Nuclear astrophysics

A survey in 6 parts

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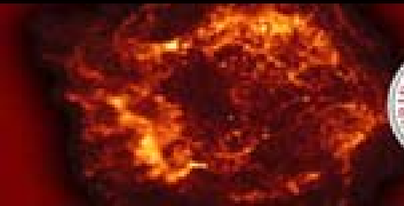
Nuclear physics plays an important role in astrophysics:

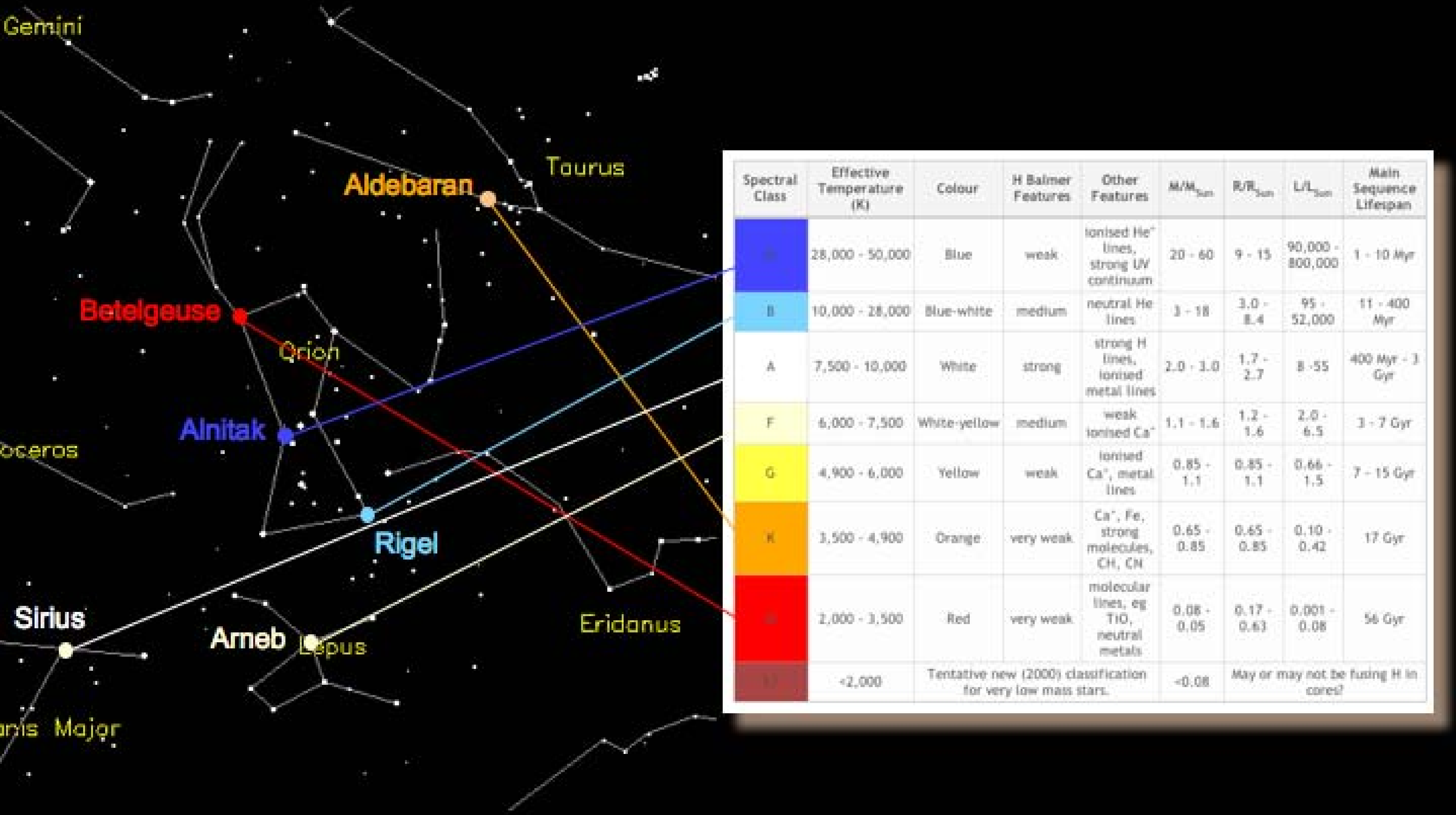
Energy generation
Synthesis of elements

astronomical observables

1. Introduction
2. Big Bang
3. Stellar structure & solar neutrinos
4. Stellar evolution & s process
5. Supernovae & r process
6. Binary systems

