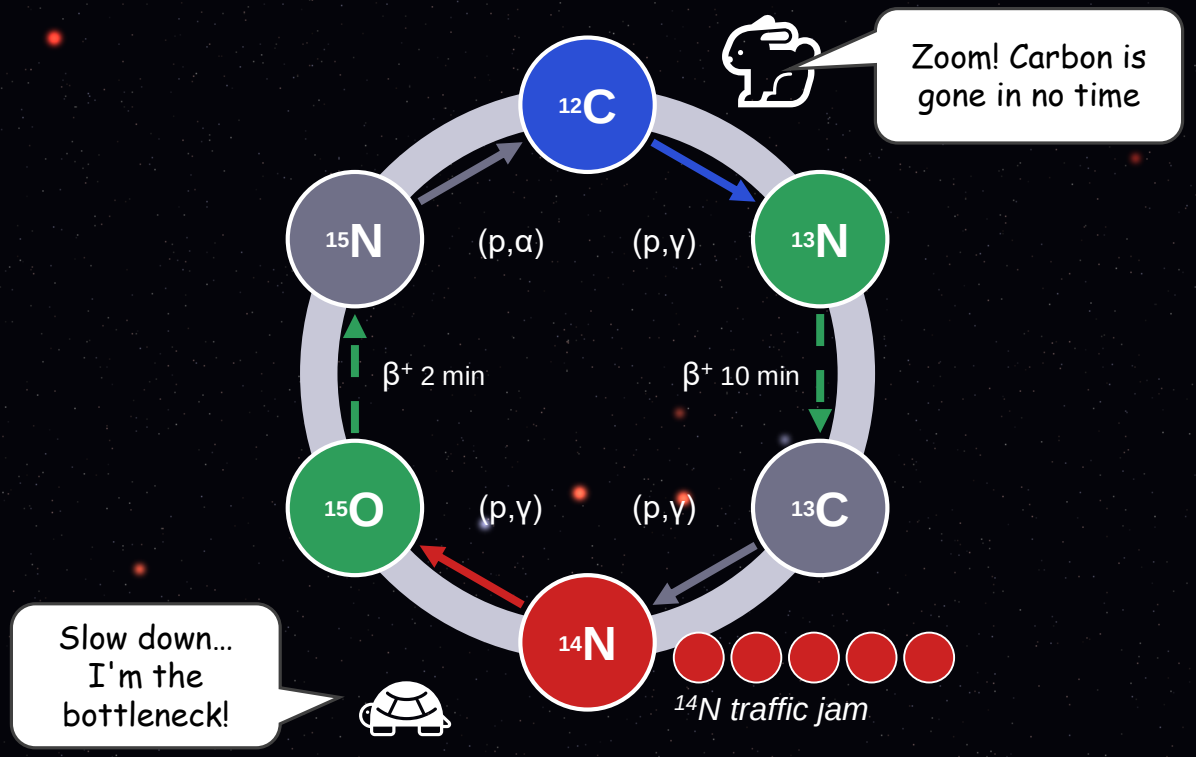
$$n_{12}\lambda_{12} = n_{13}\lambda_{13} = n_{14}\lambda_{14} = n_{15}\lambda_{15}$$

$\Rightarrow\ n_i \propto 1/\lambda_i$: the slowest step holds the most nuclei

③ The N/C ratio measures the reaction-rate ratio

$$\mathrm{N/C} = \frac{n(^{14}\mathrm{N})}{n(^{12}\mathrm{C})} = \frac{\lambda_{12}}{\lambda_{14}} = \frac{N_A\langle\sigma v\rangle\ ^{12}\mathrm{C}(p,\gamma)}{N_A\langle\sigma v\rangle\ ^{14}\mathrm{N}(p,\gamma)}$$

$Y_p\,\rho$ is common to both captures and cancels: only the two (p,γ) rates remain.

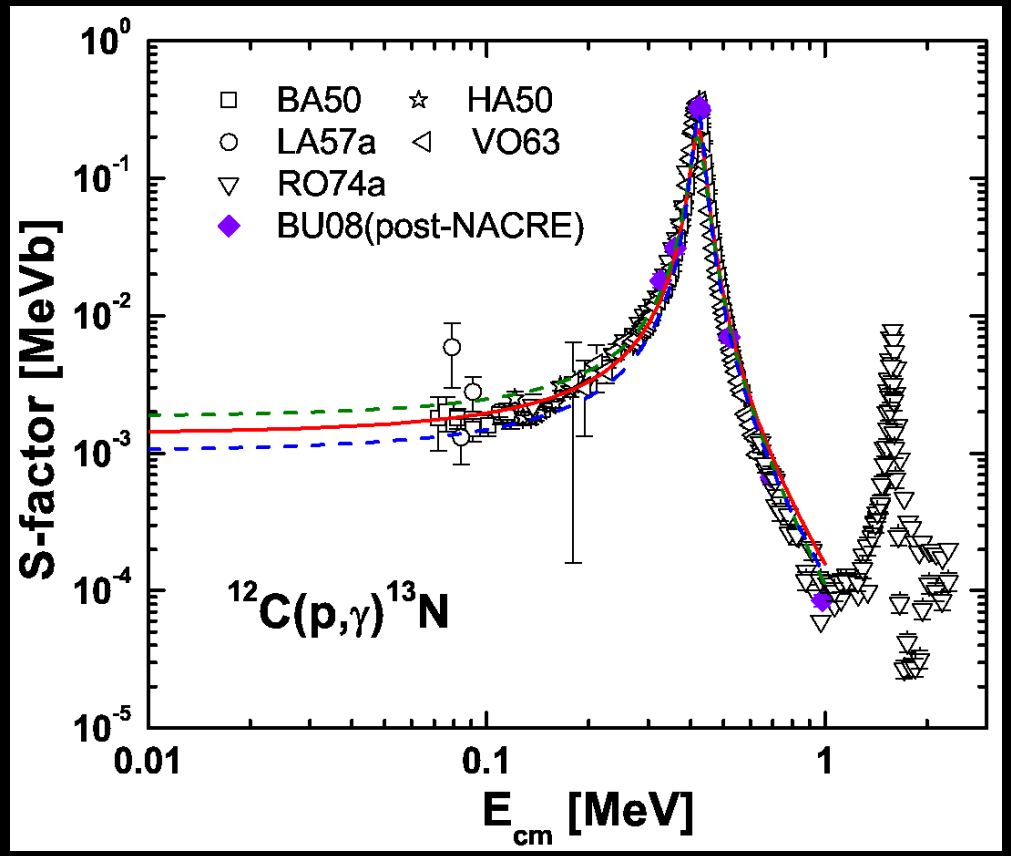


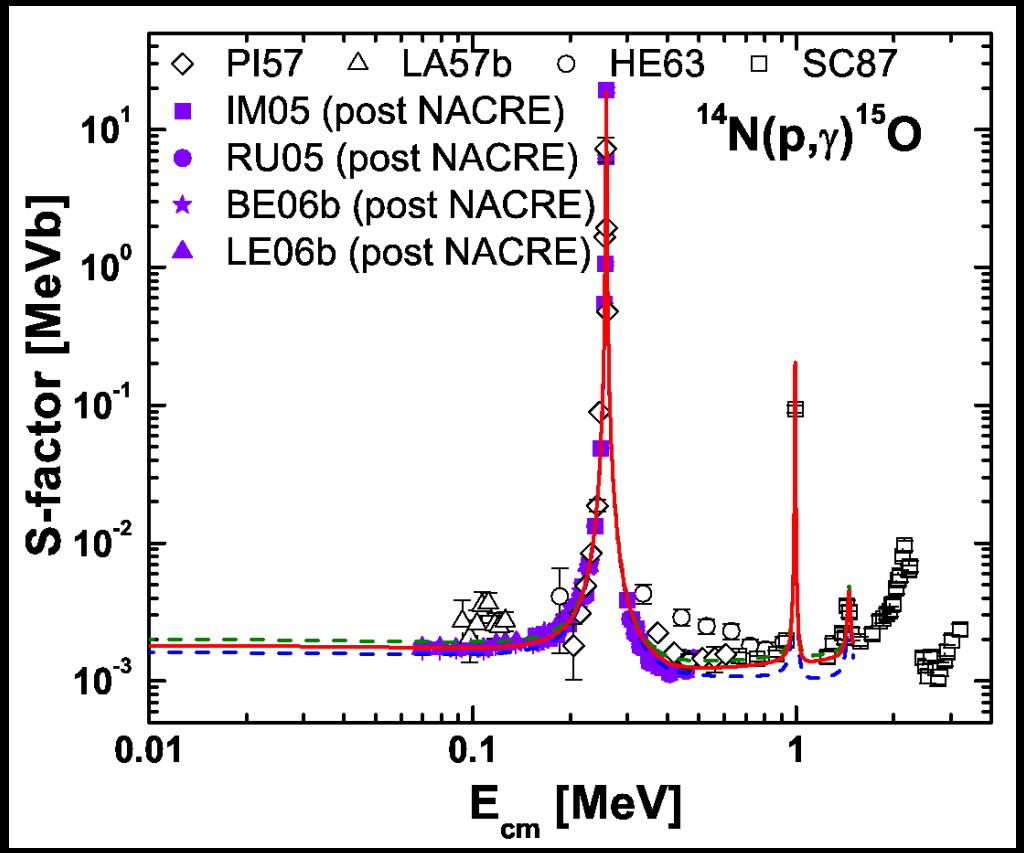
400
N/C at the Sun's centre (15.7 MK), BS05 model

