

核天体物理：用极小探寻极大

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上海交大

2021年5月19日

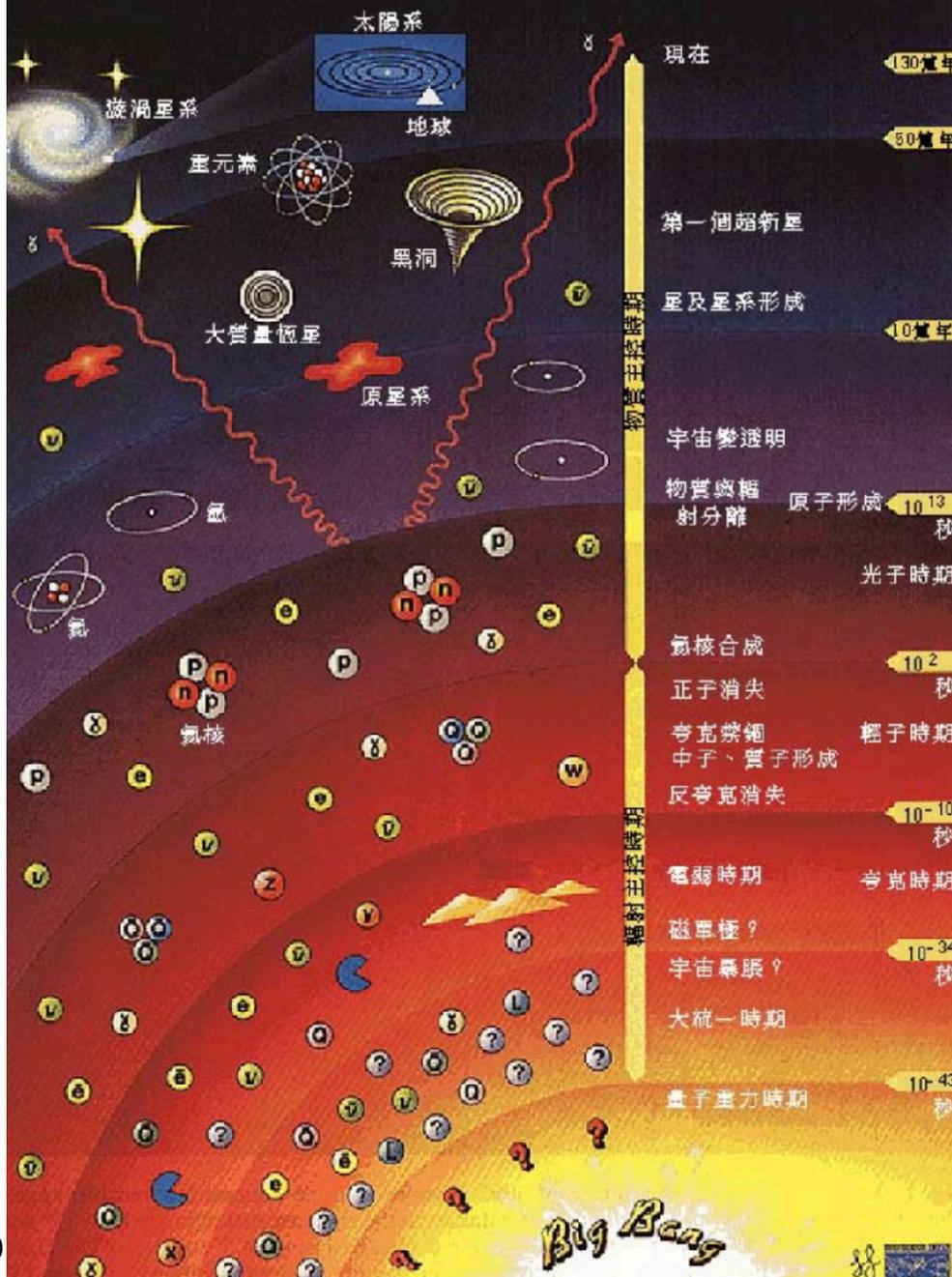
万物是怎么形成的



报告内容概要

- 研究领域
- 国际进展
- 我国情况
- 关键科学问题
- 展望与建议

History of the Universe



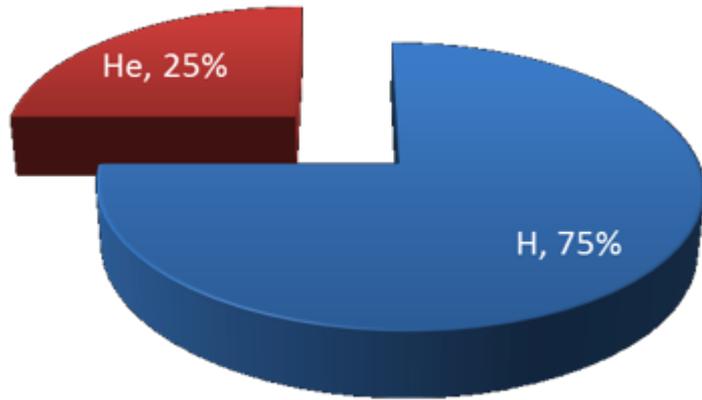
宇宙大爆炸的圖像

元素的起源

origin of elements



其他核素 ($^2\text{H}, ^3\text{He}, ^6\text{Li}, ^7\text{Li}$) < 0.00001



宇宙大爆炸后三分钟

Human Body Ingredients

The four ingredients below are essential parts of the body's protein, carbohydrate and fat architecture.

O

OXYGEN
65.0%
Critical to the conversion of food into energy.

C

CARBON
18.5%
The so-called backbone of the building blocks of the body and a key part of other important compounds, such as testosterone and estrogen.

H

HYDROGEN
9.5%
Helps transport nutrients, remove wastes and regulate body temperature. Also plays an important role in energy production.

N

NITROGEN
3.3%
Found in amino acids, the building blocks of proteins; an essential part of the nucleic acids that constitute DNA.

Other Key Elements

Calcium 1.5%
Lends rigidity and strength to bones and teeth; also important for the functioning of nerves and muscles, and for blood clotting.

Phosphorus 1.0%
Needed for building and maintaining bones and teeth; also found in the molecule ATP (adenosine triphosphate), which provides energy that drives chemical reactions in cells.

Potassium 0.4%
Important for electrical signaling in nerves and maintaining the balance of water in the body.

Sulfur 0.3%
Found in cartilage, insulin (the hormone that enables the body to use sugar), breast milk, proteins that play a role in the immune system, and keratin, a substance in skin, hair and nails.

Chlorine 0.2%
Needed by nerves to function properly; also helps produce gastric juices.

Sodium 0.2%
Plays a critical role in nerves' electrical signaling; also helps regulate the amount of water in the body.

Magnesium 0.1%
Plays an important role in the structure of the skeleton and muscles; also found in molecules that help enzymes use ATP to supply energy for chemical reactions in cells.

Iodine (trace amount)
Part of an essential hormone produced by the thyroid gland; regulates metabolism.

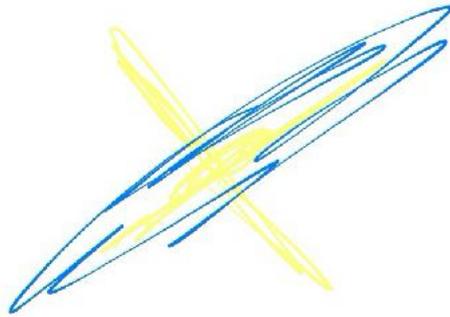
Iron (trace amount)
Part of hemoglobin, which carries oxygen in red blood cells.

Zinc (trace amount)
Forms part of some enzymes involved in digestion.

(Percentage of body weight. Source: *Biology*, Campbell and Reece, eighth edition.)

最初三分钟后

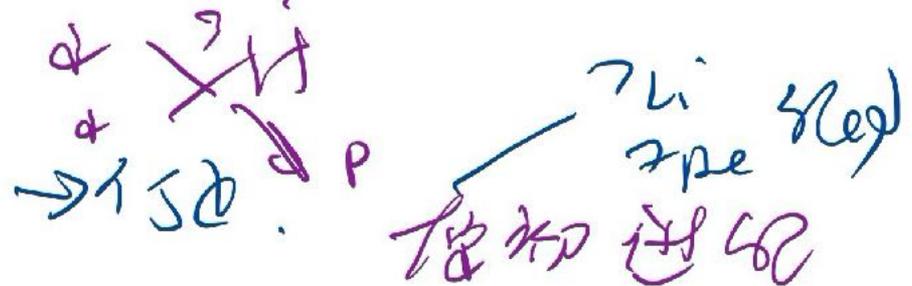
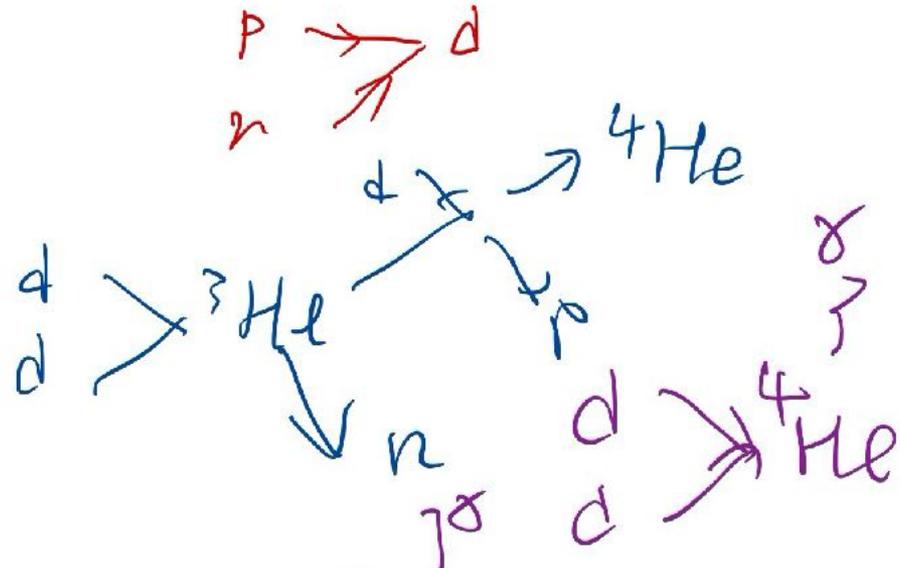
138亿年前 大爆炸



2^1H 2^2He

$M=5$ 及 7He

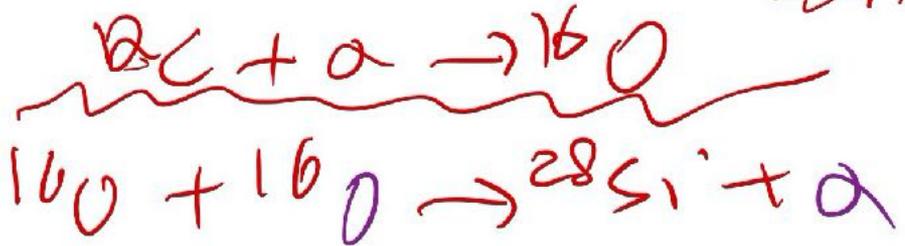
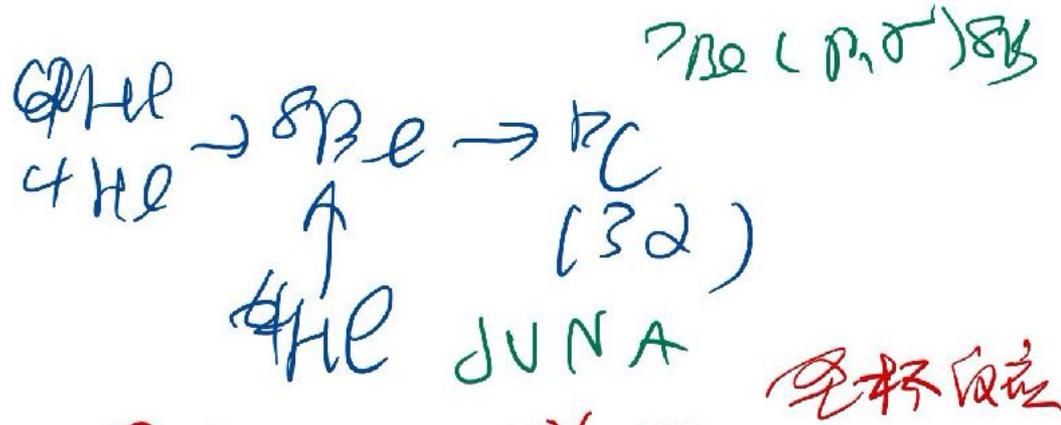
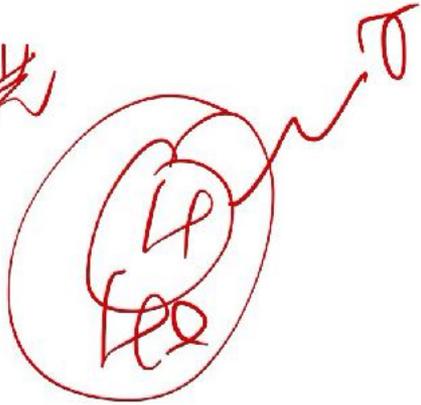
解释一下 3分钟时的
3分钟 α
 γ 10^8 T



平稳核燃烧

1 氦气核

发光



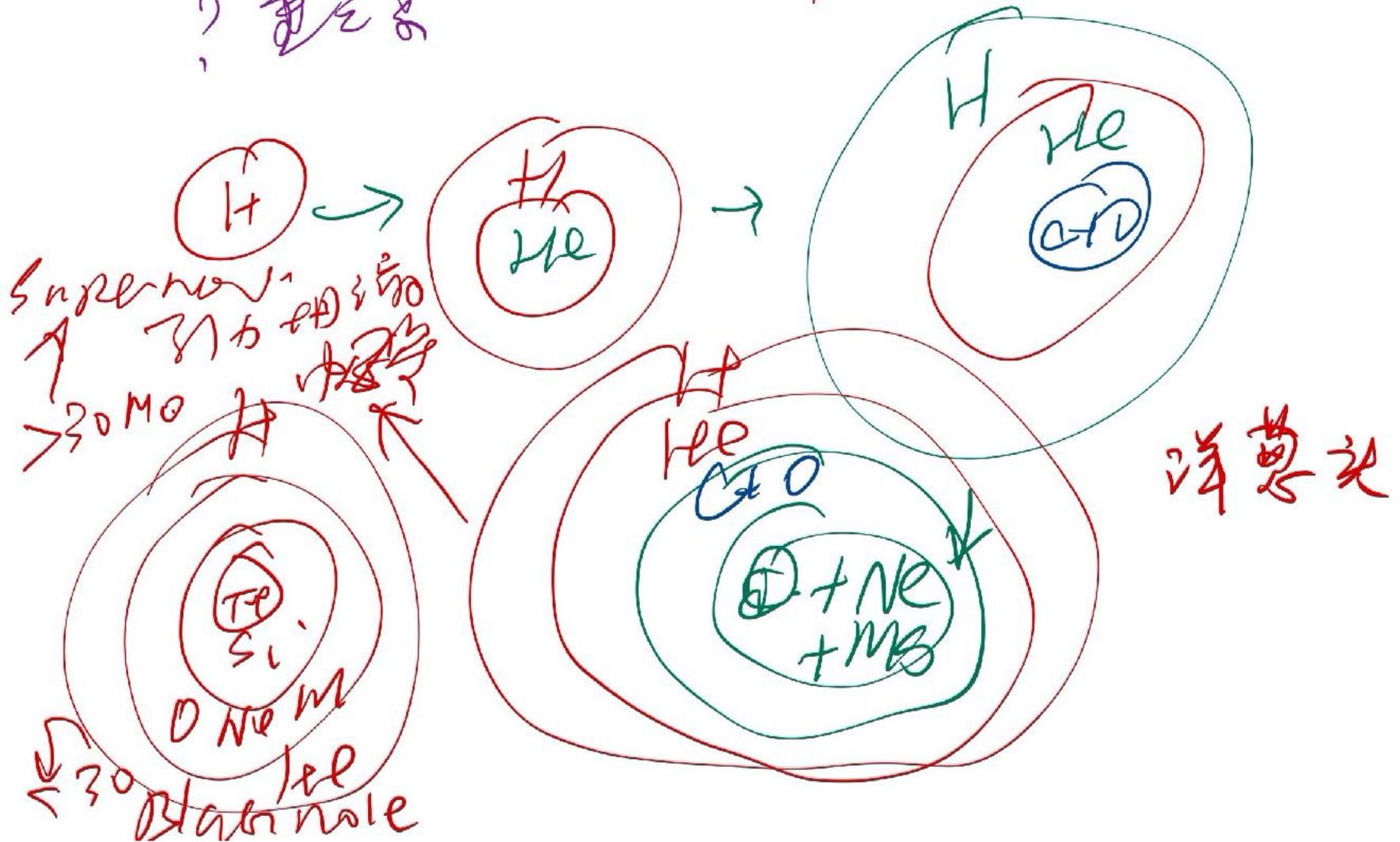
空杯反应

... $56Fe$ Fe 力大 $P \rightarrow n$ 核中子 \rightarrow 中子

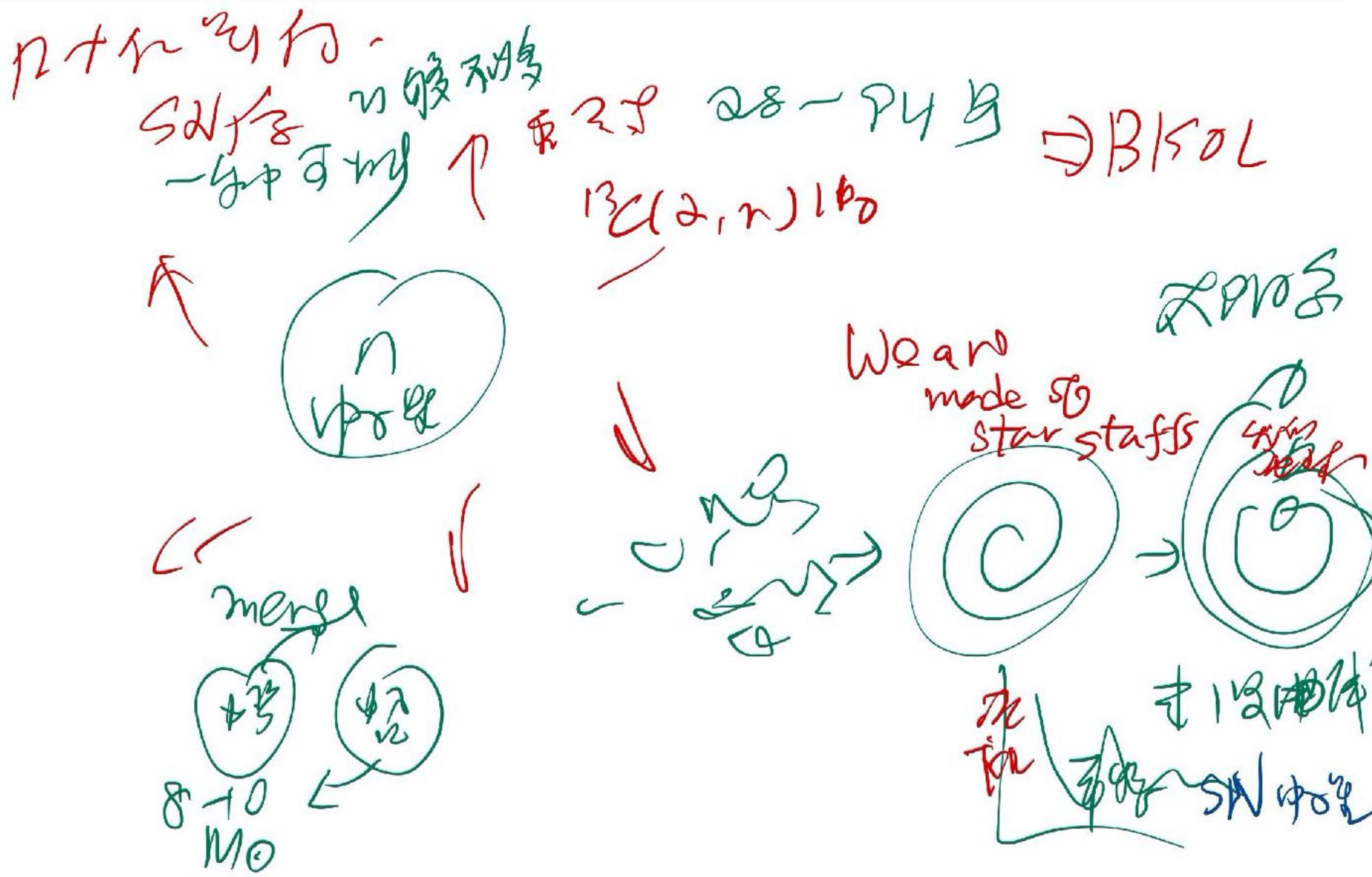
Fe 逆不 2-个... 云... 核... 核...

平稳核燃烧 stellar burning

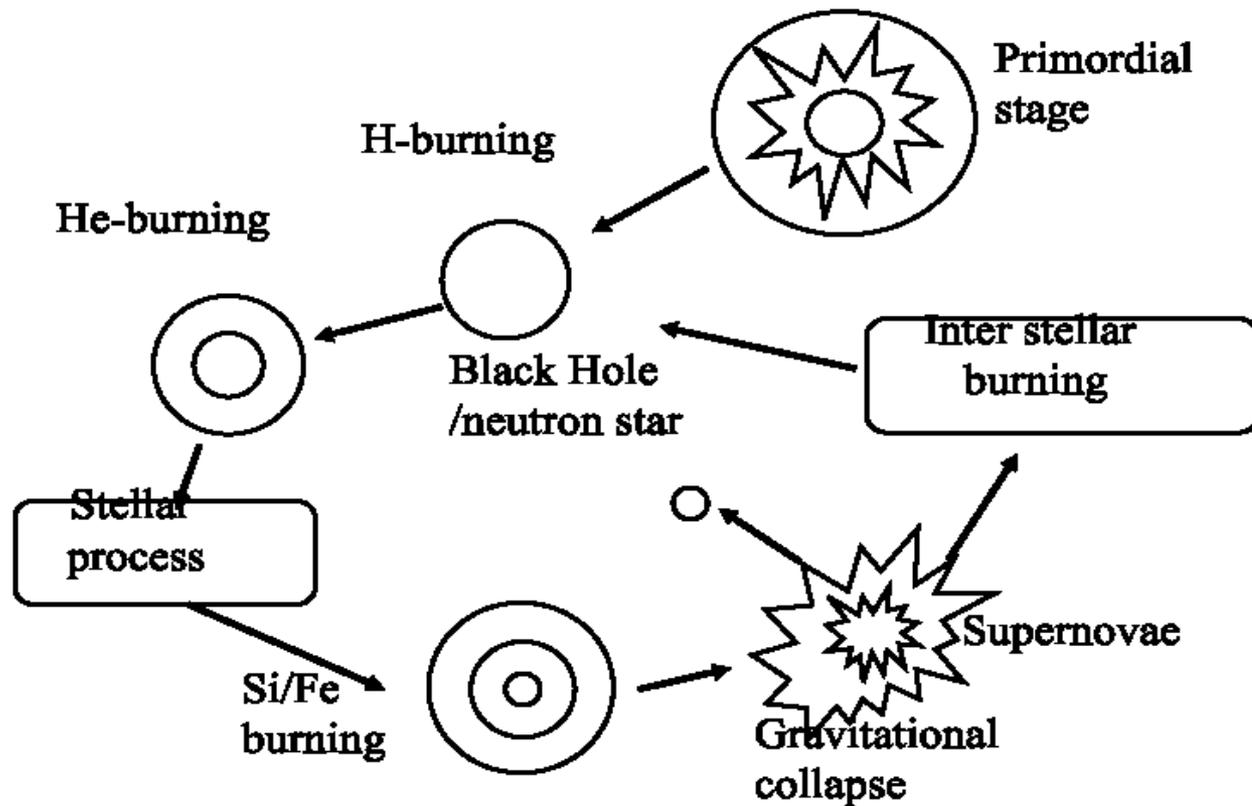
? 重元素 10^{12} yr



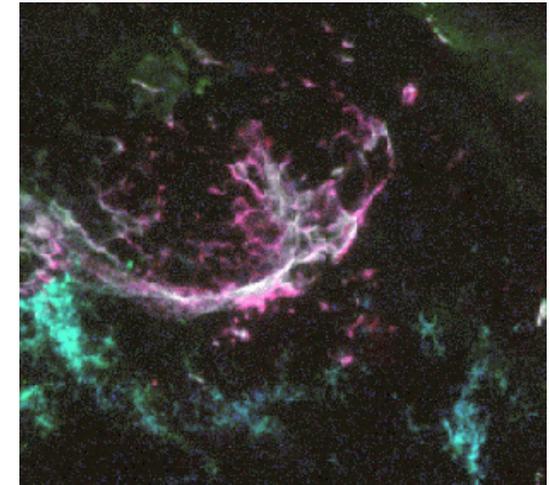
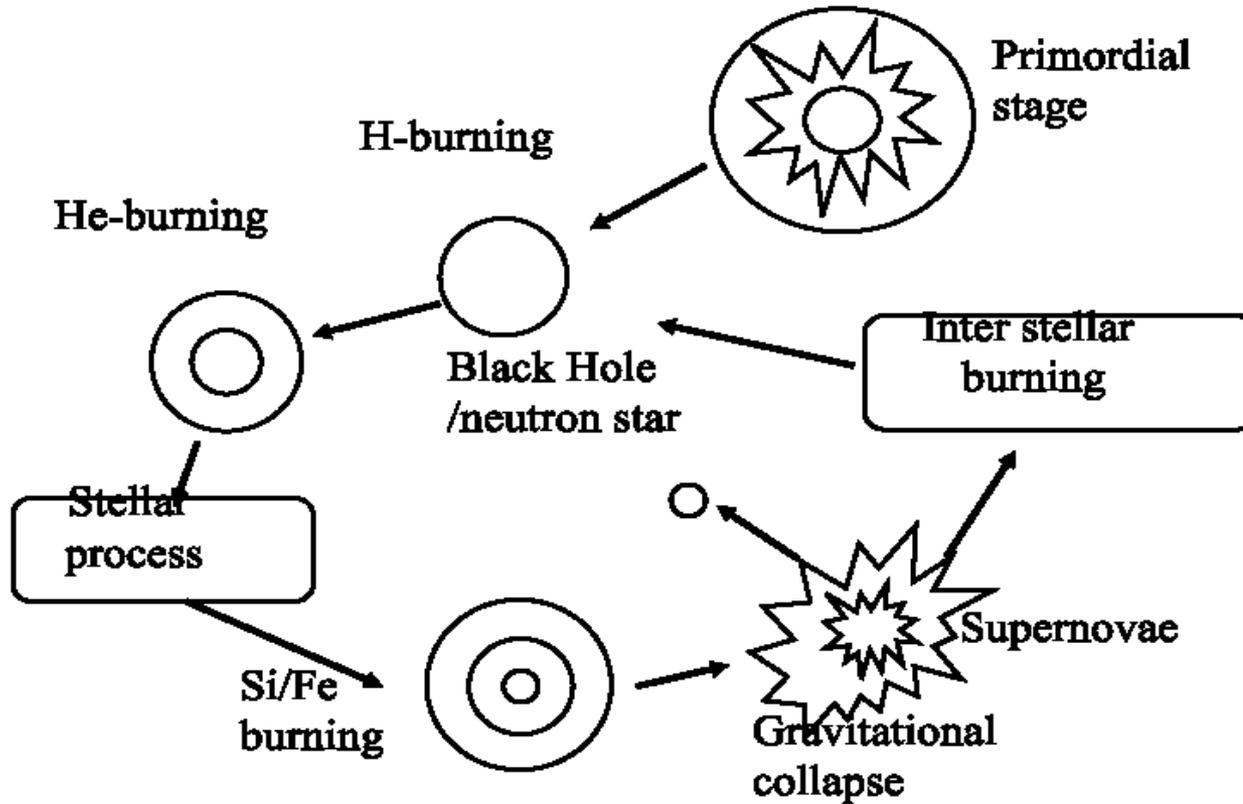
重元素和星体演化 HI star evolution



Primordial and stellar elements syntheses

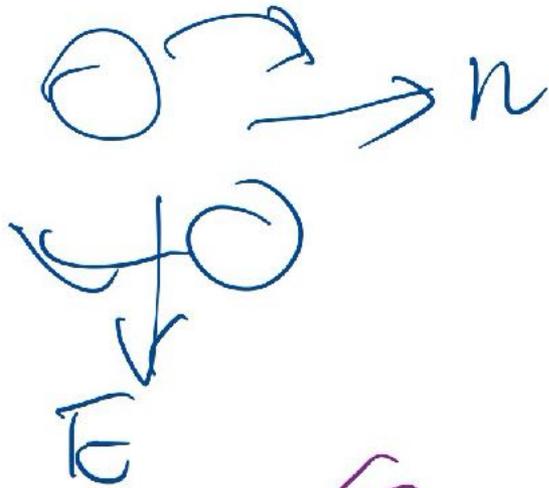


Primordial and stellar elements syntheses



中子星并合 NSM

今後!

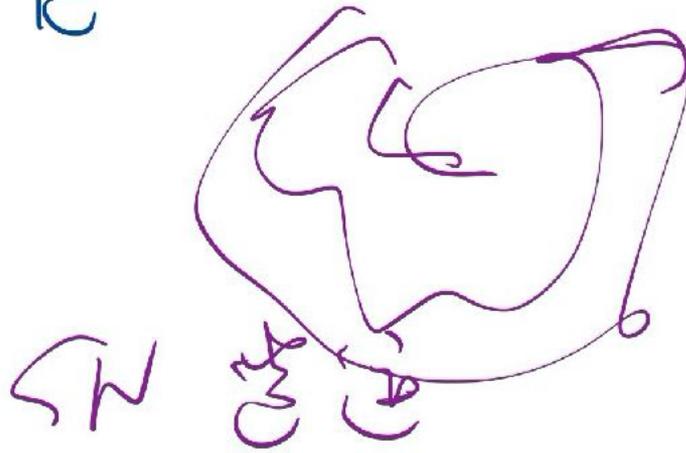


2017年 9月 14日

観測 LIGO

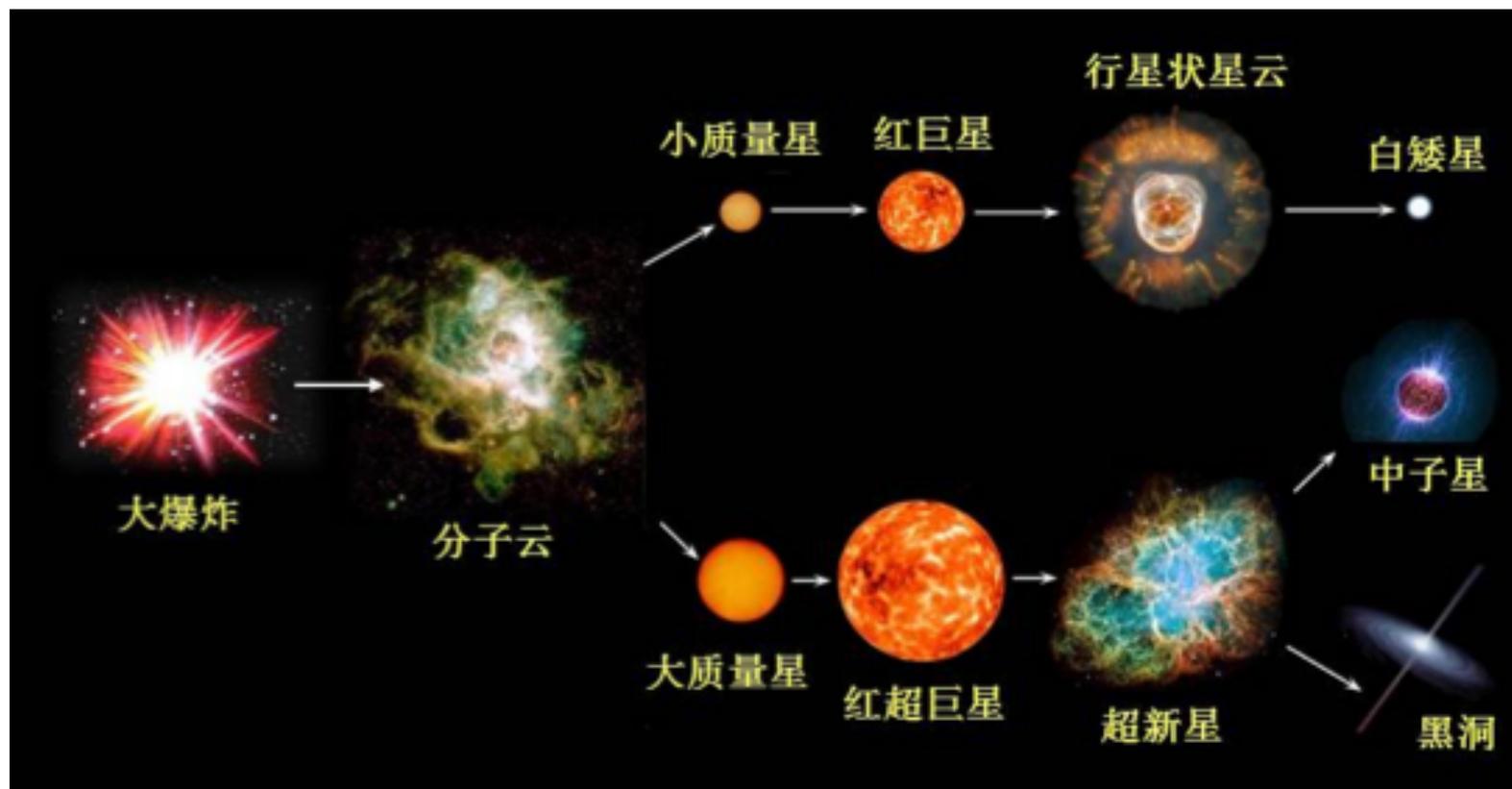
→ 子 脉冲

2-10 地球 (Golden?)
多 (多) 来



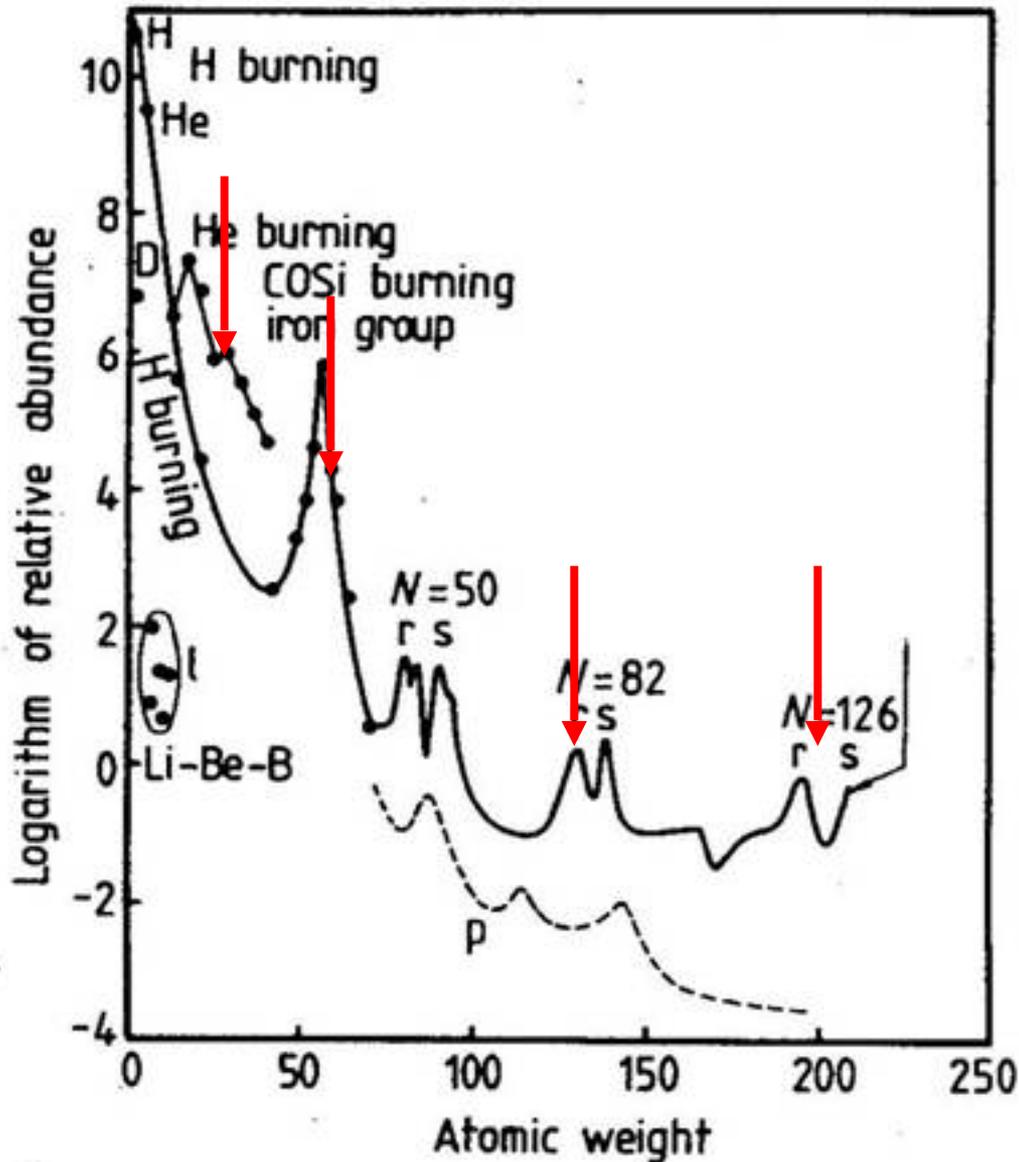
SN 1987A

天体演化中的核过程



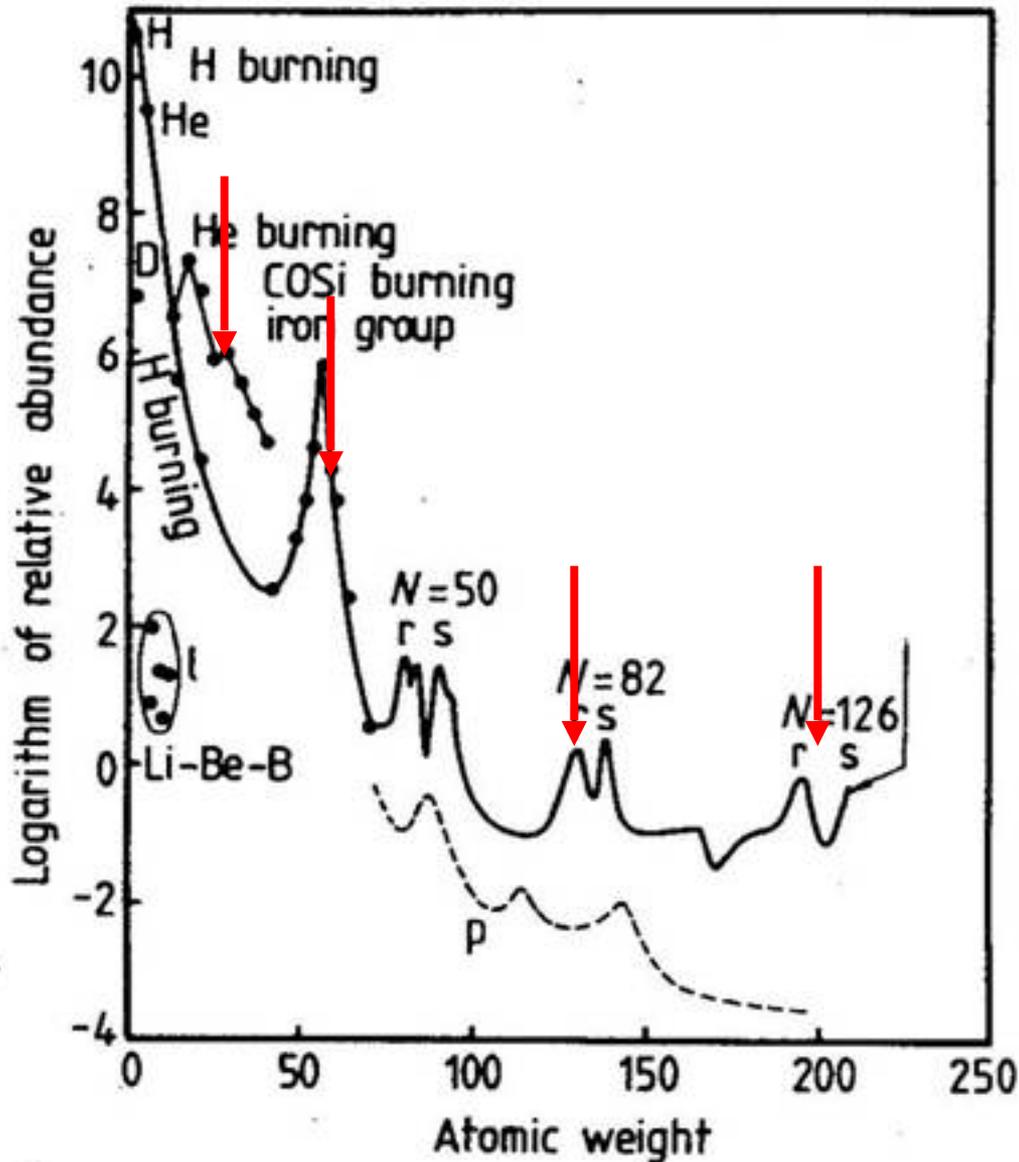
- 小质量恒星在经历某个轻元素燃烧阶段后，因剩下的核芯区质量不足以通过引力收缩使下一级聚变反应点火，随着核燃烧的结束而走向死亡，形成各类白矮星
- 大质量恒星，在经历H、He、C、Ne、O和Si各平稳核燃烧阶段后，呈现由内至外依次为Fe核芯、未燃尽的Si、Mg、Ne、O、C、He和H的分层结构
- 由于铁以上的聚变反应成为吸能过程，失去了阻止其引力塌缩的能源，最终导致II型超新星爆发
- 冲击波抛向星际空间的大量外层物质变为气体和尘埃，进而凝聚成新的恒星；占初始质量一小部分的残体形成中子星或黑洞

