Network of Nuclear Process in Astrophysics

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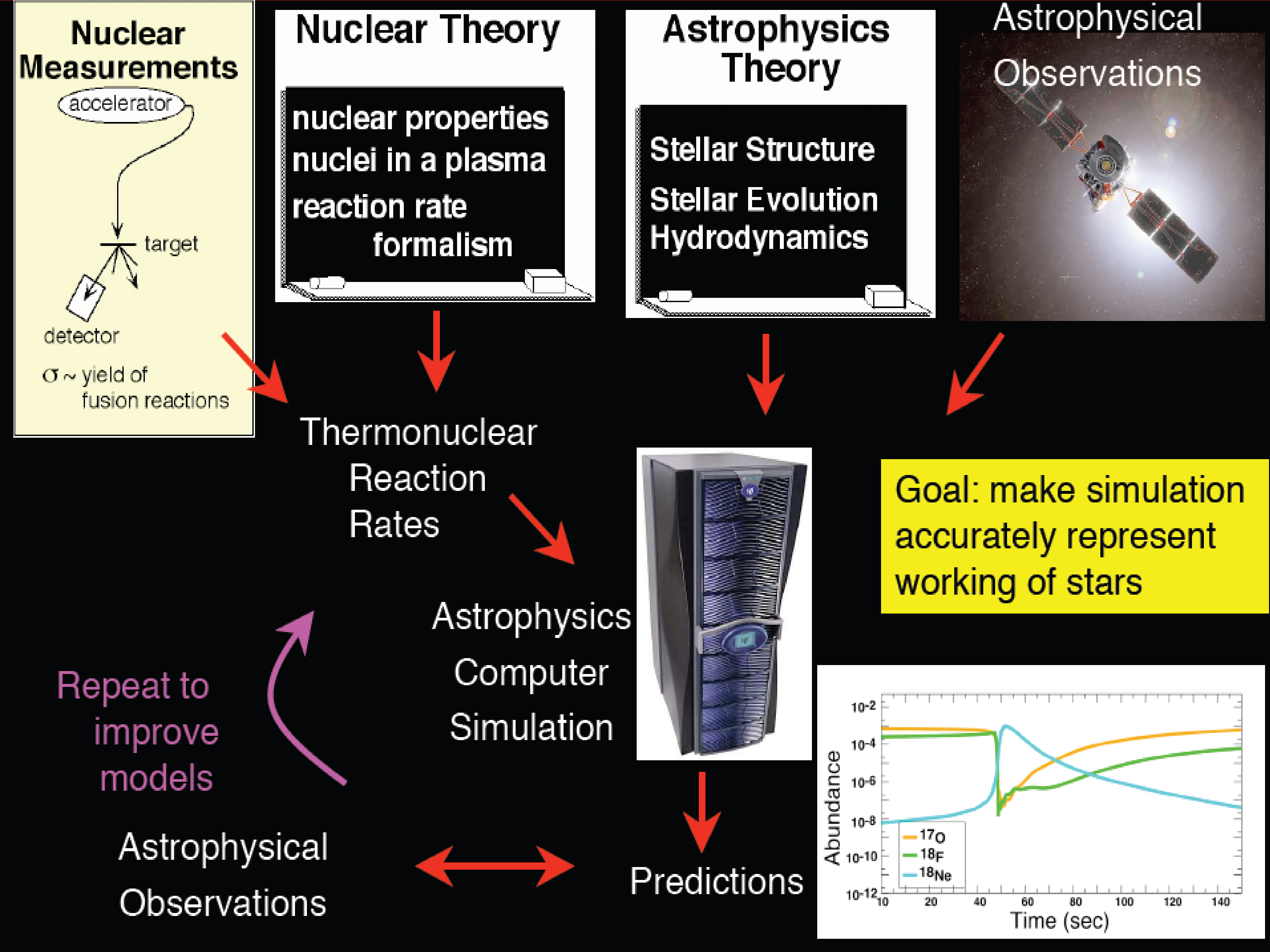
1. Introduction
2. Theory of capture reaction
3. Theory of β-decay
4. Network equation and nuclear data base
5. Our task

Introduction

Why nuclear astrophysics?