≈ 350
rate ratio from the Gamow peak, S(0) = 1.34 / 1.66 keV b

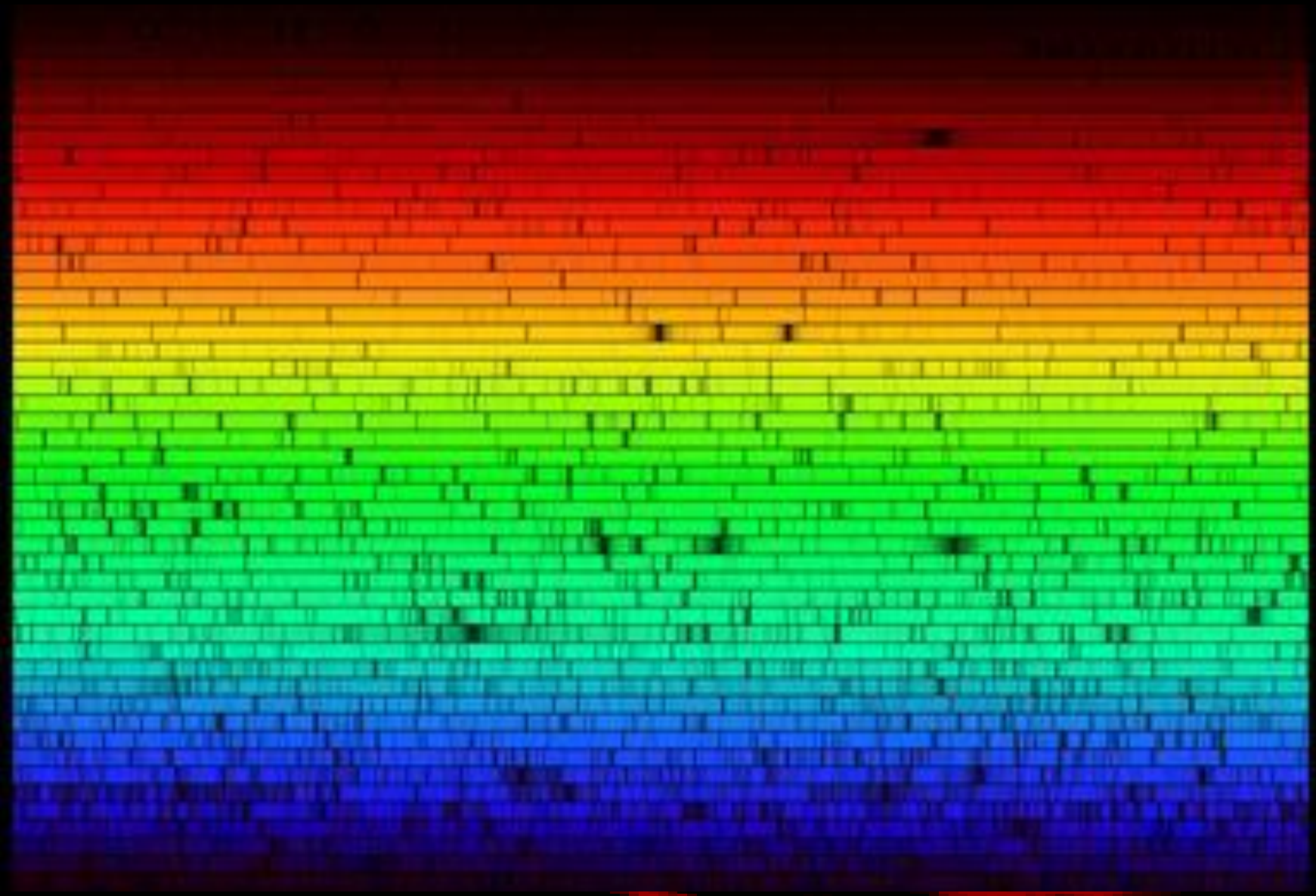
0.25
N/C in unprocessed layers (original mix)

Group activity: compute the Reaction Rates using S factors



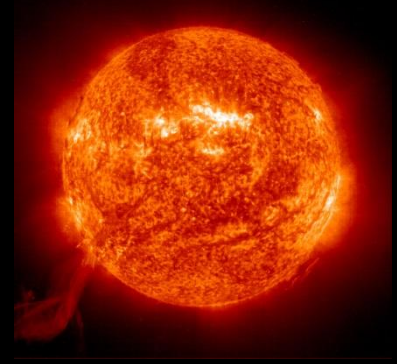


- S* factors: https://www.astro.ulb.ac.be/nacreii/index.html
- Compute your rate using the formula in the page above and compare your results with Reaction Rates Library : https://reaclib.jinaweb.org/

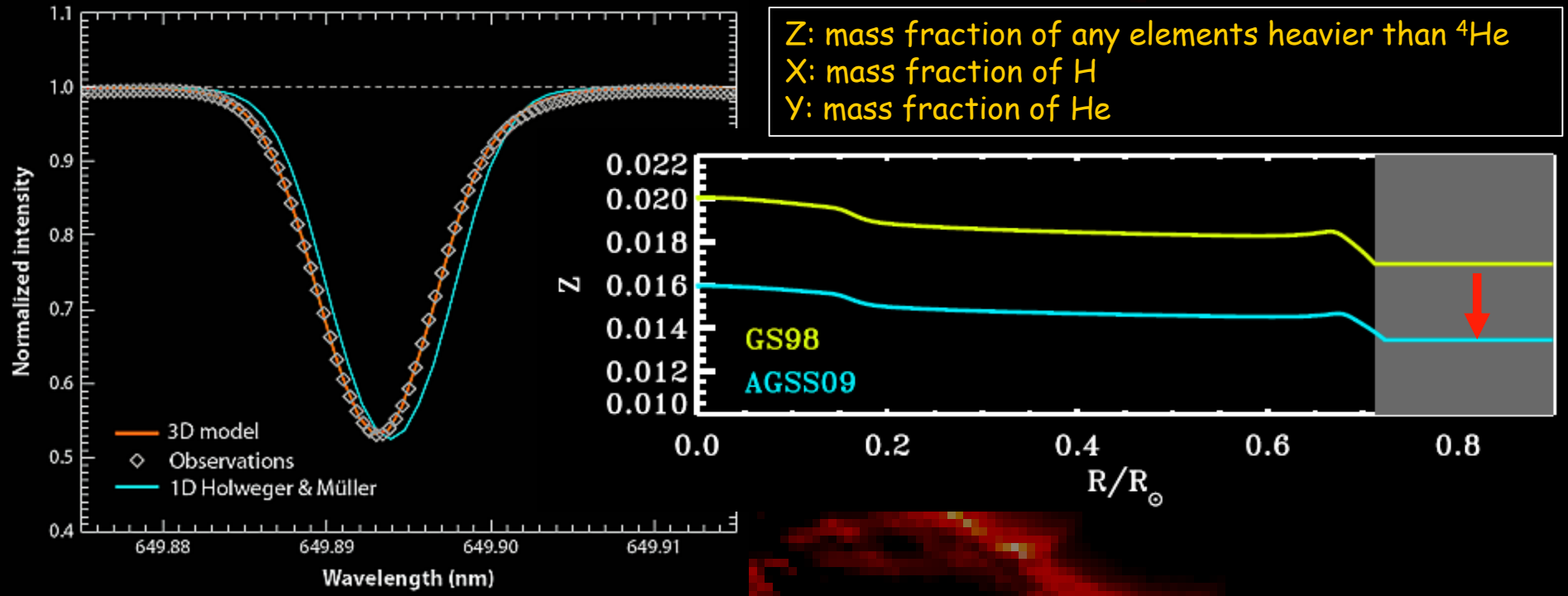


Solar Spectrum by NOAO

solar metallicity puzzle



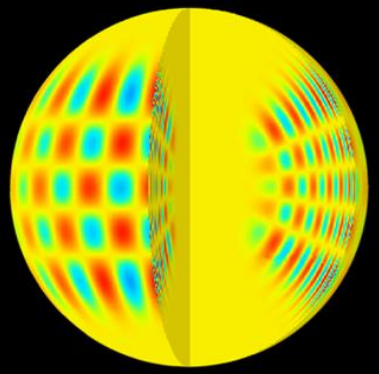
- New 3D hydrodynamic models of the solar atmosphere
- Parameter free
- significantly improving consistency of line analysis
- Makes sun more consistent with similar stars in local neighborhood