Nuclear reaction:
alchemist in universe



Peak: finger print of
nuclear physics:
Shell model magic
number

Nuclear reaction:
alchemist in universe

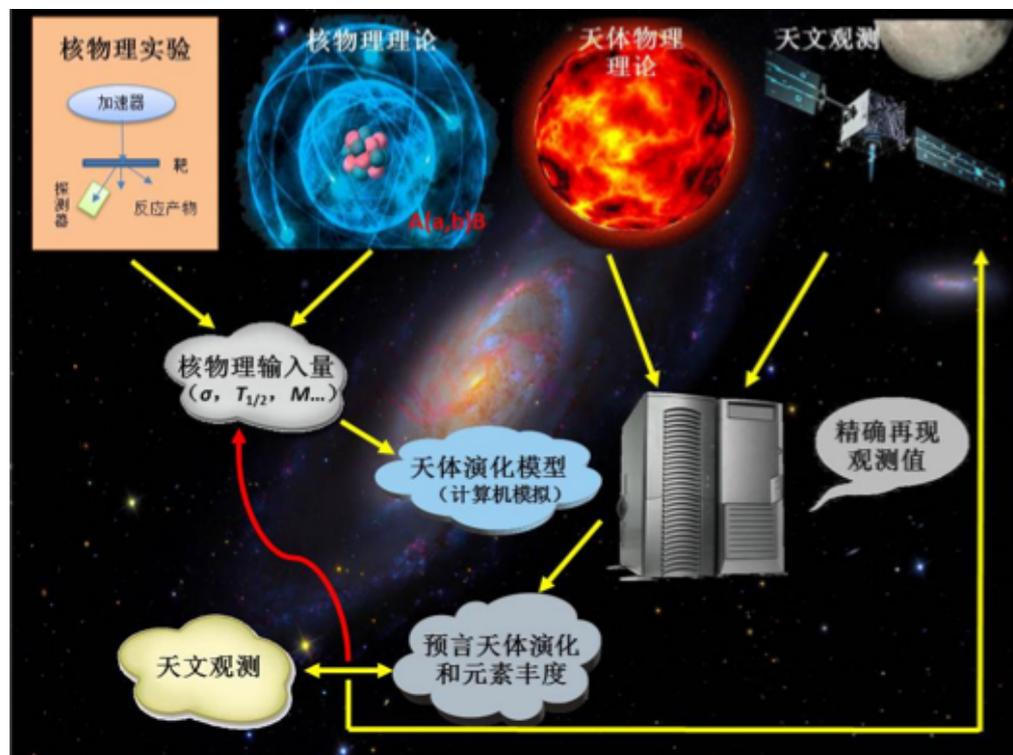


Peak: finger print of
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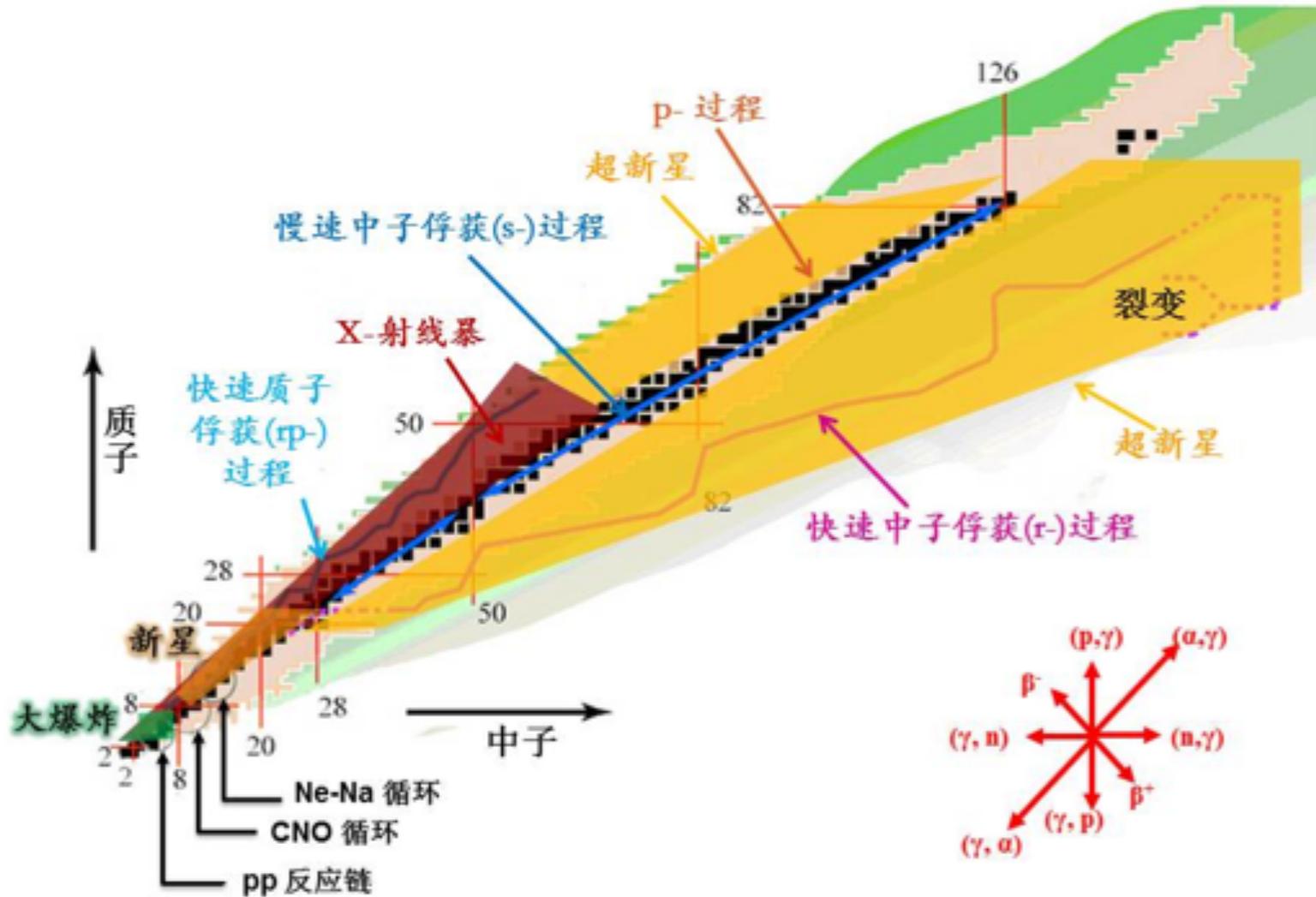


核天体物理的研究领域

- 对微观尺度(10^{-15} m)的核过程的了解, 可以解释对宇观尺度(10^{14} m)的天文观测, 构成了学科发展和交叉的动力和挑战, 使核天体物理始终处于物理学的前沿
- 应用核物理的知识和规律阐释恒星中核过程产生的能量及其对恒星结构和演化的影响, 自然界中化学元素的起源

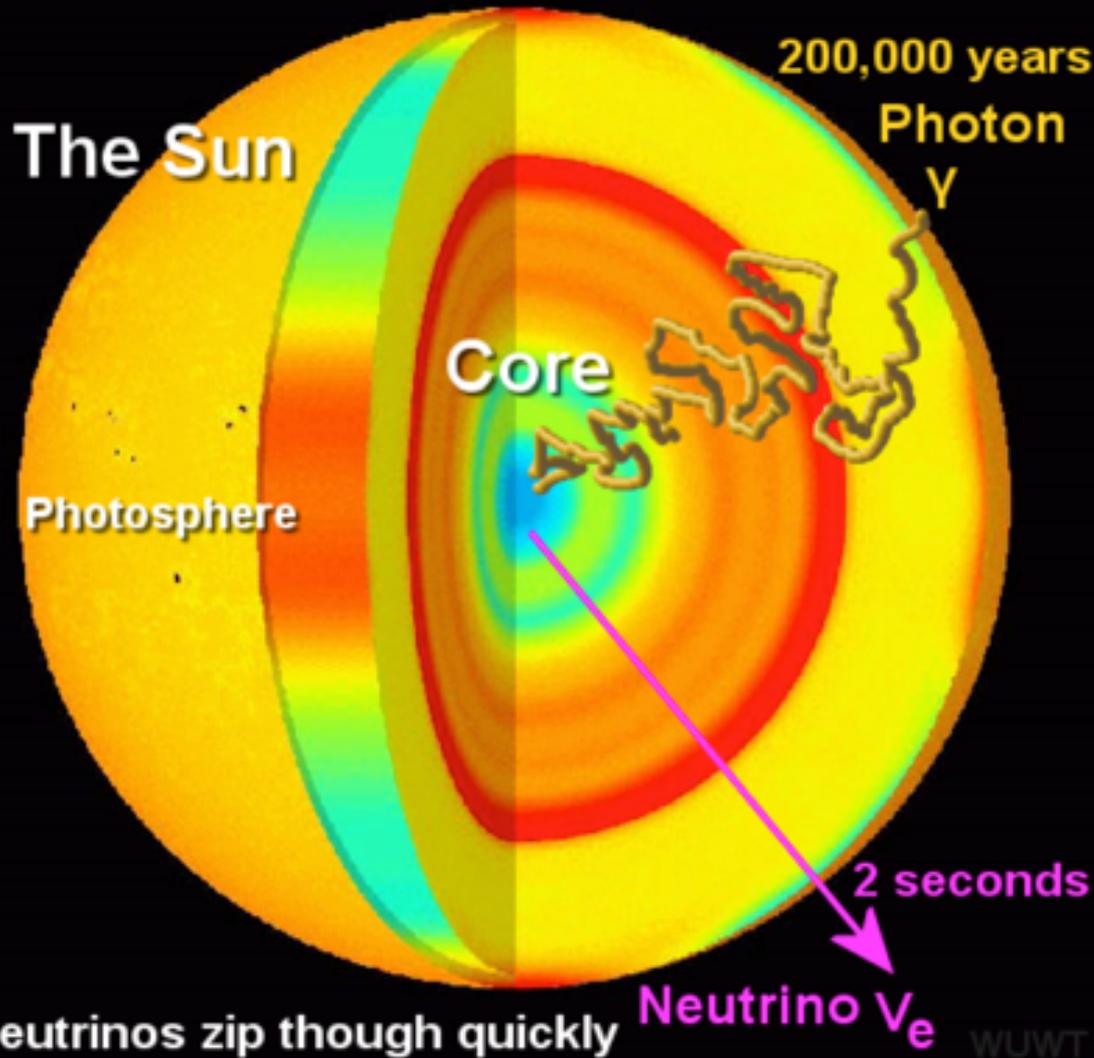


天体元素核合成的各种过程



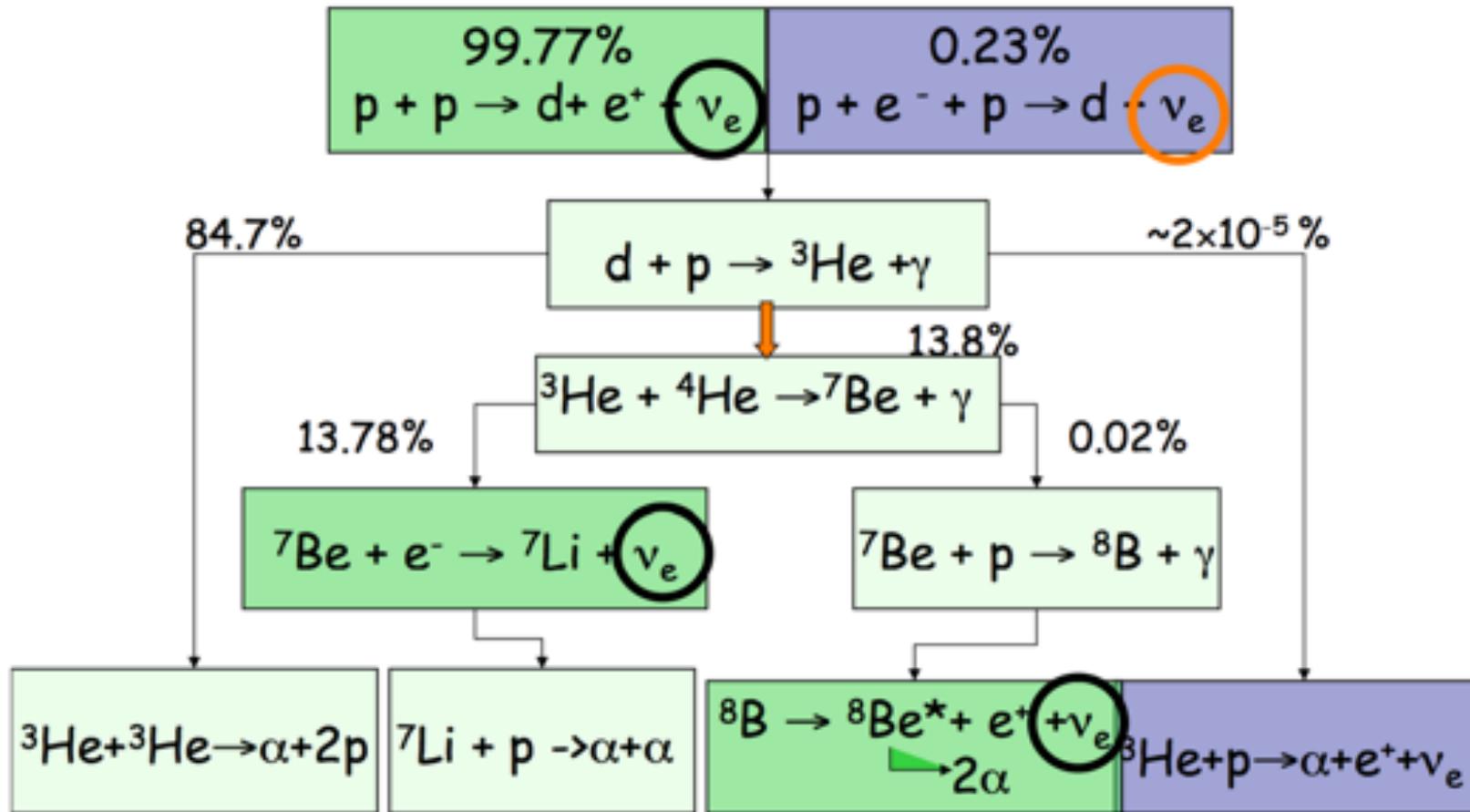
Nuclear burning inside sun

Photons take a long and tortuous path



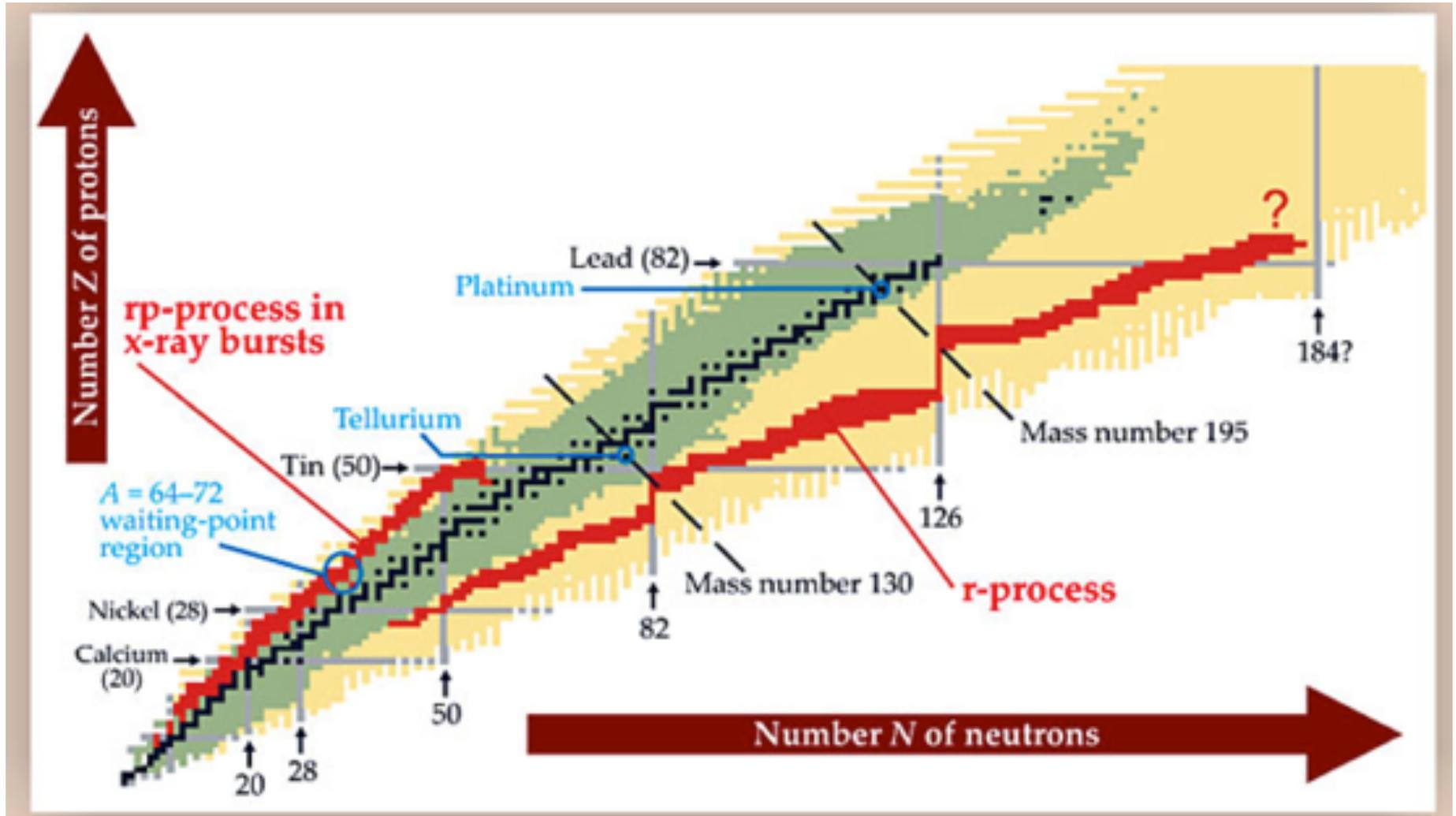
Nuclear burning inside sun

Nuclear reaction network in the Sun



Three paths leading to neutrinos are called pp-I, pp-II and pp-III chains, respectively.

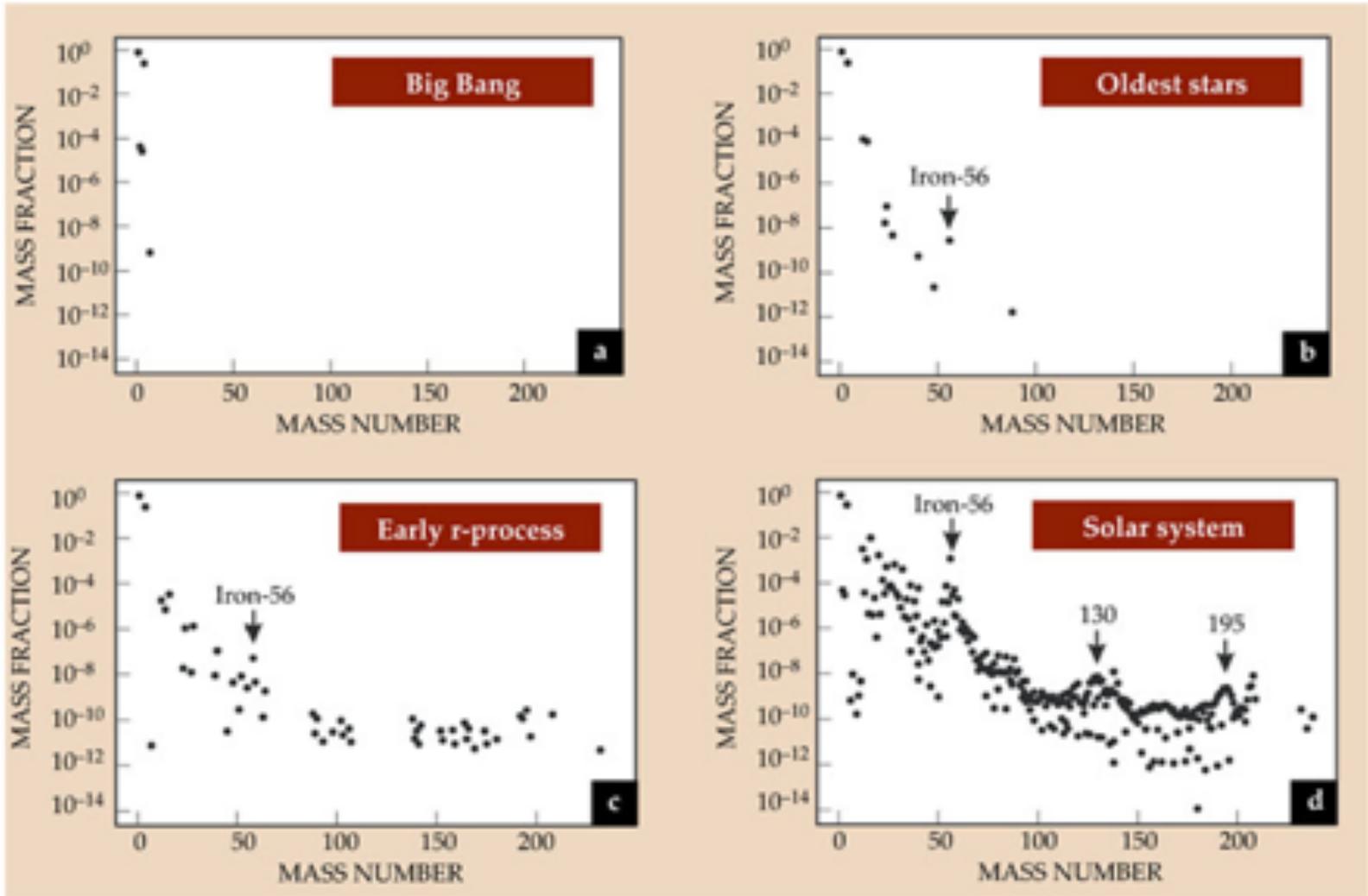
Combination of stages



Combination of stages

Number Z of protons

C



From H. Schatz

Some of the great discovery of astrophysics

- 3K microwave background radiation, 1965, experimental support for Big-Bang theory
- Detection of solar neutrino, 1960, gave the hints of neutrino oscillation
- Detection of ^{26}Al γ -ray, 1980, direct support of explosive nuclear synthesis, and triggering γ -ray astronomy
- Detection of SN1987A supernova explosion, 1987
- Experimental explanation of solar neutrino missing, 2003

核天体物理处于国际物理学科前沿

- 基金委数理科学13个优先领域中
 - 恒星的形成、演化与太阳活动
 - 极端条件下的核物理和核天体物理
- 2007 美国DOE核科学中长期规划中
 - What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes?
 - What is the origin of simple patterns in complex nuclei?
 - What is the nature of neutron stars and dense nuclear matter?
 - What is the origin of the elements in the cosmos?元素起源
 - What are the nuclear reactions that drive stars and stellar explosions?驱动恒星演化和爆发的核反应
- 美国科学院在发现杂志上认为世纪之谜的第三个问题：
铁到铀元素是如何合成出来的？

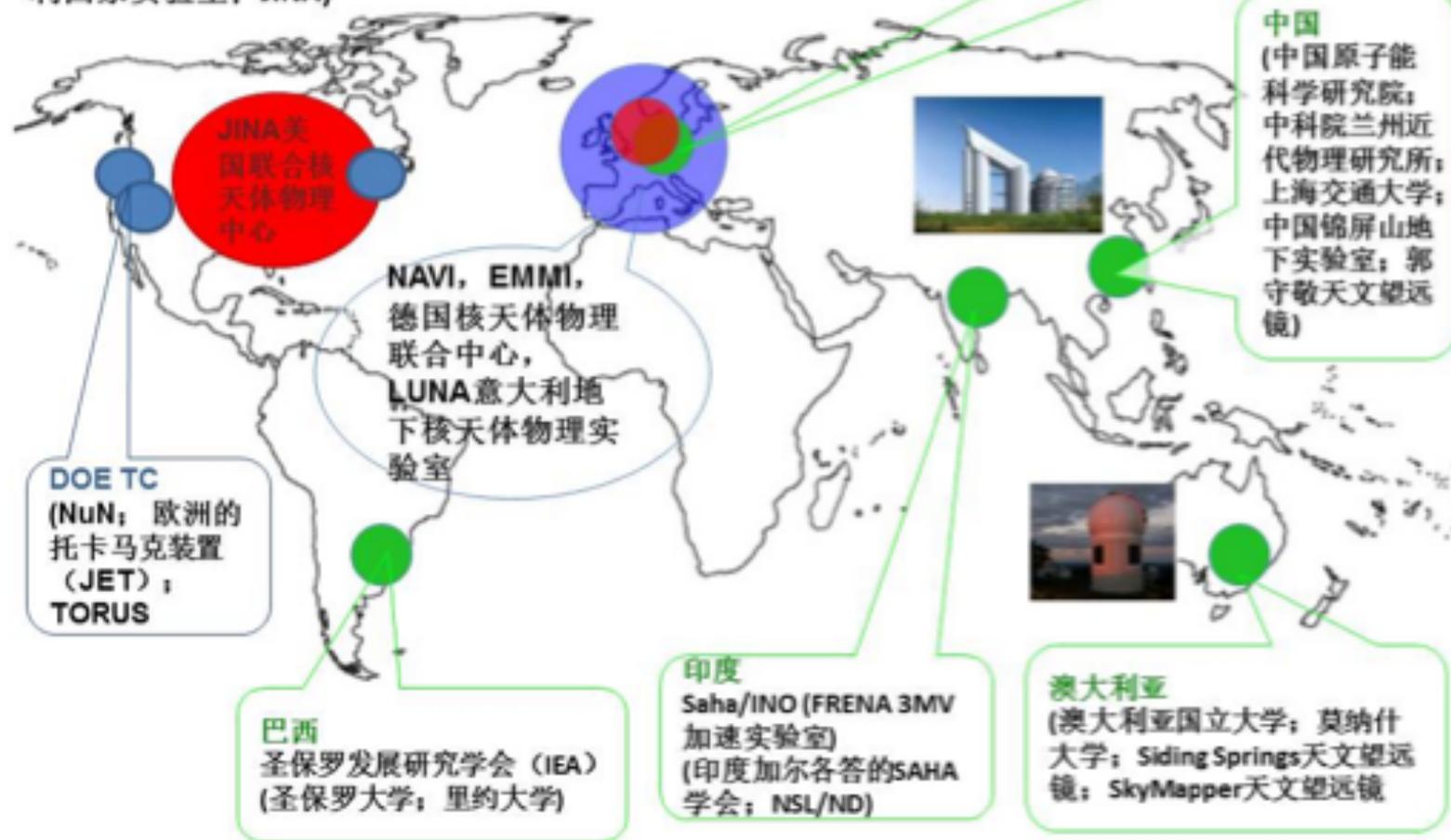
近十多年来核天体物理研究新进展

- 许多地面加速器实验室测量了一系列缺少截面数据的天体物理反应，其中不少重要反应需要以不稳定核作炮弹。
- 人造卫星上的X-射线和 γ -射线探测器揭示了新星、X-射线暴和超新星中核合成的详细信息
- 意大利格兰萨索地下核天体物理实验室（LUNA）直接测量了恒星氢燃烧阶段若干关键的反应，其中有个别测量接近了天体物理感兴趣的Gamow窗口能区
- 地下实验室中的探测器已经测到来自太阳核芯和超新星的中微子，直接揭示了太阳核芯中的核反应并基本肯定了通用的超新星模型

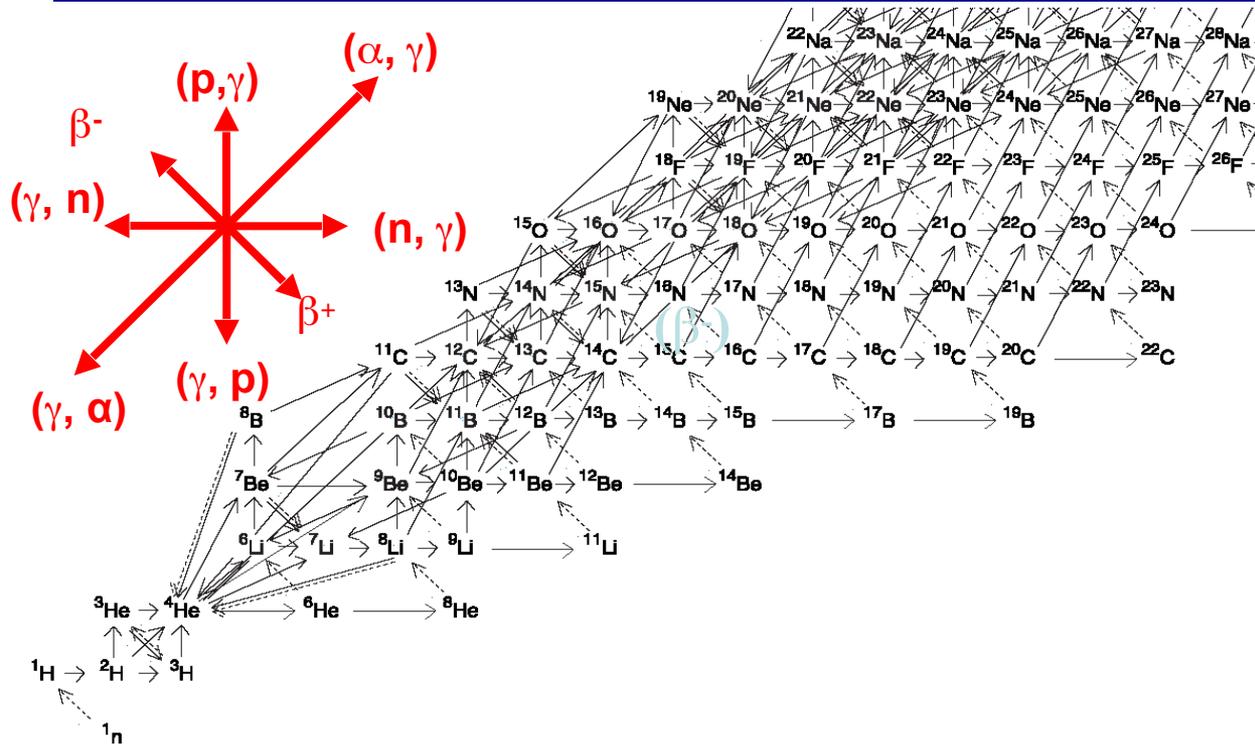
国际核天体物理研究分布

国际核天体物理研究分布

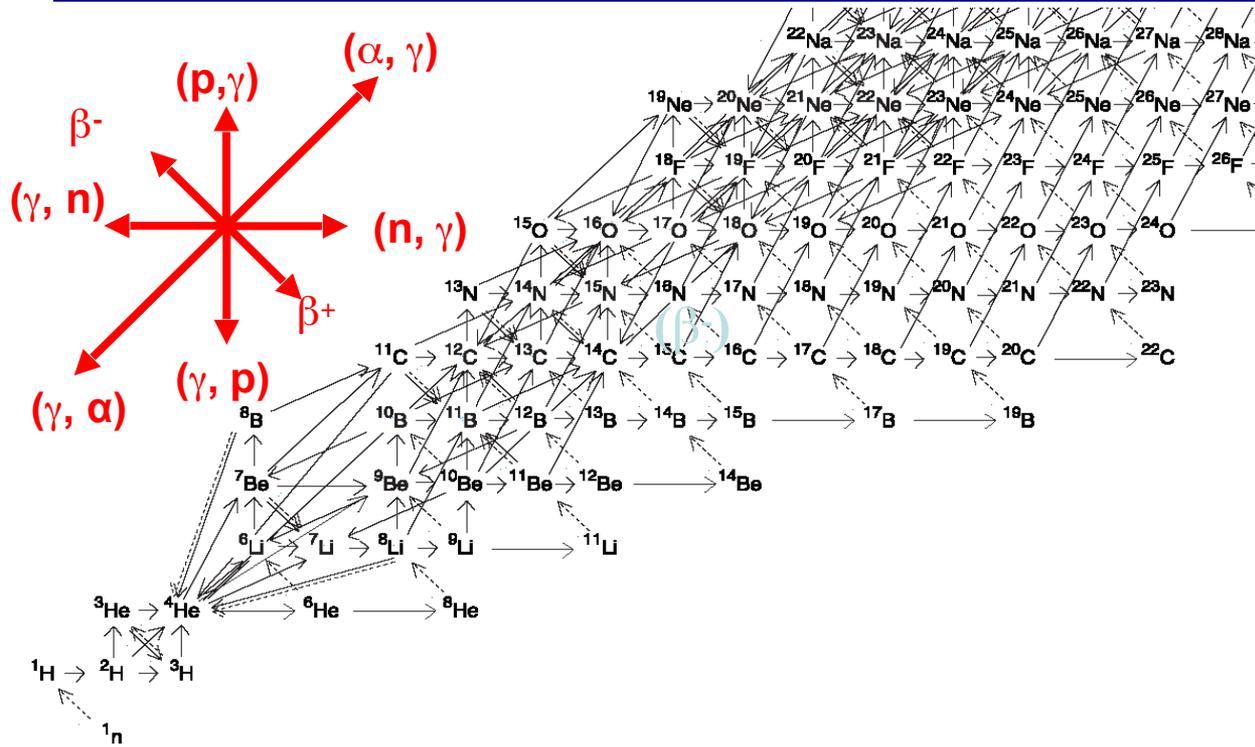
(德国的GSI; 日本东京大学; 法国巴黎大学; 美国劳伦斯伯克利国家实验室; JINA)



Element synthesis network

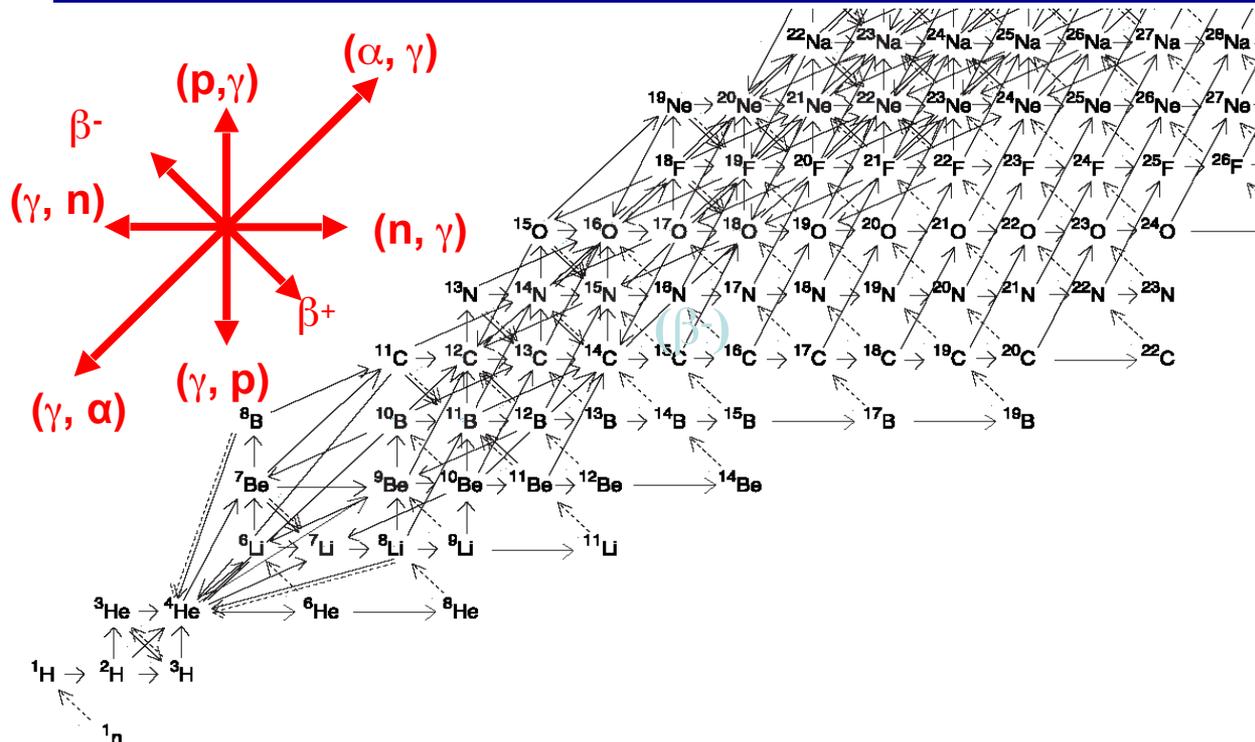


Element synthesis network



$$\frac{dY_i}{dt} = \sum_j N_j^i \lambda_j Y_j + \sum_{j,k} N_{j,k}^i \rho N_A \langle \sigma V \rangle_{jk,i} Y_j Y_k + \sum_{j,k,l} N_{j,k,l}^i \rho^2 N_A^2 \langle \sigma V \rangle_{jkl,i} Y_j Y_k Y_l$$