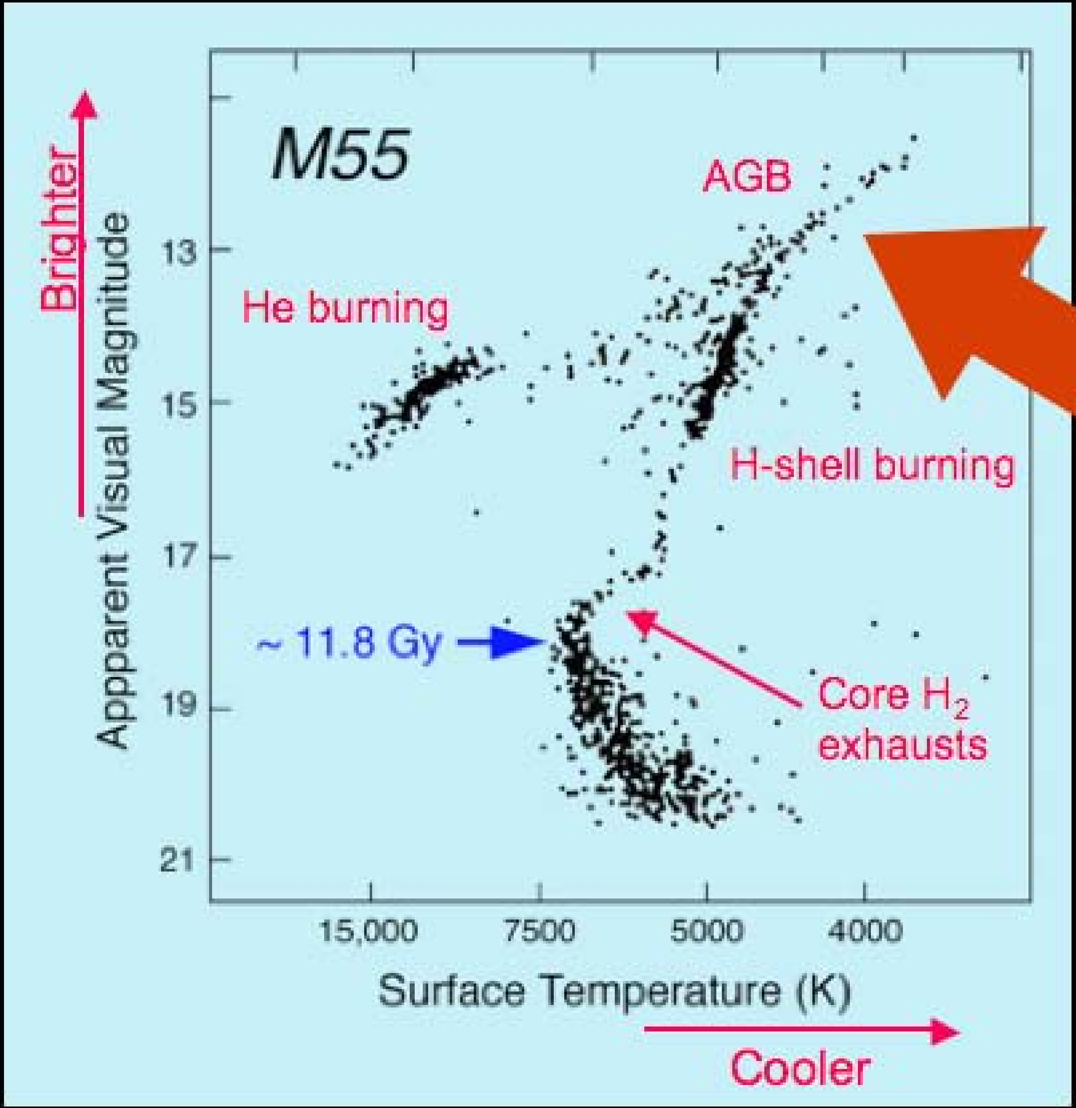


Stellar Classification



Spectral Class	Effective Temperature (K)	Colour	H Balmer Features	Other Features	M/M_{Sun}	R/R_{Sun}	L/L_{Sun}	Main Sequence Lifespan
O	28,000 - 50,000	Blue	weak	ionised He^+ lines, strong UV continuum	20 - 60	9 - 15	90,000 - 800,000	1 - 10 *Myr*
B	10,000 - 28,000	Blue-white	medium	neutral He lines	3 - 18	3.0 - 8.4	95 - 52,000	11 - 400 *Myr*
A	7,500 - 10,000	White	strong	strong H lines, ionised metal lines	2.0 - 3.0	1.7 - 2.7	8 -55	400 Myr - 3 Gyr
F	6,000 - 7,500	White-yellow	medium	weak ionised Ca^+	1.1 - 1.6	1.2 - 1.6	2.0 - 6.5	3 - 7 Gyr
G	4,900 - 6,000	Yellow	weak	ionised Ca^+, metal lines	0.85 - 1.1	0.85 - 1.1	0.66 - 1.5	7 - 15 Gyr
K	3,500 - 4,900	Orange	very weak	Ca^+, Fe, strong molecules, CH, CN	0.65 - 0.85	0.65 - 0.85	0.10 - 0.42	17 Gyr
M	2,000 - 3,500	Red	very weak	molecular lines, eg TiO, neutral metals	0.08 - 0.05	0.17 - 0.63	0.001 - 0.08	56 Gyr
L	<2,000	Tentative new (2000) classification for very low mass stars.			<0.08	May or may not be fusing H in cores?		