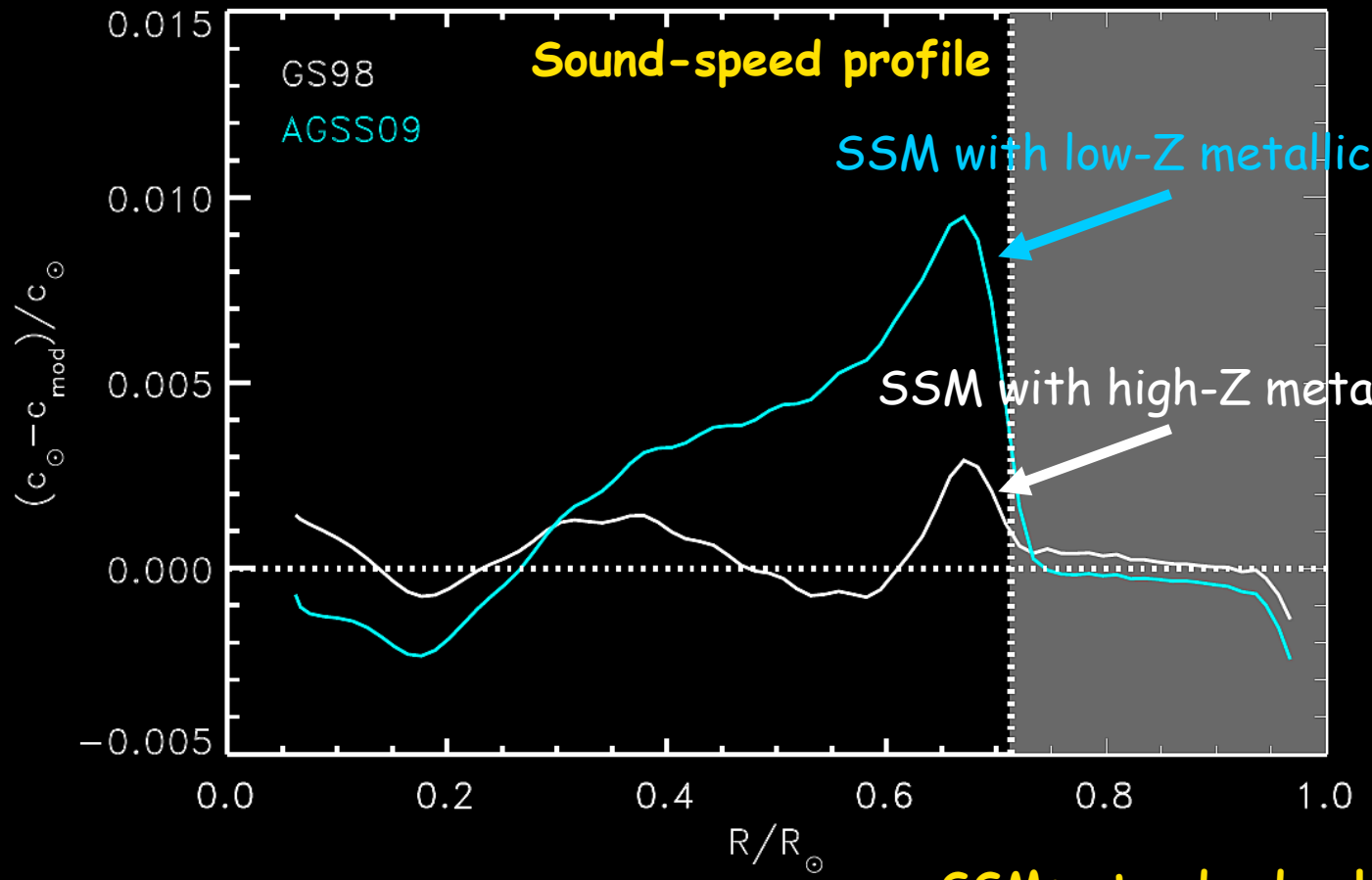


But abundances in the photosphere significantly reduced Z: 0.0169 ⇒ 0.0122

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

Solar Metallicity Puzzle



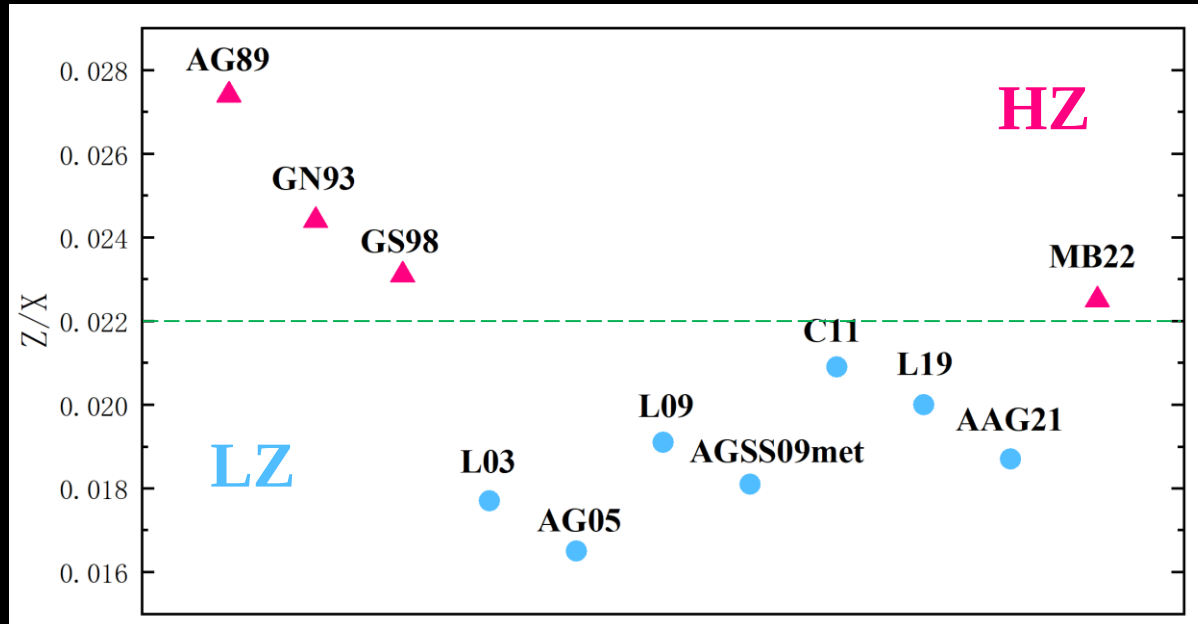


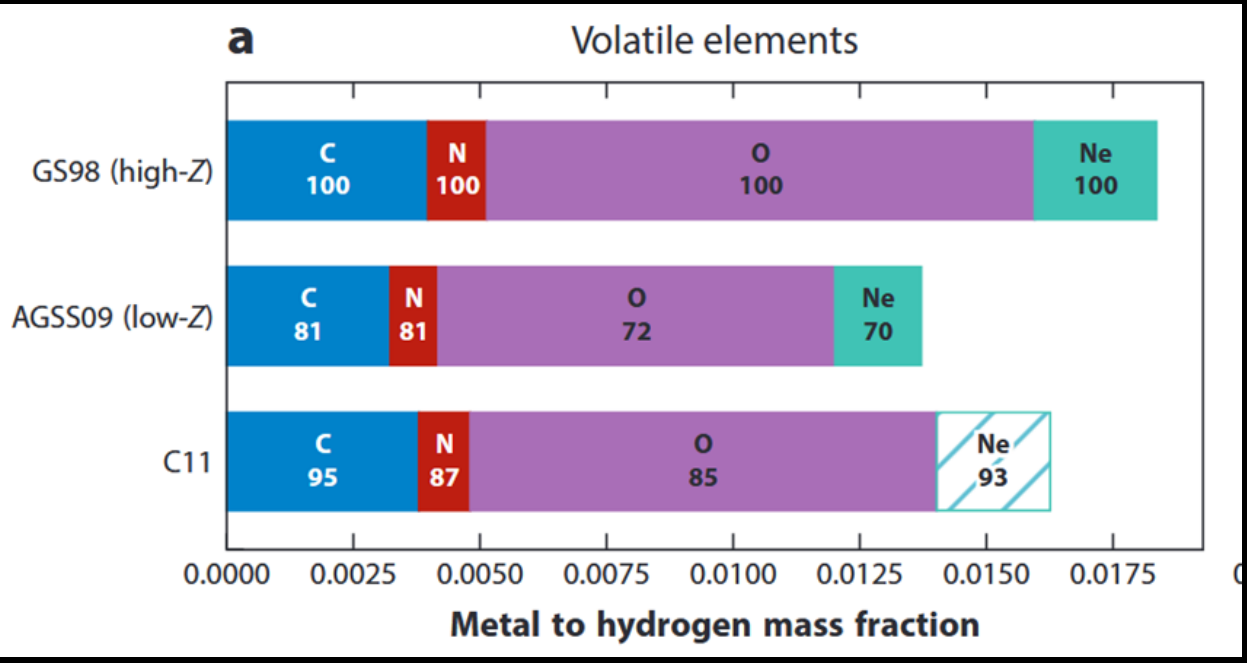
Sound speed – Precision 10^{-4}

SSM: standard solar model

Serenelli, Haxton, Peñay-Garay (2011); E. Magg et al, Astron. Astrophys. 661, A140 (2022)