Element synthesis network



Cross section

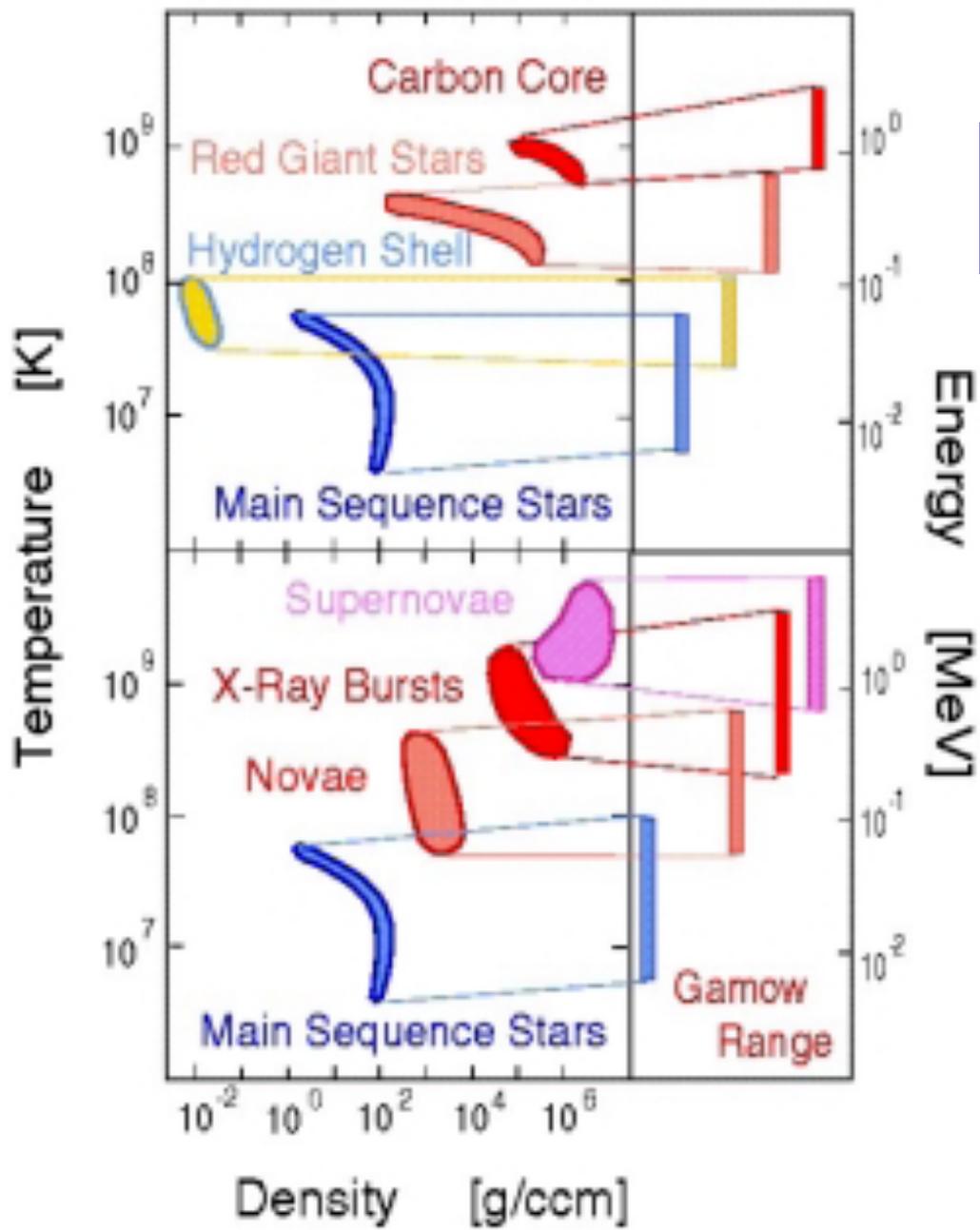
$$\frac{dY_i}{dt} = \sum_j N_j^i \lambda_j Y_j + \sum_{j,k} N_{j,k}^i \rho N_A \langle \sigma V \rangle_{jk,i} Y_j Y_k + \sum_{j,k,l} N_{j,k,l}^i \rho^2 N_A^2 \langle \sigma V \rangle_{jkl,i} Y_j Y_k Y_l$$

Decay half-life

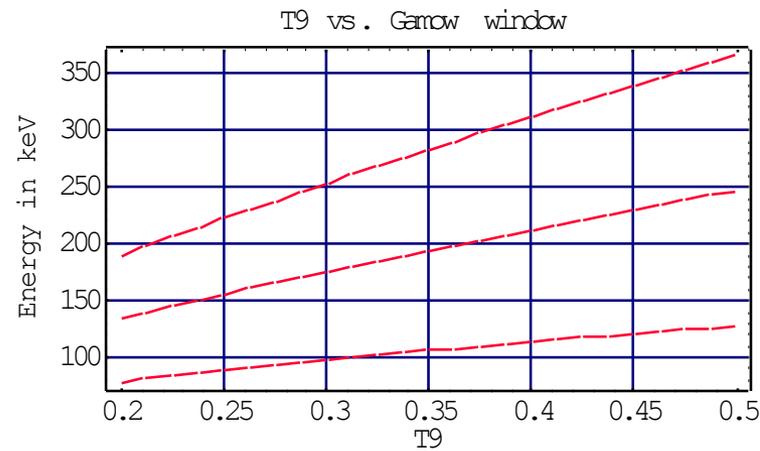
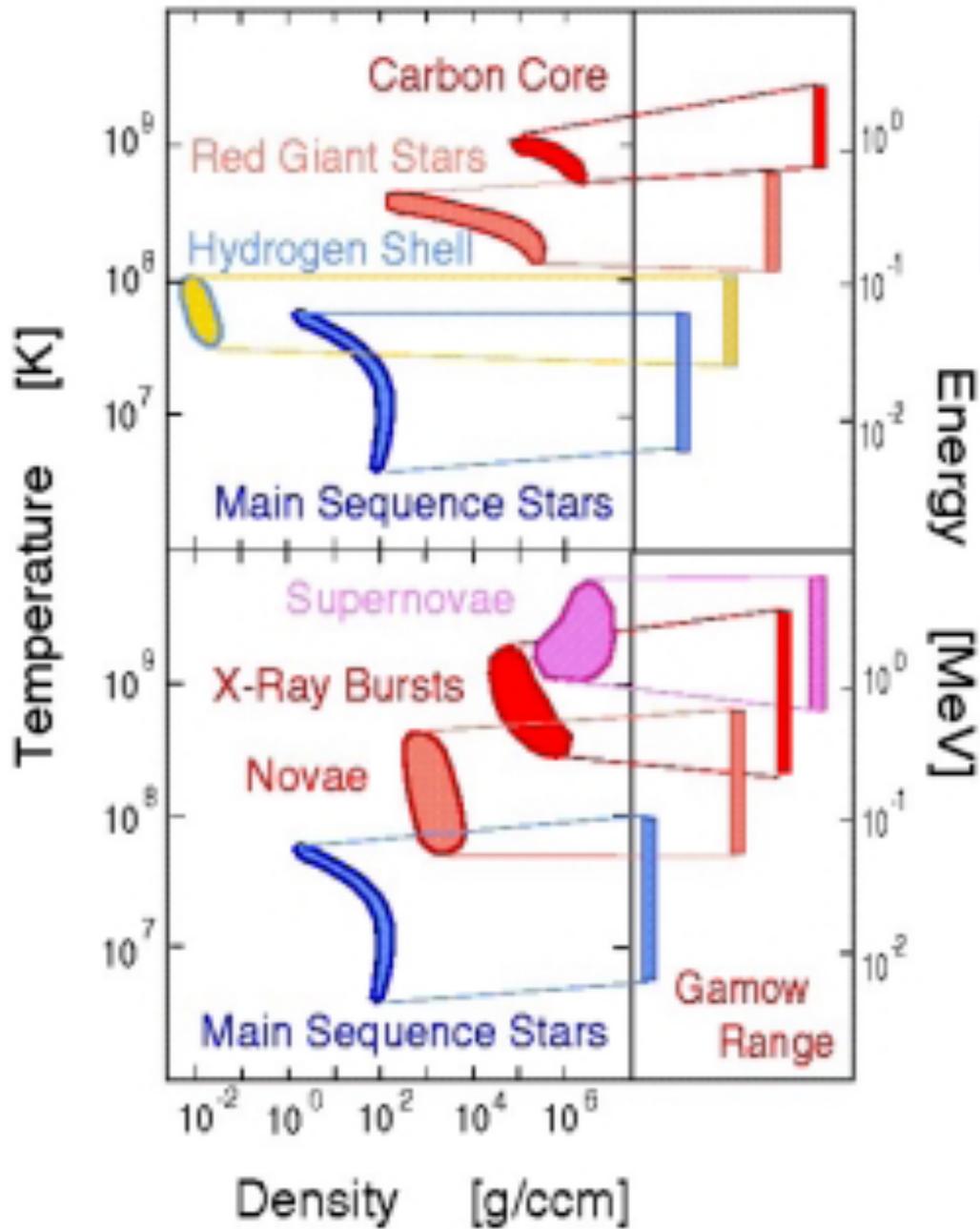
Important nuclear physics data

- S-factor, focus on NP, down to astrophysics energies
- Reaction rates, direct input to network calculation
- Direct capture, direct reactions
- Resonance, level scheme, level width, and partial width
- Mass and decay half-life and branching ratio

$^{11}\text{C}(p, \gamma)^{12}\text{N}$ example

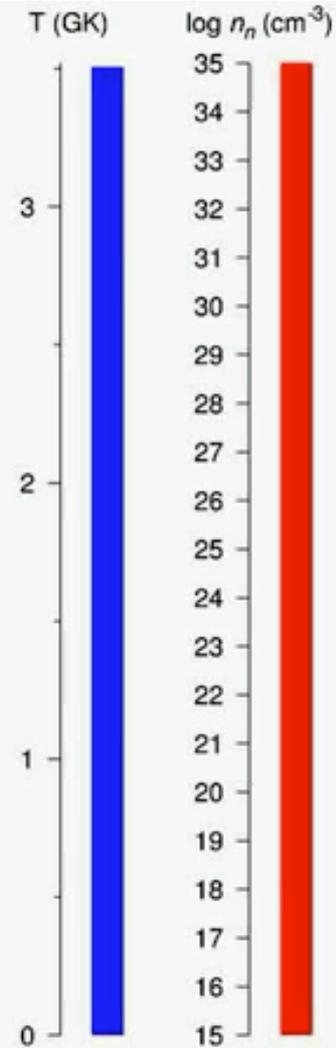
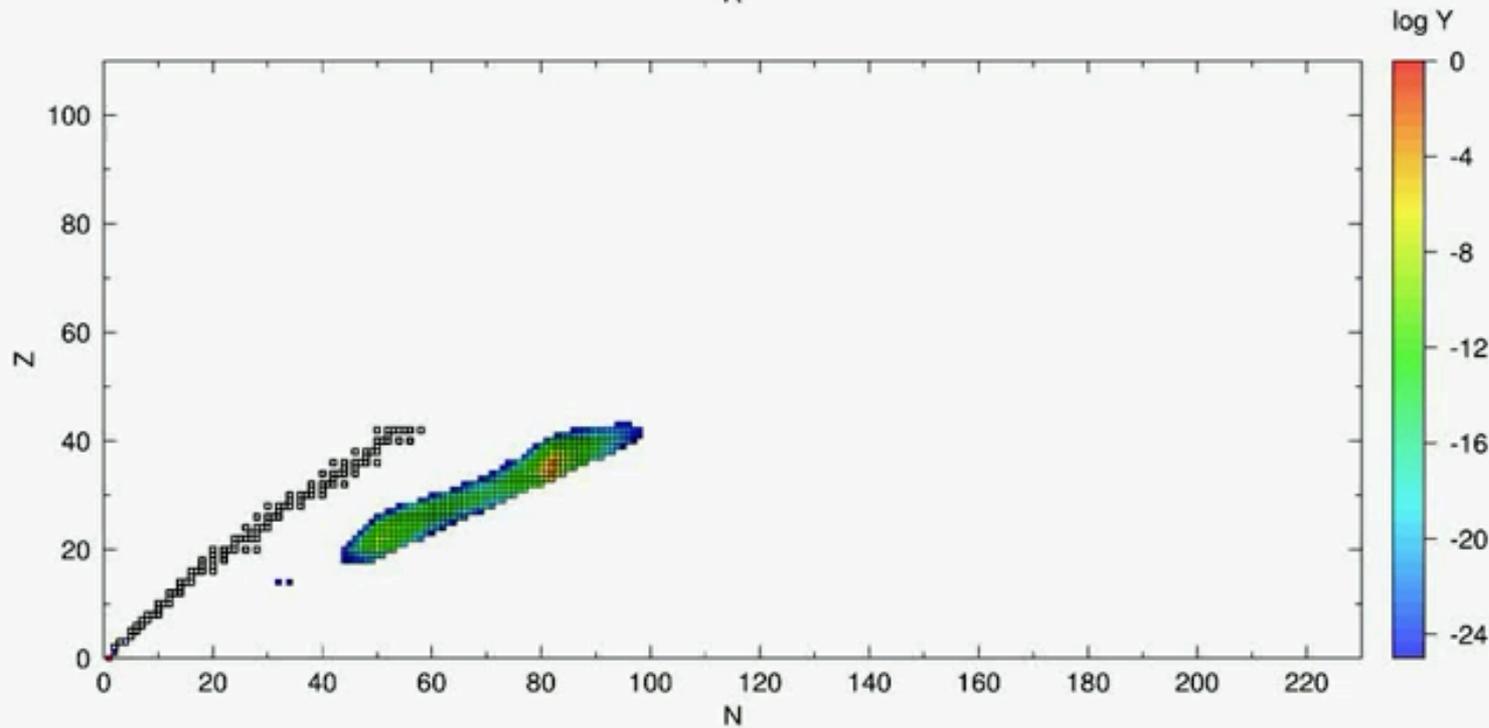
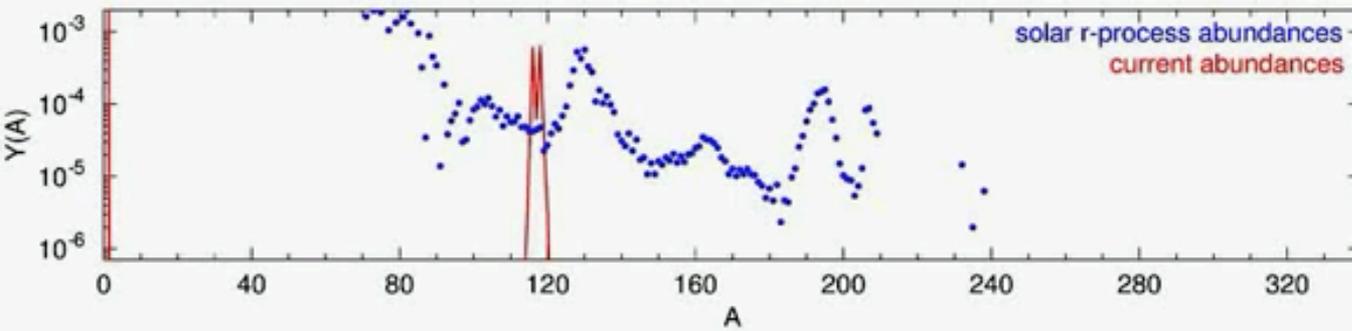


$^{11}\text{C}(p, \gamma)^{12}\text{N}$ example



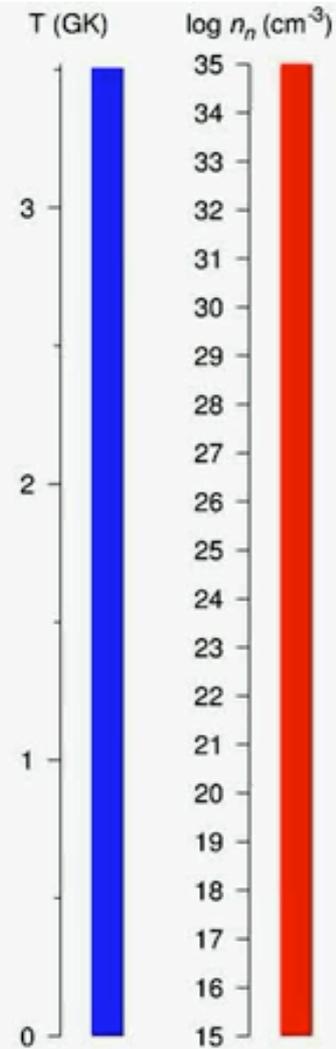
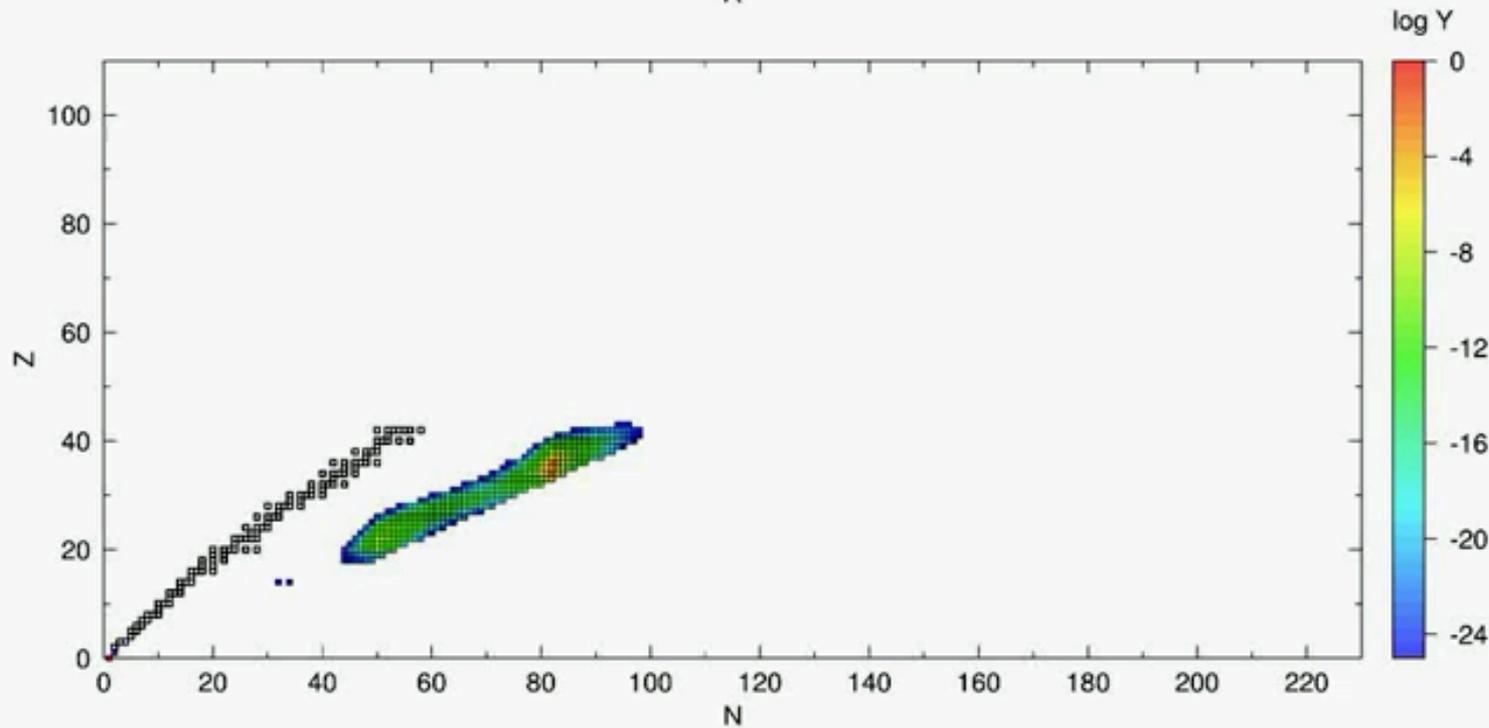
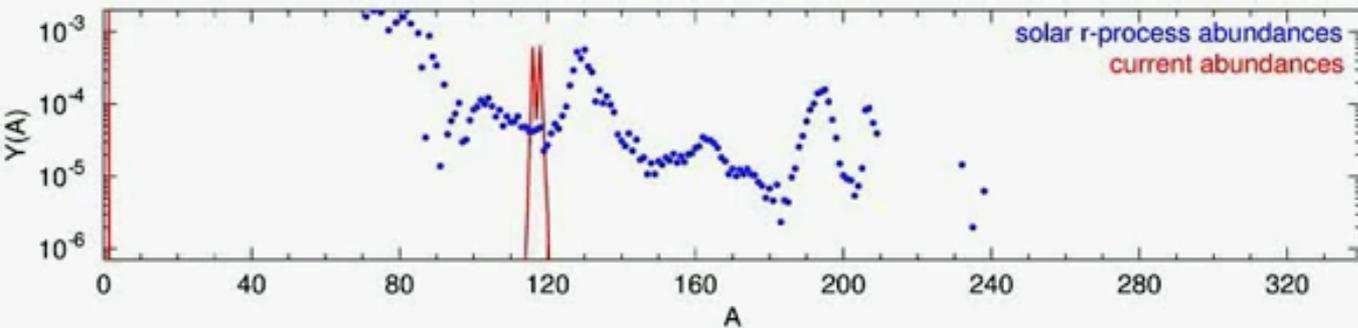
r过程的简单模拟

$T = 3.50$ GK, $n_n = 2.937e+35$ cm⁻³, $R_{n/s} = 623.3$, $s = 0.621$ k_B/nuc, $t = 0.0131$ s

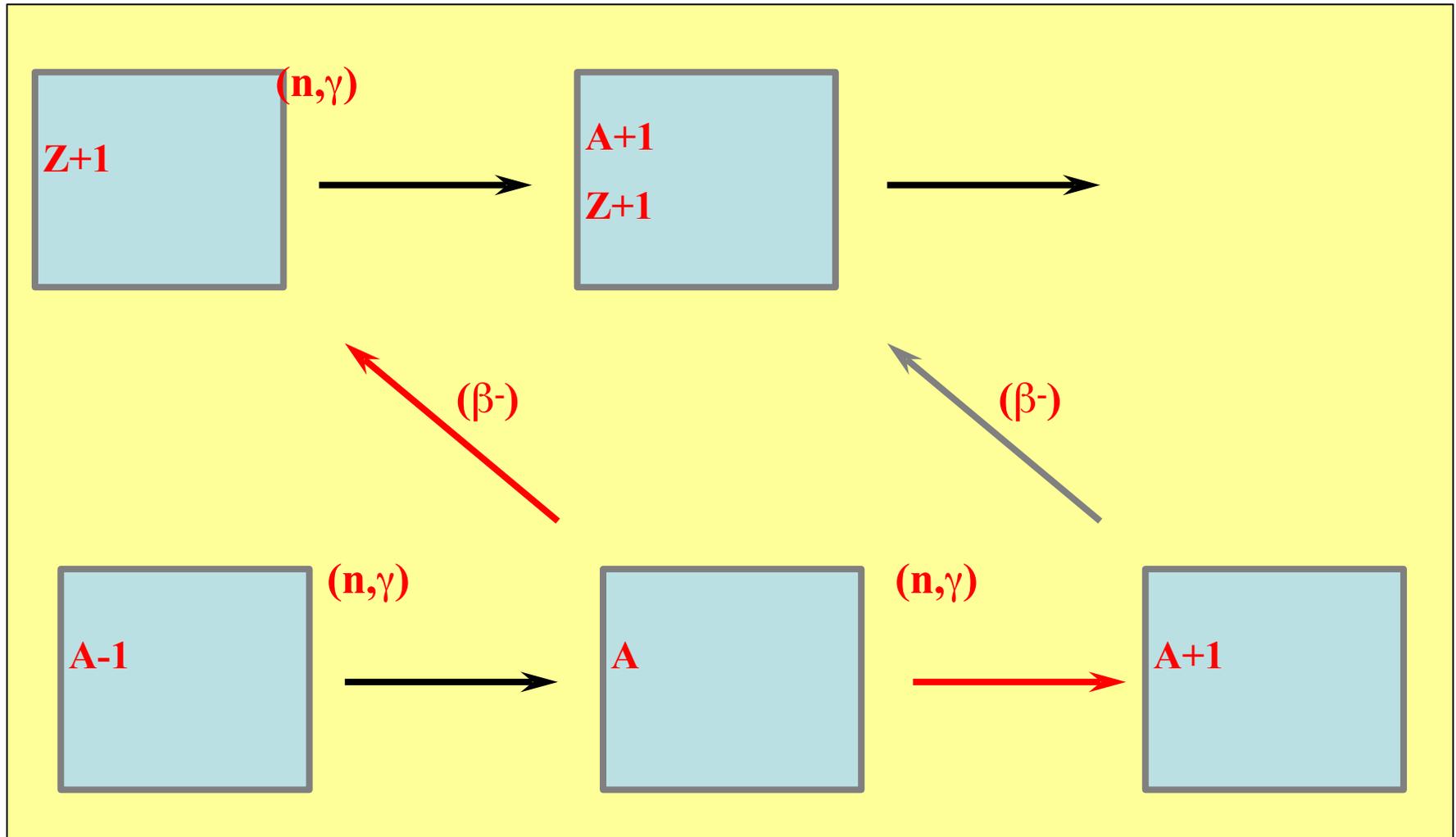


r过程的简单模拟

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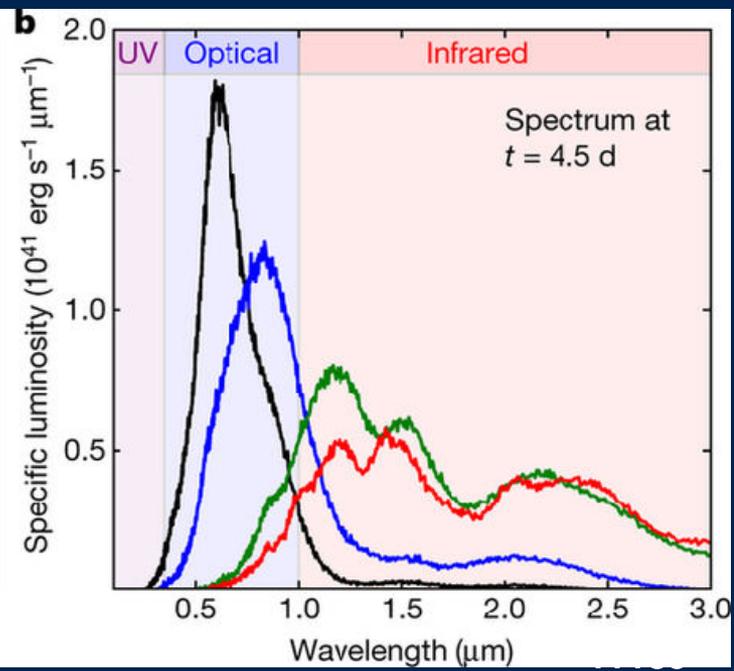
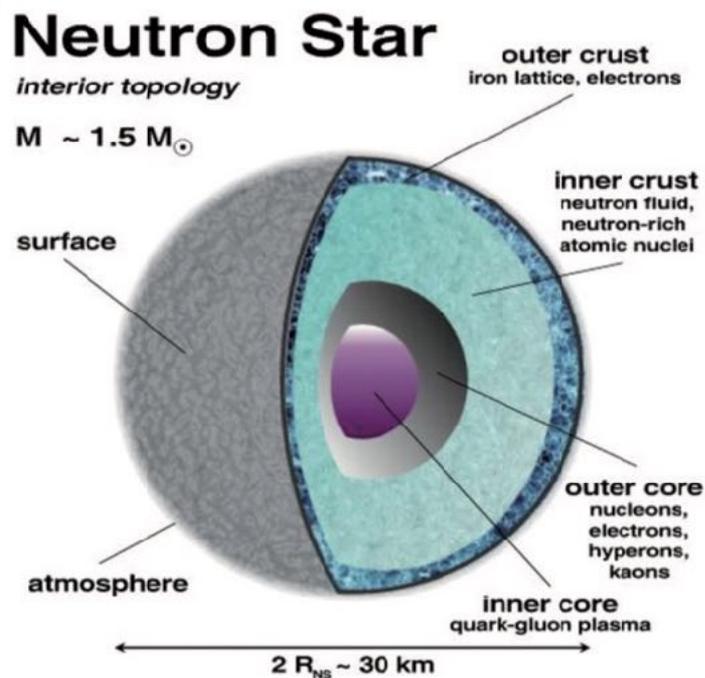
How elements become heavier



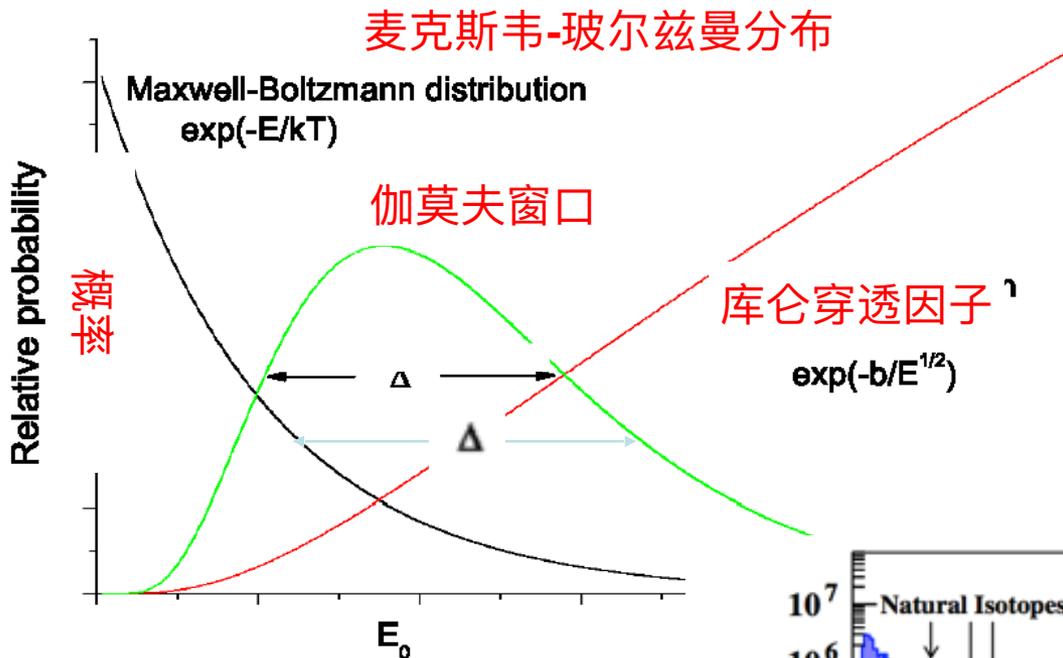
NSM 和 r 过程重元素产生



W. P. Liu

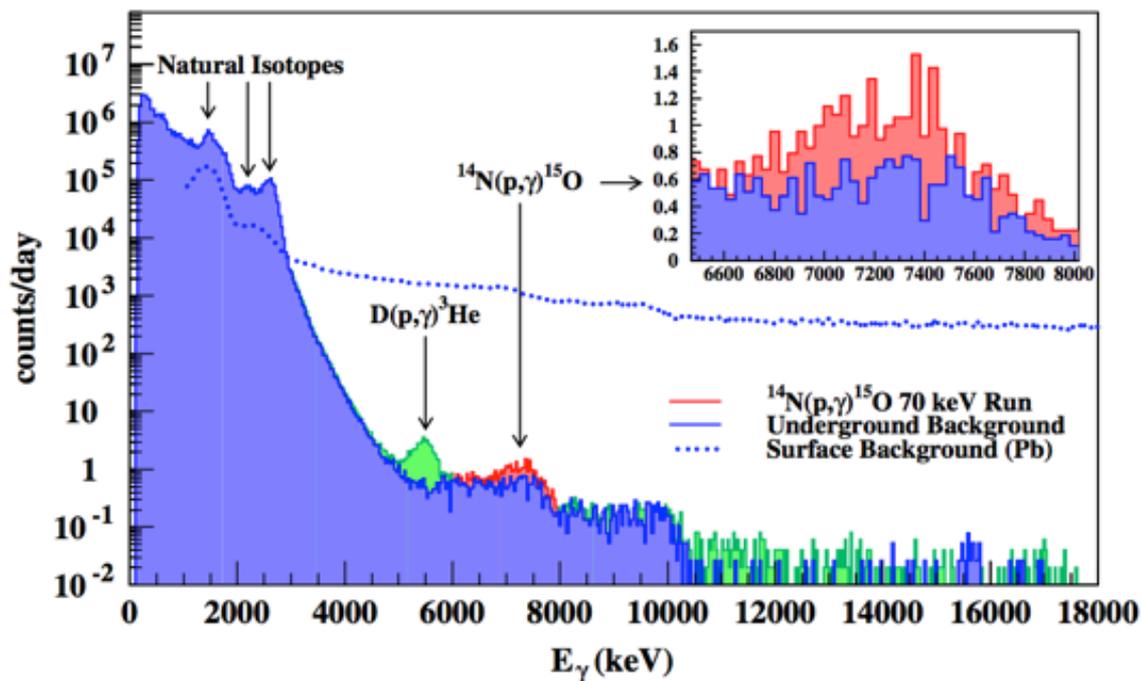


深地核天体物理直接测量必要性 Why underground



➤ 伽莫夫窗口-能量低-截面低-要求极低本底-需要深地环境

➤ 不借助间接手段和理论方法, 最可靠 (没有外推模型依存)



我国研究基础

- 我国的实验核天体物理研究起步于上世纪90年代初期。次级束流线，北京93，兰州97，CSR07
- 开创和发展了利用低能次级束和高强度稳定束进行核天体物理研究的新领域，并在国际核天体物理学界占有了一席之地
- CSR和320 kV高压平台上完成了若干重要的核天体物理研究工作。首次测量了近质子滴线短寿命核素 ^{63}Ge ， ^{65}As ， ^{67}Se 和 ^{71}Kr 的质量
- r和 rp过程远离核的质量和核素丰度的网络计算，以及温度、密度及核-核相互作用对天体环境中电子俘获率影响的计算

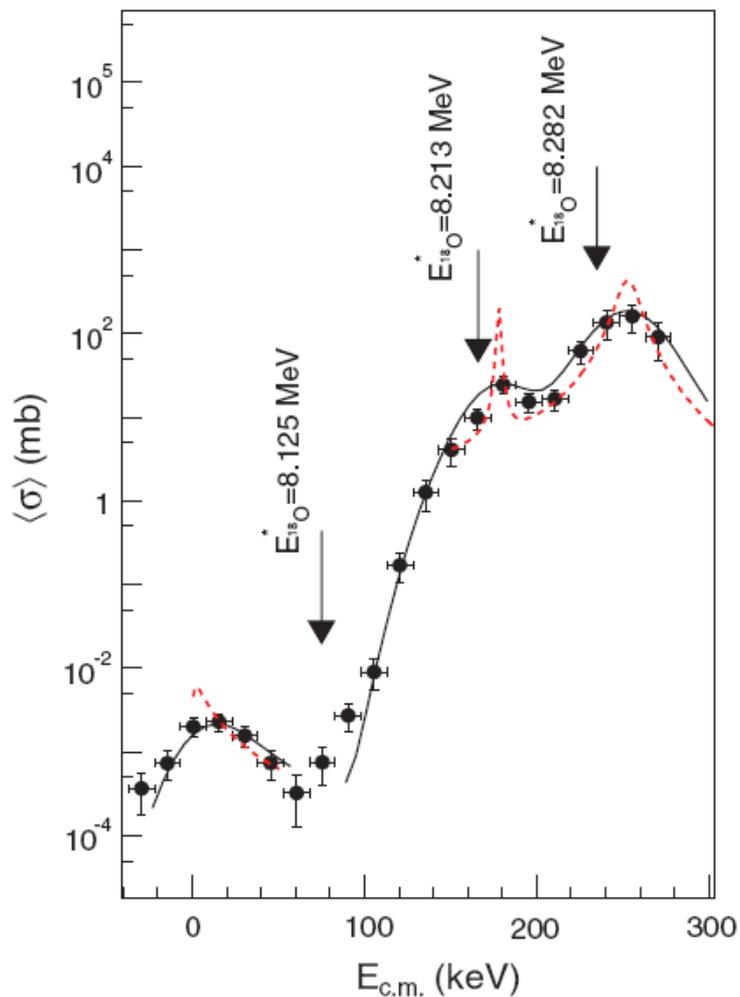
我国核天体物理研究

- 直接测量, ${}^6\text{Li}(p,\gamma){}^7\text{Be}$ 等
- 间接测量, ${}^7\text{Be}(p,\gamma){}^8\text{B}$, ..., ${}^{13}\text{C}(\alpha,n){}^{16}\text{O}$ 中子源反应等
- 衰变测量, rp过程中 ${}^{53}\text{Ni}$ 附近核的衰变等
- 质量测量, rp过程核等
- 理论计算, 衰变, 质量
- 网络计算, rp过程, r-过程
- 天文观测, NLTE, 贫金属星
- 对关键科学问题进行全面研究!