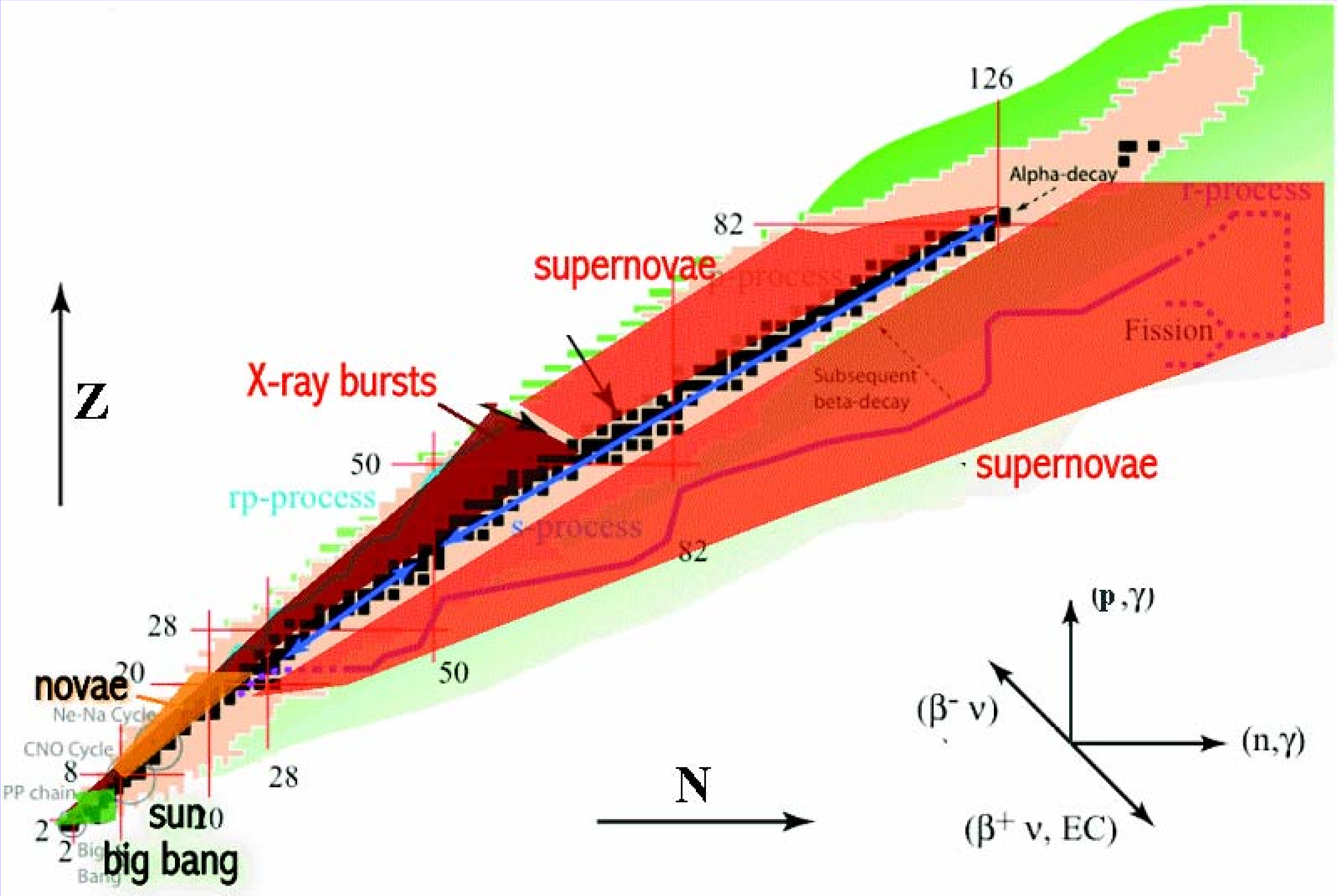
Nuclear scientists have tools that enable studies of the cosmos that are impossible with any telescope !

We can use accelerators to recreate – and - measure the nuclear reactions that power the stars & create elements of our life and world.



Nuclear Measurements
accelerator
target
detector
σ ~ yield of fusion reactions
Nuclear Theory
nuclear properties
nuclei in a plasma
reaction rate formalism
Astrophysics Theory
Stellar Structure
Stellar Evolution
Hydrodynamics
Astrophysical Observations
Thermonuclear Reaction Rates
Goal: make simulation accurately represent working of stars
Astrophysics Computer Simulation
Repeat to improve models
Abundance
10-2
10-4
10-6
10-8
10-10
10-12
17O
18F
18Ne
10
20
40
60
80
100
120
140
Time (sec)
Astrophysical Observations
Predictions

Relevant nuclei of each frontier region



Theory of Capture Reaction

Useful Theory for Cross Section

ANC method

Spectroscopic factor

Transition Amplitude for B + p → A + γ

$$T = \langle \Phi_A(\xi_B, \xi_p, \vec{r}) \,|\, \hat{O}(\vec{r}) \,|\, \Phi_B(\xi_B)\varphi_p(\xi_p)\psi^{(+)}(\vec{r}) \rangle$$

$\vec{r} \equiv \vec{r}_{Bp}$ relative between B and p

integrate over ξ

$$T = \langle I^{A}_{Bp}(\vec{r}) \,|\, \hat{O}(\vec{r}) \,|\, \psi^{(+)}(\vec{r}) \rangle$$

the overlap integral

$$I^{A}_{Bp}(\vec{r}) = \langle \Phi_B(\xi_B)\varphi_p(\xi_p) \,|\, \Phi_A(\xi_B, \xi_p, \vec{r}) \rangle$$

For peripheral reaction (p,γ)

$$I_{\lambda_f j_f I}(r) = C_{\lambda_f j_f I} W_{\eta,\lambda_f+1/2}(2\kappa r)/r \qquad (r \geq R_N)$$

$C_{\lambda_f j_f I}$ is the ANC

$W_{\eta,\lambda_f+1/2}(2\kappa r)$ is the Whittaker function,

$\kappa = \sqrt{2\mu E_B}/\eta$ for bound state

The Asymptotic Normalization Constant (ANC):
the amplitude of
the tail of the overlap integral

For peripheral transfer reaction: B(d,n)A

two virtual captures:

$$B + p \rightarrow A$$
$$n + p \rightarrow d$$

two ANC's : C_{Bp}^{A} and C_{np}^{d}

$$\frac{d\sigma}{d\Omega} = \sum \frac{(C_{Bpl_A j_A}^{A})^2 (C_{npl_d j_d}^{d})^2}{b_{Bpl_A j_A}^2 b_{npl_d j_d}^2} \sigma_{l_A j_A l_d j_d}^{DWBA}$$