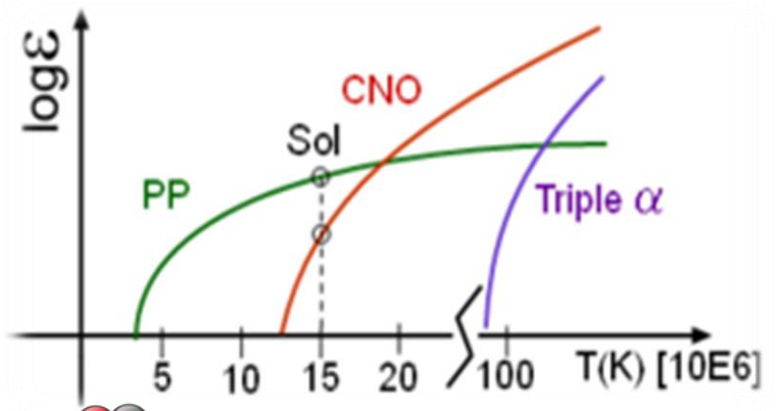
Solar metallicity puzzle

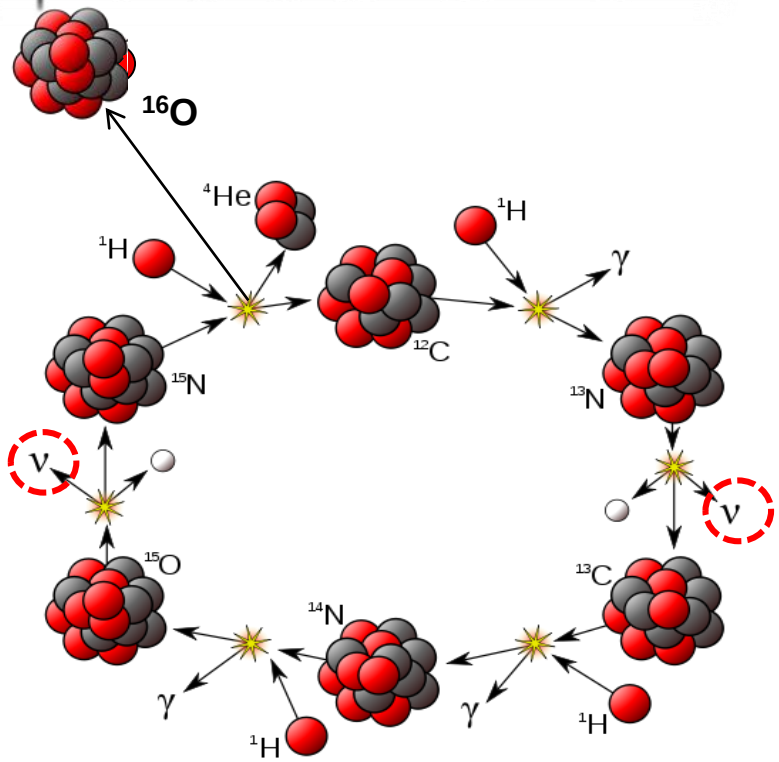


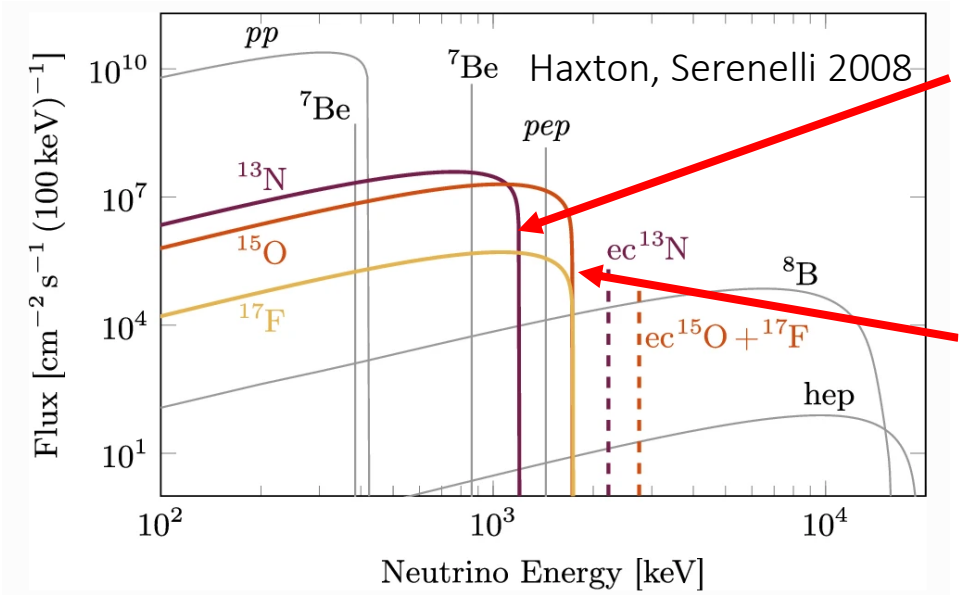


G. D. O. Gann et al., Annu. Rev. Nucl. Part. Sci. 2021. 71:491–528

CNO cycles





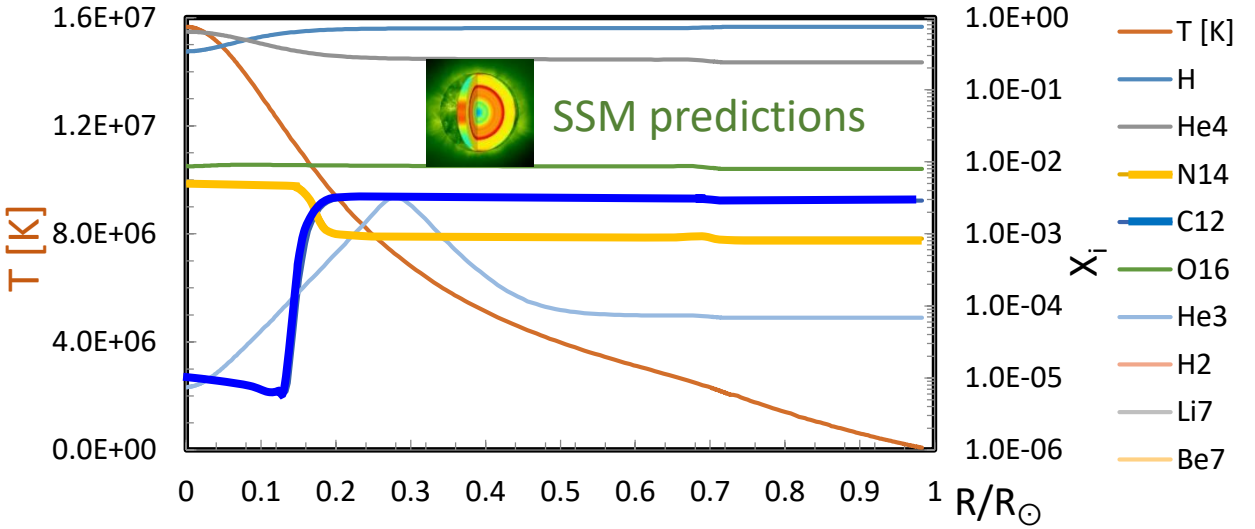


$^{13}\mathrm{N}(\beta^+)^{13}\mathrm{C}\quad E_\nu \lesssim 1.199\ \mathrm{MeV}$

$\phi = (2.93^{+0.91}_{-0.82}) \times 10^8/\mathrm{cm}^2\mathrm{s}$

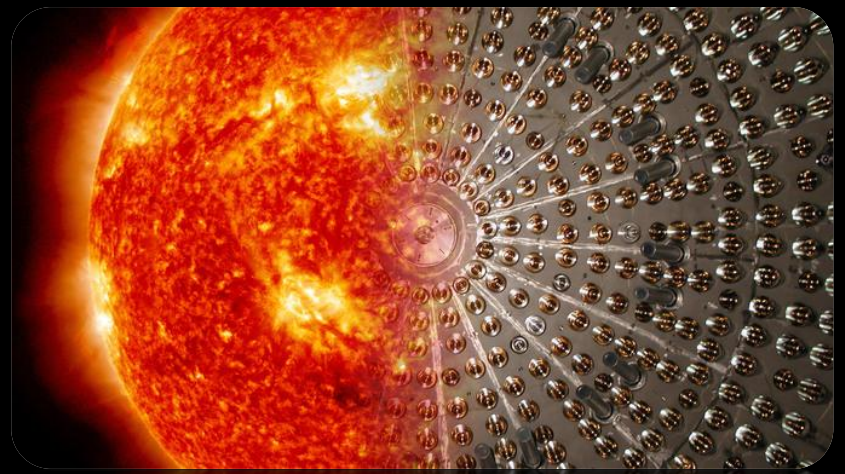
$^{15}\mathrm{O}(\beta^+)^{15}\mathrm{N}\quad E_\nu \lesssim 1.732\ \mathrm{MeV}$