关键科学问题

- 开展天体物理能区最重要热核反应截面的直接测量
- 高能区带电粒子反应截面向天体物理能区的合理外推
- 恒星平稳核燃烧阶段和爆发性天体事件中关键核反应截面的间接测量
- 新星、超新星和X射线暴等爆发性天体事件中远离稳定线核素的质量、衰变特性、反应截面和共振态性质的测量和理论
- 建立并不断完善核天体物理数据库，发展网络模拟程序，系统研究元素核合成的过程、天体场所及丰度分布和核反应如何控制恒星的演化过程和结局

直接测量

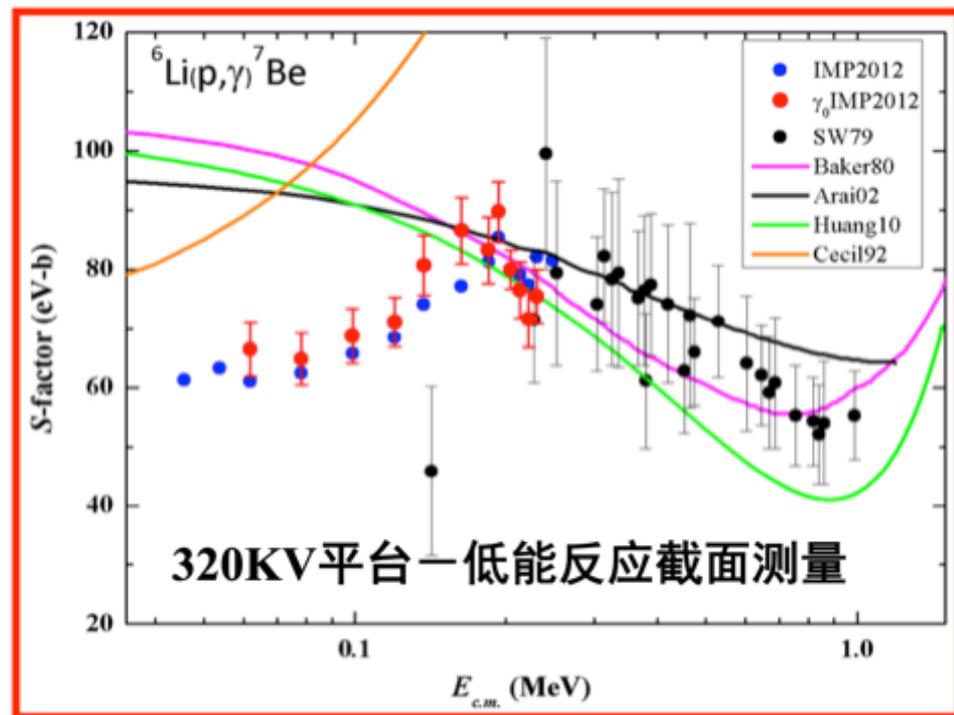


M. Gulino, 唐晓东等

PRC87(2013)012801(R)

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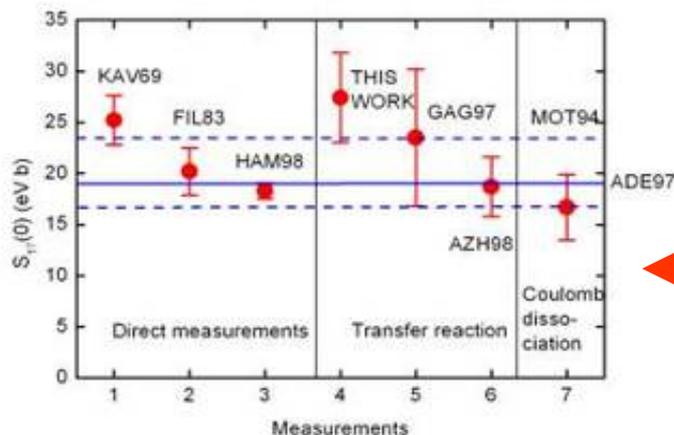
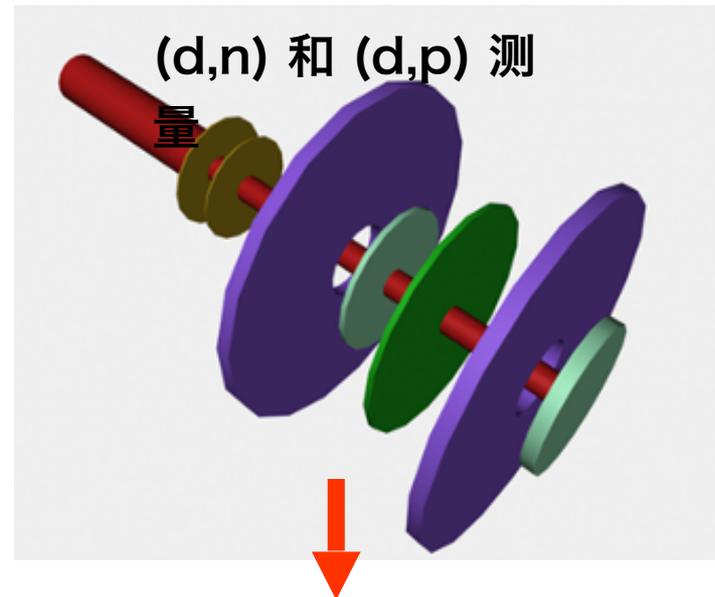
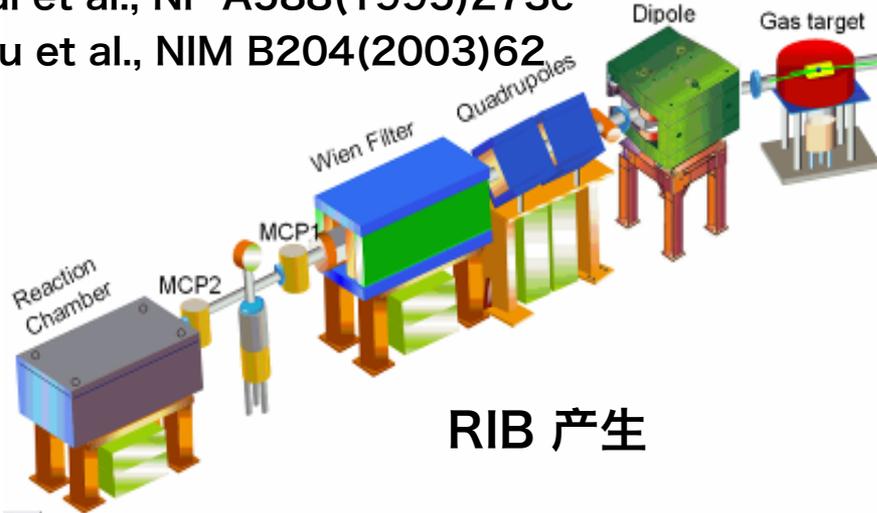


近物所何建军等, NIC2012口头报告

间接测量

X. X. Bai et al., NP A588(1995)273c

W. P. Liu et al., NIM B204(2003)62



$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} - \left(\frac{d\sigma}{d\Omega}\right)_{\text{CN}} = \sum_{j_l j_f} (C_{l_j j_l}^d)^2 (C_{l_j j_f}^{12\text{N}})^2 \frac{d\sigma_{l_j j_f l_j j_l}^{\text{DW}}/d\Omega}{b_{l_j j_l}^2 b_{l_j j_f}^2}$$

$$\sigma_t = \frac{16\pi}{9} \left(\frac{E_\gamma}{\hbar c}\right)^3 \frac{1}{\hbar v} \frac{e_{\text{eff}}^2}{k^2} \frac{(2j_f + 1)}{(2I_1 + 1)(2I_2 + 1)} C_{\ell_f j_f}^2 \times \left| \int_{R_N}^{\infty} r^2 dr f_{\ell_j}(kr) W_{\eta, \ell_f + 1/2}(2kr) \right|^2$$

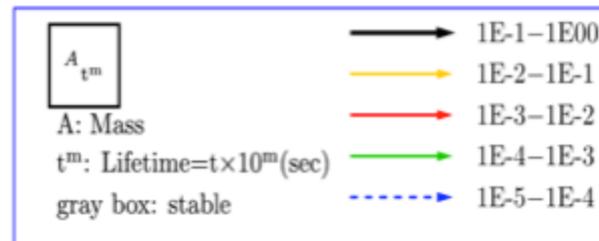
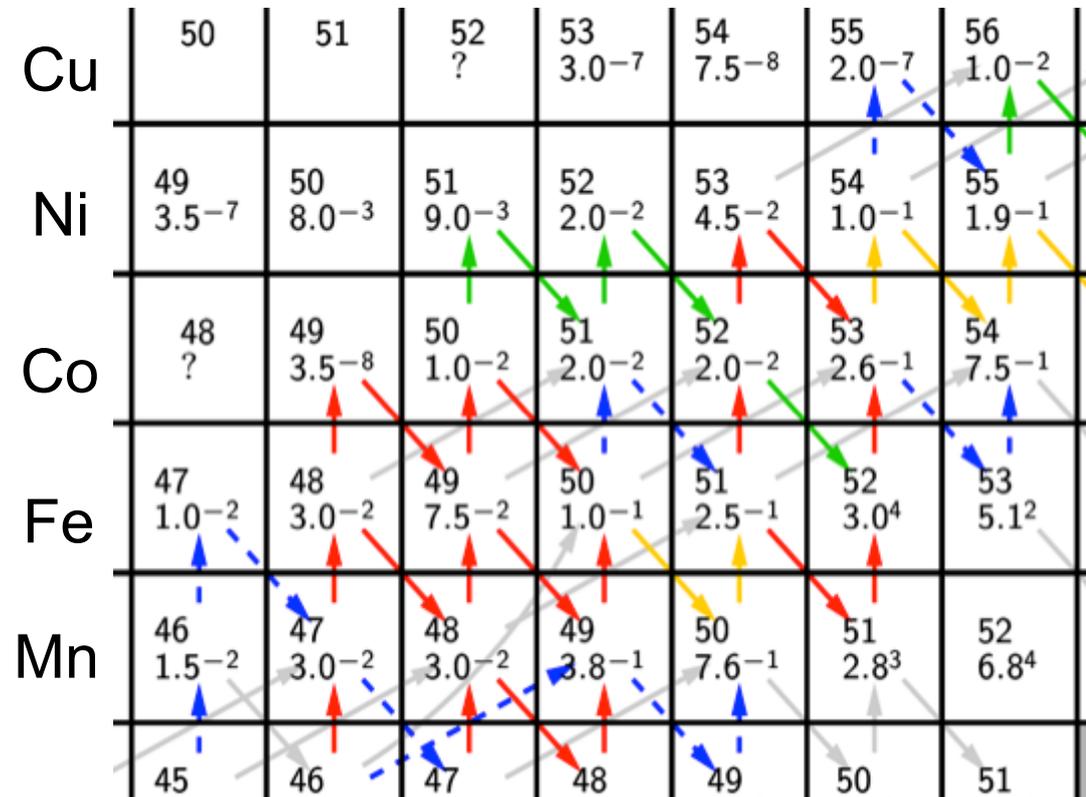
⁷Be(p, γ)⁸B天体物理S因子的测量

W.P. Liu et al., PRL77(1996)611

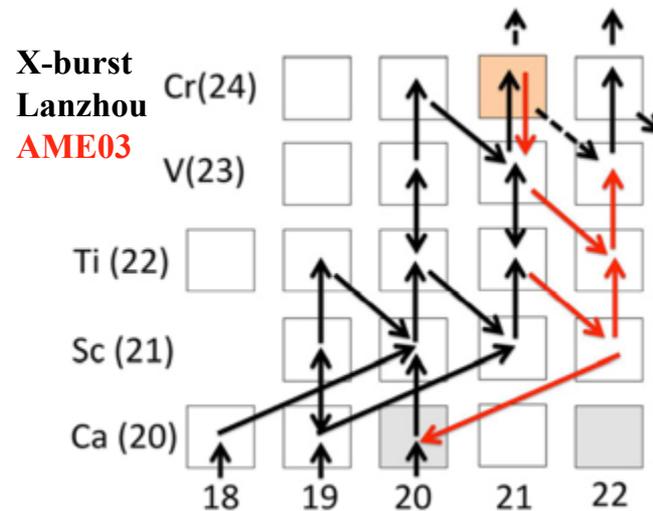
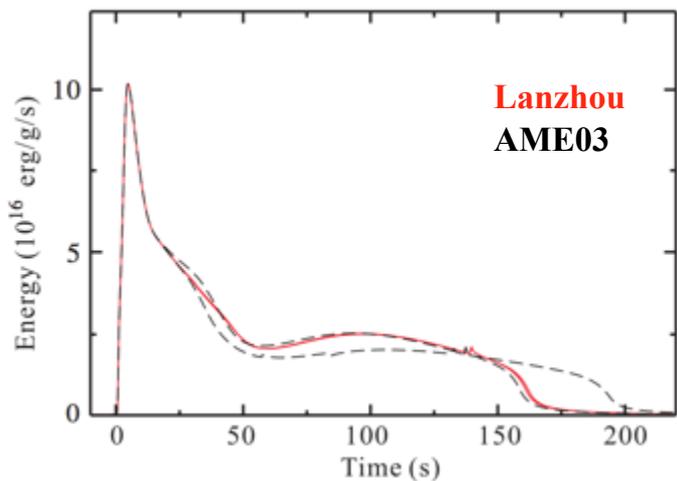
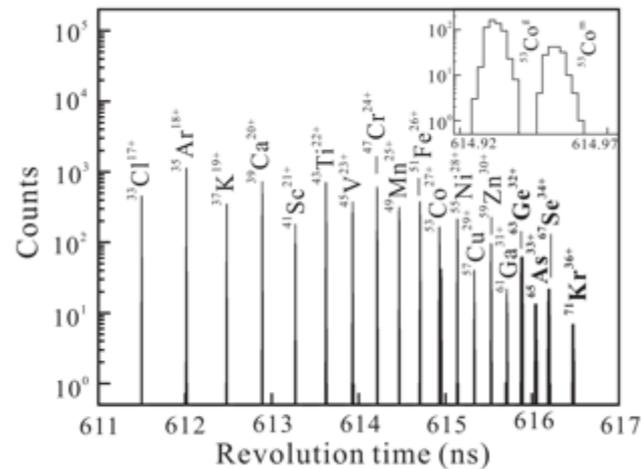
ANC方法

俊, 柳卫平等, Phys. Rev. C 87 ,024312 (2013)

Isotope	$T_{1/2}(\text{ms})$	
	Present Work	NNDC
^{53}Ni	52 ± 5	55 ± 0.7
^{54}Ni	111 ± 6	104 ± 7
^{52}Co	108 ± 4	115 ± 23
^{53}Co	248 ± 12	240 ± 9^a 247 ± 12^b
^{51}Fe	298 ± 5	305 ± 5
^{50}Mn	286 ± 7	283.3 ± 0.8

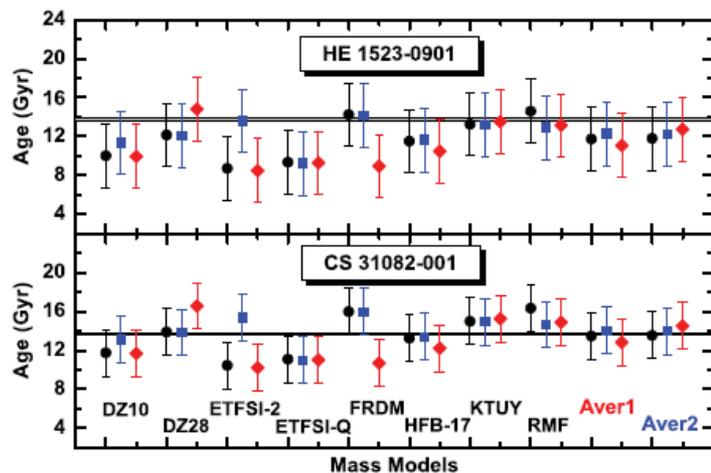


近物所CSR上的质量测量

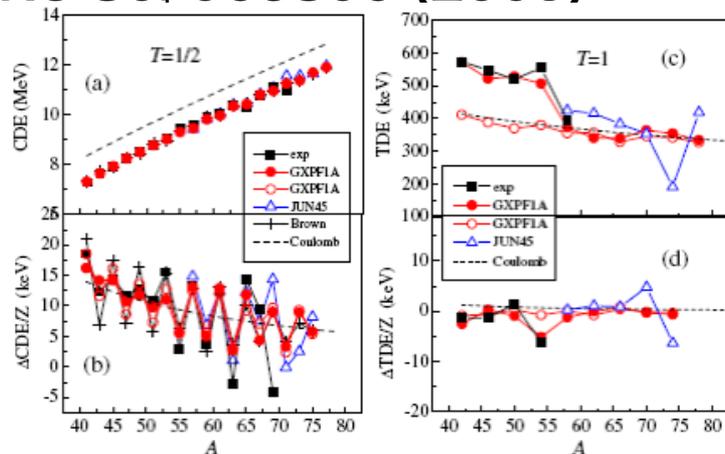


涂小林, 徐珊珊等, PRL106(2011)102501; 徐珊珊等, ApJL 766(2013)8

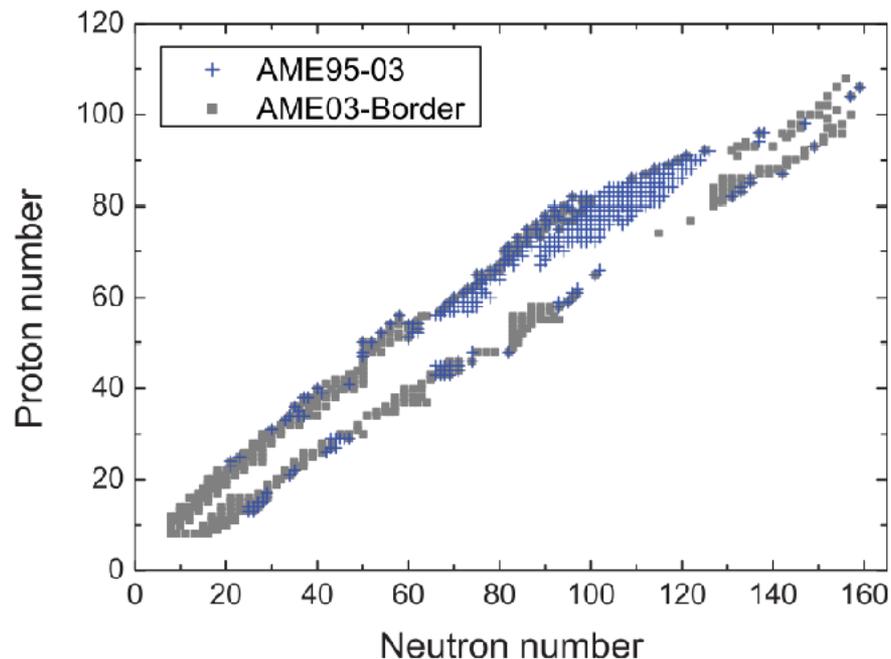
理论研究进展



Z. M. Niu, B. H. Sun, J. Meng,
 PRC 80, 065806 (2009)

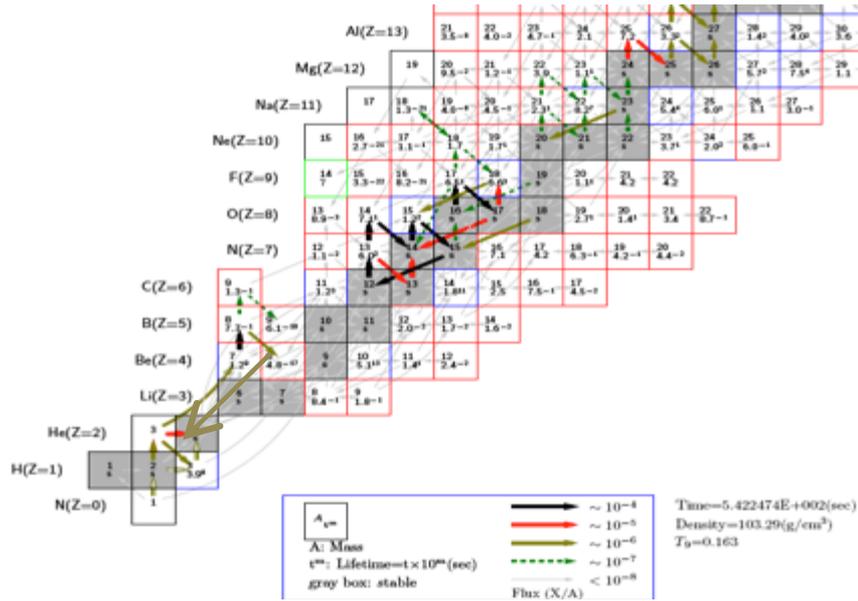


K. Kaneko, Y. Sun, et al.,
 PRL 110, 172505 (2013)

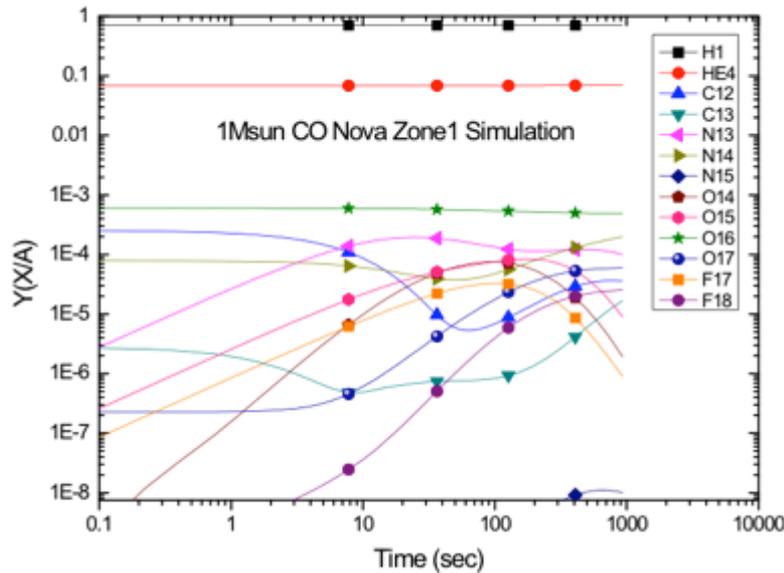
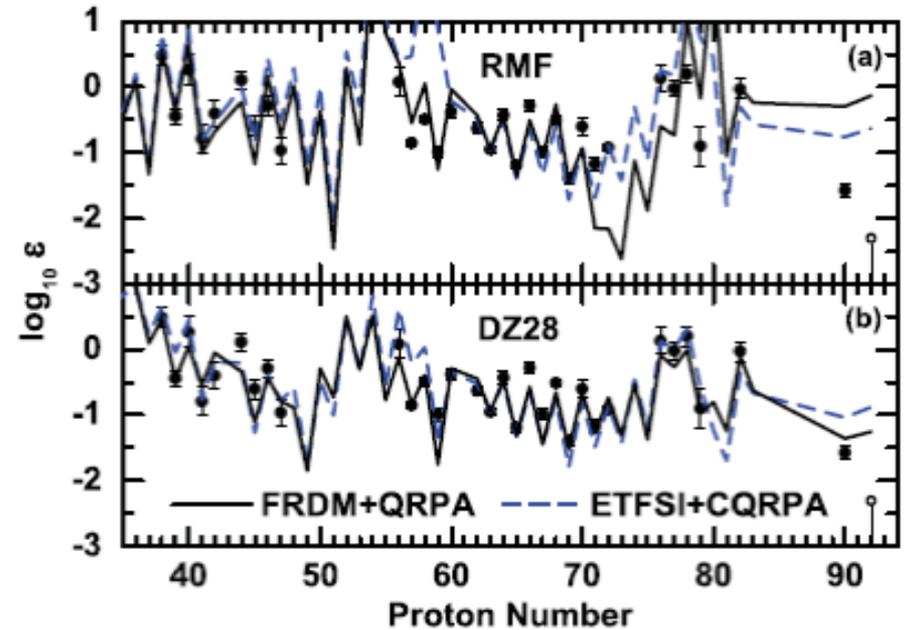


王宁, 质量, PRC84, 051303R(2011)

网络计算



N. C. Shu, Y. S. Chen et al., NPA 758 (2005) 419c



Z. M. Niu, B. H. Sun, J. Meng, PRC 80, 065806 (2009)

我国研究已覆盖核天体物理的关键环节

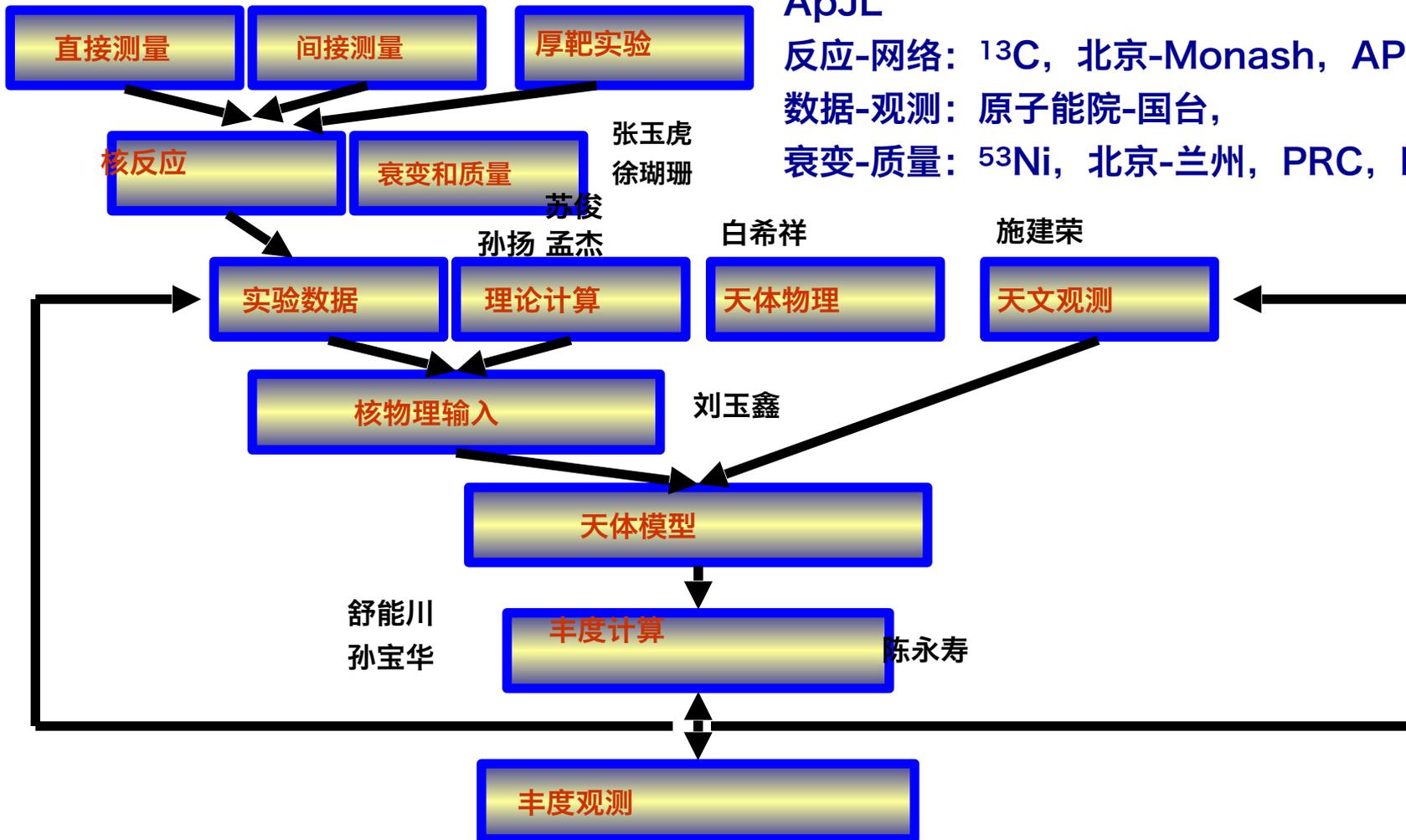
唐晓东 柳卫平 李志宏
李云居 郭冰 连钢 王友宝 何建军

质量-理论-网络: 兰州-上海-MSU, PRL, ApJL

反应-网络: ^{13}C , 北京-Monash, APJ

数据-观测: 原子能院-国台,

衰变-质量: ^{53}Ni , 北京-兰州, PRC, PRL



我国核天体物理研究的里程碑 Milestone of Nuclear Astrophysics in China

1993年, 我国第一条次级束流线

2005年, ${}^8\text{Li}(n, \gamma){}^9\text{Li}$ 原初反应

PRCR

2011, 基金委群体支持

2013, ${}^6\text{Li}(p, \gamma){}^7\text{Be}$ 原创直接测量 PLB

2015, 基金委JUNA重大项目支持

1993

1996

2005

2010

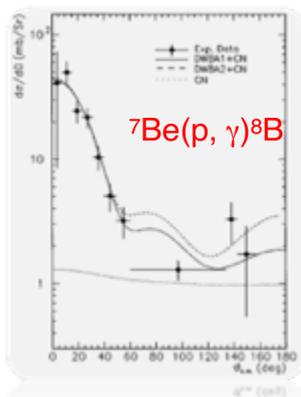
2012

2014

2015

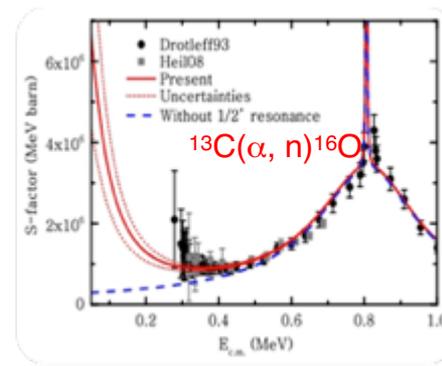
20

1996年, ${}^7\text{Be}(p, \gamma){}^8\text{B}$ 中微子反应, PRL



2011, rp过程质量 PRL, APJ

2012, ${}^{13}\text{C}(\alpha, n){}^{16}\text{O}$ 中子源反应 APJ



2021, JUNA重大成果

展望与建议

- 在地面实验室对恒星氢燃烧、氦燃烧和碳燃烧阶段若干重要热核反应进行直接测量
- 中子俘获反应的直接测量对更好地了解s-过程
- 基于我国已有的和即将竣工的放射性离子束大科学工程，对恒星平稳和爆发性核燃烧中的 (p, γ) 、 (n, γ) 、 (α, p) 、 (α, n) 和 (α, γ) 反应截面进行间接测量
- 对新星、超新星和X射线暴等爆发性天体事件中所涉及的远离稳定线核素的质量、衰变特性、反应截面和共振态性质进行实验测量和理论研究
- 加强在这个领域从事研究的核物理学家、天体物理模型学家和天文学家之间的协作
- 建设地下核天体物理实验室JUNA，将恒星平稳演化阶段关键反应的直接测量推进到伽莫夫窗口

我国核天体物理发展的计划

- 利用北京、兰州和上海的大科学工程，通过间接测量(p, r)和(n, r)反应充实关键核天体物理反应数据库，从轻核推到中等质量核区，并启动 r 过程的间接测量
- 通过国际合作，开展平稳和爆发性核过程的直接测量，检验和改进Fowler及Hindrance低能外推模型
- 开展快速质子俘获 (rp) 和快速中子俘获 (r) 过程相关核素的衰变性质和质量测量，得出核天体物理网络计算的重要输入量
- 启动锦屏山地下实验室核天体物理实验
- 通过实验与理论相结合，将反应、衰变和质量数据带入网络计算，与天文观测丰度数据相比较

结论

- 核天体物理是国际前沿的交叉学科，尚存在许多挑战性的科学问题
- 我国通过在核天体物理领域近二十年的研究工作，开创和发展了利用低能放射性束流开展关键核天体物理反应测量的新领域，取得了一系列开创性的研究成果，在国际核天体物理学界占有了一定的地位
- 未来瞄准核天体物理关键科学问题，利用国内外的大科学平台，系统测量关键核天体物理反应及衰变数据，将实验数据代入网络计算，并与天文观测相比较，在恒星演化和元素核合成方面取得创新成果

具体研究示例：圣杯反应间接研究

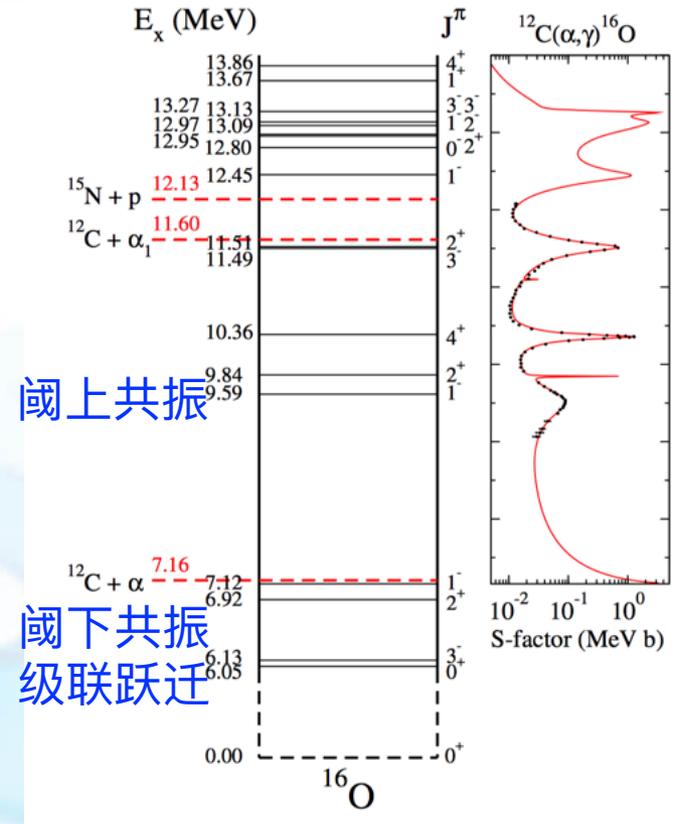
- 复杂的反应机制
 - 无主导共振贡献
 - 2个阈下共振 (6.92, 7.12)
 - 基态外部俘获贡献
 - E1与E2并存
 - 外部俘获与共振强烈干涉

Sayre PRL 109 (2012) Morais NPA 857 (2011)
Adhikari PLB 682 (2009), JPG 44 (2017)

基态ANC存在240
倍的分歧

13.9 to 3390 fm^{-1/2}

- 复杂的反应机制
 - 无主导共振贡献
 - 2个阈下共振 (6.92, 7.12)
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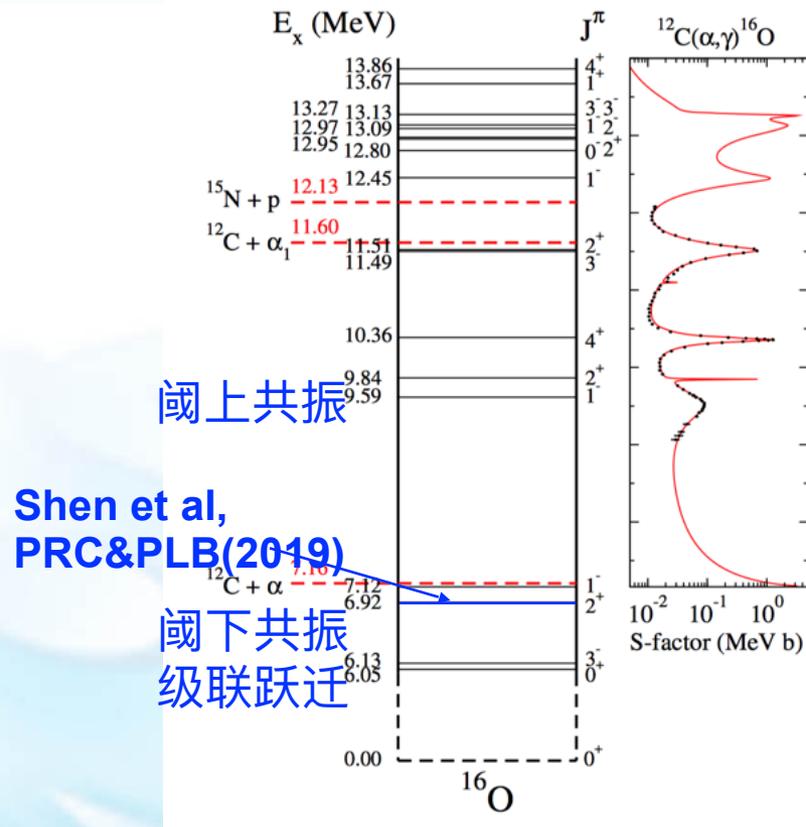


Sayre PRL 109 (2012) Morais NPA 857 (2011)
 Adhikari PLB 682 (2009), JPG 44 (2017)

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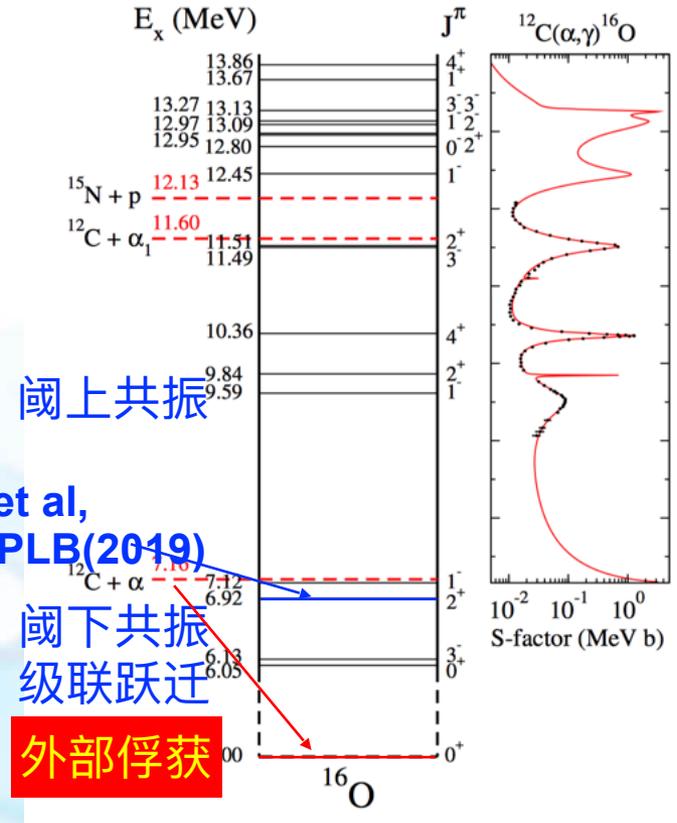
Sayre PRL 109 (2012) Morais NPA 857 (2011)
 Adhikari PLB 682 (2009), JPG 44 (2017)

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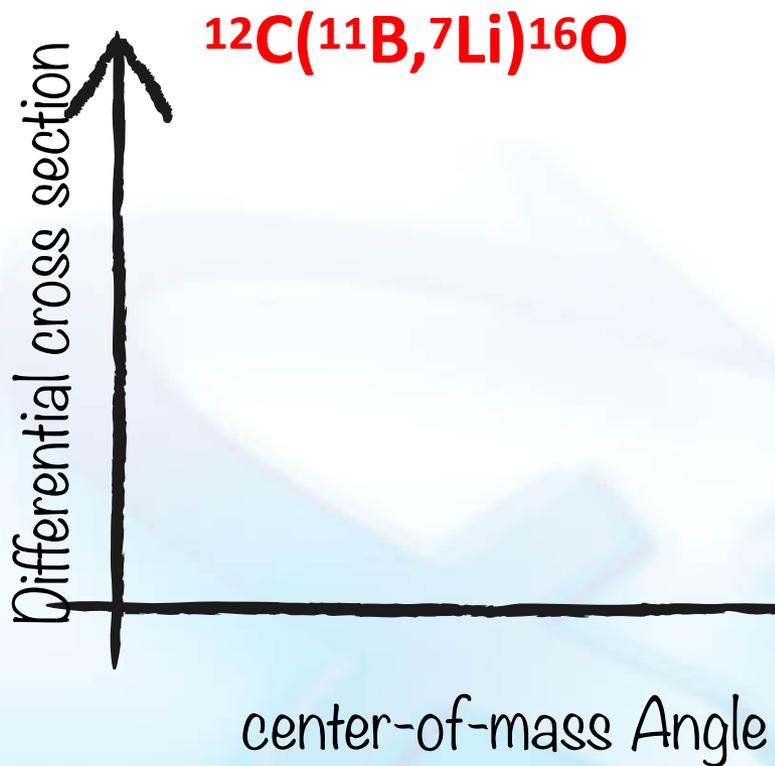