$(C_{np}^{d})^2 = 0.76\, fm^{-1}$ known value

$(C_{Bp}^{A})^2$ can be obtained from $(\frac{d\sigma}{d\Omega})_{\exp}$

For non-peripheral reaction (n,γ)

Standard approach (Spectroscopic factor)

$$I^{A}_{Bpl_A j_A}(r) = (S_{l_A j_A})^{1/2} R_{n_A l_A j_A}(r)$$

$$I^{d}_{npl_d j_d}(r) = (S_{l_d j_d})^{1/2} R_{n_d l_d j_d}(r)$$

$$\frac{d\sigma}{d\Omega} = \sum S_{Bpl_A j_A} S_{npl_d j_d} \sigma^{DWBA}_{l_A j_A l_d j_d}$$

Spectroscopic factor S is very sensitive to single particle parameters in DW. But ANC is not so sensitive.

β-Decay Theory

β-decay theory for deformed heavy nuclei

$$\hat{H} = \hat{H}_0 - \frac{1}{2}\chi \sum_\mu \hat{Q}^\dagger_\mu \hat{Q}_\mu - G_M \hat{P}^\dagger \hat{P} - G_Q \sum_\mu \hat{P}^\dagger_\mu \hat{P}_\mu .$$

$$+2\chi_{ph} \sum_\mu \beta^-_{1\mu}(-1)^\mu \beta^+_{1-\mu} - 2\chi_{pp} \sum_\mu \Gamma^-_{1\mu}(-1)^\mu \Gamma^+_{1-\mu}$$

GT-forces

particle-hole

particle-particle

$$\beta^-_{1\mu} = \sum_{\pi,\nu} \langle \pi | \sigma_\mu \tau_- | \nu \rangle b^+_\pi b_\nu$$

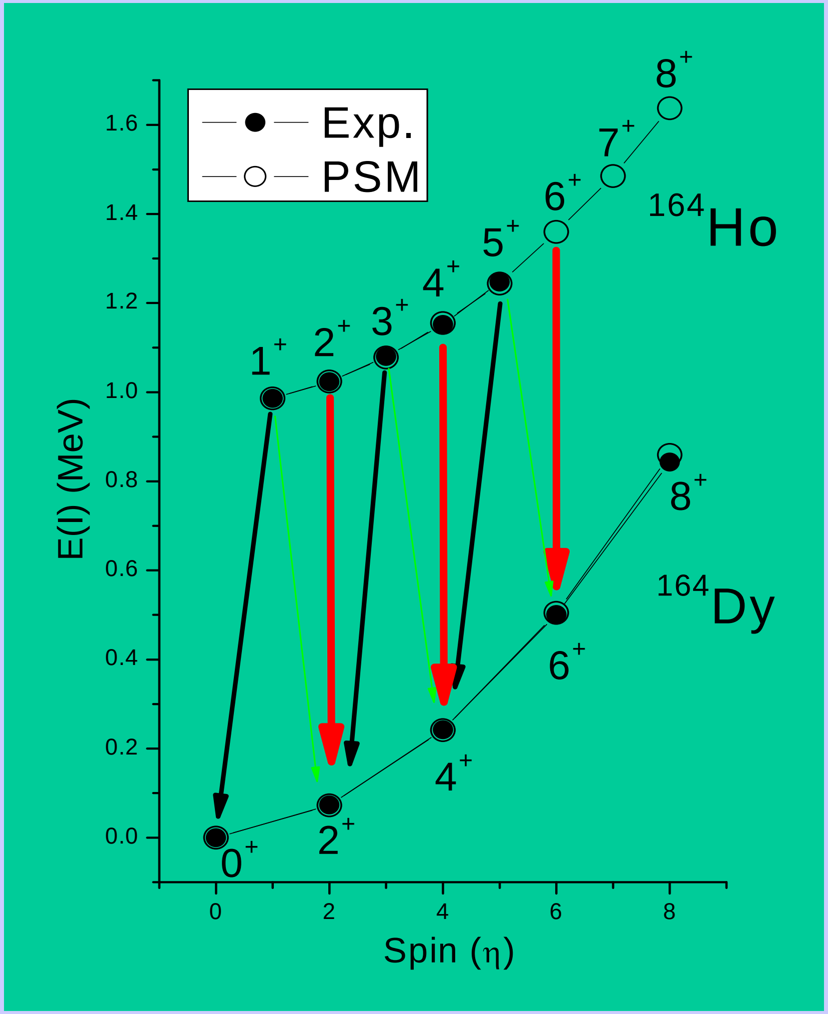
$$\beta^+_{1\mu} = (-)^\mu (\beta^-_{1-\mu})^\dagger$$