$\phi = (2.20^{+0.73}_{-0.63}) \times 10^8/\mathrm{cm}^2\mathrm{s}.$

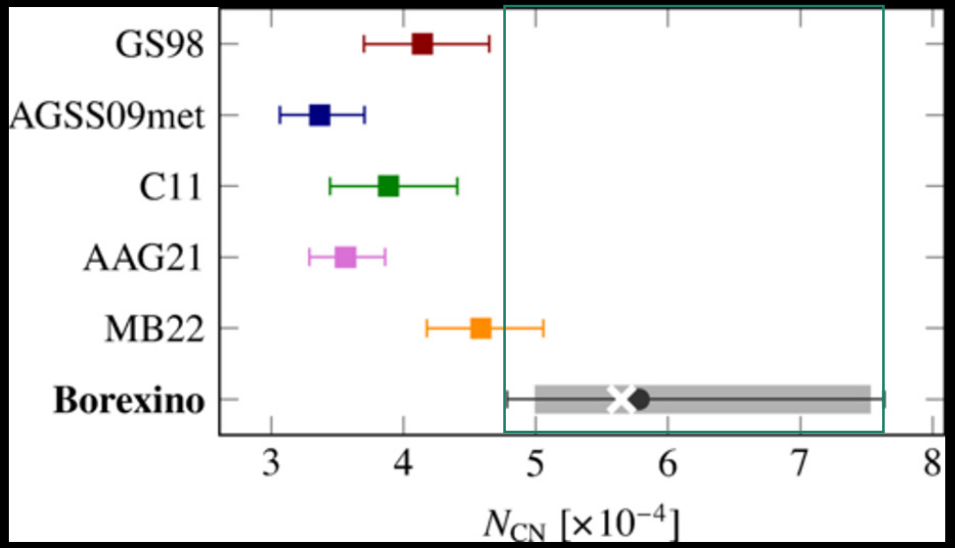


Solar metallicity puzzle

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



arXiv:2307.14636v1



S. Appel et al, Phys. Rev. Letts. 129, 252701 (2022)

Neutrino flux

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

metallicity of C+N

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

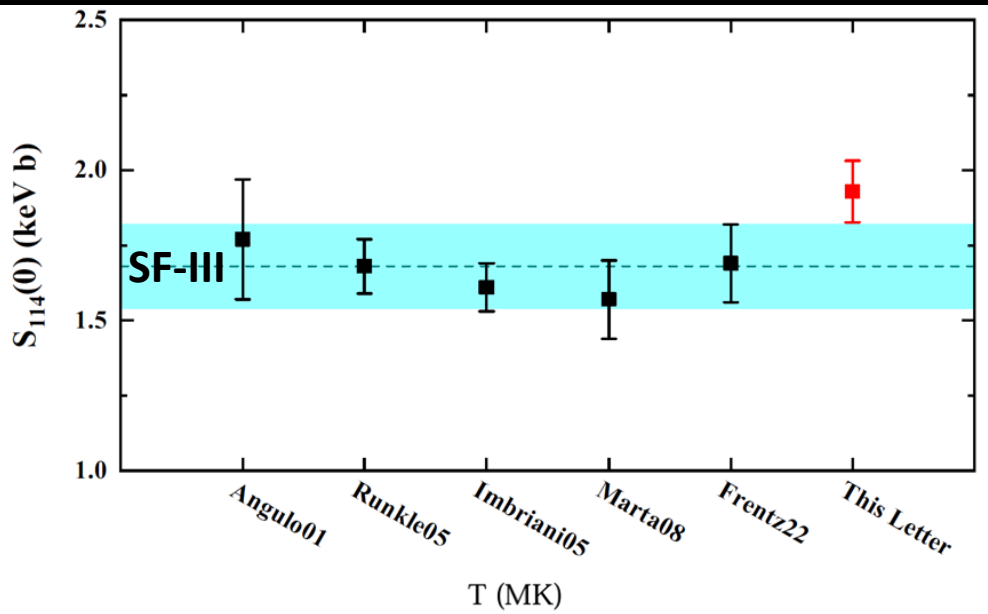
Nuclear Physics is the biggest uncertainty !

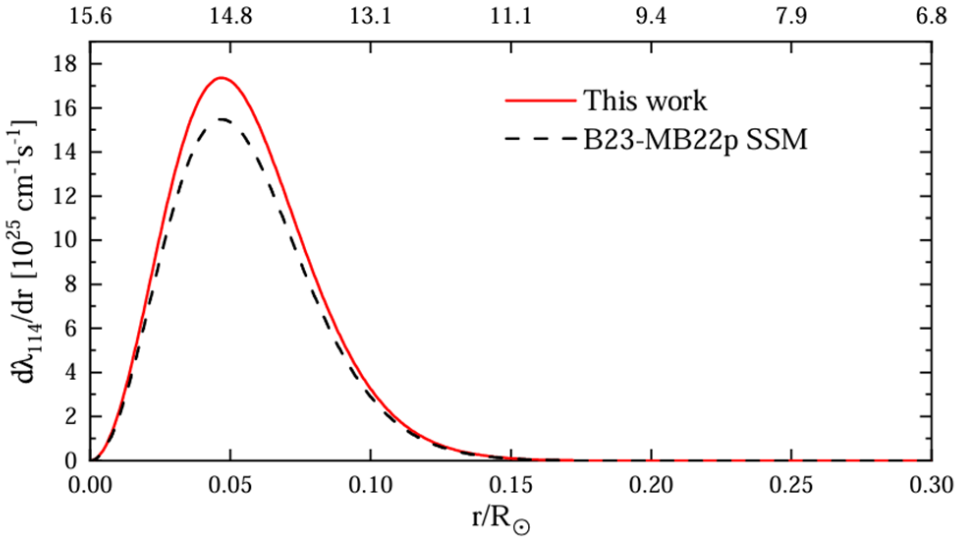
^{7}Be(p,γ)^{8}B (5.5%→3.4%)

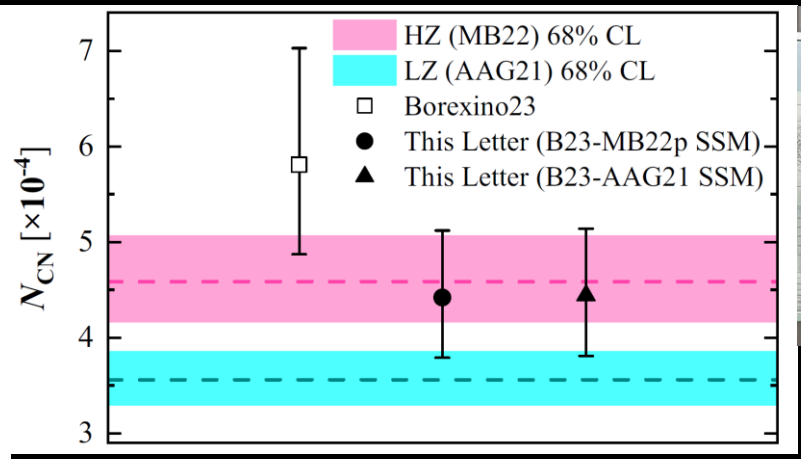
^{14}N(p,γ)^{15}O (7.2%→8.4%)