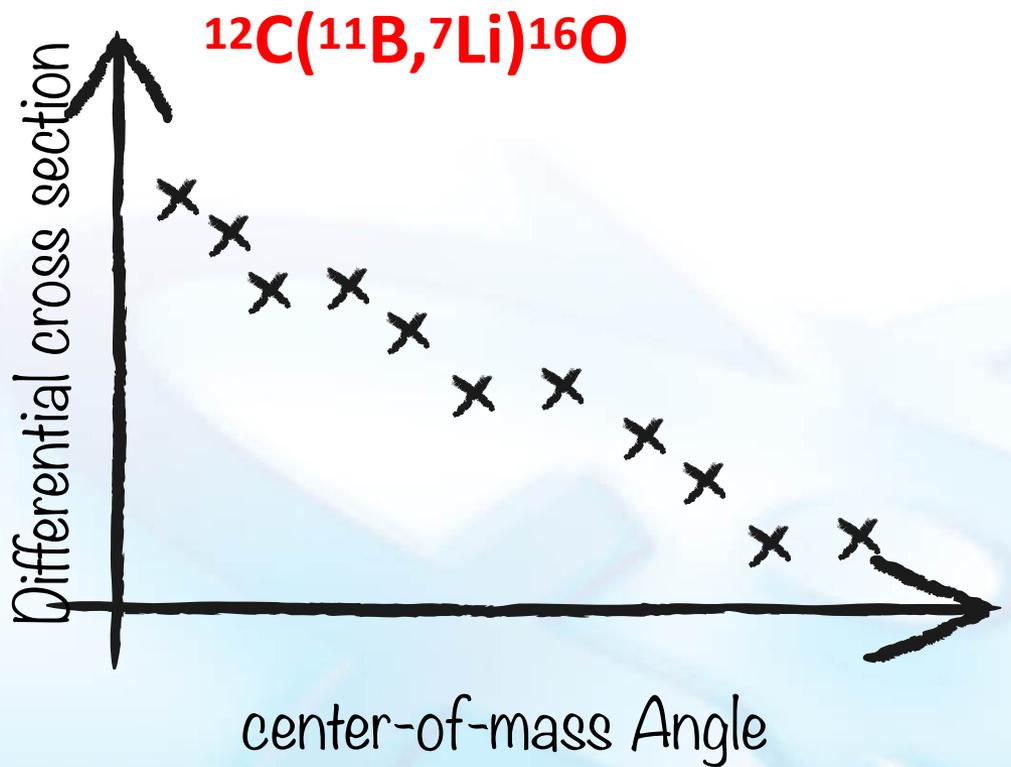
Sayre PRL 109 (2012) Morais NPA 857 (2011)
Adhikari PLB 682 (2009), JPG 44 (2017)

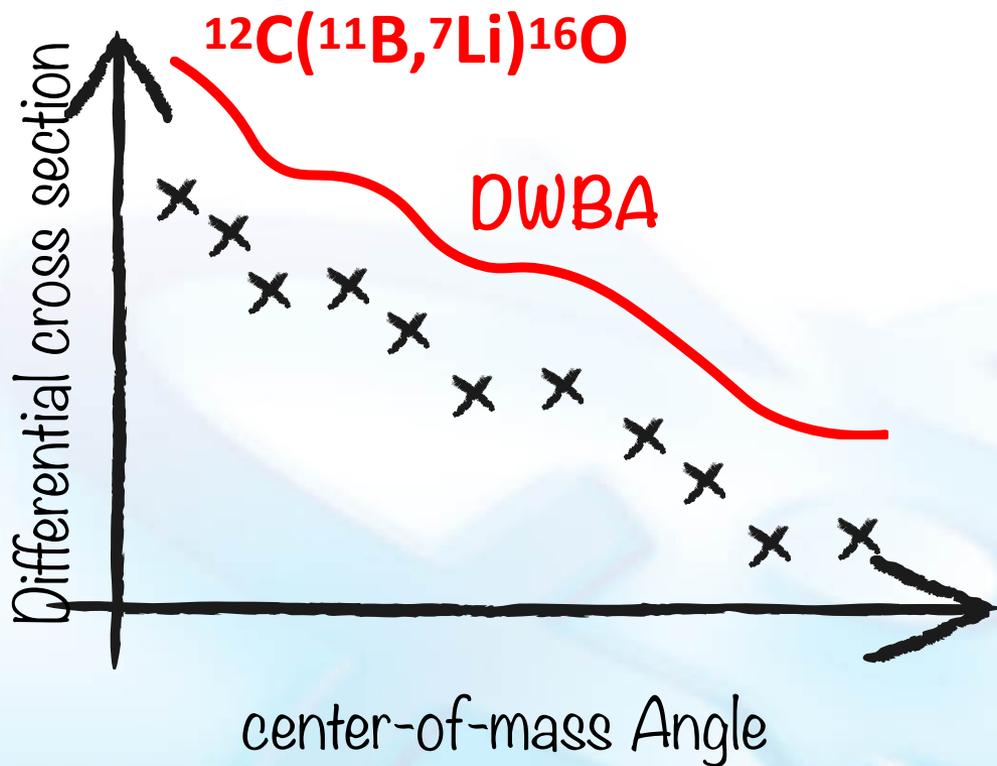
基态ANC存在240
倍的分歧

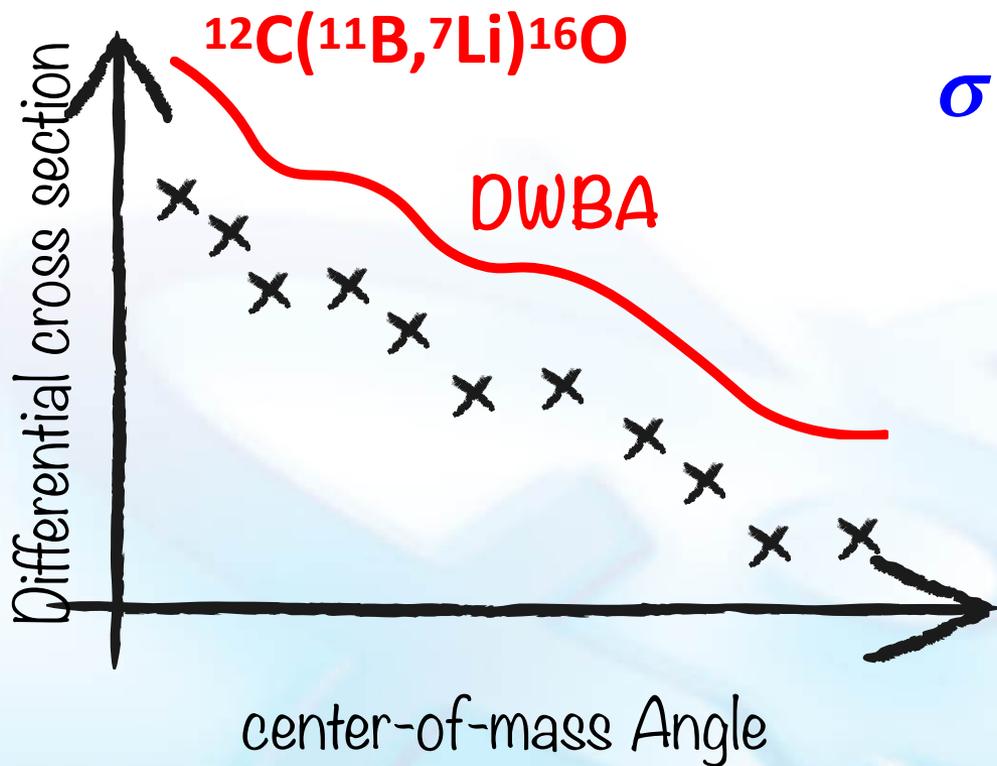
13.9 to 3390 fm^{-1/2}



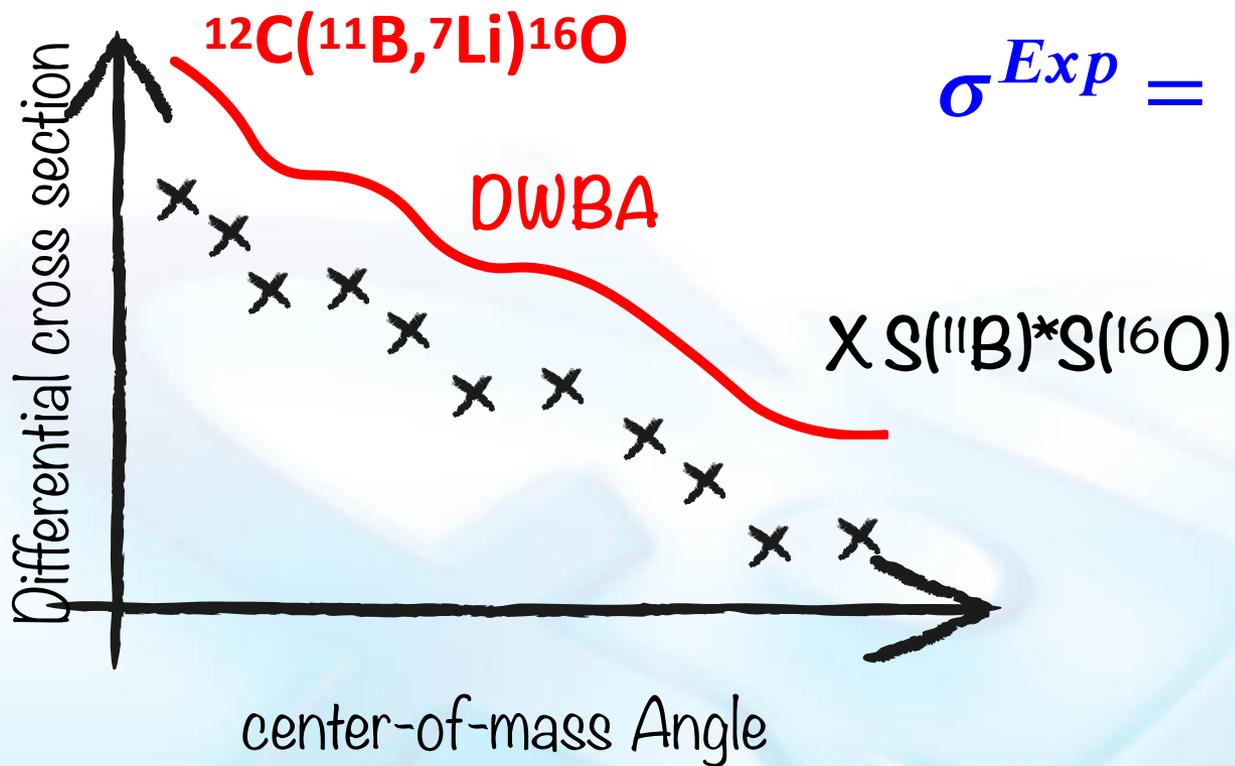




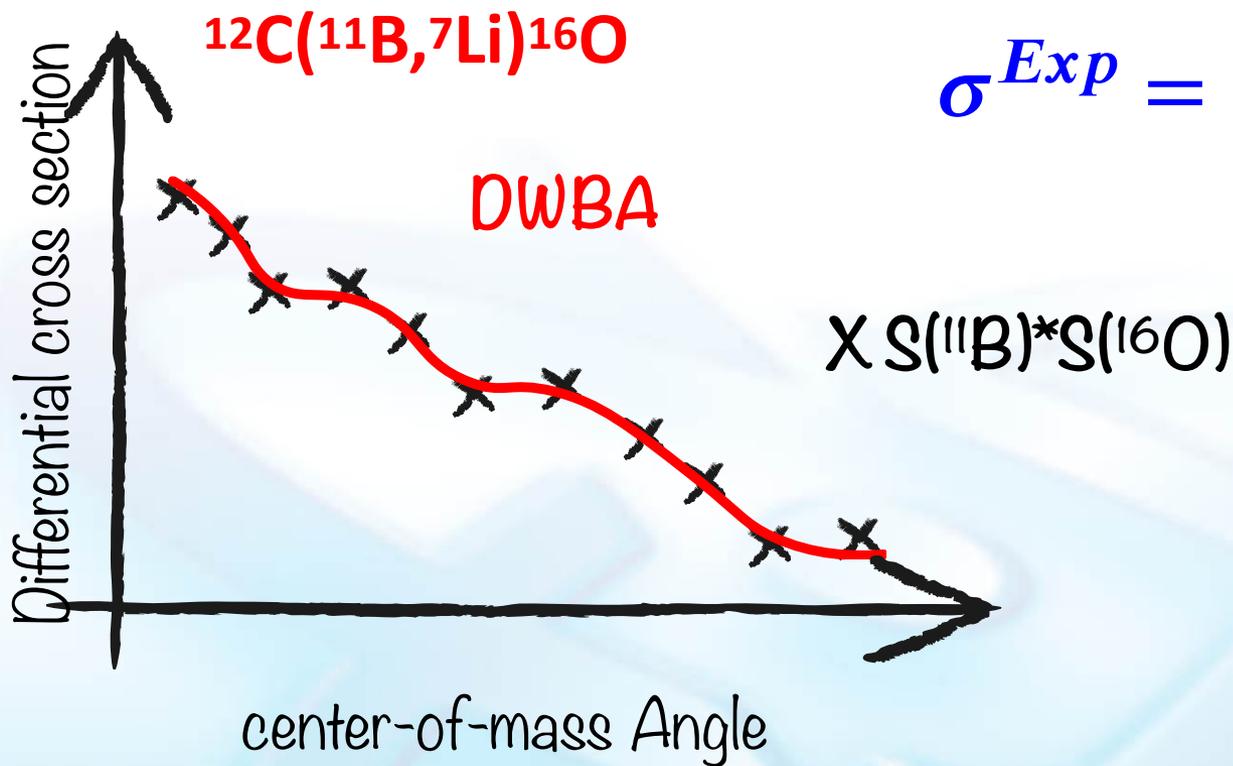




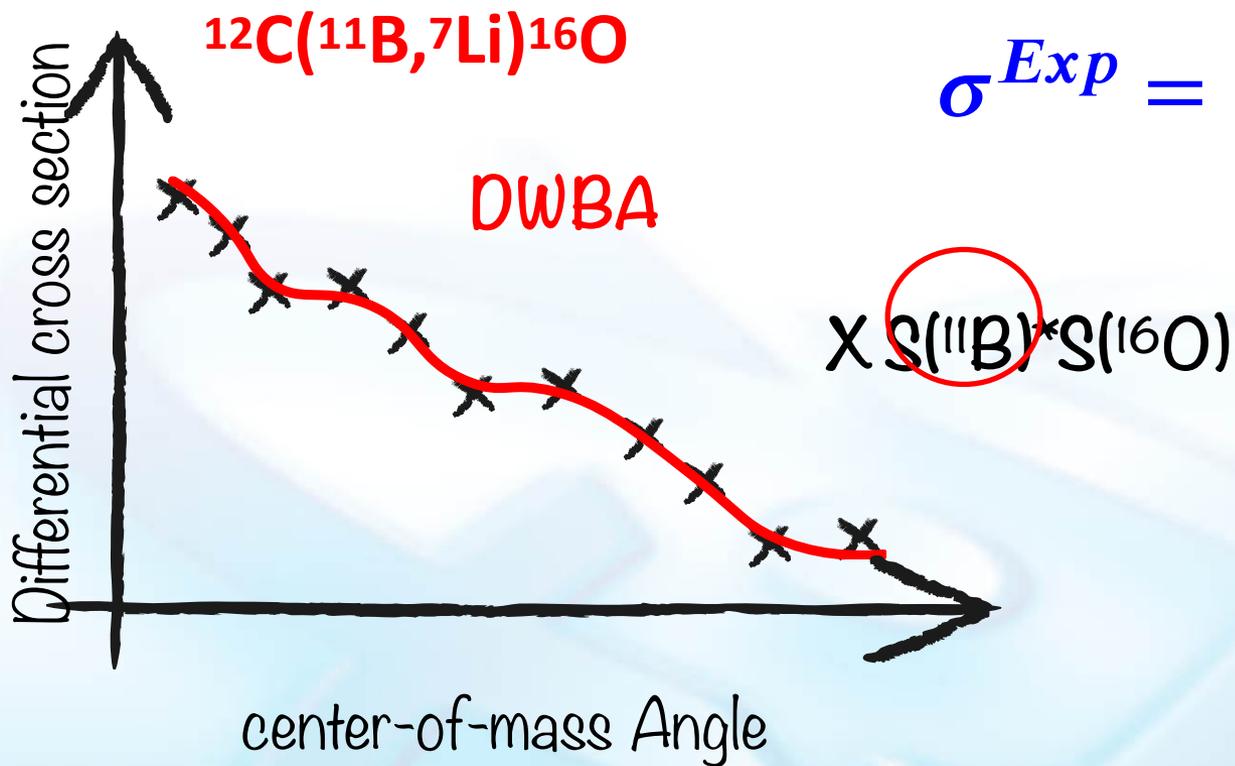
$$\sigma^{Exp} = S_{\alpha}^{11B} S_{\alpha}^{16O} \sigma^{DWBA}$$



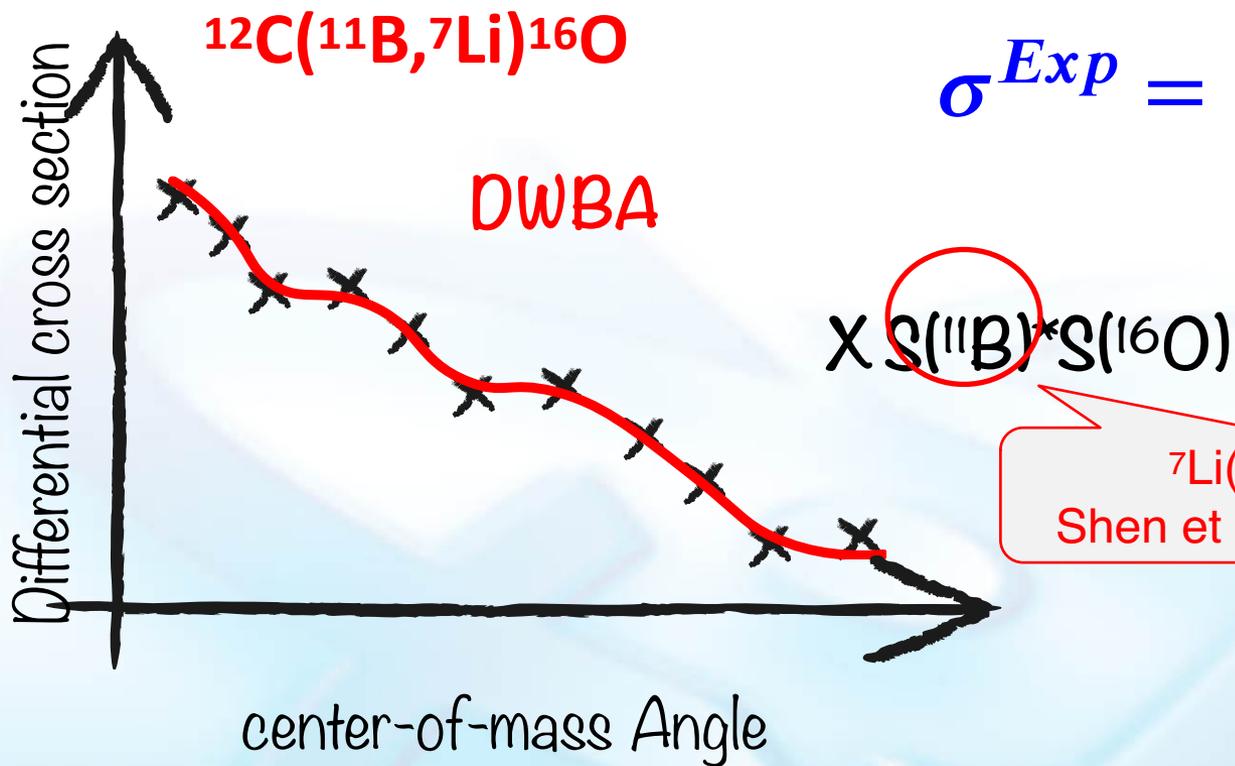
$$\sigma^{Exp} = S_{\alpha}^{11B} S_{\alpha}^{16O} \sigma^{DWBA}$$



$$\sigma^{Exp} = S_{\alpha}^{11B} S_{\alpha}^{16O} \sigma^{DWBA}$$

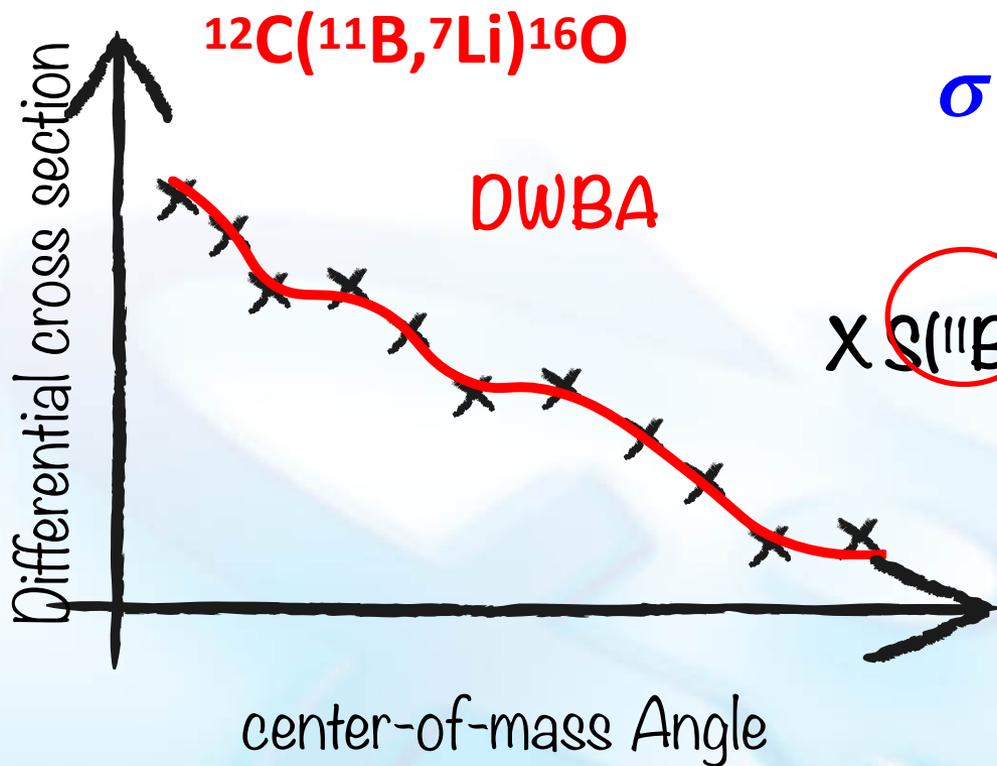


$$\sigma^{Exp} = S_{\alpha}^{11B} S_{\alpha}^{16O} \sigma^{DWBA}$$



$$\sigma^{Exp} = S_{\alpha}^{11B} S_{\alpha}^{16O} \sigma^{DWBA}$$

$^7\text{Li}(^6\text{Li}, d)^{11}\text{B}$
 Shen et al. PLB (2019)

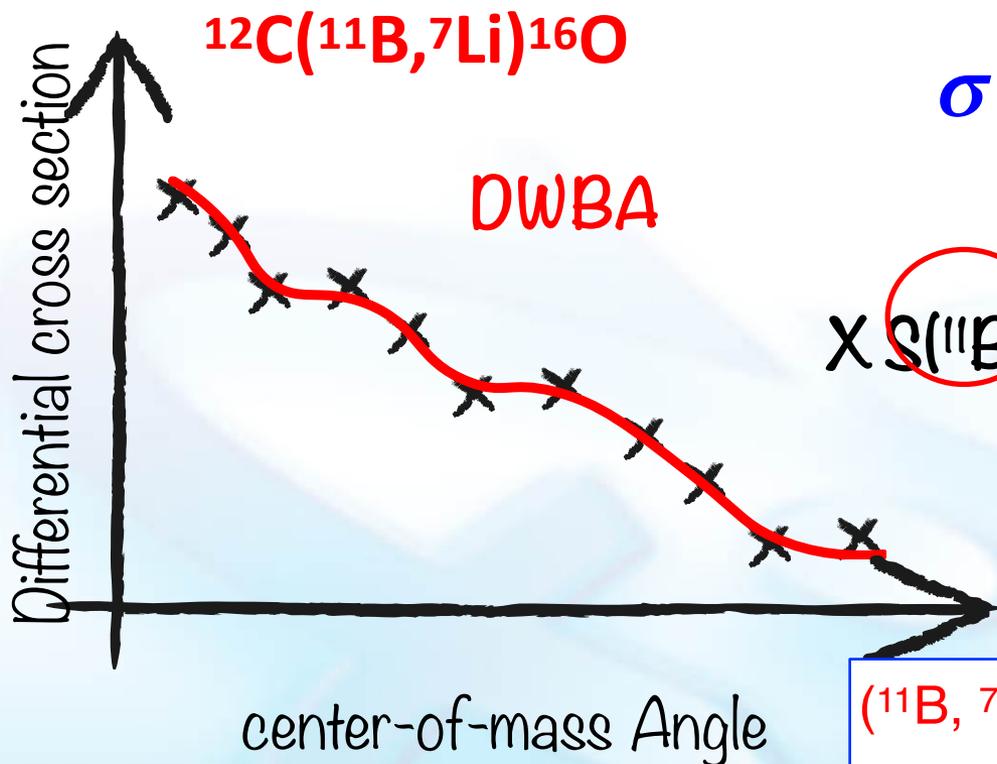


$$\sigma^{Exp} = S_{\alpha}^{11B} S_{\alpha}^{16O} \sigma^{DWBA}$$

$\times S(11B) * S(16O) \rightarrow {}^{16}O \text{ ANC}$

${}^7\text{Li}({}^6\text{Li}, d){}^{11}\text{B}$
 Shen et al. PLB (2019)





$$\sigma^{Exp} = S_{\alpha}^{11B} S_{\alpha}^{16O} \sigma^{DWBA}$$

$$X S(11B) * S(16O) \rightarrow {}^{16}O \text{ ANC}$$

${}^7\text{Li}({}^6\text{Li}, d){}^{11}\text{B}$
 Shen et al. PLB (2019)

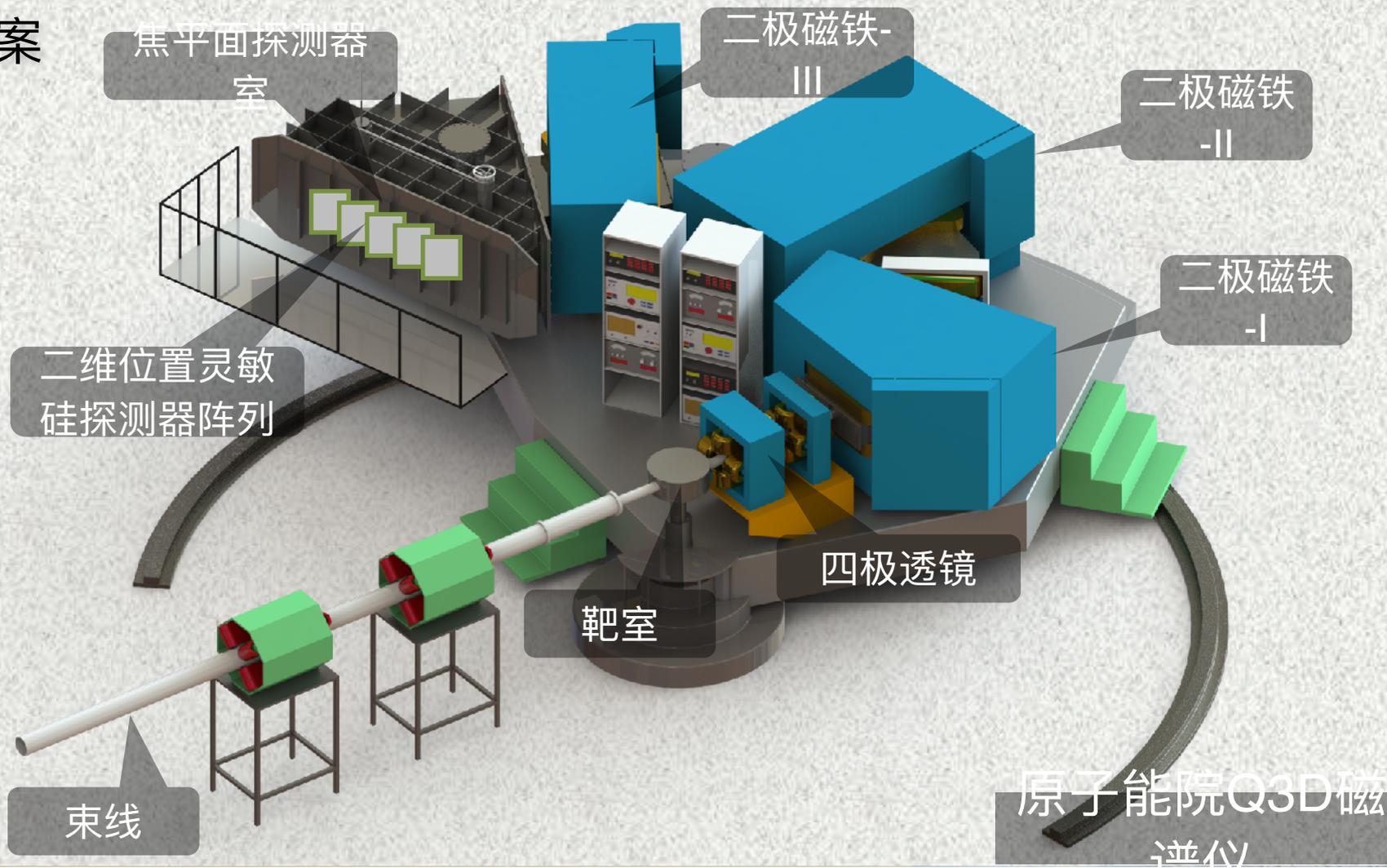
(${}^{11}\text{B}$, ${}^7\text{Li}$) 转移体系的优势

★ ${}^{11}\text{B}$ 紧束缚

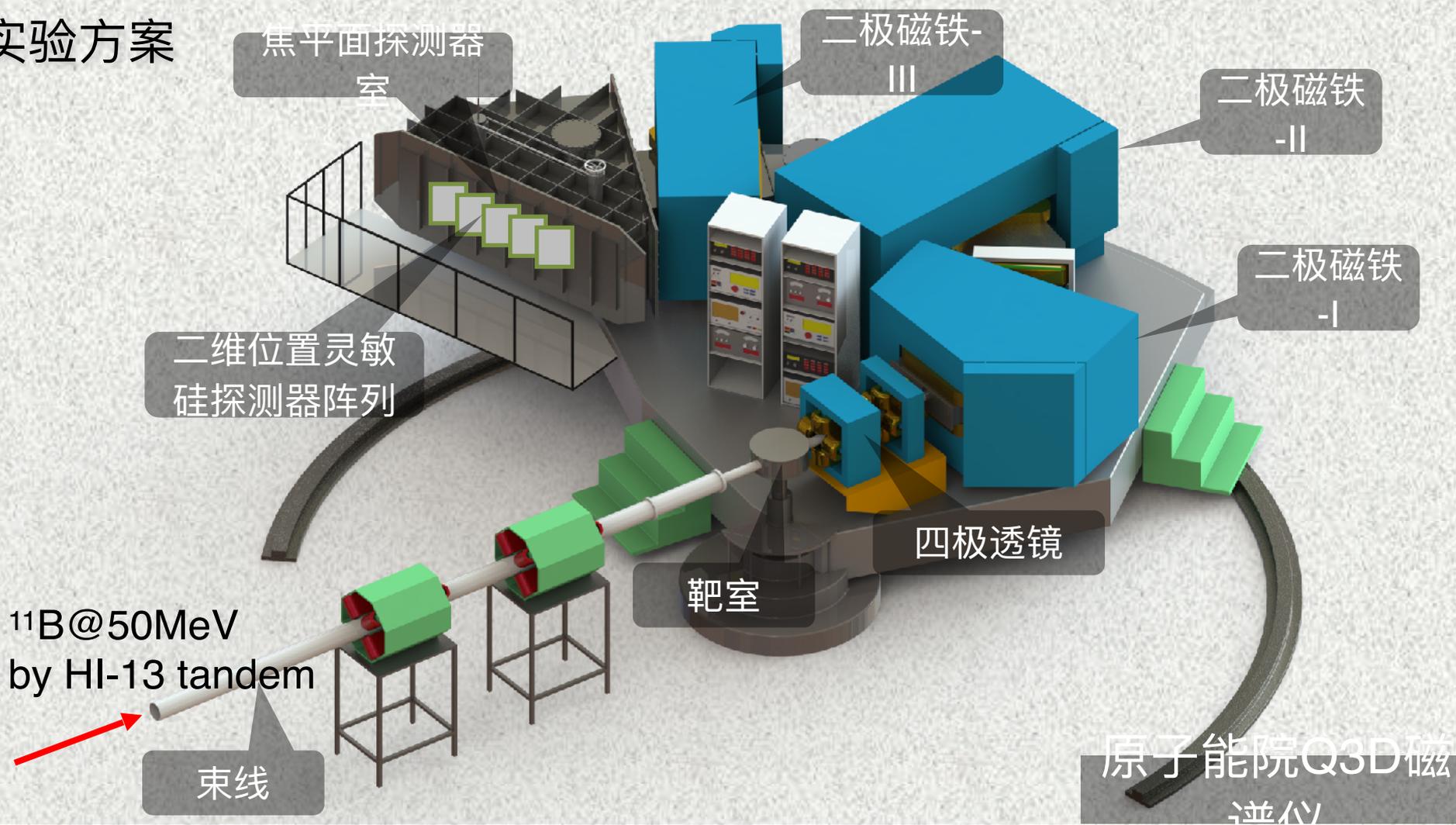
$Q_{\alpha}({}^{11}\text{B}) = 8.66 \text{ MeV}$ v.s. $Q_{\alpha}({}^6\text{Li}) = 1.48 \text{ MeV}$