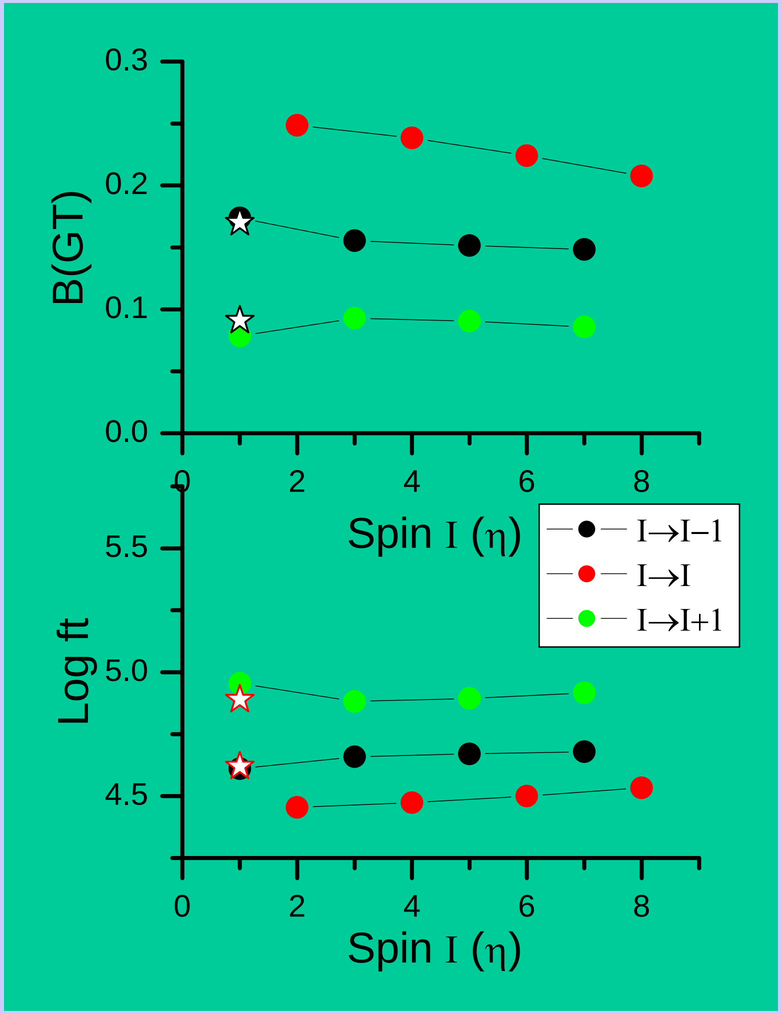
$$\Gamma^-_{1\mu} = \sum_{\pi,\nu} \langle \pi | \sigma_\mu \tau_- | \nu \rangle b^+_\pi b^+_{\bar{\nu}}$$

$$\Gamma^+_{1\mu} = (-)^\mu (\Gamma^-_{1-\mu})^\dagger$$

$$|\Psi^\sigma_{IM}\rangle = \sum_{K\kappa} f^\sigma_{IK_\kappa} \hat{P}^I_{MK} |\Phi_\kappa\rangle$$

Gamow-Teller transitions between the excited states





Z.C. Gao et al., Phys. Rev. C74, 054303 (2006)

- The Projected Shell Model has been applied to calculate the GT transitions for heavy, deformed nuclei

- The testing calculation of the e-capture $^{164}\text{Ho}(Z=67) \rightarrow {}^{164}\text{Dy}(Z=66)$ is in a good agreement with data.

Network equation
and nuclear data base

The reaction network
--- a set of differential equations

$$\frac{dY_i}{dt} = \sum_j N^i_j \lambda_j Y_j + \sum_{j,k} N^i_{j,k} \rho N_A < \sigma V >_{jk,i} Y_j Y_k$$
$$+ \sum_{j,k,l} N^i_{j,k,l} \rho^2 N_A{}^2 < \sigma V >_{jkl,i} Y_j Y_k Y_l$$

$Y_i = n_i / \rho N_A$ ***The nuclear abundance***

N_A ***Avagadro constant number***

ρ ***The density***

n_i ***The number density of species 'i'***

N_i ***Positive or negative numbers to specify how many particles of species i are created or destroyed in the reaction***