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

A new measurement of S_{114} of $^{14}N(p,\gamma)^{15}O$







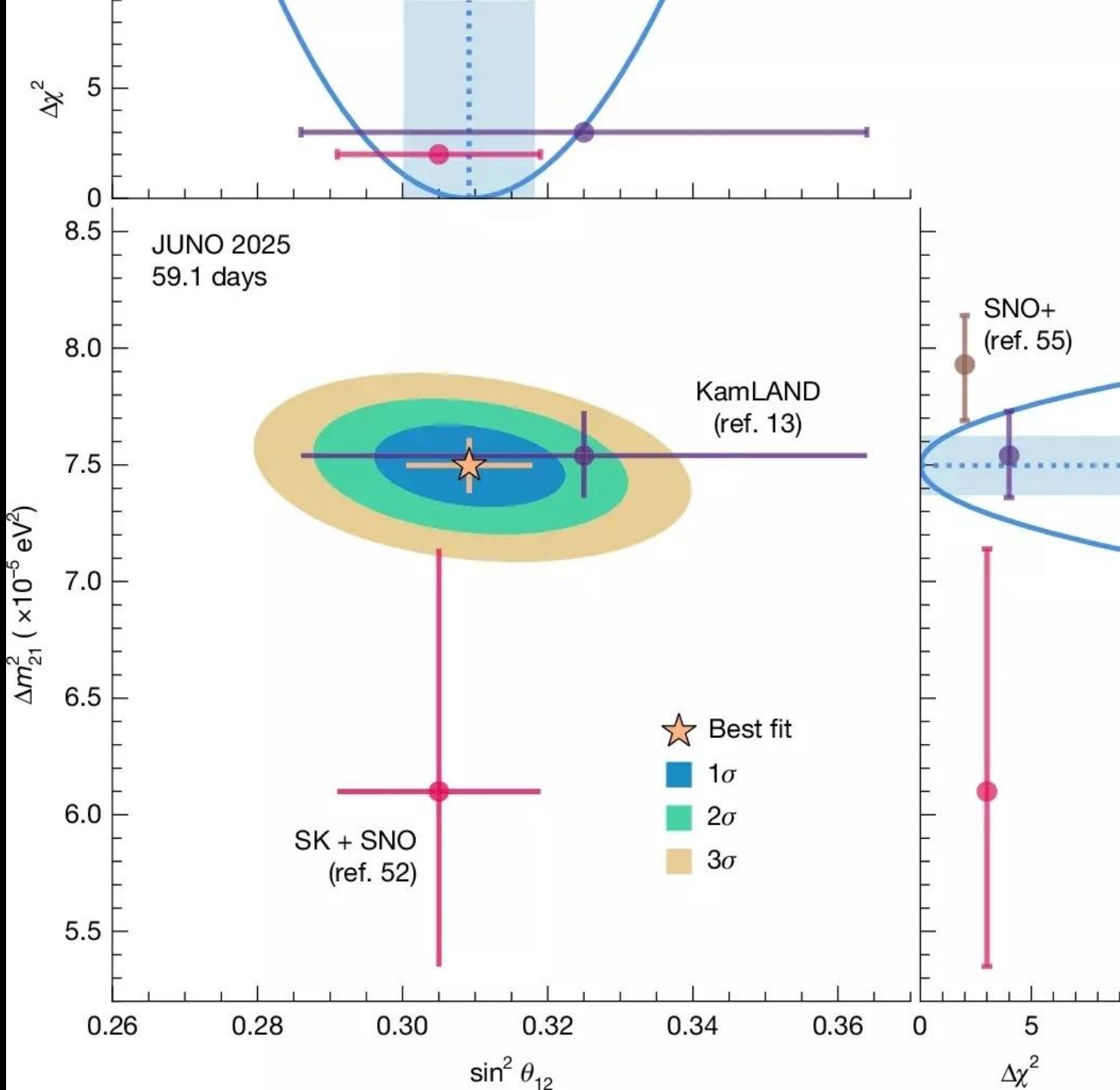


New $S_{114}(0)$ is 15% higher than the SF-III recommendation, with a 40% better accuracy

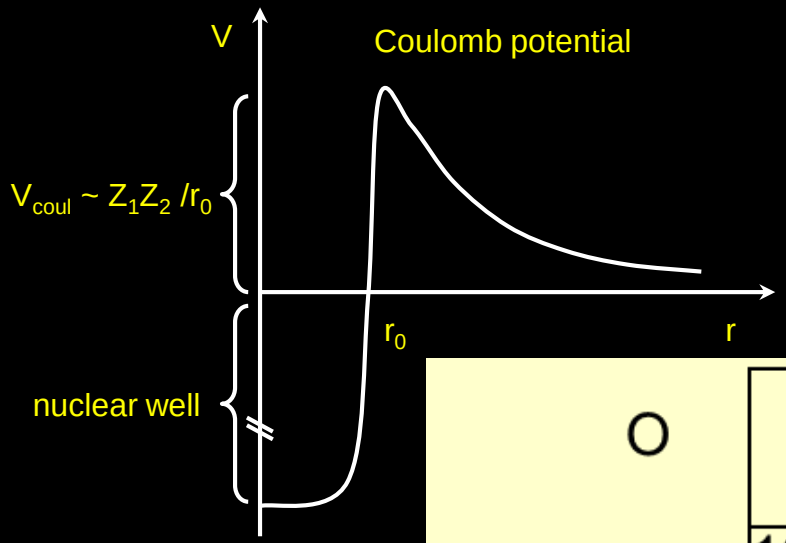
$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} = \left[\frac{\phi(^{8}\mathrm{B})}{\phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right]^{0.729} x_{C+N}$$

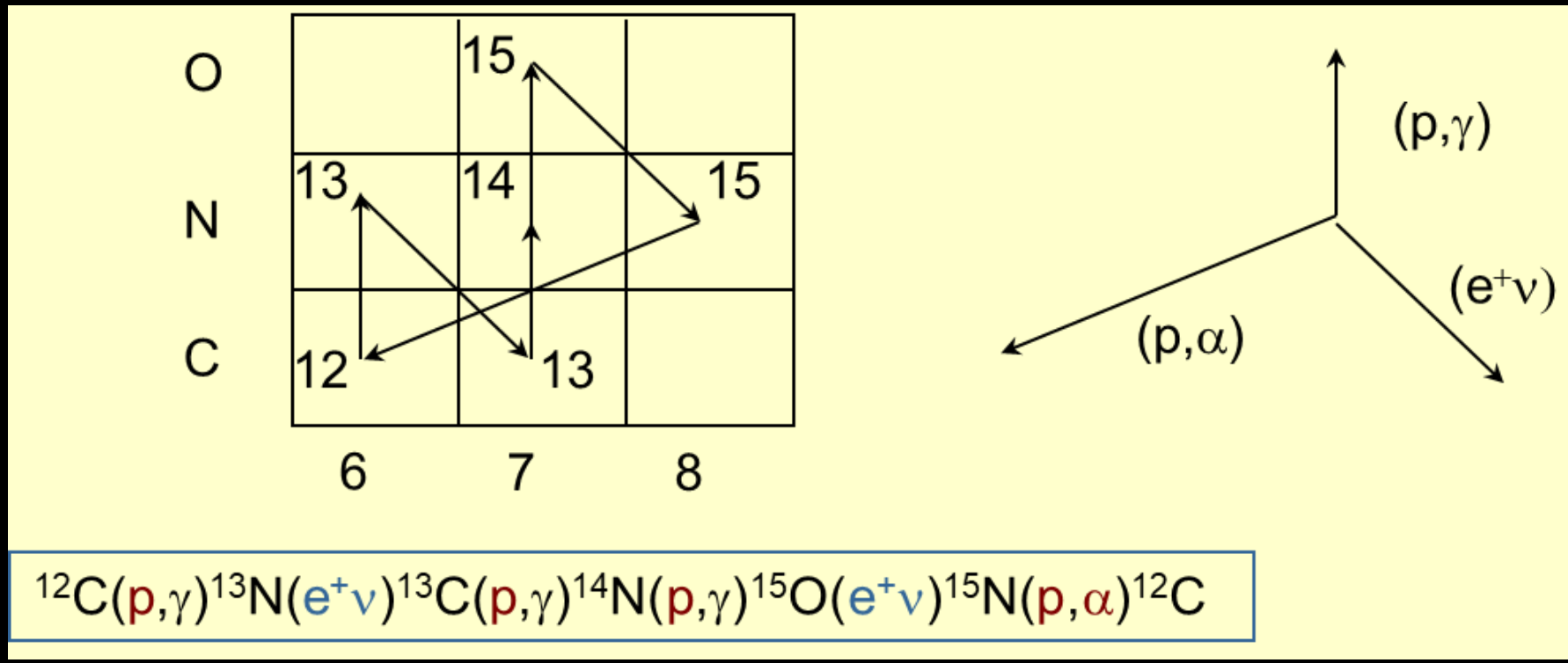
X. Chen, J. Su*, Y. P. Chen*,…, W. P. Liu*, Phys. Rev. Letts 135, 232701 (2025)


The international journal of science / 11 June 2026
spotlight
Drug discovery
nature
FLAVOUR PROFILES
Early JUNO data capture neutrino oscillations with improved precision
Now trending
Is the hype around peptide drugs backed up by the science?
Proof of concept
How AI use might add up to success for maths and physics
Framework for life
3D structures of protein lattices in mouse egg cells


JUNO 2025
59.1 days
KamLAND
(ref. 13)
SK + SNO
(ref. 52)
SNO+
(ref. 55)
Best fit
1σ
2σ
3σ
Δm^2_{21} ($\times 10^{-5}$ eV^2)
$\sin^2 \theta_{12}$
$\Delta\chi^2$
8.5
8.0
7.5
7.0
6.5
6.0
5.5
0.26
0.28
0.30
0.32
0.34
0.36
0
5

Group Activity 3: Why is 14N(p,g)15O the lowest reaction in the CN cycle?
Hint: Compare the Coulomb barrier for the charged induced reaction in the CN cycle, Identify the reaction with highest Coulomb barrier.