★ 更少的破裂效应和复合核贡献

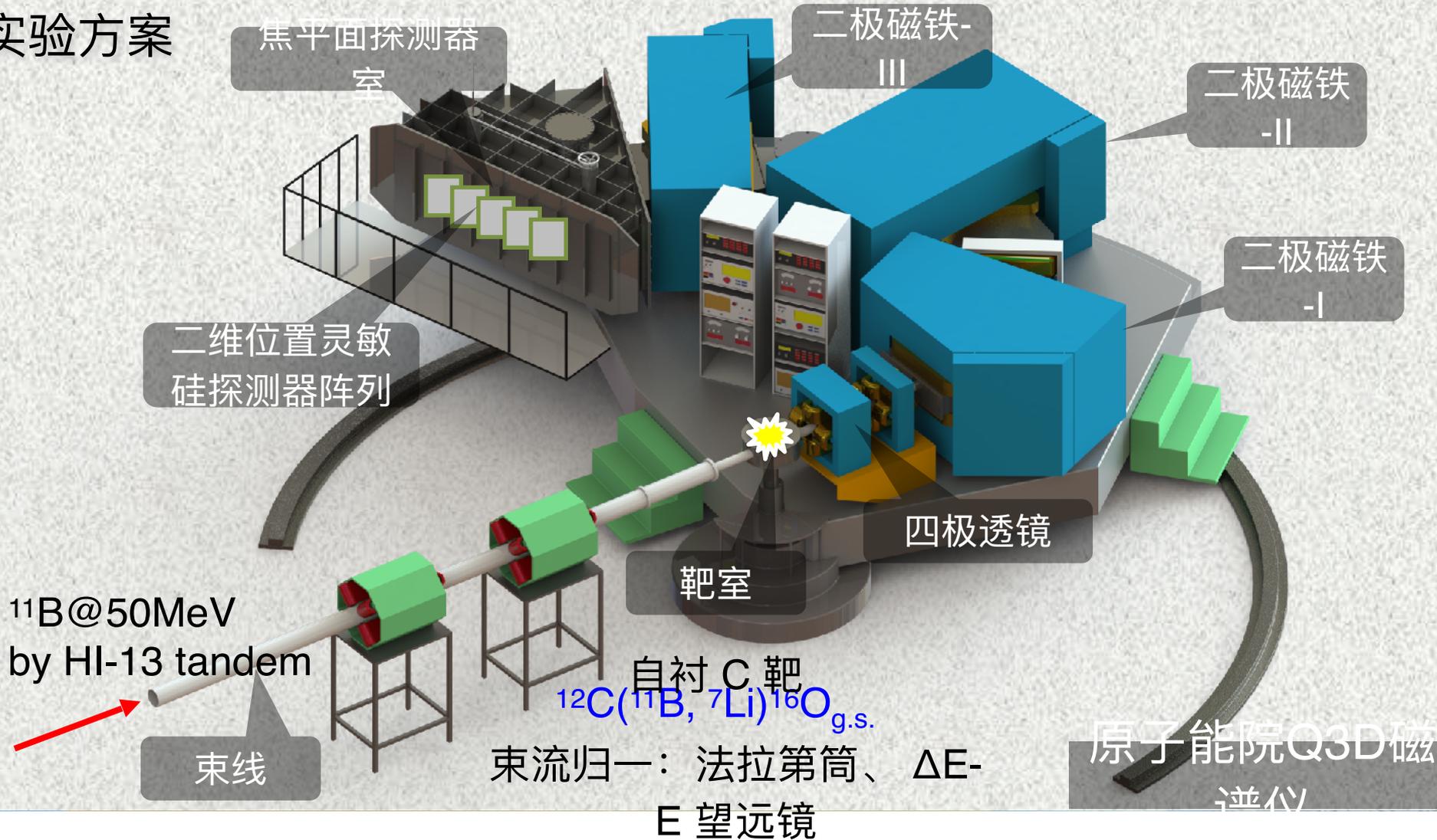
实验方案



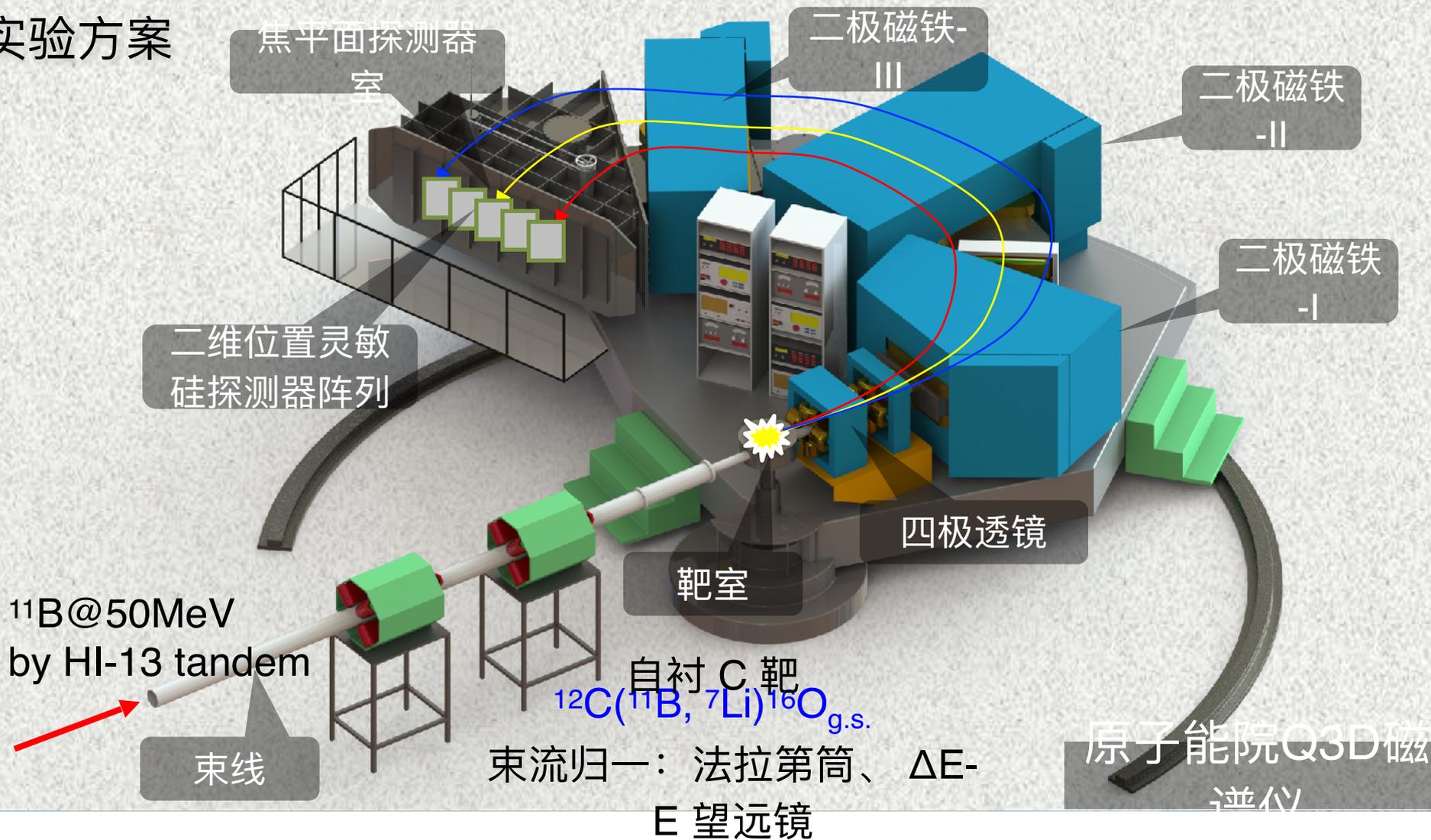
实验方案

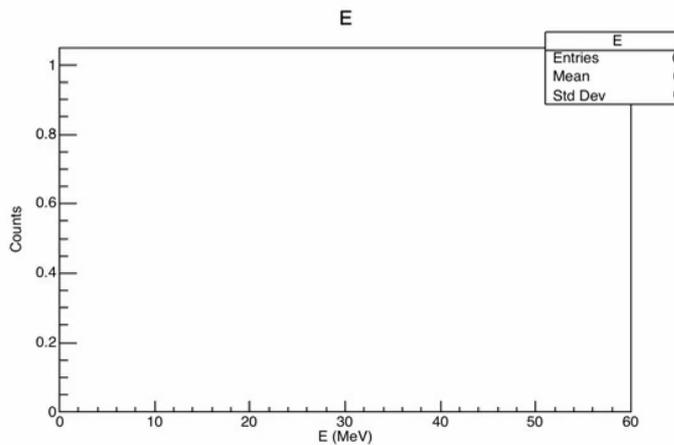
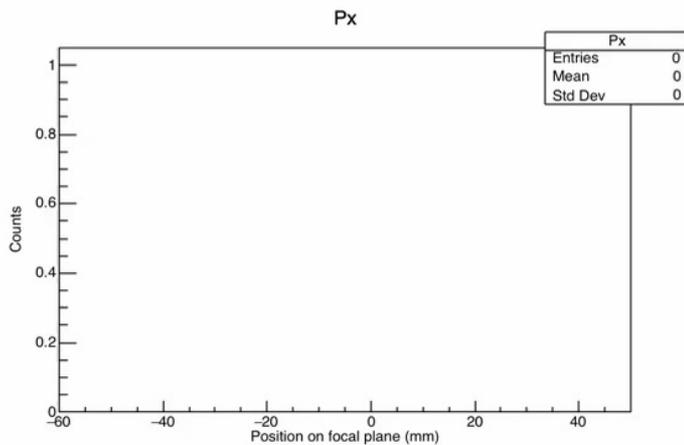
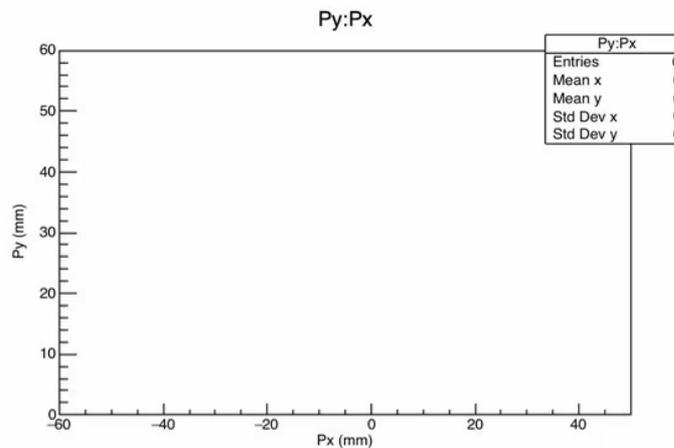
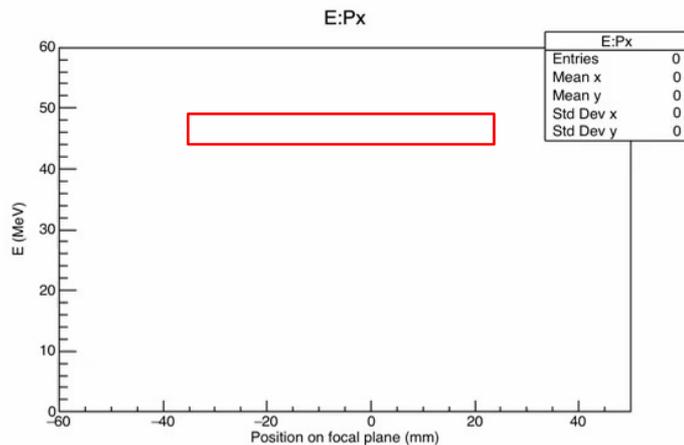


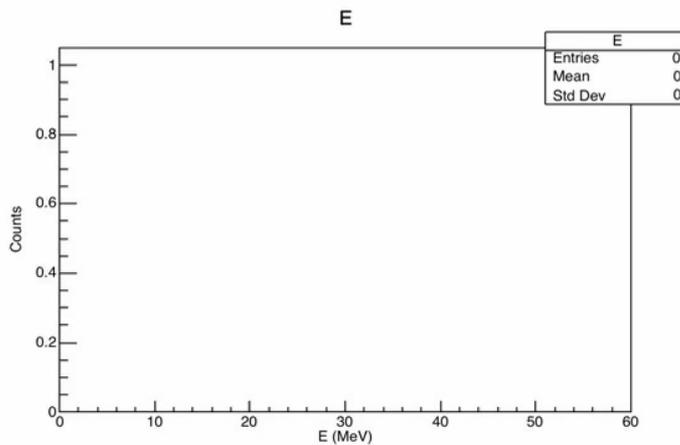
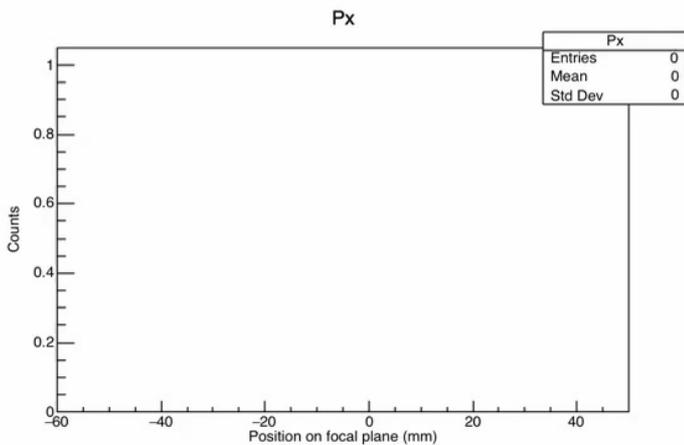
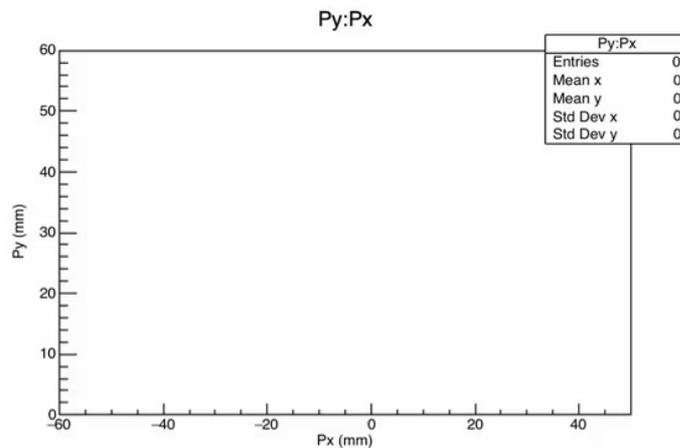
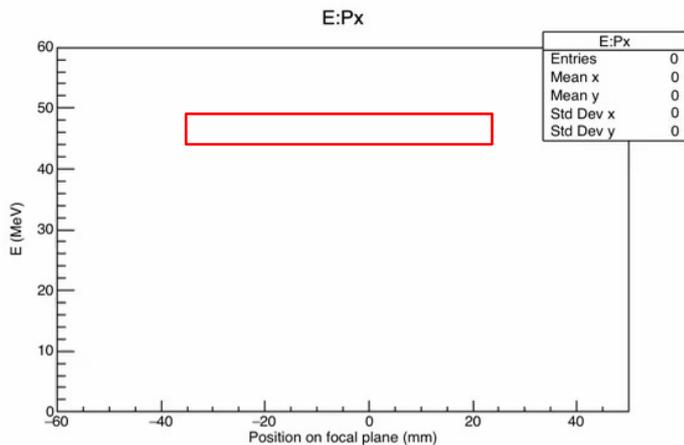
实验方案

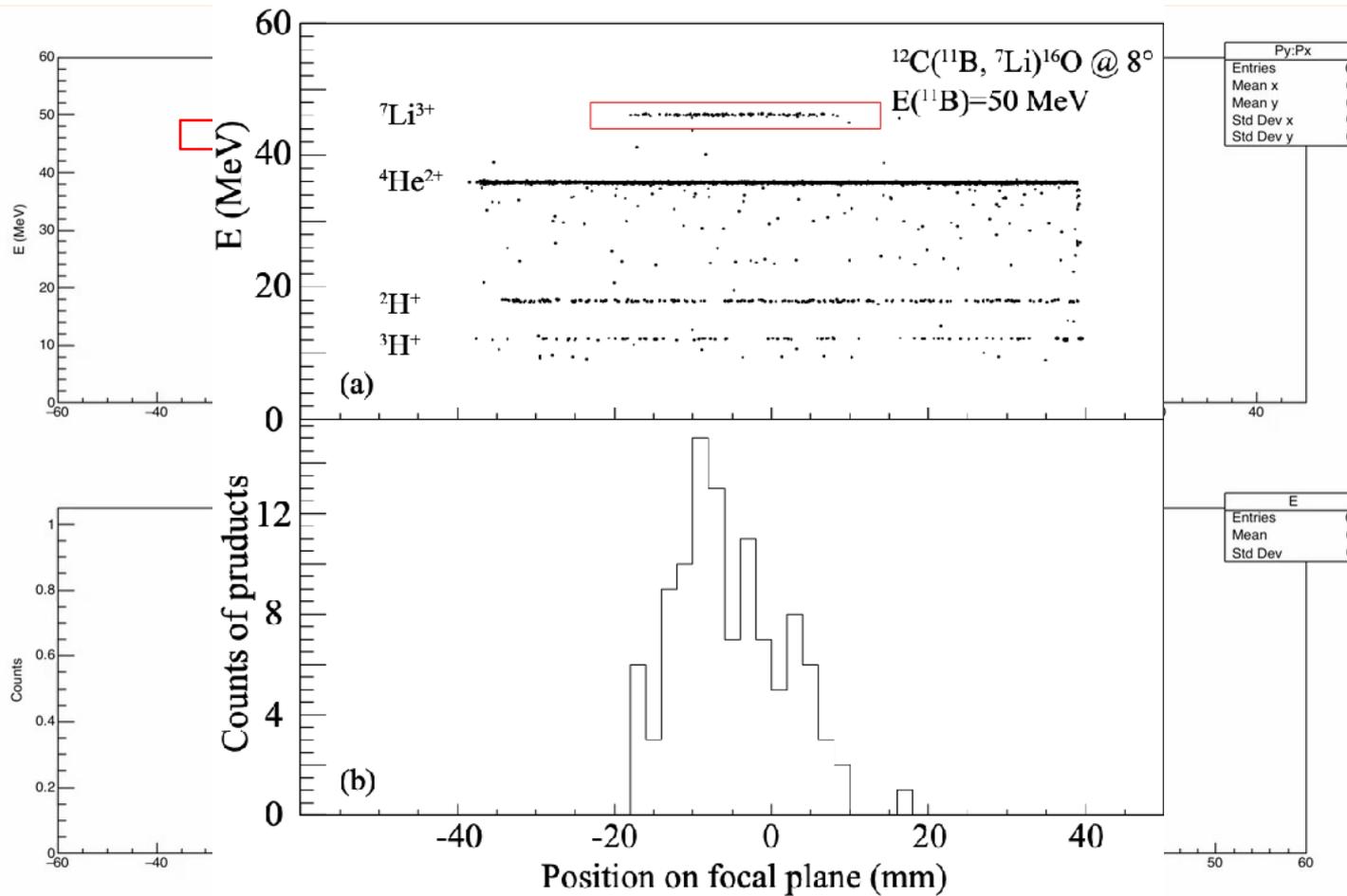


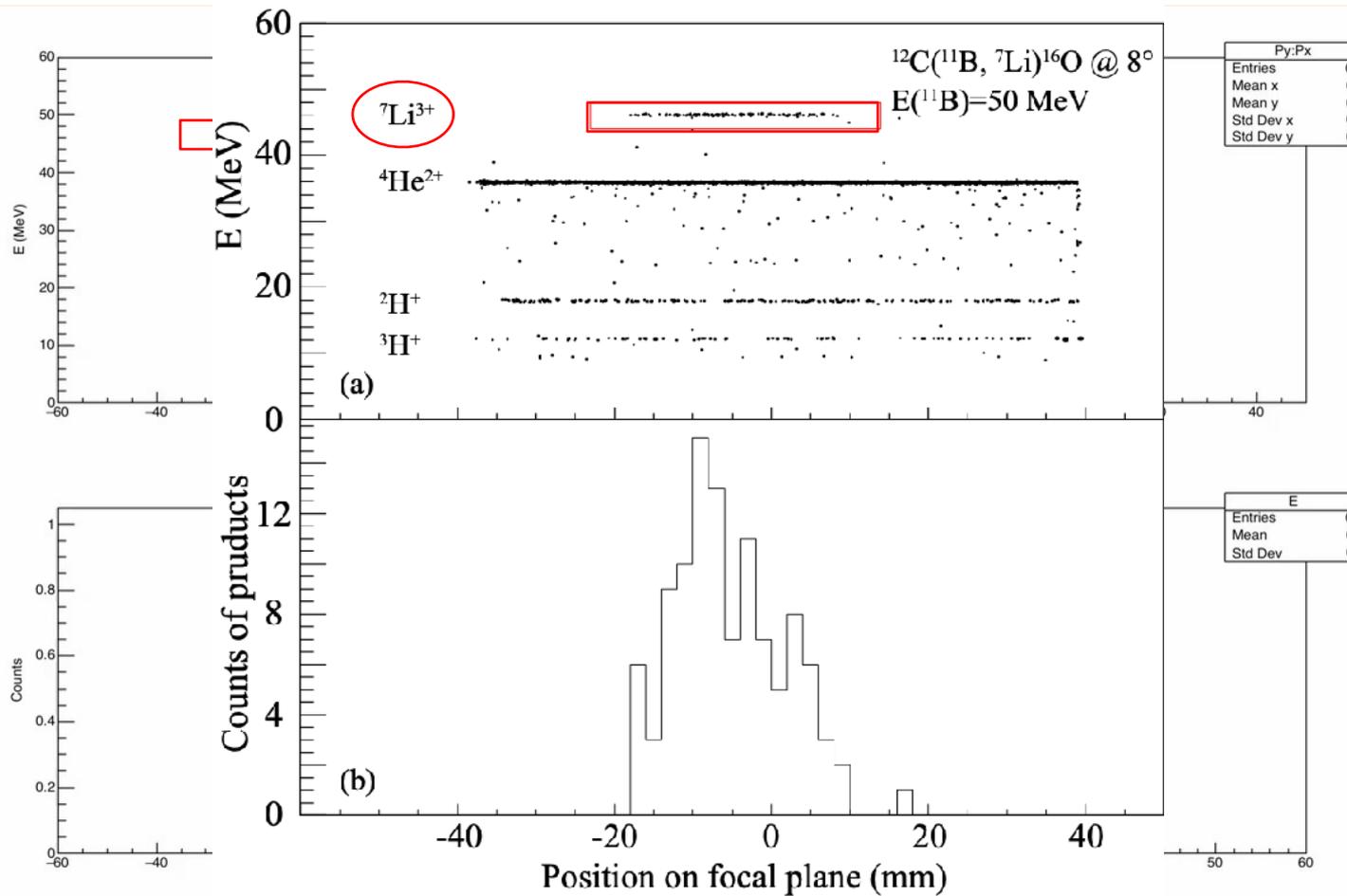
实验方案

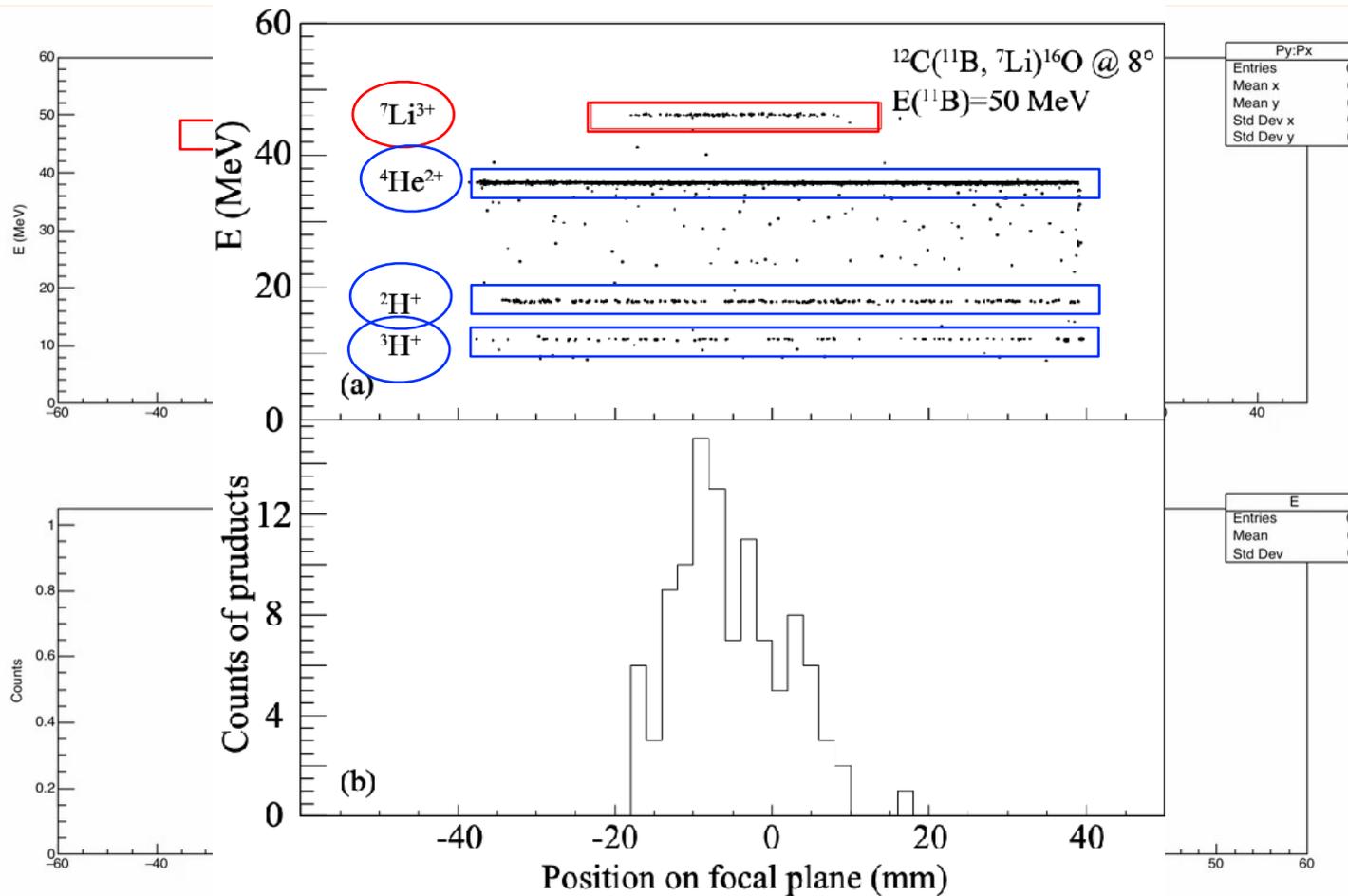


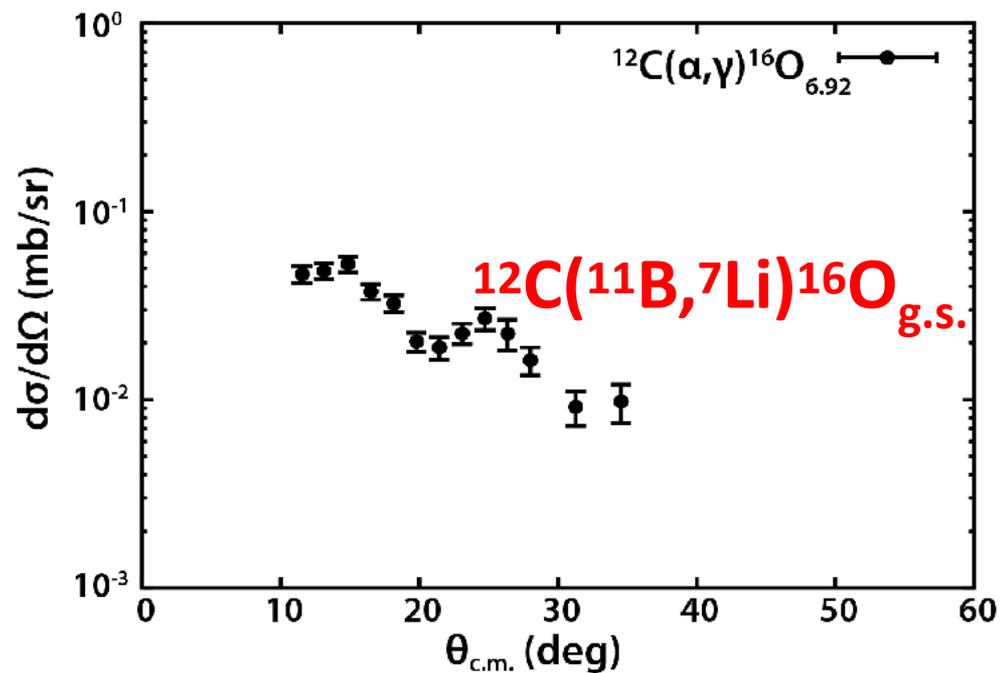
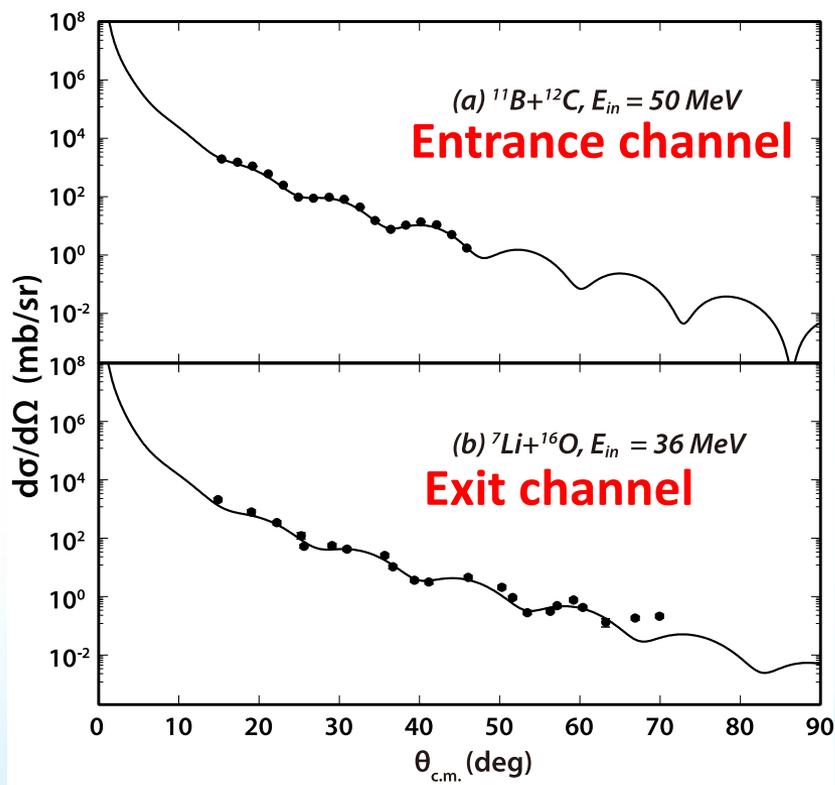












$$\sigma^{Exp} = S_{\alpha}^{11B} S_{\alpha}^{16O} \sigma^{DWBA}$$

DWBA 输入参数

入射道光学势

出射道光学势

核心-核心势

($\alpha+^7\text{Li}$) 束缚态参数

($\alpha+^{12}\text{C}$) 束缚态参数

^{11}B 谱幅度



$$\sigma^{Exp} = S_{\alpha}^{11B} S_{\alpha}^{16O} \sigma^{DWBA}$$

DWBA 输入参数

入射道光学势

出射道光学势

核心-核心势

($\alpha+^7\text{Li}$) 束缚态参数

($\alpha+^{12}\text{C}$) 束缚态参数

^{11}B 谱幅度

- 采用单折叠势形式
- 从实验数据导出



$$\sigma^{Exp} = S_{\alpha}^{11B} S_{\alpha}^{16O} \sigma^{DWBA}$$

DWBA 输入参数

入射道光学势

出射道光学势

核心-核心势

($\alpha+{}^7\text{Li}$) 束缚态参数

($\alpha+{}^{12}\text{C}$) 束缚态参数

${}^{11}\text{B}$ 谱幅度

- 采用单折叠势形式
- 从实验数据导出

考虑 ${}^7\text{Li}$ 形变带来的耦合道效应

$$\sigma^{Exp} = S_{\alpha}^{11B} S_{\alpha}^{16O} \sigma^{DWBA}$$

DWBA 输入参数

入射道光学势

出射道光学势

核心-核心势

($\alpha+{}^7\text{Li}$) 束缚态参数

($\alpha+{}^{12}\text{C}$) 束缚态参数

${}^{11}\text{B}$ 谱幅度

- 采用单折叠势形式
- 从实验数据导出

考虑 ${}^7\text{Li}$ 形变带来的耦合道效应

${}^7\text{Li}({}^6\text{Li},d){}^{11}\text{B}$ 实验确定

$$\sigma^{Exp} = S_{\alpha}^{11B} S_{\alpha}^{16O} \sigma^{DWBA}$$

DWBA 输入参数

入射道光学势

出射道光学势

核心-核心势

($\alpha+{}^7\text{Li}$) 束缚态参数

($\alpha+{}^{12}\text{C}$) 束缚态参数

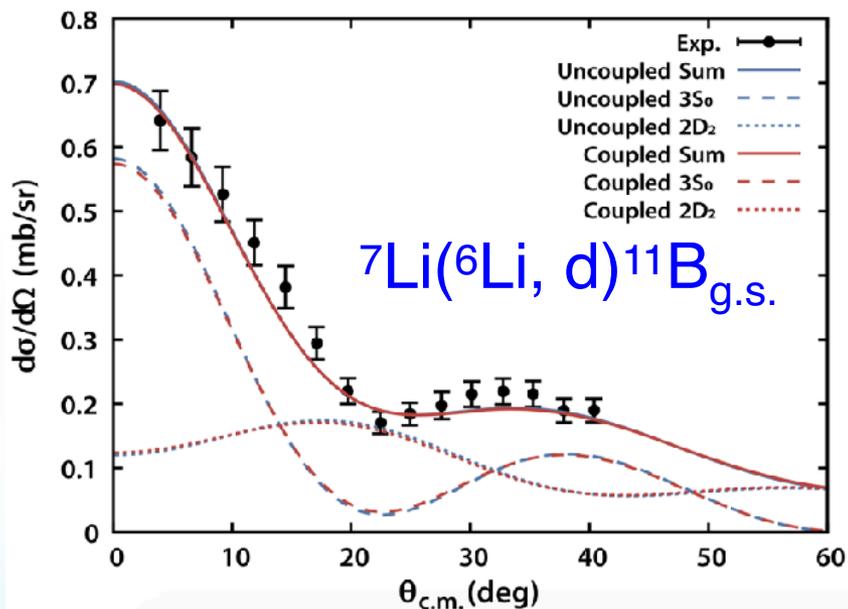
${}^{11}\text{B}$ 谱幅度

- 采用单折叠势形式
- 从实验数据导出

考虑 ${}^7\text{Li}$ 形变带来的耦合道效应

基于核半径参数的最小 χ^2 约束

${}^7\text{Li}({}^6\text{Li},d){}^{11}\text{B}$ 实验确定



SA for ${}^{11}\text{B}$ ground state

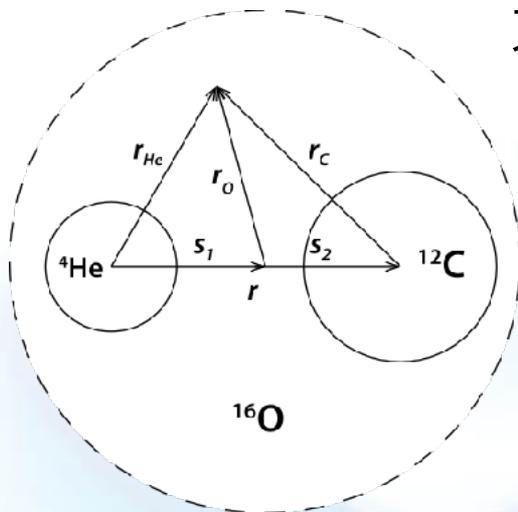
	$3S_0$	$2D_2$	$3S_0/2D_2$
Coupled	0.66±0.09	0.73±0.09	0.90
Kurath	-0.509	0.629	0.81
Rudchik	-0.638	-0.422	1.5

Uncertainty source	Relative error	
	$2D_2$	$3S_0$
Entrance channel potential	2.1%	1.5%
Exit channel potential	5.1%	8.3%
($\alpha+d$) binding potential	8.9%	3.5%
($\alpha+{}^7\text{Li}$) binding potential	5.2%	3.4%
ANC for $\alpha+d \rightarrow {}^6\text{Li}$	4.7%	4.7%
Target thickness	5.0%	5.0%
Statistics	2.6%	2.8%
Total	13.8%	12.2%

Y P Shen, B Guo*, et al, PLB 797 (2019) 134820

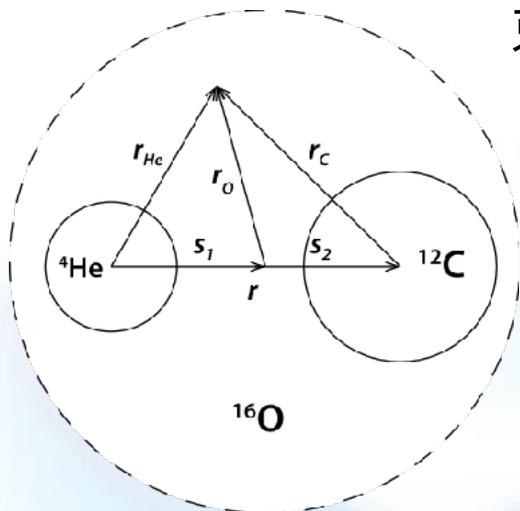
束缚态光学势半径 r_0 和弥散 a 与核物质半径的关系

$$\langle r_O^2 \rangle = \frac{m_{\text{He}}}{m_O} \langle r_{\text{He}}^2 \rangle + \frac{m_{\text{C}}}{m_O} \langle r_{\text{C}}^2 \rangle + \frac{m_{\text{He}}m_{\text{C}}}{m_O^2} \langle r^2 \rangle$$



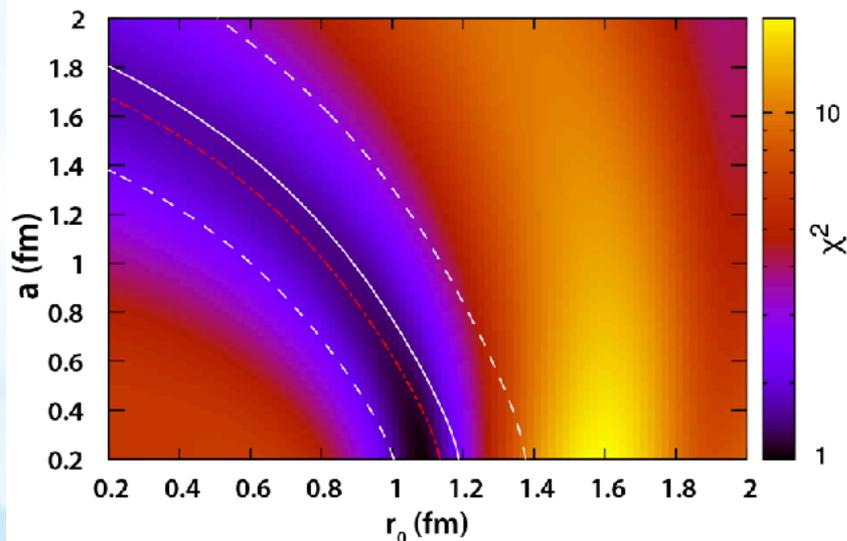
束缚态光学势半径 r_0 和弥散 a 与核物质半径的关系

$$\langle r_O^2 \rangle = \frac{m_{\text{He}}}{m_O} \langle r_{\text{He}}^2 \rangle + \frac{m_{\text{C}}}{m_O} \langle r_{\text{C}}^2 \rangle + \frac{m_{\text{He}}m_{\text{C}}}{m_O^2} \langle r^2 \rangle$$



利用核物质半径进行最

小 χ^2 约束



数据量少，误差大，方法可靠性

DWBA计算 (^{16}O g.s.)

TABLE I. Present ANC of the ^{16}O GS and other available results in the literature.

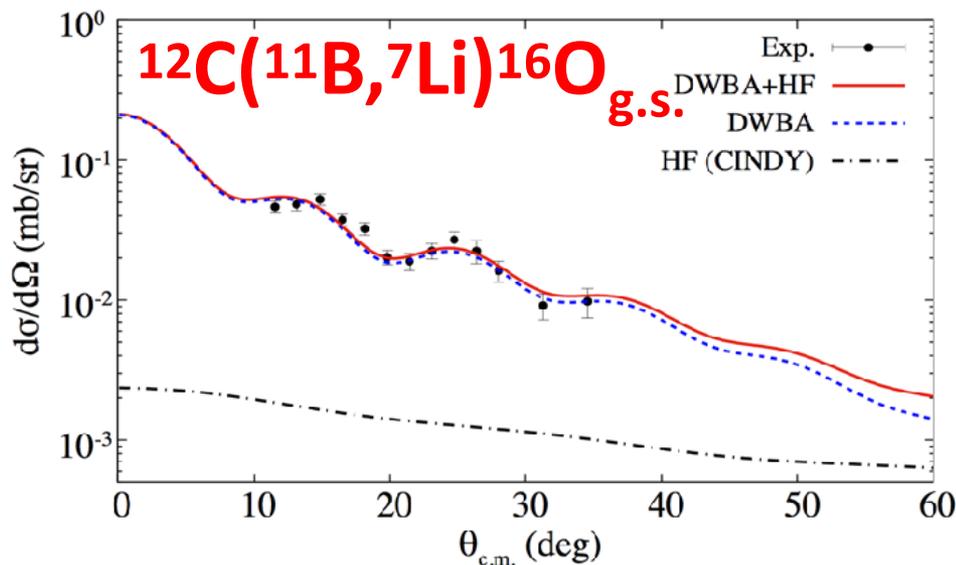
Reference	ANC ($\text{fm}^{-1/2}$)	Method
Adhikari (2009) [14]	13.9 ± 2.4 3390 (WS1)	$^{16}\text{O}+\text{Pb}$ breakup
Morais (2011) [16]	1230 (WS2) 750 (FP)	$^{12}\text{C}(^{16}\text{O}, ^{12}\text{C})^{16}\text{O}$
Sayre (2012) [11]	709	<i>R</i> -matrix
Adhikari (2017) [15]	637 ± 86	$^{12}\text{C}(^7\text{Li}, t)^{16}\text{O}$
Present	337 ± 45	$^{12}\text{C}(^{11}\text{B}, ^7\text{Li})^{16}\text{O}$

周边性差

基于直接测量外推

缺乏前用区数据，误差大

- Q3D磁谱仪高分辨
- ^{16}O 束缚态参数约束，数据重现好
- 复合核贡献小，(^{11}B , ^7Li)优势



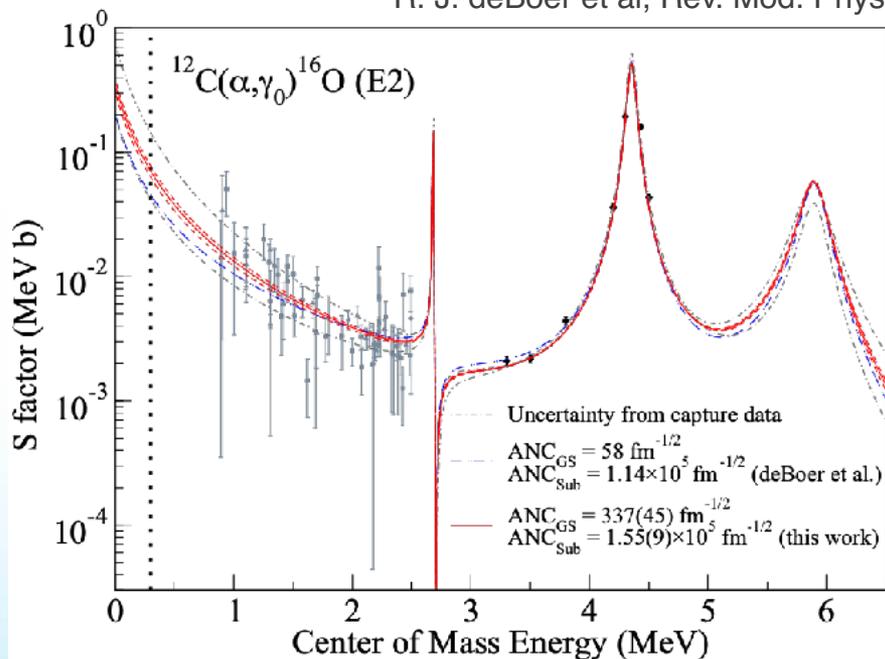
显著影响核合成模型预言的核素丰度

例如氦同位素的丰度将会增加约70%
Astrophysical Impact

E2 S-factor: $45^* \rightarrow 70 \pm 7 \text{ keV}\cdot\text{b}$ $\uparrow 55\%$

Total S-factor: $140^* \rightarrow 162 \text{ keV}\cdot\text{b}$ $\uparrow 16\%$

* R. J. deBoer et al, Rev. Mod. Phys. 89, 035007 (2017).