The set of differential equations ruling BBN

$$\frac{\dot{R}}{R} = H = \sqrt{\frac{8\pi G_N \rho}{3}}$$

$$\frac{\dot{n}_B}{n_B} = -3H$$

$$\dot{\rho} = -3H(\rho + p)$$

$$\rho = \rho_B + \rho_\gamma + \rho_e + \rho_\nu$$

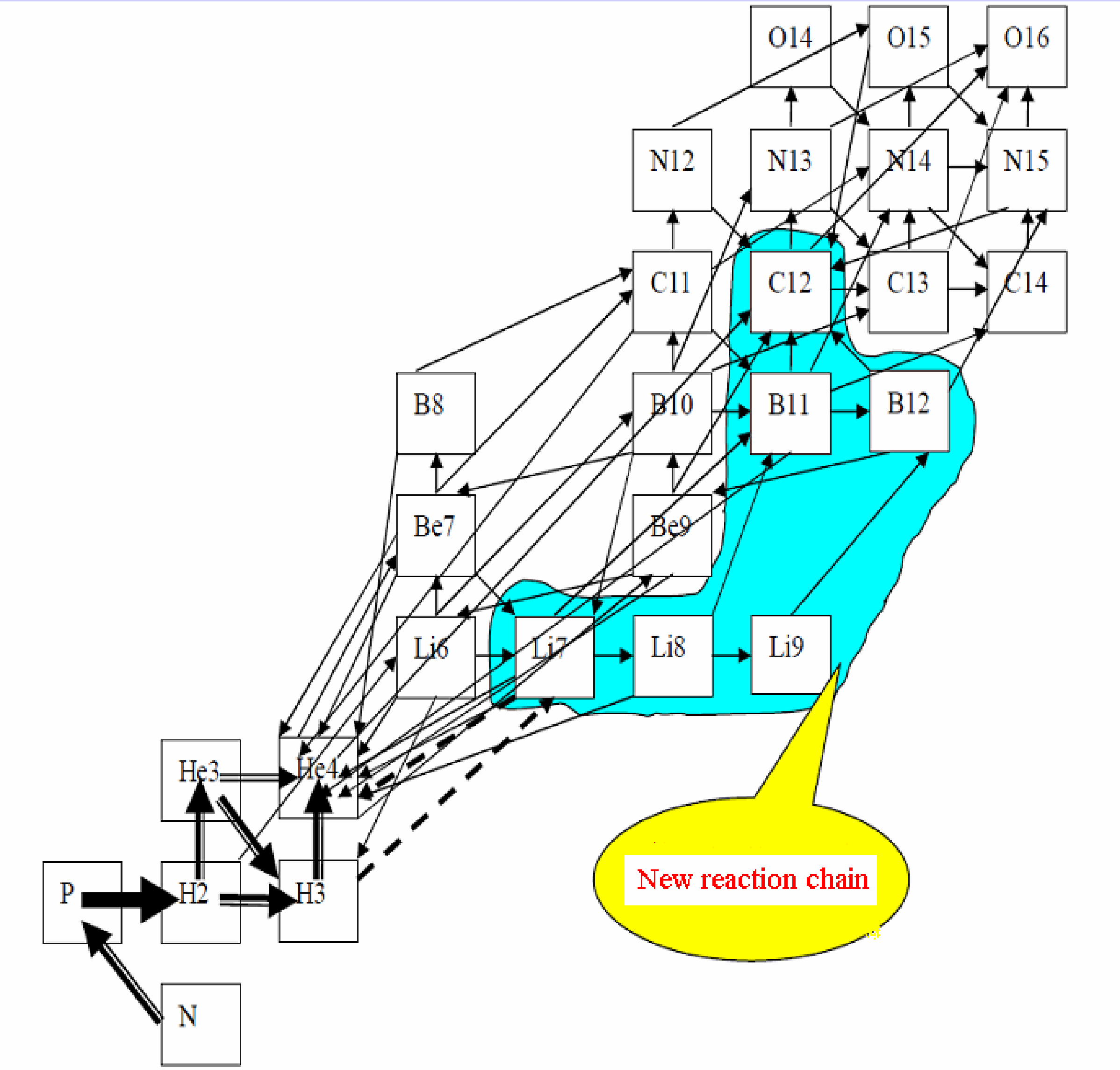
$$\frac{dY_i}{dt} = \sum_j N^i_j \lambda_j Y_j + \sum_{j,k} N^i_{j,k} \rho_B N_A < \sigma V >_{jk,i} Y_j Y_k$$

$$+ \sum_{j,k,l} N^i_{j,k,l} \rho_B{}^2 N_A{}^2 < \sigma V >_{jkl,i} Y_j Y_k Y_l$$

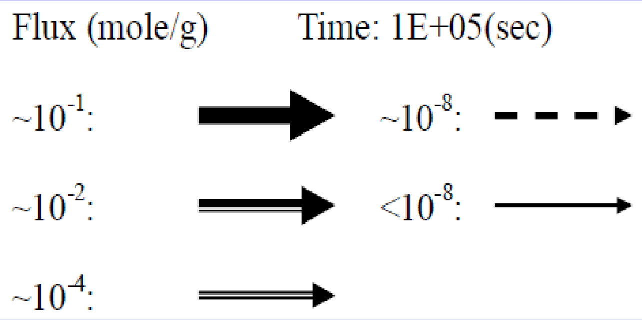
$$n_B \sum_i Z_i X_i = n_{e^-} - n_{e^+} \equiv L(\frac{m_e}{T}, \phi_e)$$

$$(\frac{\partial}{\partial t} - H|p|\frac{\partial}{\partial |p|}) f_{\nu_\alpha}(|p|, t) = I_{\nu_\alpha}[f_{\nu_e}, f_{\bar{\nu}_e}, f_{\nu_x}, f_{\bar{\nu}_x}, f_{e^-}, f_{e^+}]$$