$^{12}C(p,\gamma)^{13}N(e^+\nu)^{13}C(p,\gamma)^{14}N(p,\gamma)^{15}O(e^+\nu)^{15}N(p,\alpha)^{12}C$

Use the simple Coulomb-barrier estimate:

$$V_C \approx \frac{1.44 Z_1 Z_2}{R_1 + R_2}$$

$$R_i \approx 1.2 A_i^{1/3} \text{ fm}$$

For proton-induced CN-cycle reactions, $Z_1 = 1$.

Reaction	Z_{target}	V_C MeV
$^{12}\text{C}(p,\gamma)^{13}\text{N}$	6	≈ 2.19
$^{13}\text{C}(p,\gamma)^{14}\text{N}$	6	≈ 2.15
$^{14}\text{N}(p,\gamma)^{15}\text{O}$	7	≈ 2.46
$^{15}\text{N}(p,\alpha)^{12}\text{C}$	7	≈ 2.42

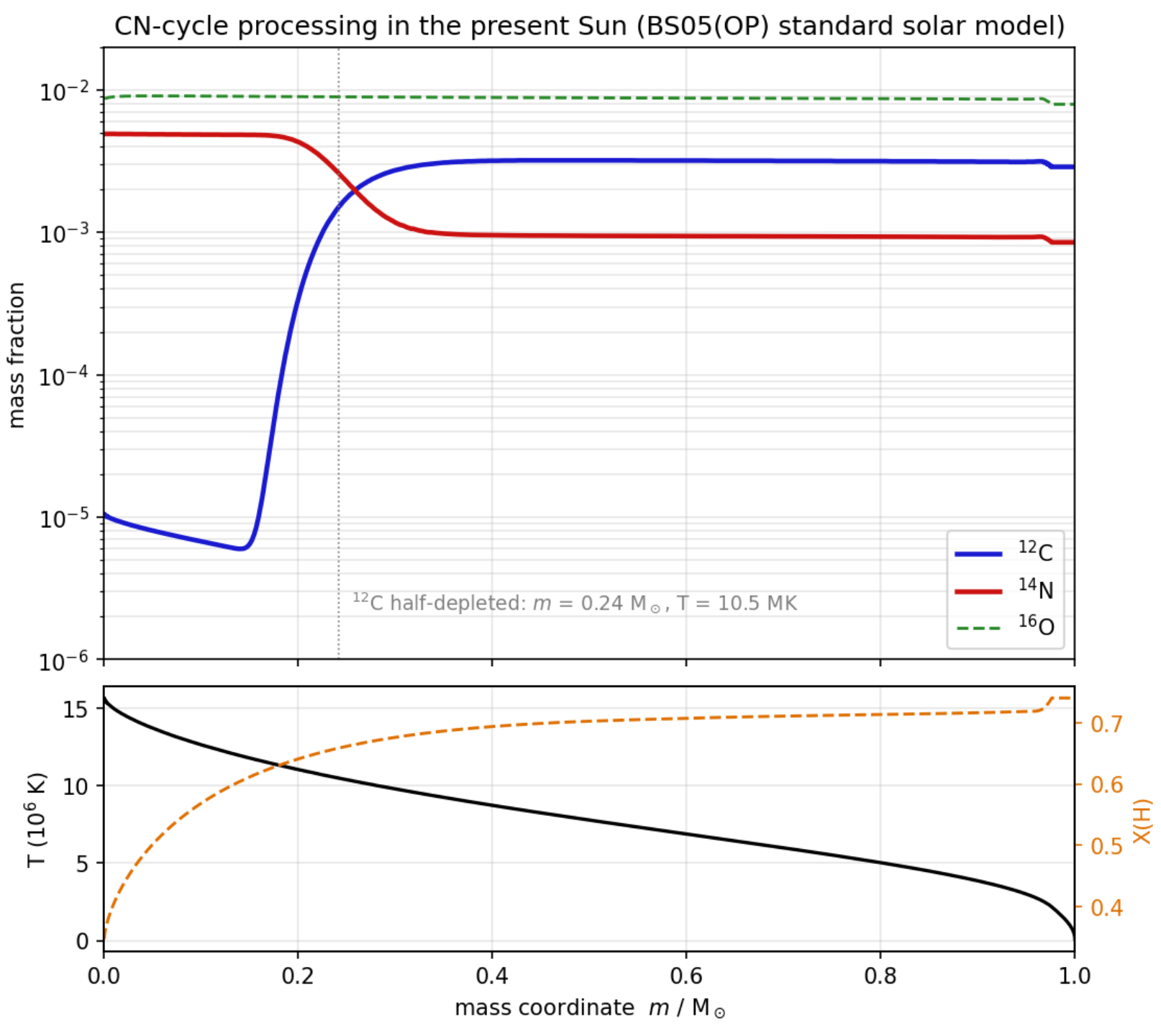
So, among the charged-particle reactions in the CN cycle shown:

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

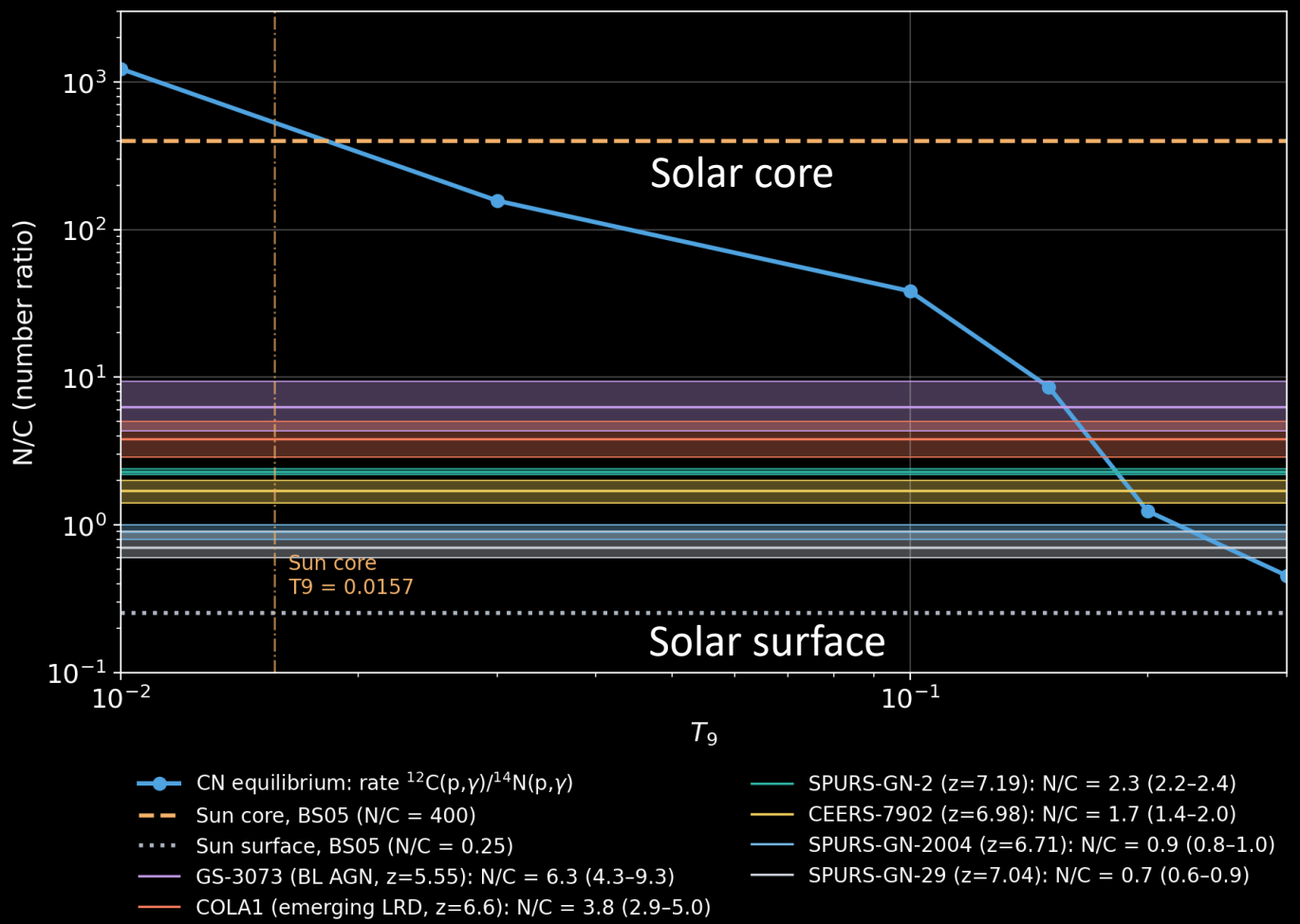
has the highest Coulomb barrier, about

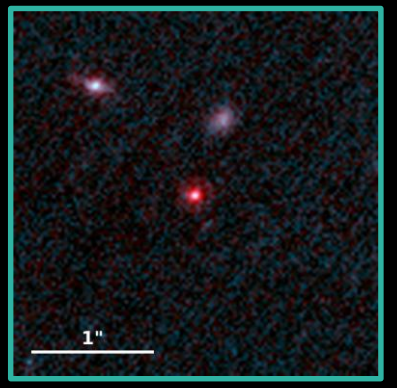
$$\boxed{V_C \approx 2.46 \text{ MeV}}$$

It is also the slowest reaction in the CN cycle and acts as the bottleneck.