^{16}O 基态ANC约束显著提高了S因子精度

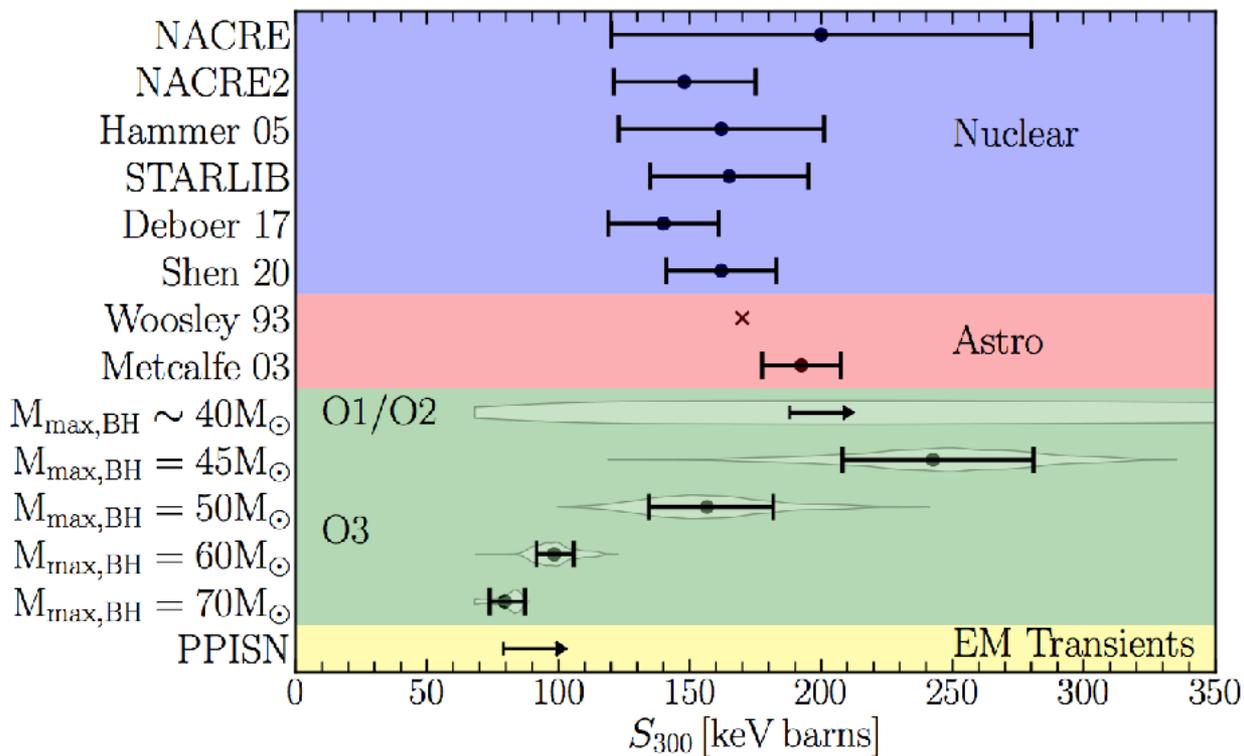
S因子误差50% \Rightarrow 10%

Y. P. Shen, B. Guo*, R. J. DeBoer*, et al.
Phys. Rev. Lett., **124**, 162701 (2020)

该工作得到PRL两位审稿人好评:

1. To my knowledge this is the first time the GS ANC is extracted using the $^{12}\text{C}(^{11}\text{B}, ^7\text{Li})^{16}\text{O}$.
2. The $^{12}\text{C}(\alpha, \gamma)$ reaction is a long-standing issue in nuclear astrophysics ... The appearance here is that (^{11}B , ^7Li) with the chosen kinematics satisfies both direct and peripheral criteria."

-matrix calculation by R. J. deBoer



荷兰阿姆斯特丹大学、美国芝加哥大学、中科院天文台等单位的联合团队在天体物理顶级期刊ApJL上发表的利用引力波约束 $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ 反应截面的结果与我们的结果

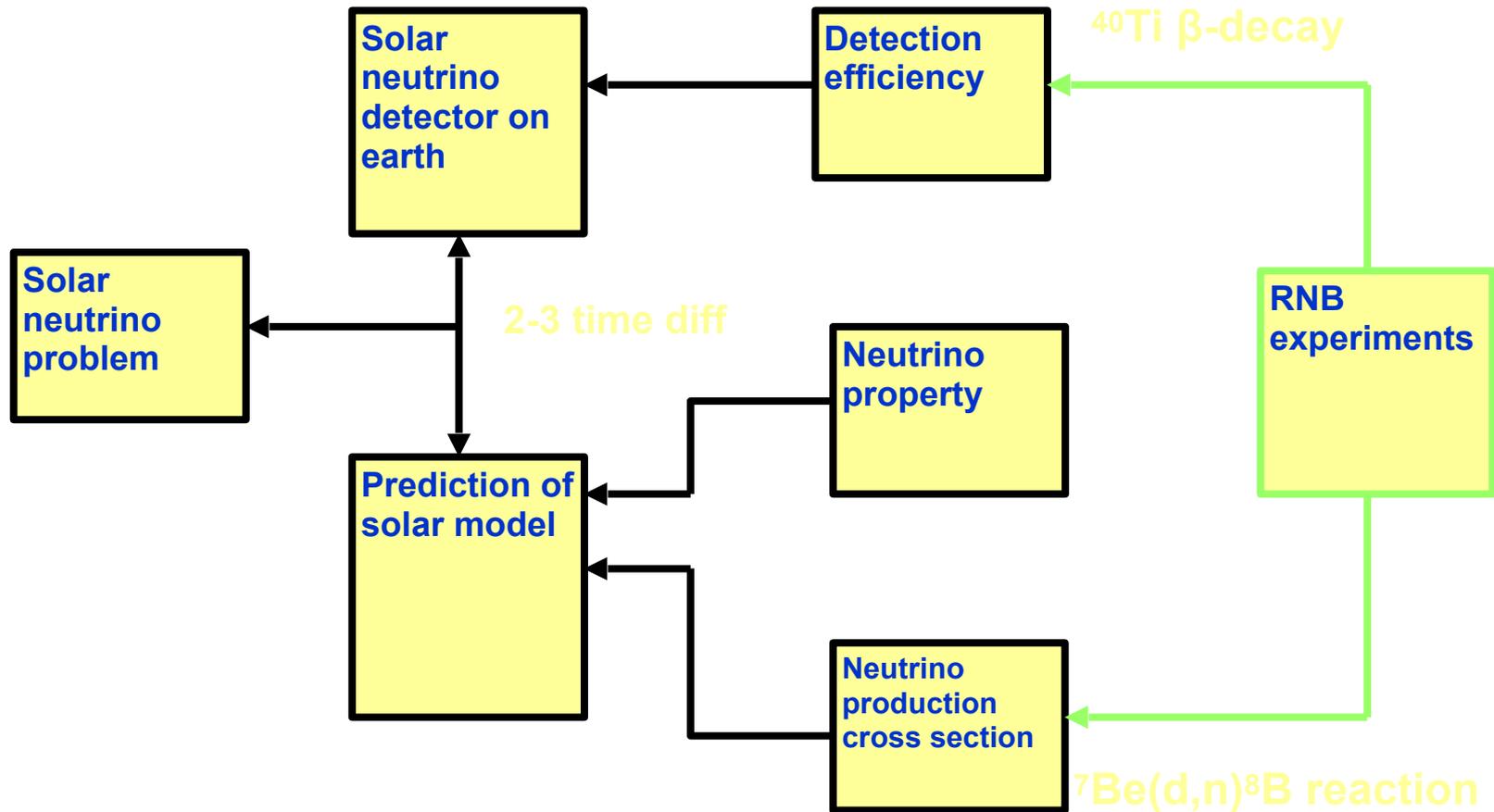
一致

Hammer, M. Renzo, S. E. de Mink et al., *Astrophys. J. Lett.* 902, 36 (2020)

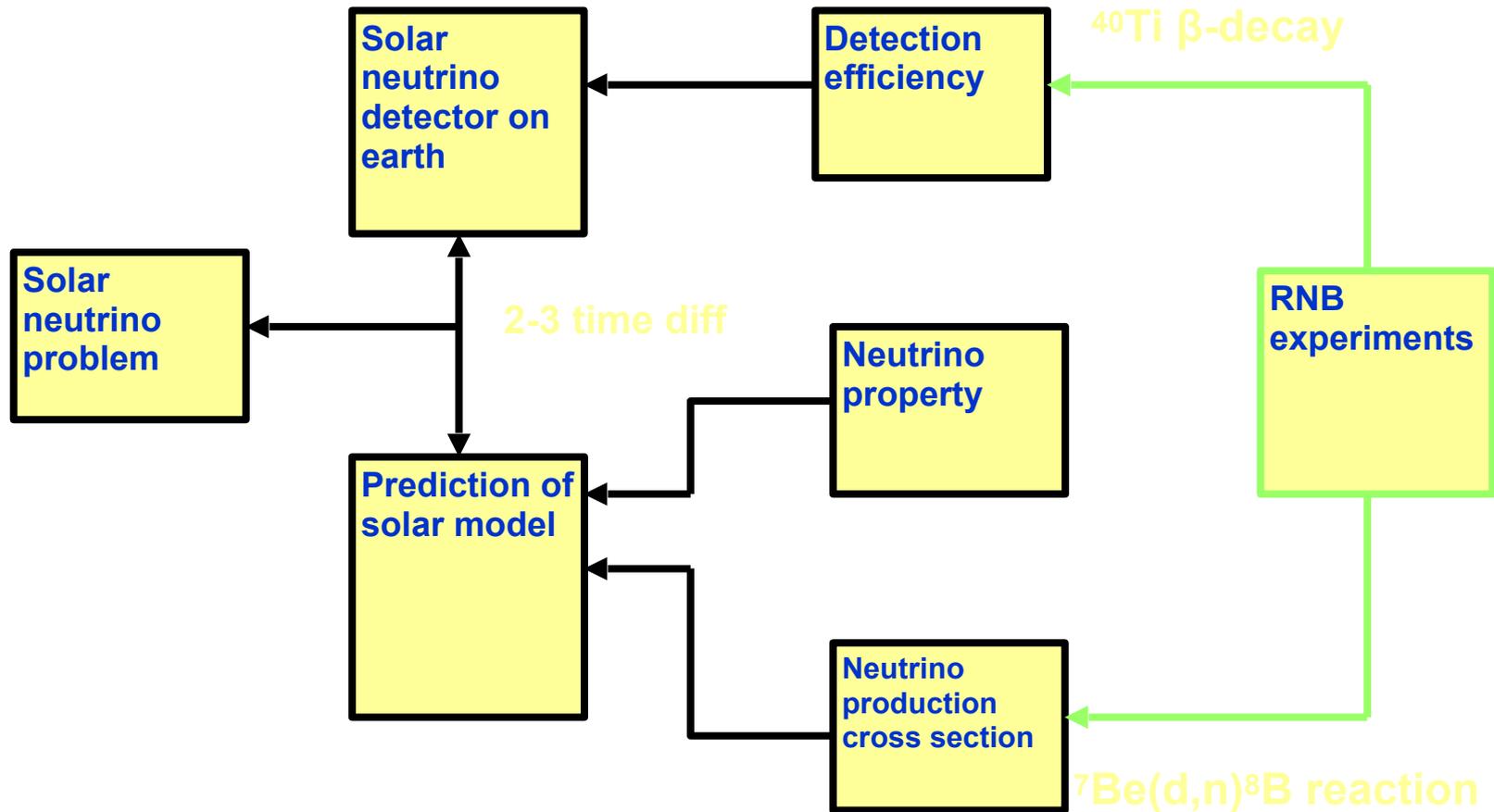


具体研究示例：太阳中微子研究

How nuclear physics connected with solar neutrino problem

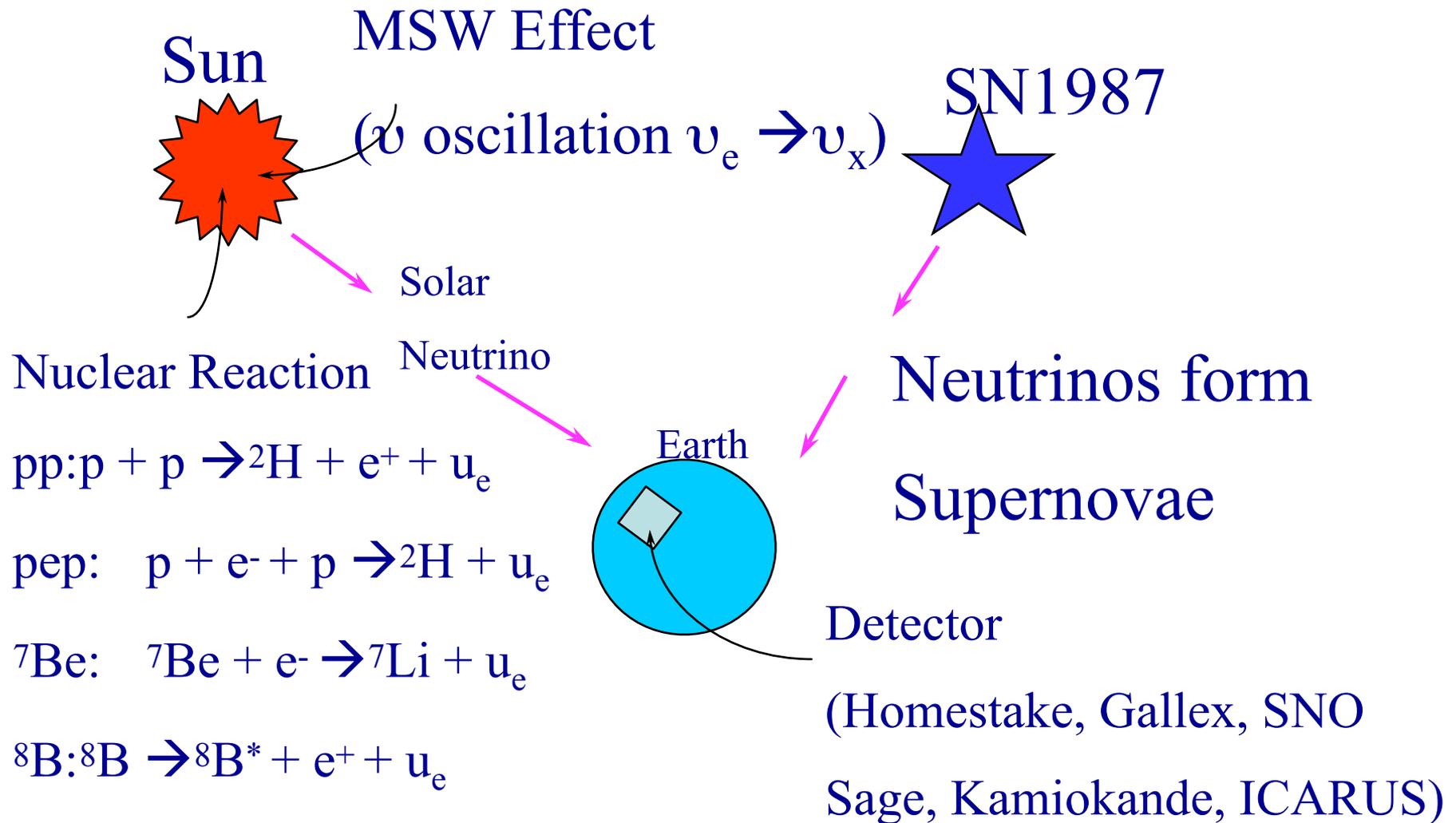


How nuclear physics connected with solar neutrino problem



Predicted reaction rates = Absorption cross section (nuclear physics input, e.g. ^{37}Ca or ^{40}Ti β -decay) \times Solar neutrino flux (solar model + nuclear physics input, e.g. $^7\text{Be}(p,\gamma)^8\text{B}$ reaction)

Where does neutrino come from?

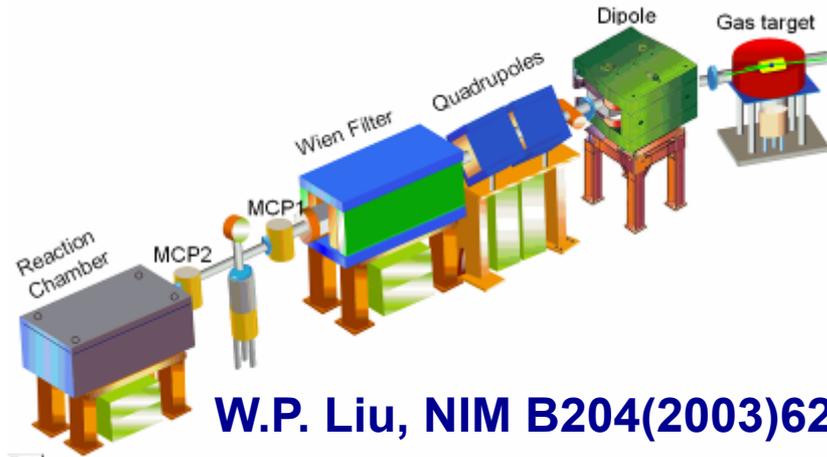


Indirect method for ${}^7\text{Be}(p,\gamma){}^8\text{B}$

W.P. Liu, PRL77(1996)611

Indirect method for ${}^7\text{Be}(p,\gamma){}^8\text{B}$

RIB production

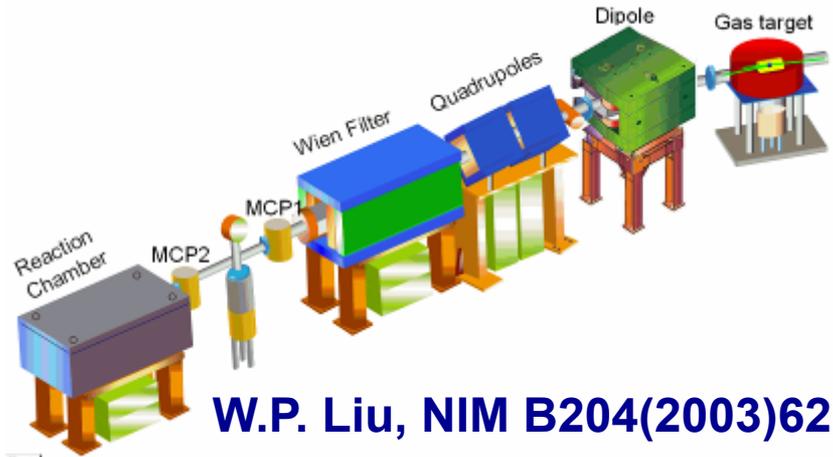


W.P. Liu, NIM B204(2003)62

W.P. Liu, PRL77(1996)611

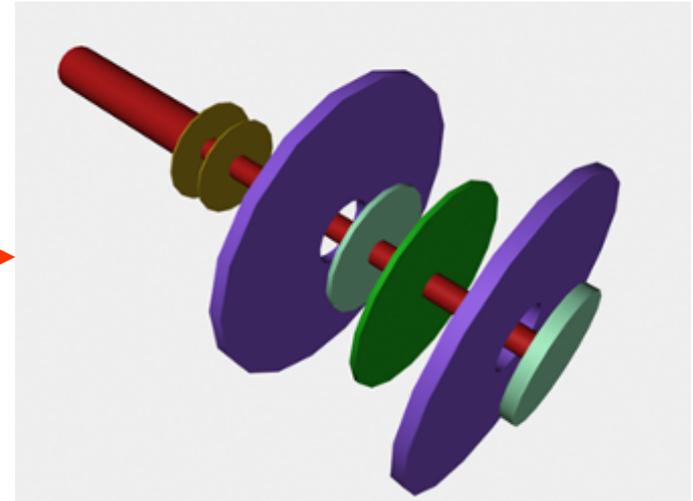
Indirect method for ${}^7\text{Be}(p,\gamma){}^8\text{B}$

RIB production



W.P. Liu, NIM B204(2003)62

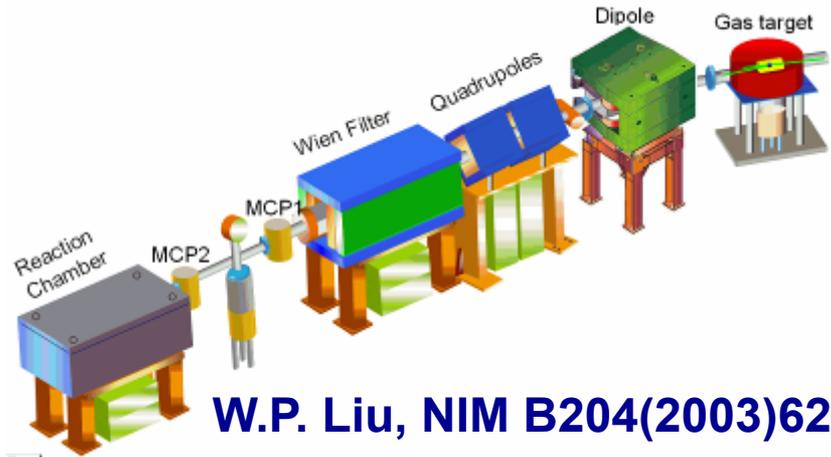
(d,n) or (d,p) measurement



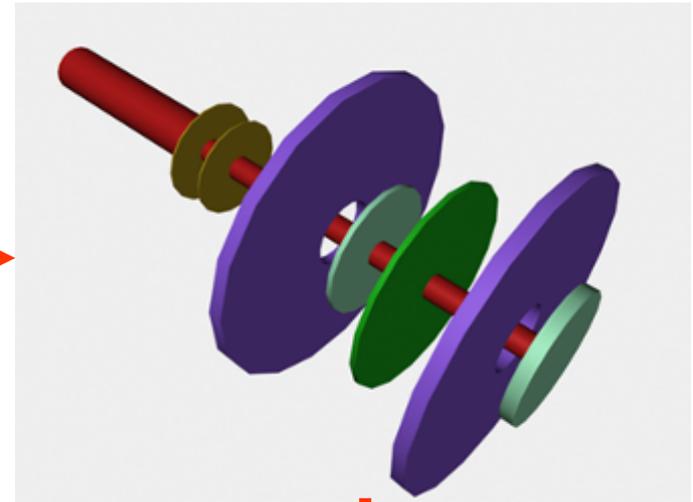
W.P. Liu, PRL77(1996)611

Indirect method for ${}^7\text{Be}(p,\gamma){}^8\text{B}$

RIB production



(d,n) or (d,p) measurement



W.P. Liu, PRL77(1996)611

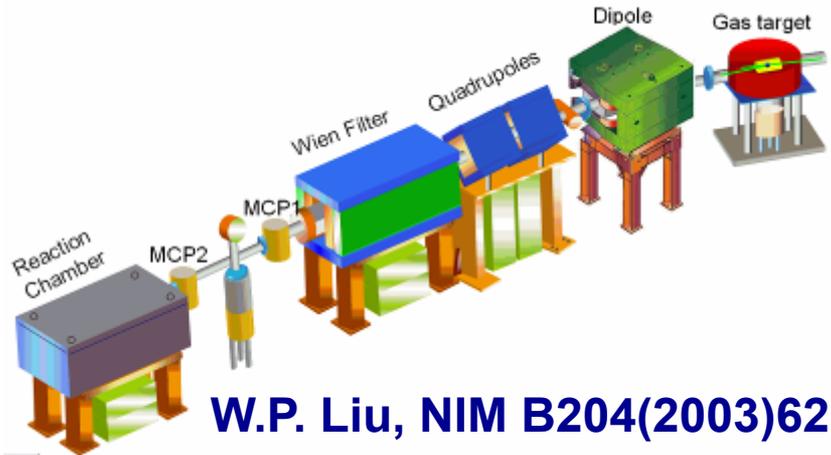
$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} - \left(\frac{d\sigma}{d\Omega}\right)_{\text{CN}} = \sum_{ji jf} (C_{liji}^d)^2 (C_{l_f jf}^{12\text{N}})^2 \frac{d\sigma_{l_f jf liji}^{\text{DW}}/d\Omega}{b_{liji}^2 b_{l_f jf}^2},$$

$$\sigma_t = \frac{16\pi}{9} \left(\frac{E_\gamma}{\hbar c}\right)^3 \frac{1}{\hbar v} \frac{e_{\text{eff}}^2}{k^2} \frac{(2j_f + 1)}{(2I_1 + 1)(2I_2 + 1)} C_{l_f jf}^2 \times \left| \int_{R_N}^{\infty} r^2 dr f_{lj}(kr) W_{\eta, l_f + 1/2}(2kr) \right|^2,$$

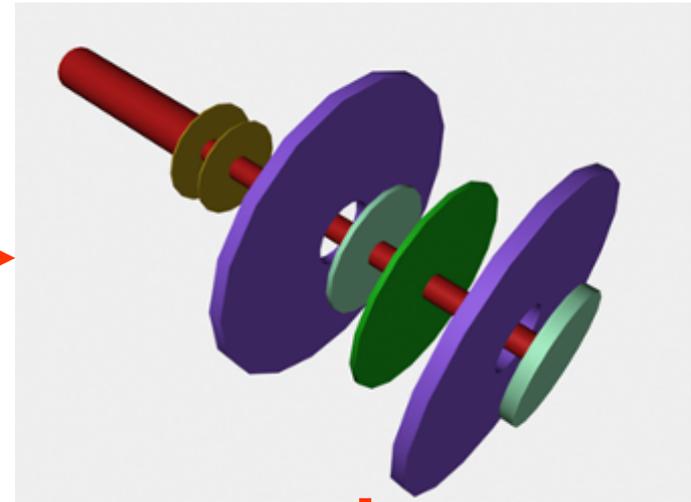
ANC or Spec factor

Indirect method for ${}^7\text{Be}(p,\gamma){}^8\text{B}$

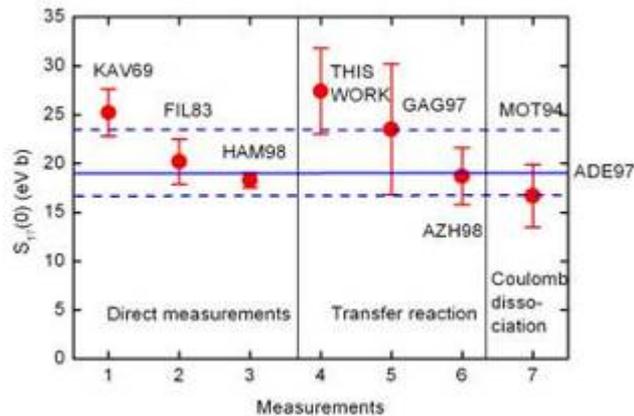
RIB production



(d,n) or (d,p) measurement



N.P. Liu, PRL77(1996)611



$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} - \left(\frac{d\sigma}{d\Omega}\right)_{\text{CN}} = \sum_{ji jf} (C_{liji}^d)^2 (C_{lfjf}^{12\text{N}})^2 \frac{d\sigma_{lfjfliji}^{\text{DW}}/d\Omega}{b_{liji}^2 b_{lfjf}^2},$$

$$\sigma_t = \frac{16\pi}{9} \left(\frac{E_\gamma}{\hbar c}\right)^3 \frac{1}{\hbar v} \frac{e_{\text{eff}}^2}{k^2} \frac{(2j_f + 1)}{(2I_1 + 1)(2I_2 + 1)} C_{\ell_f j_f}^2 \times \left| \int_{R_N}^{\infty} r^2 dr f_{\ell_j}(kr) W_{\eta, \ell_f + 1/2}(2kr) \right|^2,$$

Astrophysical reaction rates

ANC or Spec factor

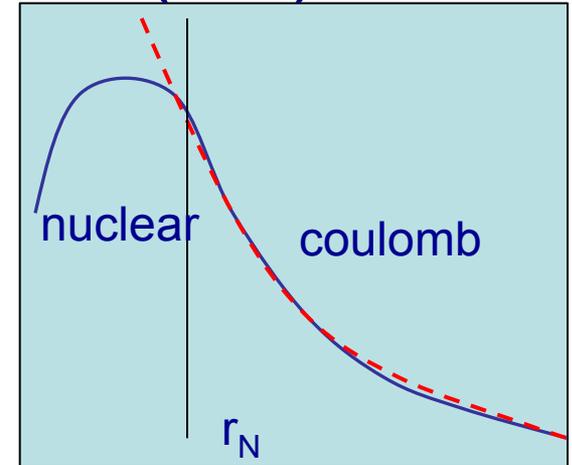
ANC method

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

two virtual captures:



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



$$\frac{d\sigma}{d\Omega} = \sum \frac{(C_{Bp_{AJA}}^A)^2 (C_{np_{djd}}^d)^2}{b_{Bp_{AJA}}^2 b_{np_{djd}}^2} \sigma_{l_{AJA} l_{djd}}^{DWBA}$$

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

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

The Cross Section for E1 capture

$$B(E1; j\pi \rightarrow j_f\pi_f) = \frac{1}{(2I_1 + 1)(2I_2 + 1)} \sum_m \sum_{I m_I} |T_{1m}|^2 =$$

$$\frac{e_{eff}^2}{k^2} \sum_{j_f I} \lambda(j_f I) C_{j_f I}^2 \left| \int_{R_N}^{\infty} r^2 dr f_{j_f I}(kr) W_{\eta, j_f I + 1/2}(2\kappa r) \right|^2$$

ANC or spec factor

$\lambda(j_f I)$ is the kinetic factor

$e_{eff} = eN/A$ for Protons

$-eZ/A$ for Neutrons

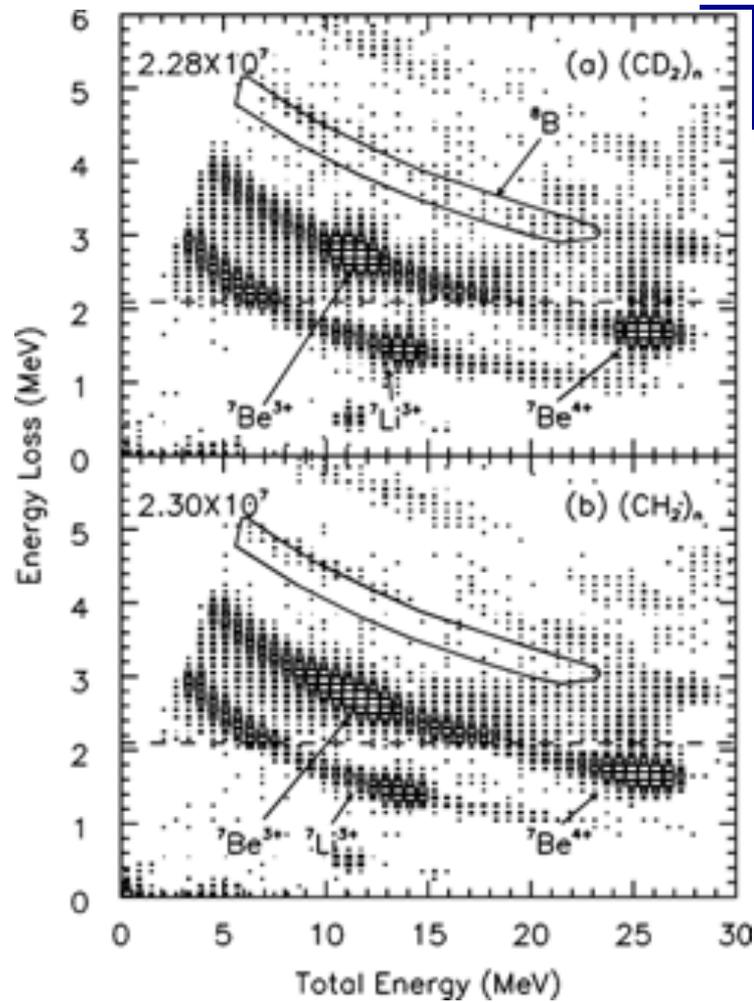
Results – ${}^7\text{Be}$

W. P. Liu

PRL77(1996)611

NPA 616(1997)131c

Results – ${}^7\text{Be}$

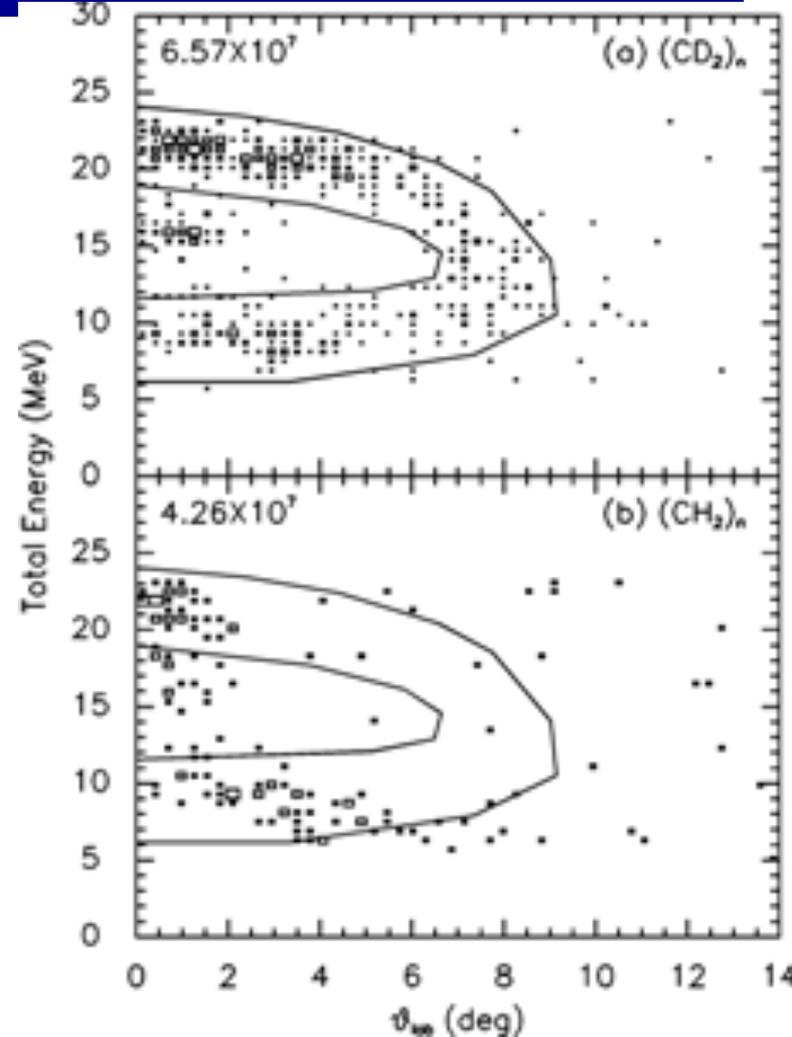
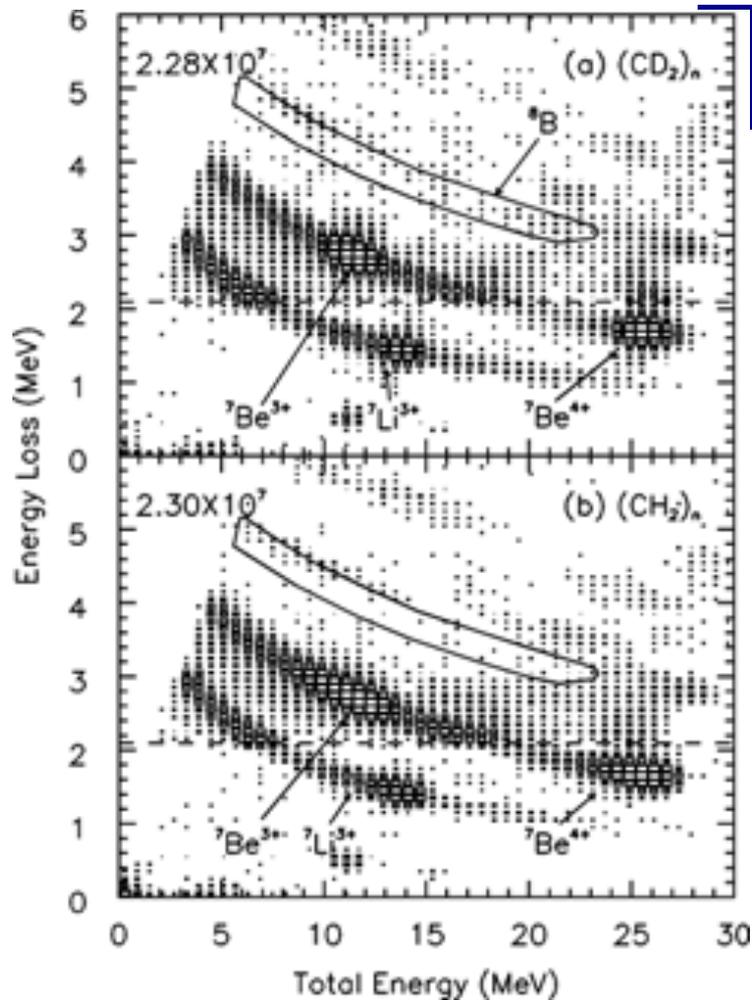