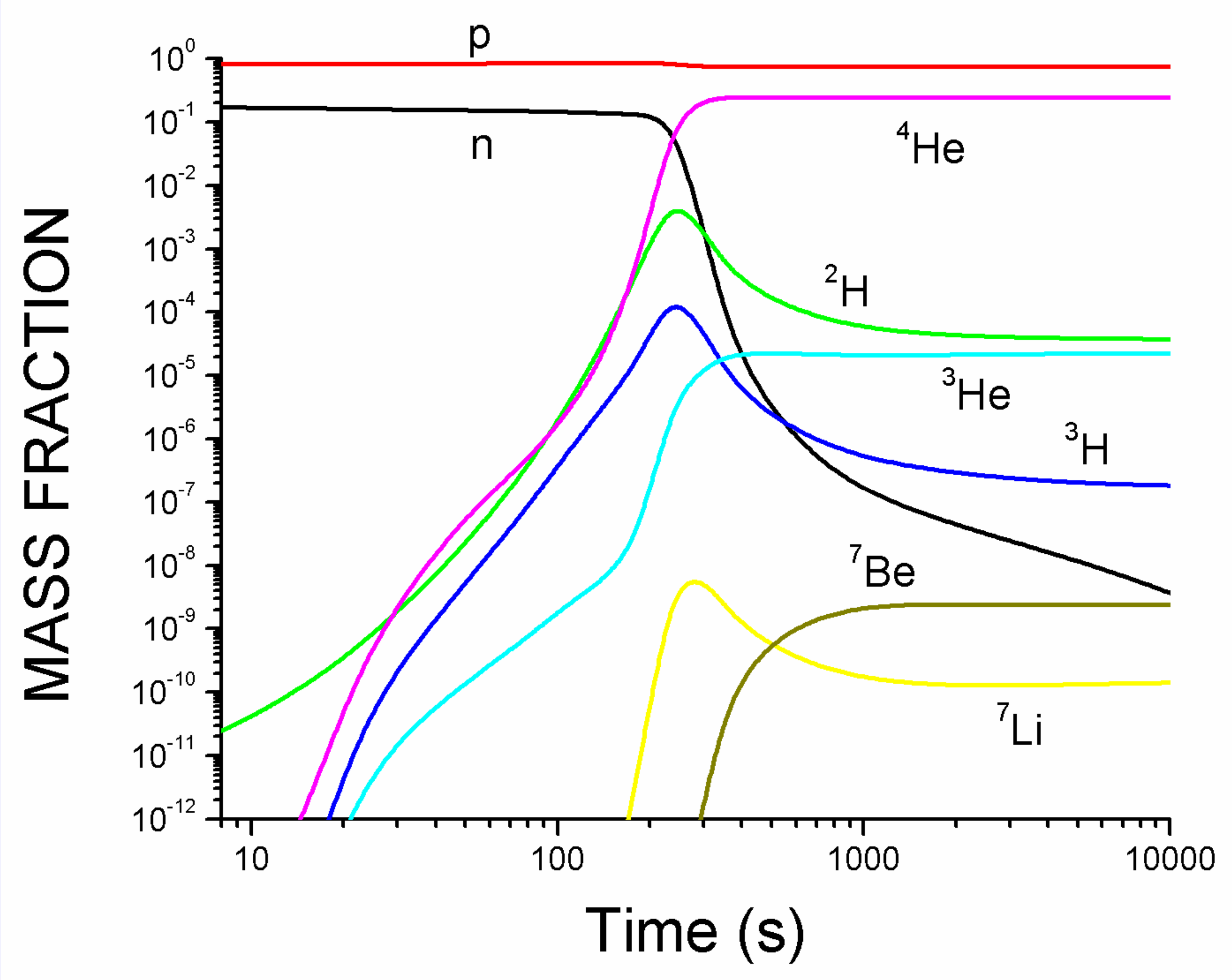
Reaction chain $^{8}Li(n,\gamma)^{9}Li(\alpha,n)^{12}B(\beta)^{12}C$