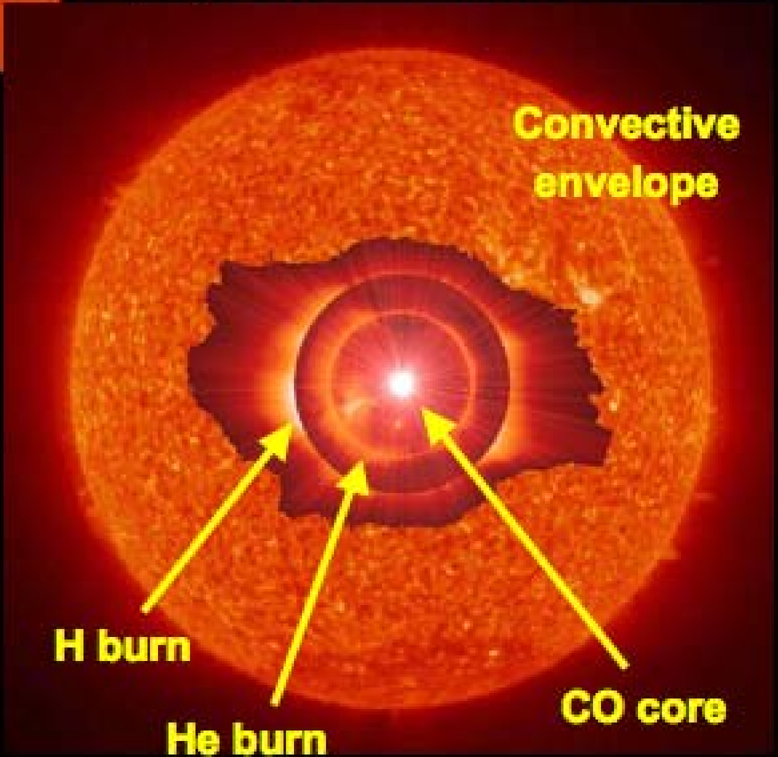
Stellar evolution



Globular cluster

Most stars formed at about the same time

Asymptotic Giant Branch Star



He burning & the "Hoyle" state

$t_{1/2}(^{8}Be)=9.7\times10^{-17}$ s

$^{8}Be \rightleftarrows \alpha+\alpha$

$$\frac{N\left(^{8}B\right)}{N(\alpha)} \approx 5\times10^{-10}$$

0⁺ resonance near the Gamow energy was predicted by Hoyle

Phys Rev 92 (1953) 1095.