W. P. Liu

PRL77(1996)611

NPA 616(1997)131c

Results – ^7Be

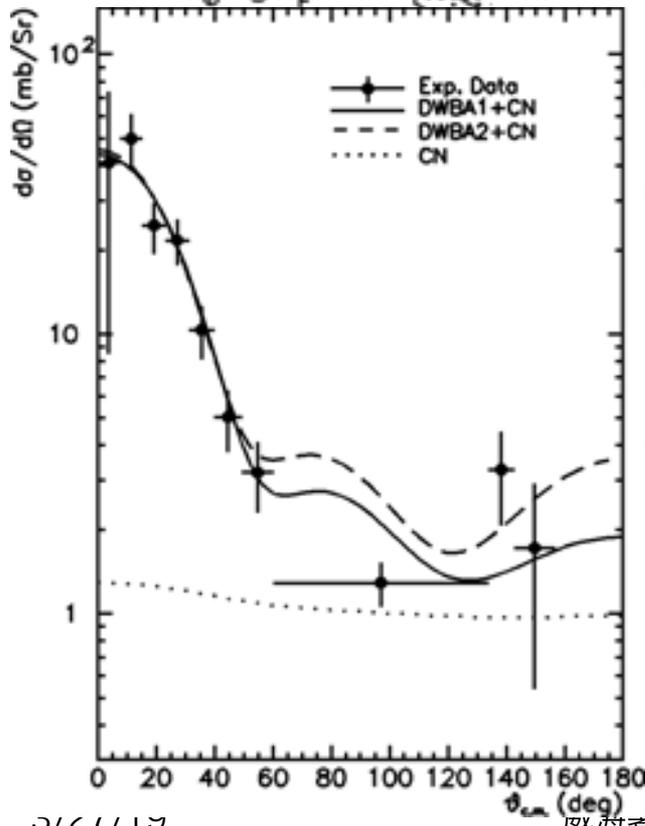
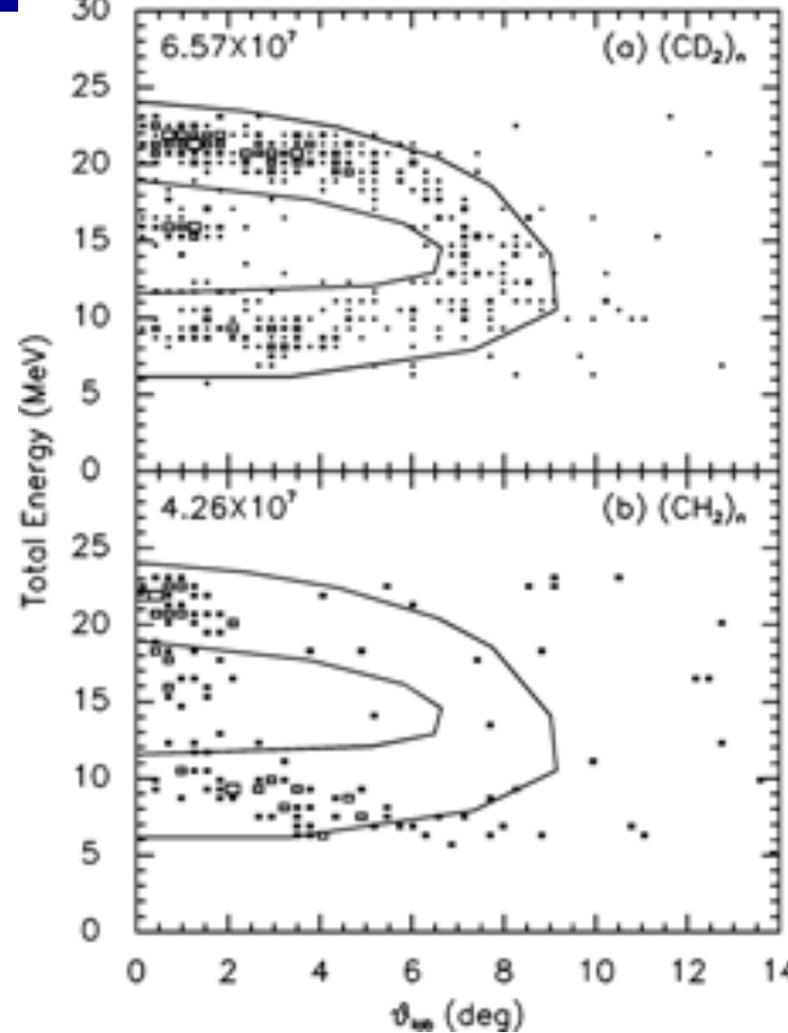
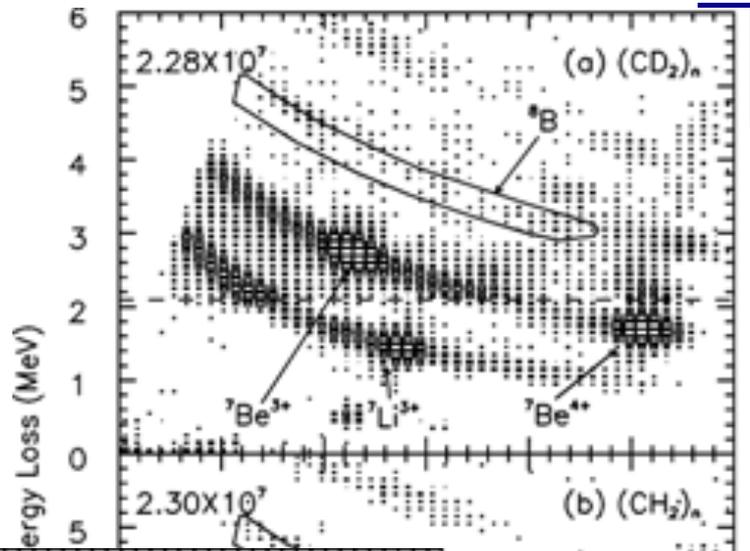


W. P. Liu

PRL77(1996)611

NPA 616(1997)131c

Results - ^7Be

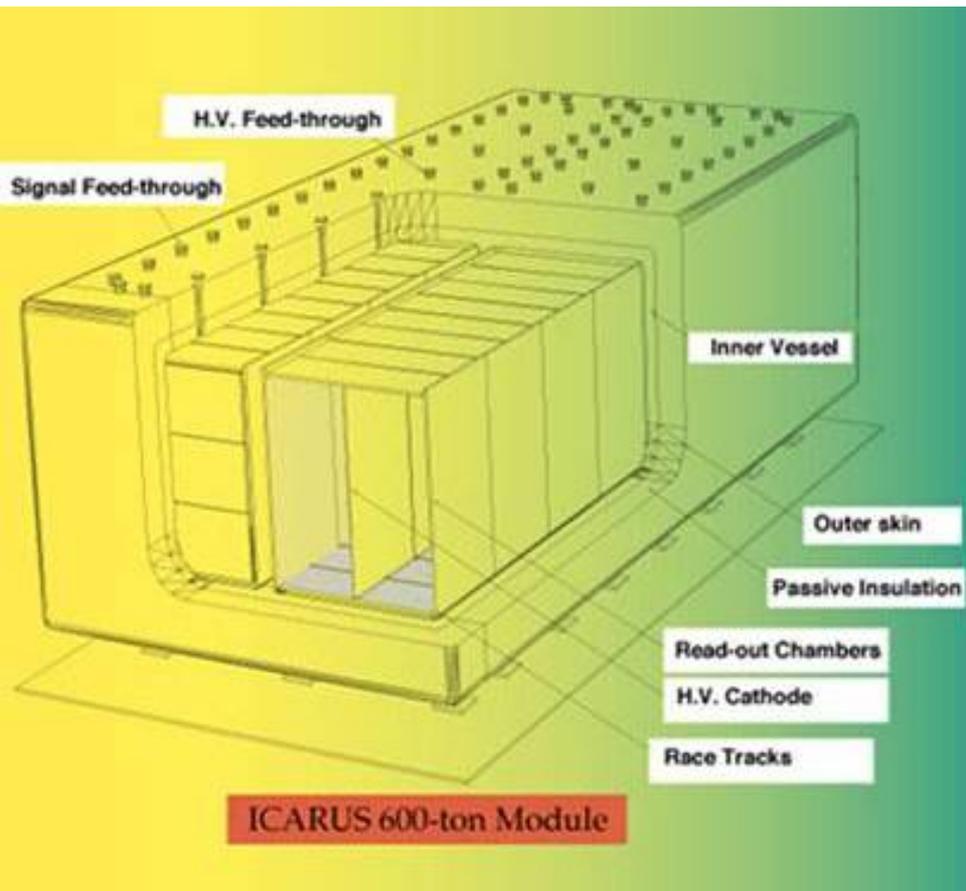


W. P. Liu

PRL77(1996)611

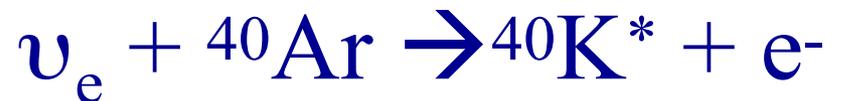
NPA 616(1997)131c

ICARUS and neutrino oscillation



Two process:

Absorption

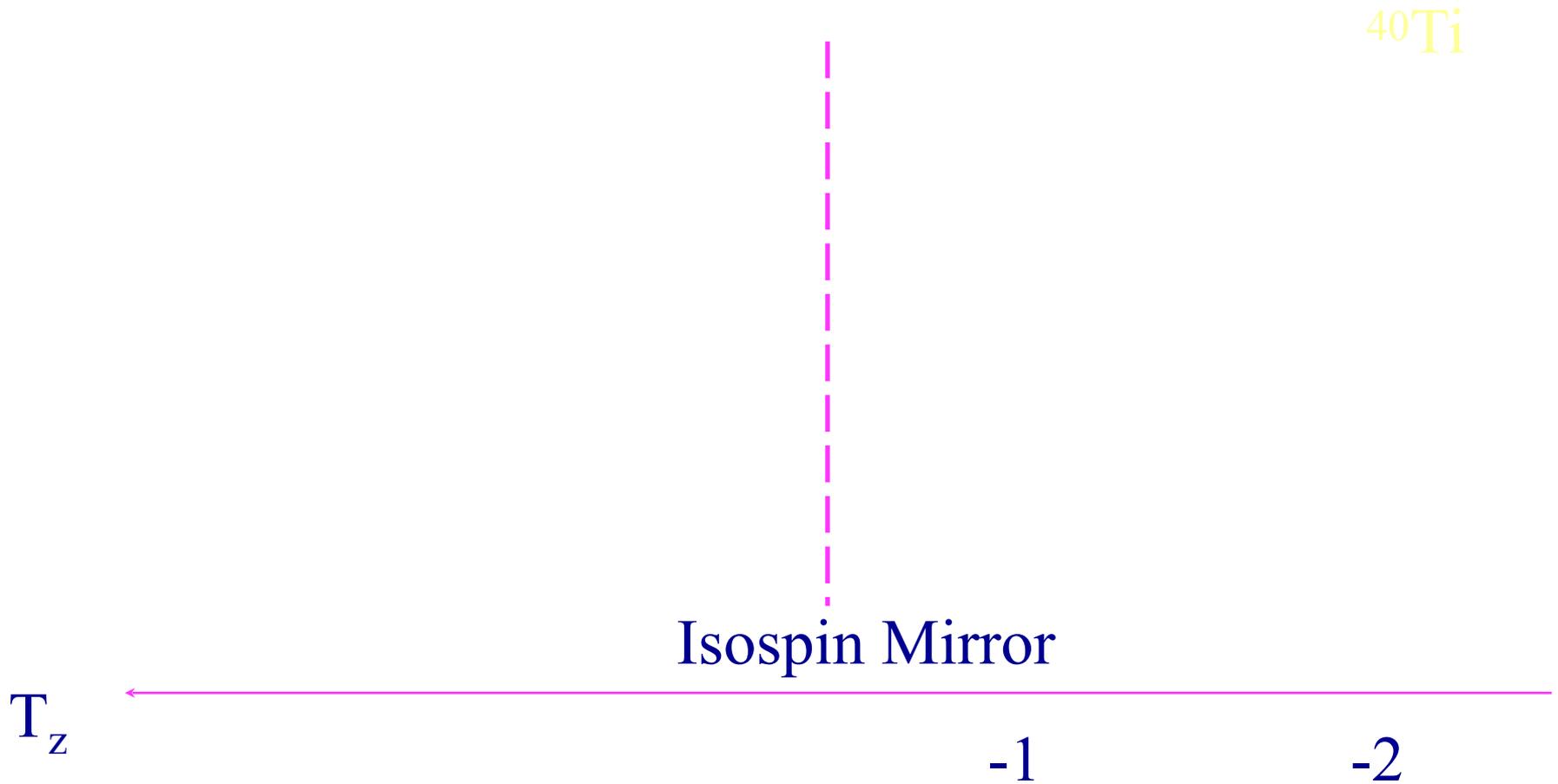


$M(e^-) = 2$

Scattering

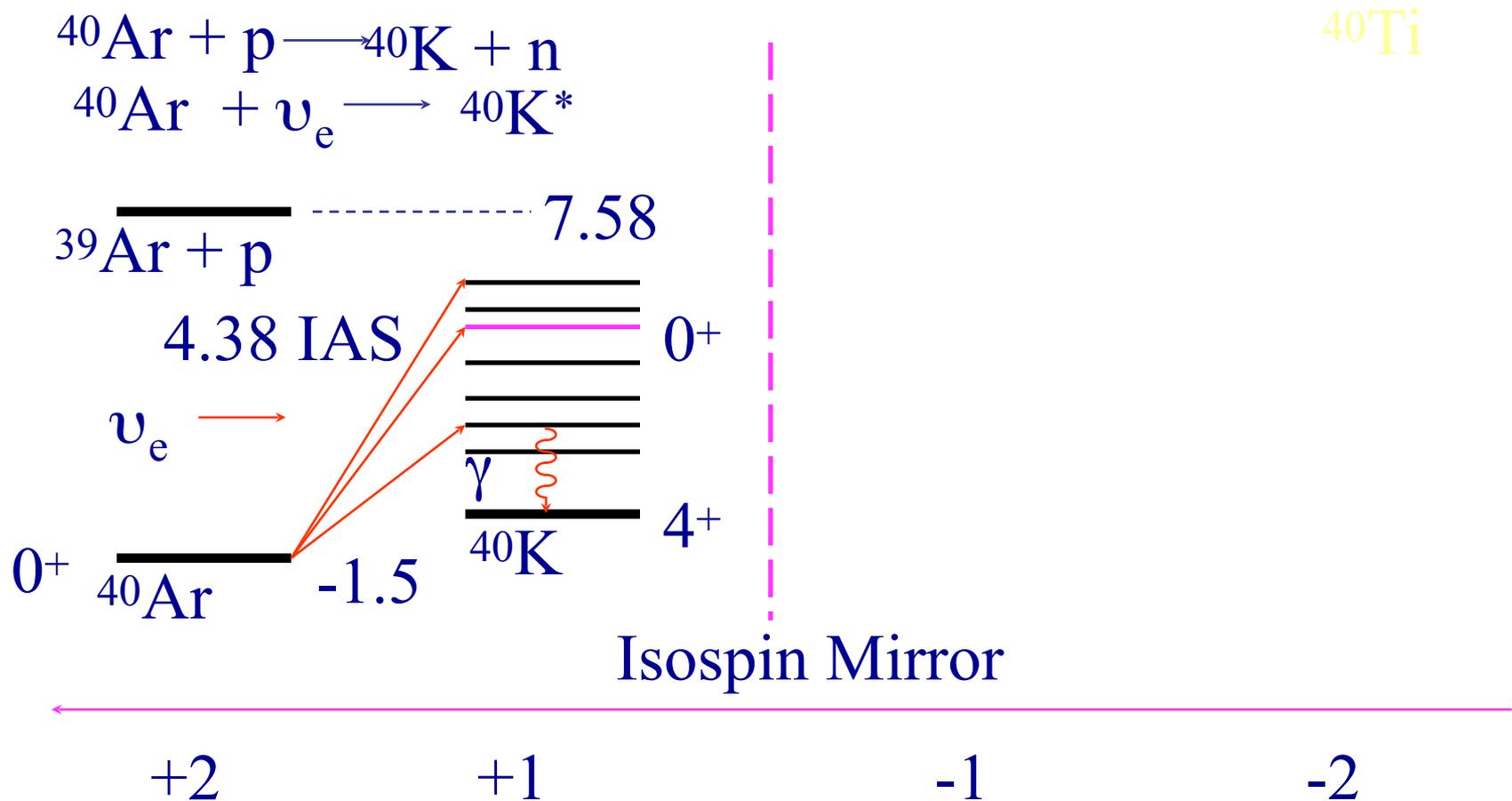
^{40}Ti and ^{40}Ar Mirror symmetry

Mirror symmetry in mass 40



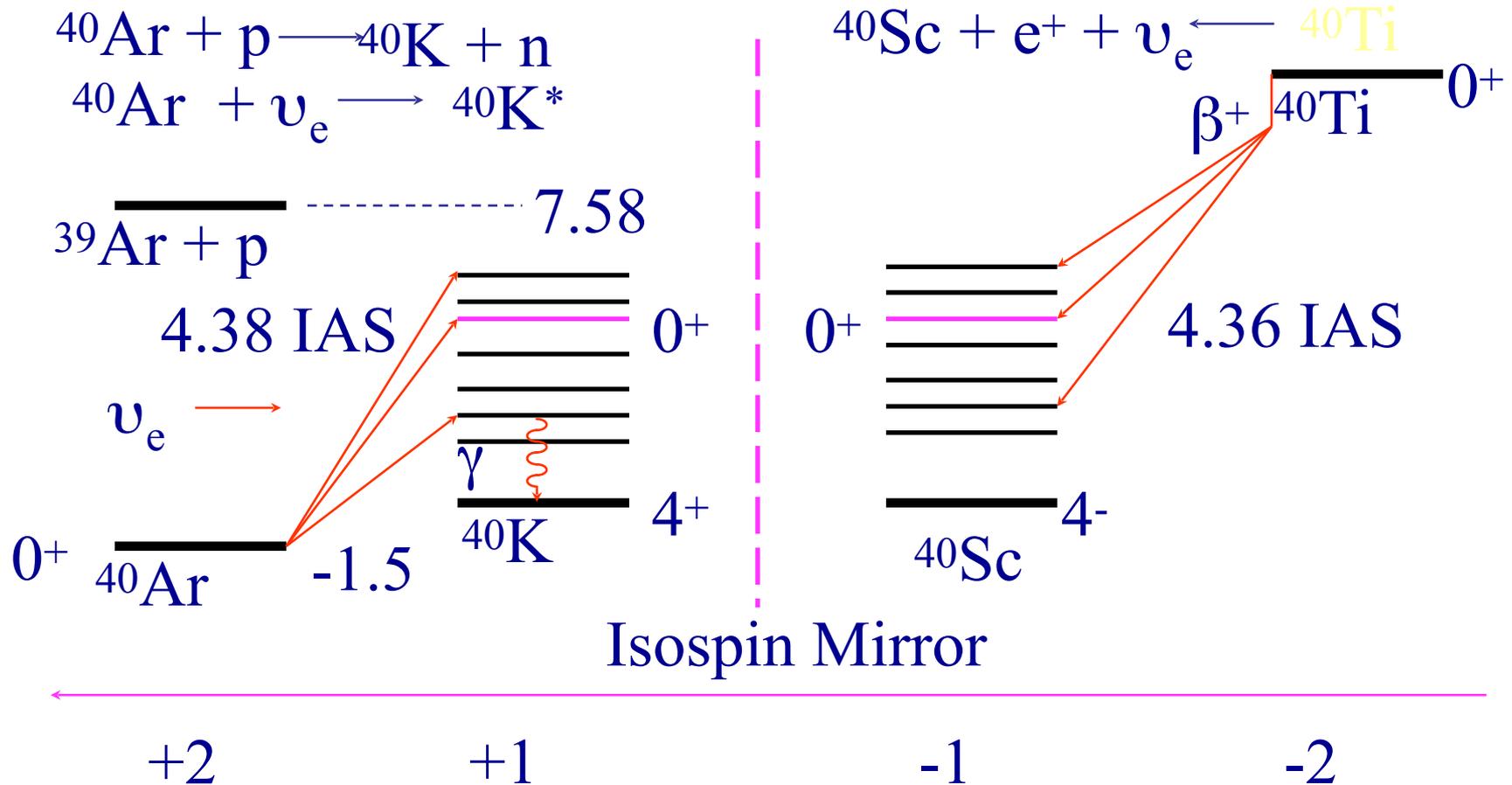
^{40}Ti and ^{40}Ar Mirror symmetry

Mirror symmetry in mass 40

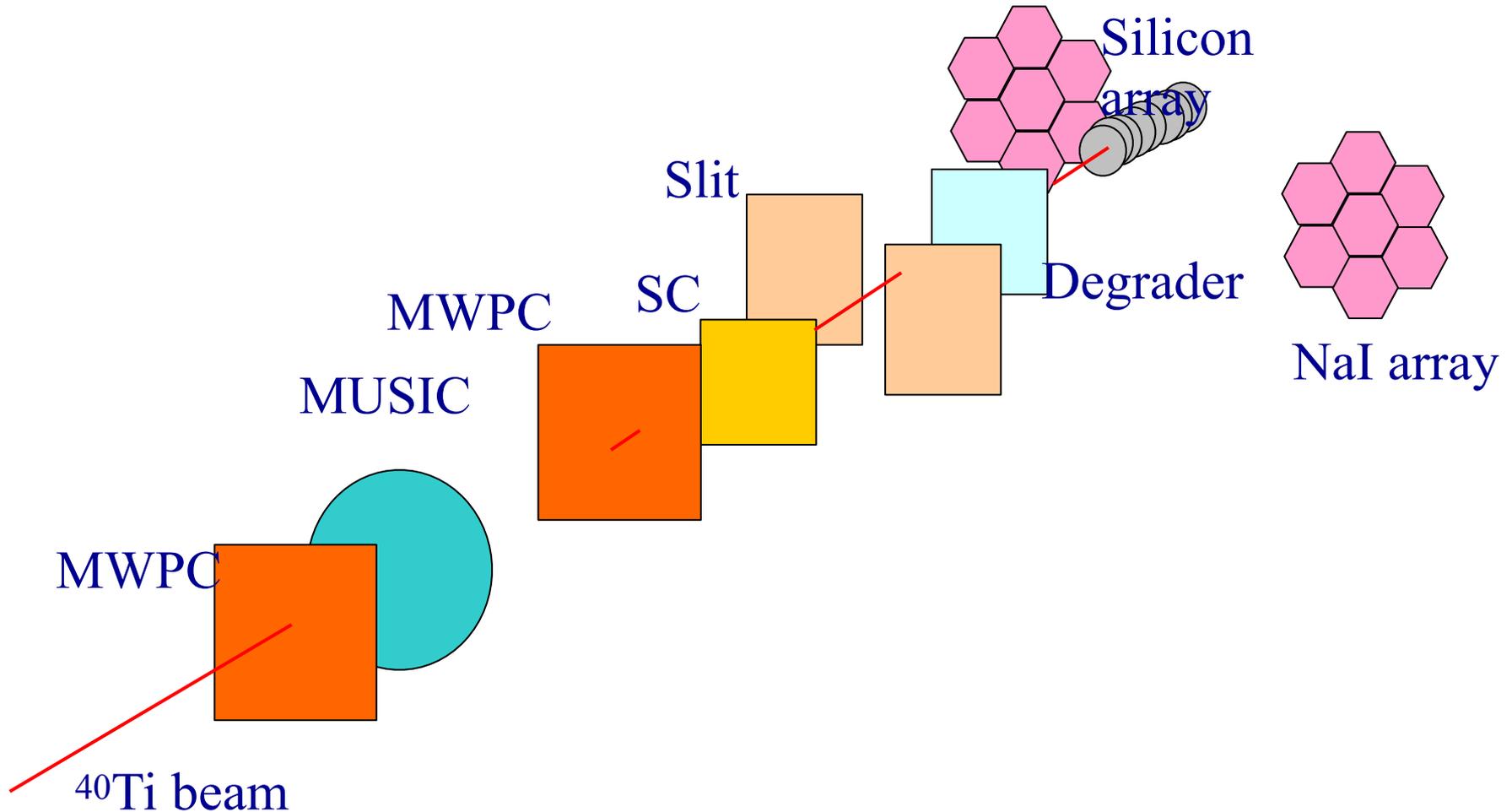


^{40}Ti and ^{40}Ar Mirror symmetry

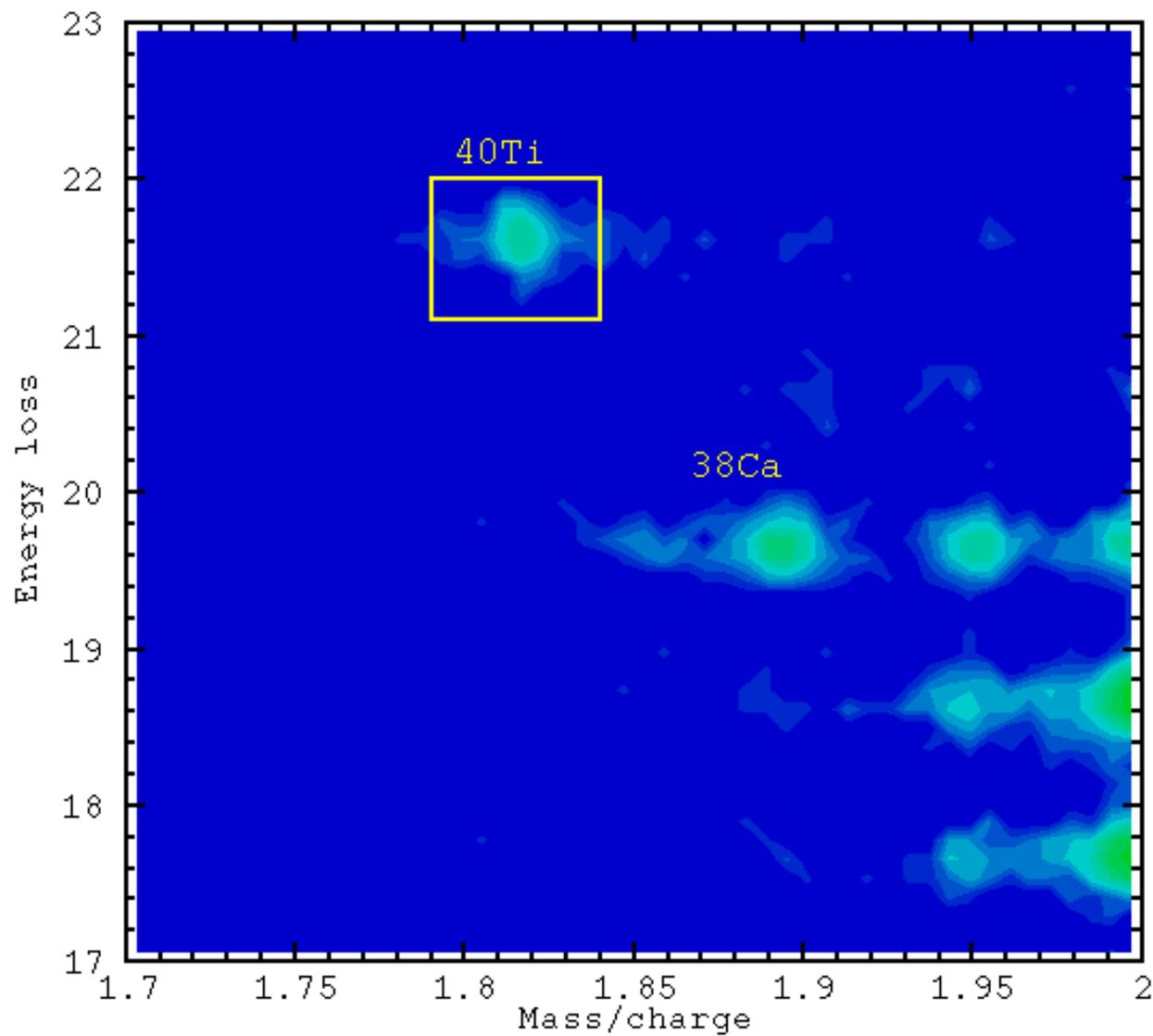
Mirror symmetry in mass 40



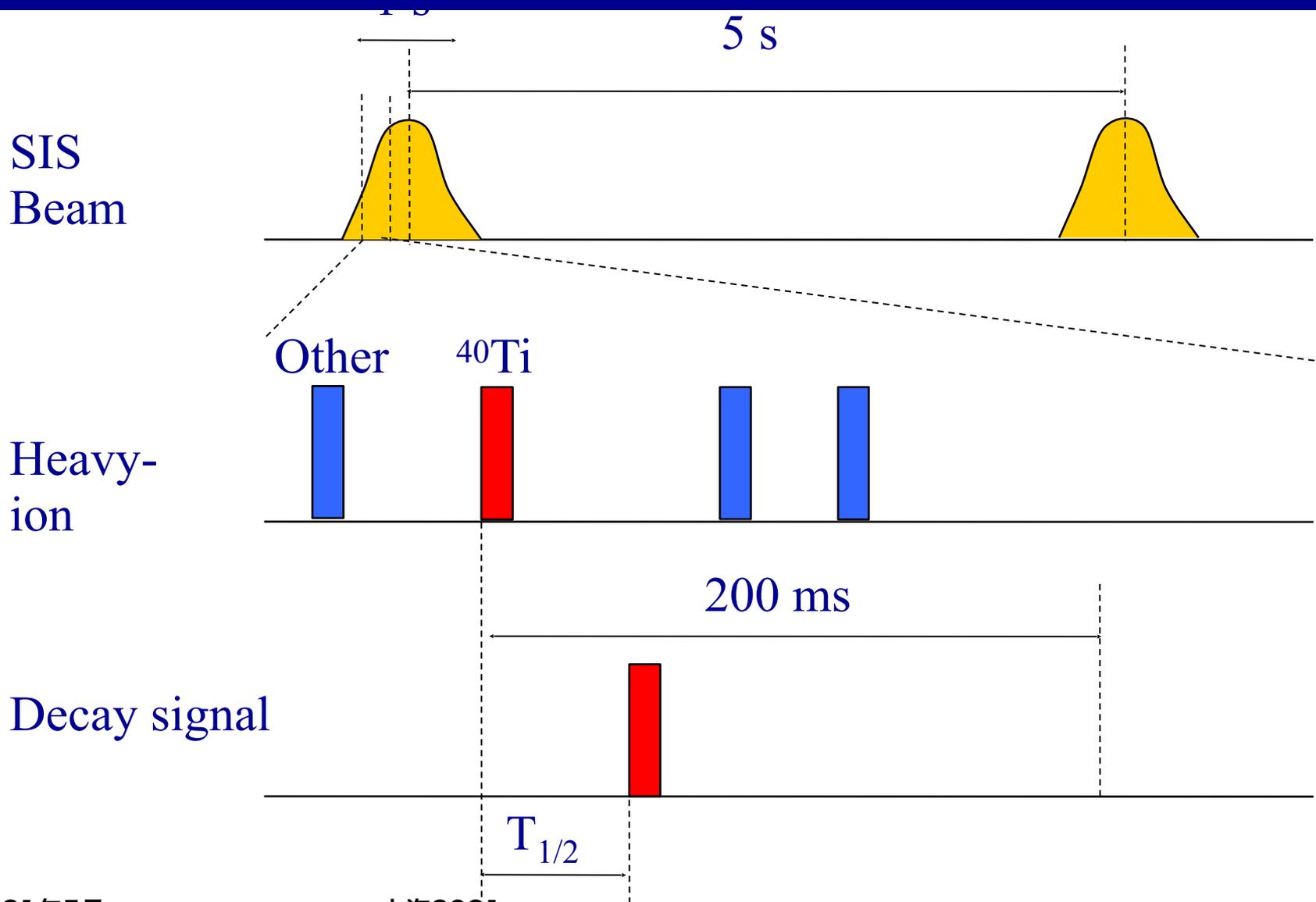
Focal plane detectors



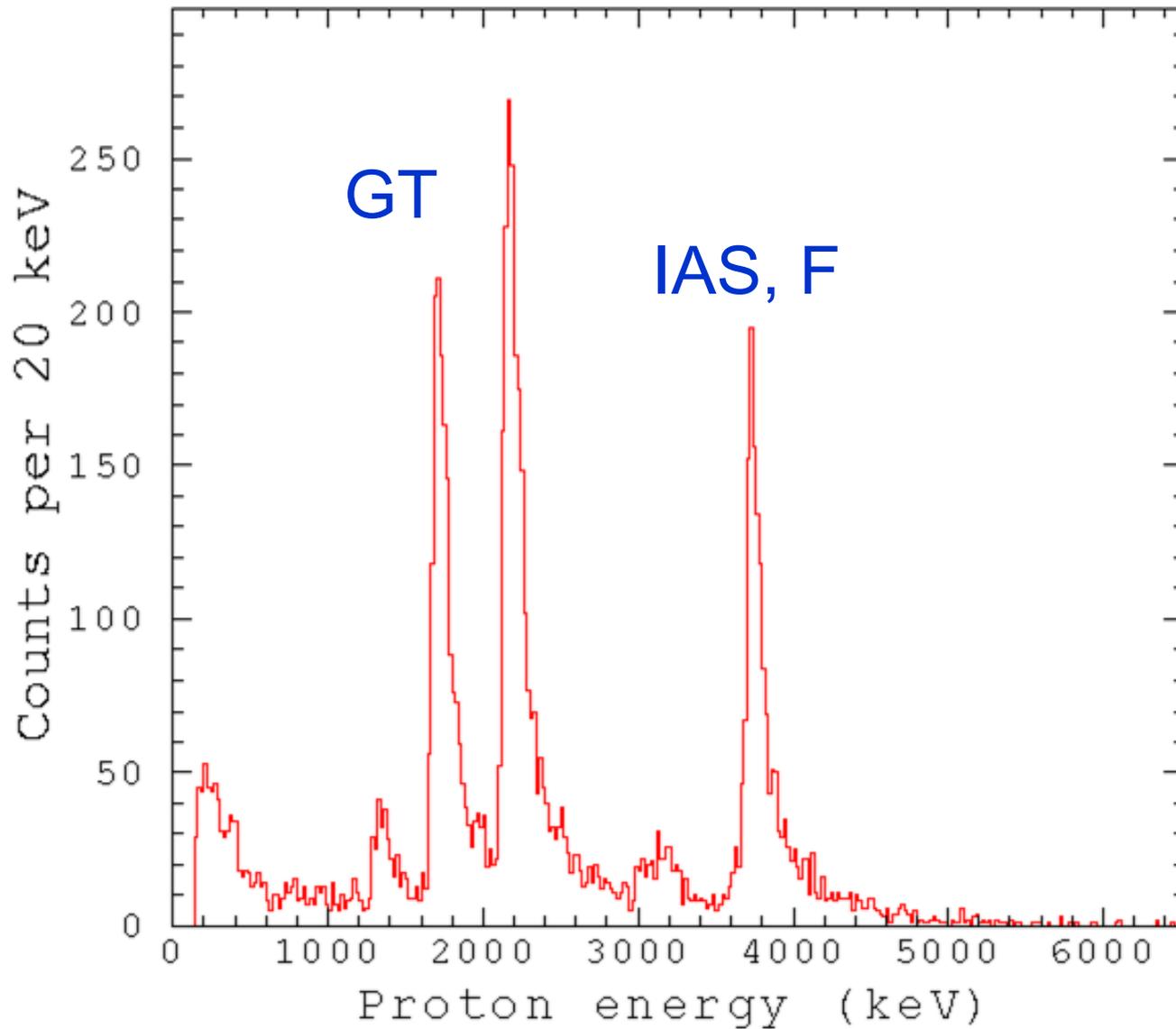
^{40}Ti selection



Delayed coincidence technique



^{40}Ti β -delayed protons



Reaction rates for ICARUS

B(GT) + B(F) from this work

$\sigma/B-E_x$ relation from

Ormond et al., Phys. Lett. B345(1995)343.

→ Absorption cross section = $13.8(6) \times 10^{-10}$ pb

^8B solar neutrino flux of

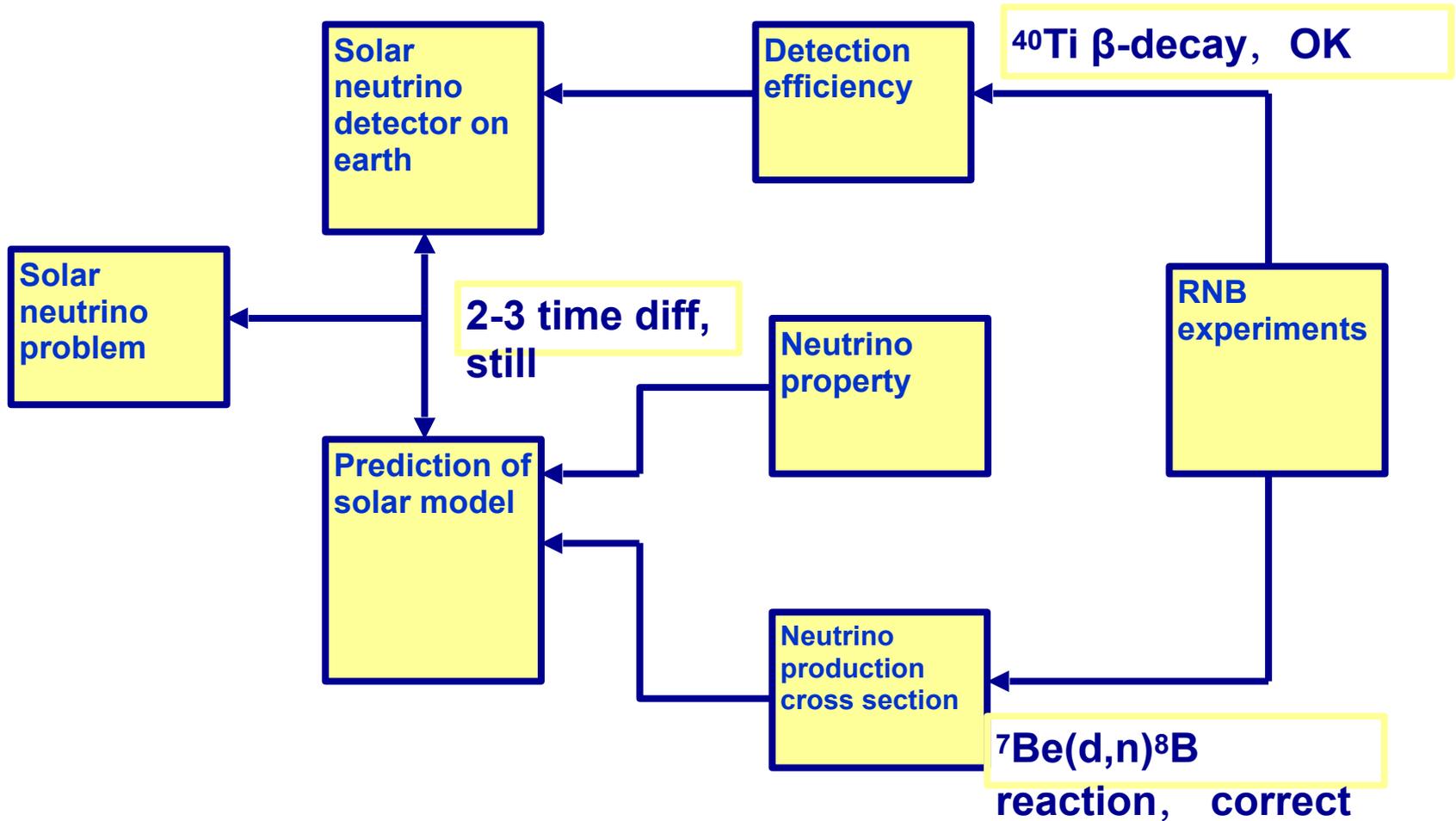
$F = 6.6(1.0) \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$ (Bahcall et al.)

→ ICARUS reaction rate

9.1(1.4) SNU (once for two days)

= 2.6 (Fermi) + 6.5 (Gamow-Teller)

Short summary



The missing of solar neutrinos must come from other reasons than nuclear reaction and detector efficiency, (neutrino oscillation).

Advice for us

- Even with simple device we can still today attack most important problems
- But, one should be very careful and should work hard (sometimes for long time) experimental developments, everyone knows physics, but the key is to get more precise and background free data

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