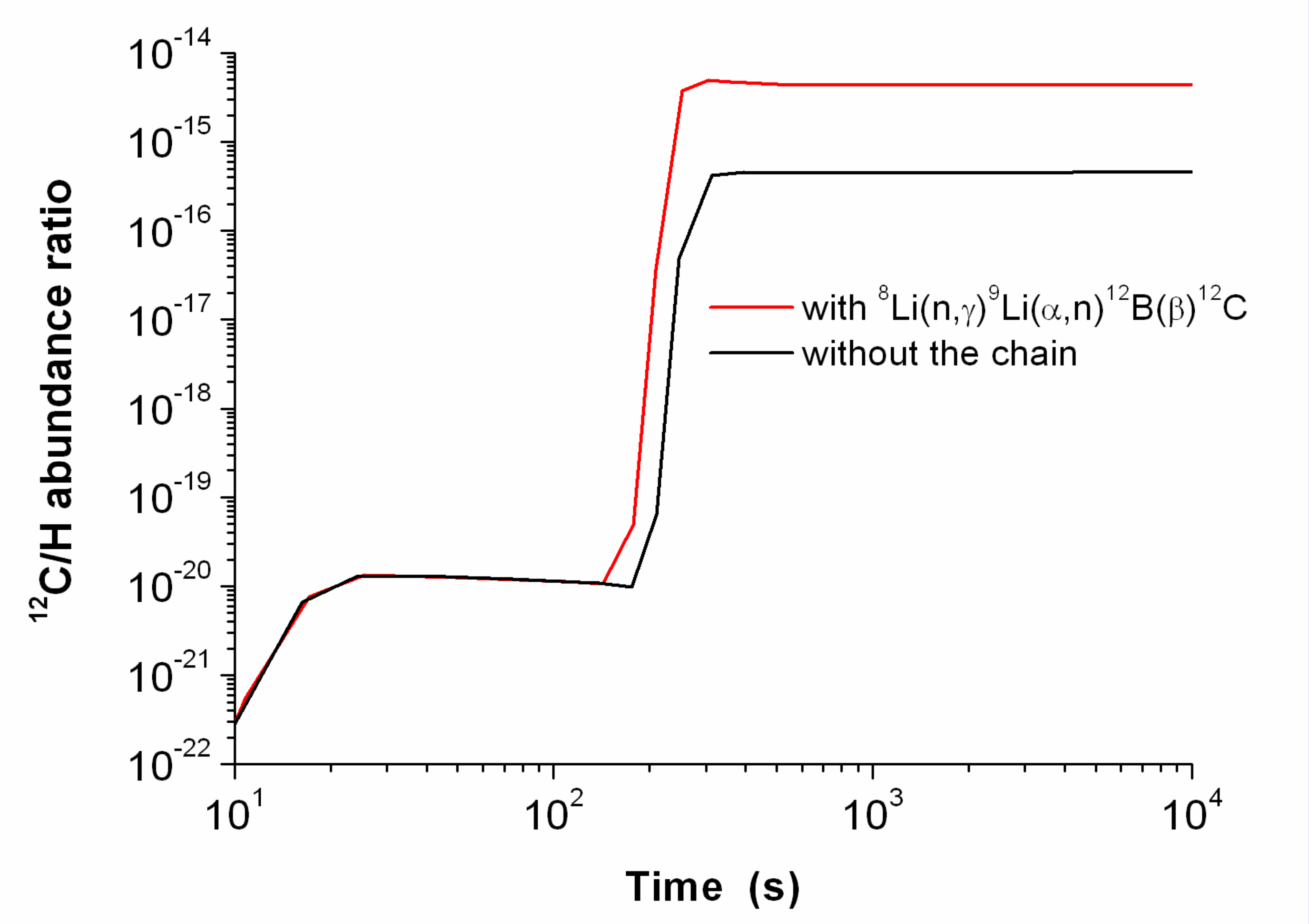
Reaction flux

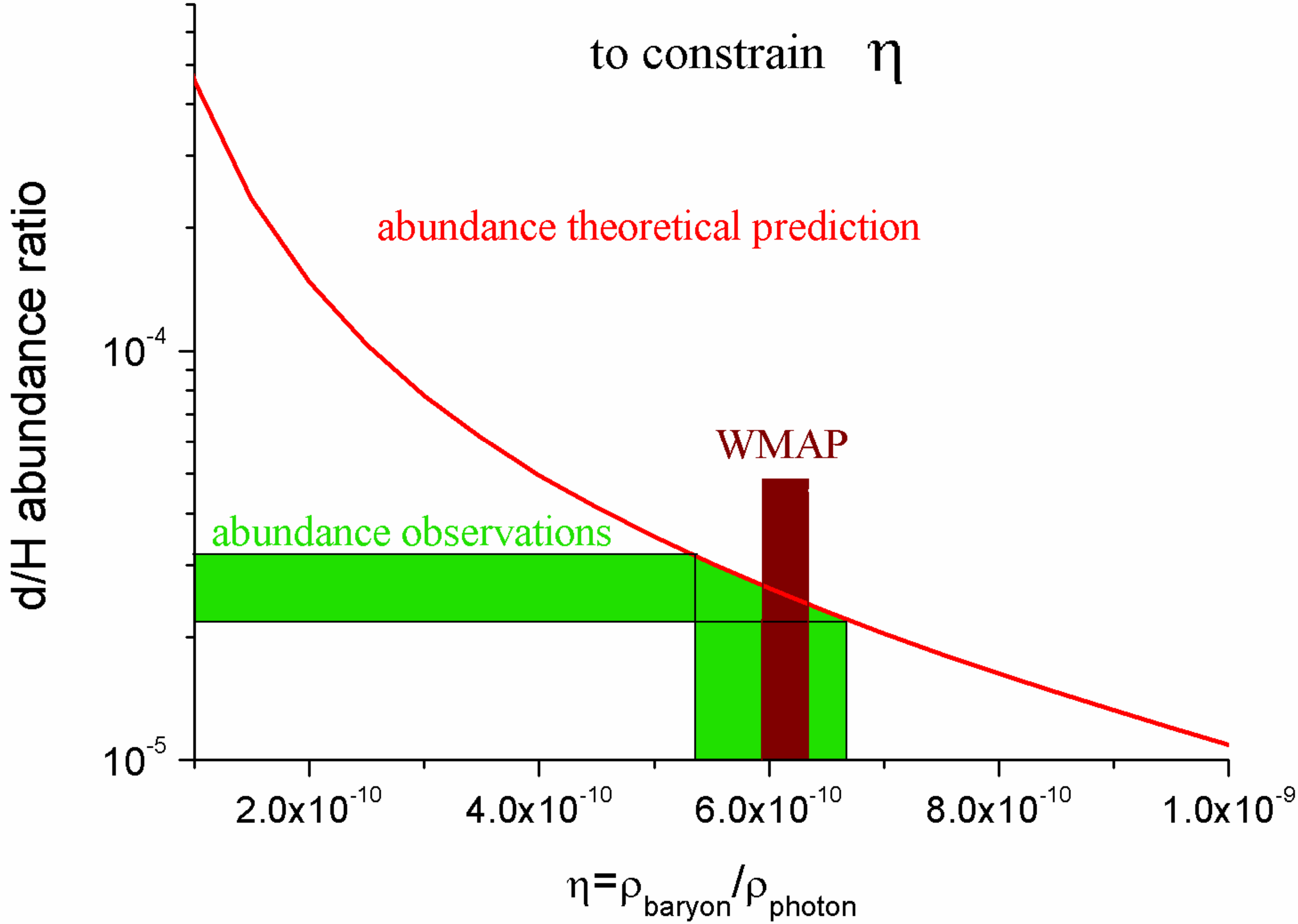


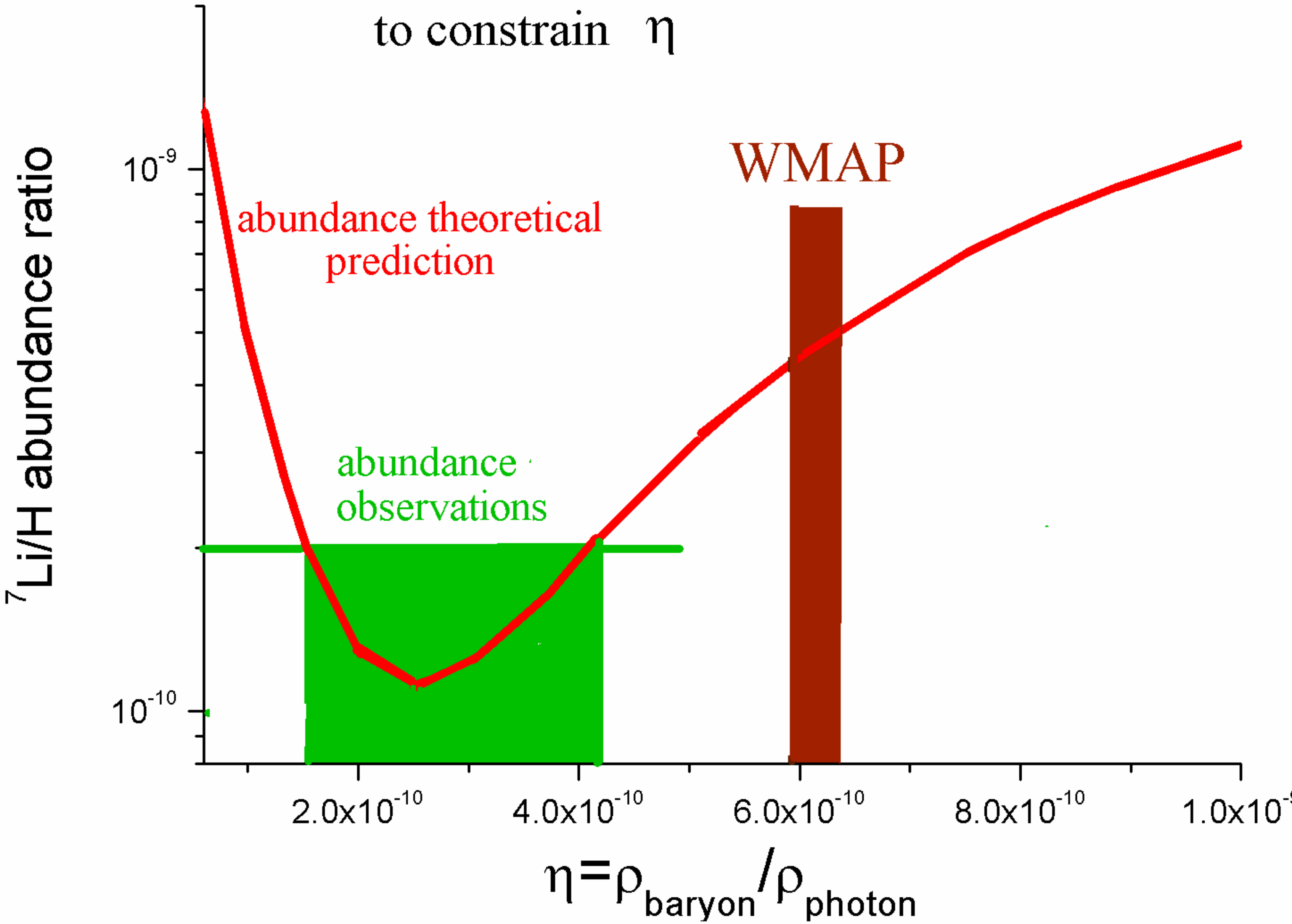
BBN calculation （侯素青）



The effect of $^{8}Li(n,\gamma)^{9}Li(\alpha,n)^{12}B(\beta)^{12}C$




to constrain η
abundance theoretical prediction
WMAP
abundance observations
d/H abundance ratio
10^{-4}
10^{-5}
$2.0x10^{-10}$
$4.0x10^{-10}$
$6.0x10^{-10}$
$8.0x10^{-10}$
$1.0x10^{-9}$
$\eta=\rho_{baryon}/\rho_{photon}$


to constrain η
WMAP
abundance theoretical prediction
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^{7}Li/H abundance ratio
10^{-9}
10^{-10}
$2.0x10^{-10}$
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$\eta=\rho_{baryon}/\rho_{photon}$

Our tasks

本项目以核物理实验及天文观测为主，理论同实验密切结合；

以国内大型科学工程的实验设备为基础，并利用国际先进实验设备。

理论紧密结合实验，着重为本项目的实验数据提升科学意义，为进一步实验提供建议。

理论在同核物理实验和天文观测的比较中和需求中发展。

重视核天体物理理论和计算方法的新发展。

网络方程数据库建立和更新

BBN

rp-process

r-process

发展核天体物理理论

Explosive events:

Big Bang   (light nuclei)

x-ray burst (rp-nuclei, proton rich)

Supernova   (r-nuclei, neutron rich)

发展核理论

Spectroscopic Factor

β-decay

Thank you