CN-cycle processing in the present Sun (BS05(OP) standard solar model)
mass fraction
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
^{12}C half-depleted: m = 0.24 M$_\odot$, T = 10.5 MK
^{12}C
^{14}N
^{16}O
T (10^6 K)
15
10
5
0
X(H)
0.7
0.6
0.5
0.4
0.0
0.2
0.4
0.6
0.8
1.0
mass coordinate m / M$_\odot$

N/C: From Solar Core to Galaxies at High Redshift





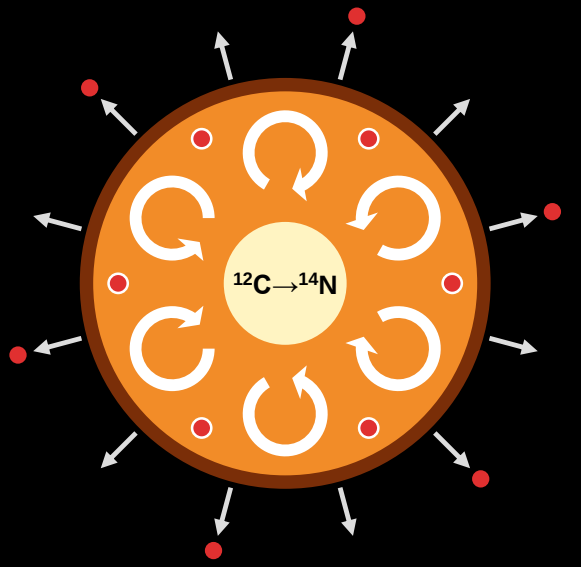
SPURS-GN-2

Little Red Dot, z = 7.19 → 13.1 Gyr

N/C = 2.3 ≈ 10× solar

JWST/NIRCam F115W/F277W/F444W (via DJA);
N/C: Tang et al. 2026

Supermassive-star (SMS) picture



① Hot core (~7×10^7 K): CN cycle turns C → N

② Convection over the whole star lifts N to the surface

③ Wind ejects N-rich gas in all directions

④ Mixing with pristine gas ⇒ N/C ≈ 1–10

- **Observed N/C ≈ 0.7–6: ~3–25× above the solar surface (0.25) but ~100× below solar-core CN equilibrium (400)**
- **Equilibrium would need T_9 ≈ 0.15–0.25; otherwise partially processed gas mixed with unprocessed gas**

Why first stars burn CNO warm

1 No metals

Pop III gas from the Big Bang: H, He, trace Li — no CNO catalyst

2 Contract & heat

pp chains are too weak for massive stars; the core contracts until $T_c \approx 10^8$ K

3 Self-made carbon

3α makes ^{12}C at a mass fraction of only $\sim 10^{-10}$–10^{-9}

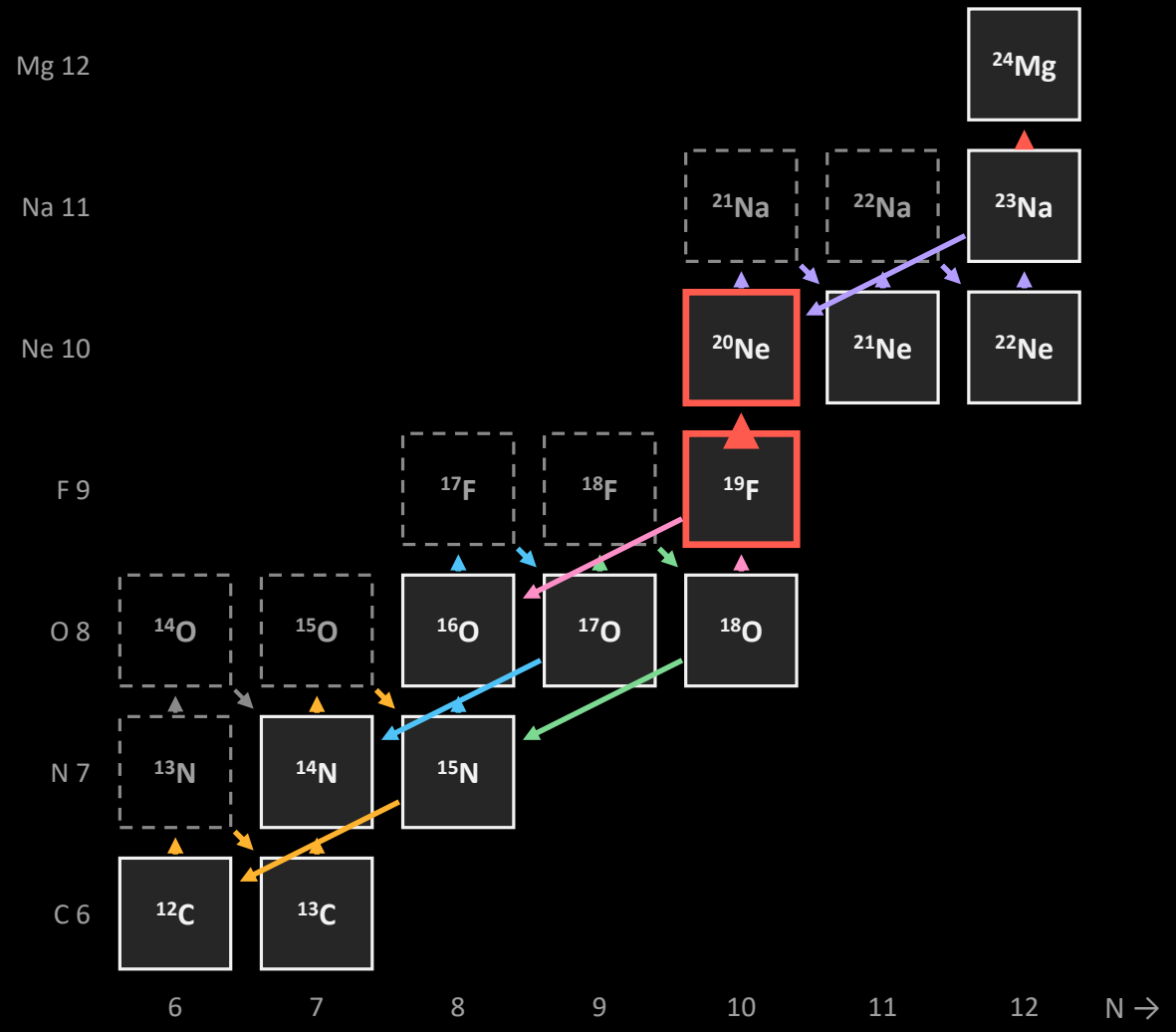
4 Warm CNO

That trace carbon runs the CNO cycle at ≈ 0.1 GK — hotter than in the Sun

The puzzle: calcium without iron

SMSS 0313-6708 (Keller et al. 2014), the most iron-poor star known, shows Ca but no detectable Fe. A supernova cannot easily make Ca without Fe, but hot H burning can — if enough material leaks out of the CNO cycle. Before 2022 this needed a $^{19}F(p,\gamma)^{20}Ne$ rate about **7–10× larger** than recommended.

The warm-CNO reaction network



- CNO-I: ^{12}C → ^{13}N → ^{13}C → ^{14}N → ^{15}O → ^{15}N
- CNO-II: ^{15}N(p,γ)^{16}O … ^{17}O(p,α)^{14}N
- CNO-III: ^{17}O(p,γ)^{18}F … ^{18}O(p,α)^{15}N
- CNO-IV: ^{18}O(p,γ)^{19}F(p,α)^{16}O
- Breakout: ^{19}F(p,γ)^{20}Ne, ^{23}Na(p,γ)^{24}Mg
- Ne–Na cycle
- Hot CNO: ^{13}N(p,γ)^{14}O(β^{+})^{14}N

How to read it

↑ (p,γ): Z+1 ↘ β^{+}: Z−1, N+1 ↙ (p,α): back to a lighter cycle

Solid boxes stable, dashed boxes radioactive. Every (p,α) closes a cycle; the only exits are (p,γ) on ^{19}F and ^{23}Na.

Warm CNO in first stars · after Zhang et al., Nature 610, 656 (2022)