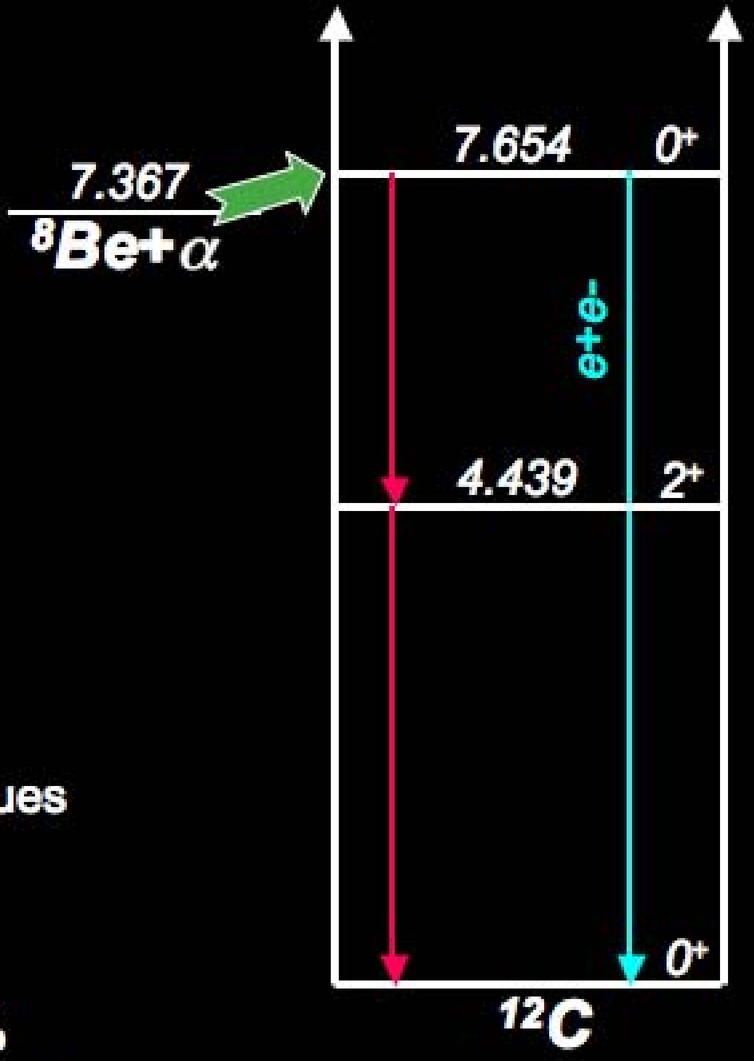
Numerous complementary techniques

$^{12}C(p,p')^{12}C^{*}$

$^{13}C(^{3}He,\alpha)^{12}C^{*}$ ➡ $\gamma\gamma$, 3α, $e^{+}e^{-}$

Largest uncertainty Γ_{ee}~12%

Experiments now at West. Mich. U.

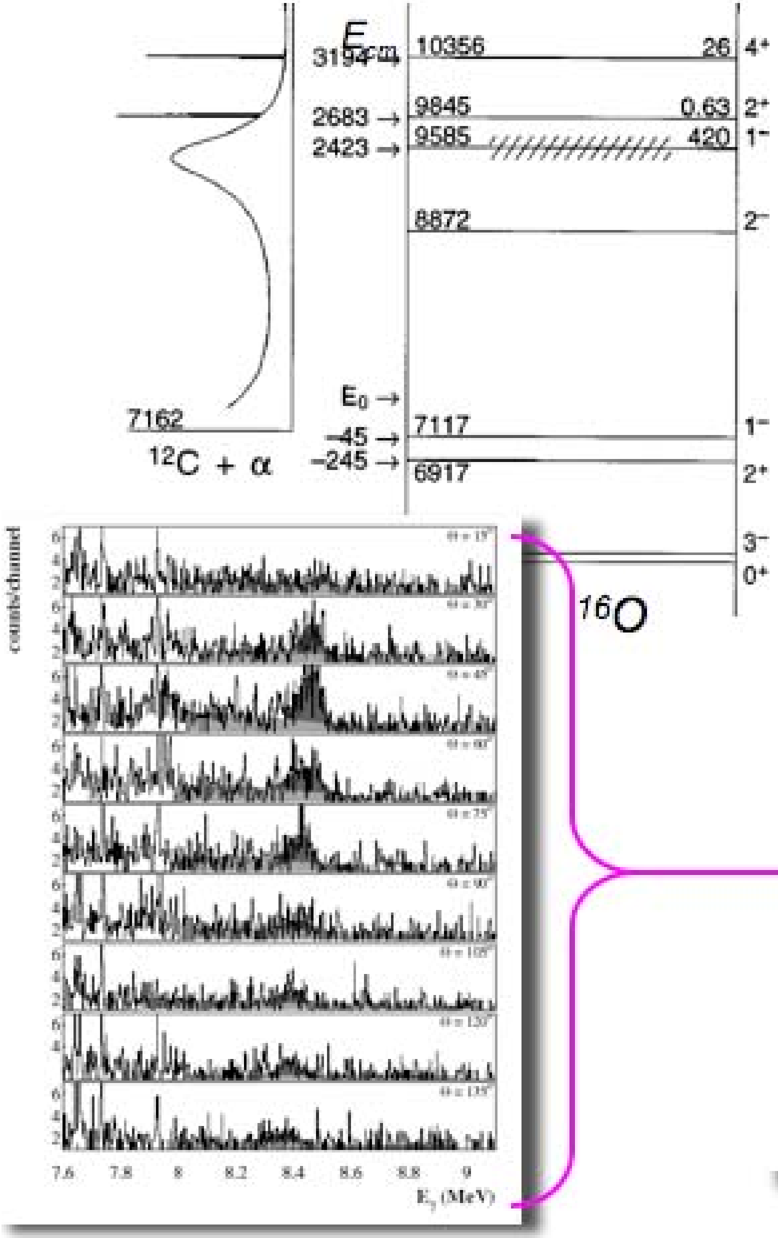


$^{12}C(\alpha,\gamma)^{16}O$ - the “holy grail” ?

The $^{12}C(\alpha,\gamma)^{16}O$ reaction rate fixes the ratio of $^{12}C/^{16}O$ in the core

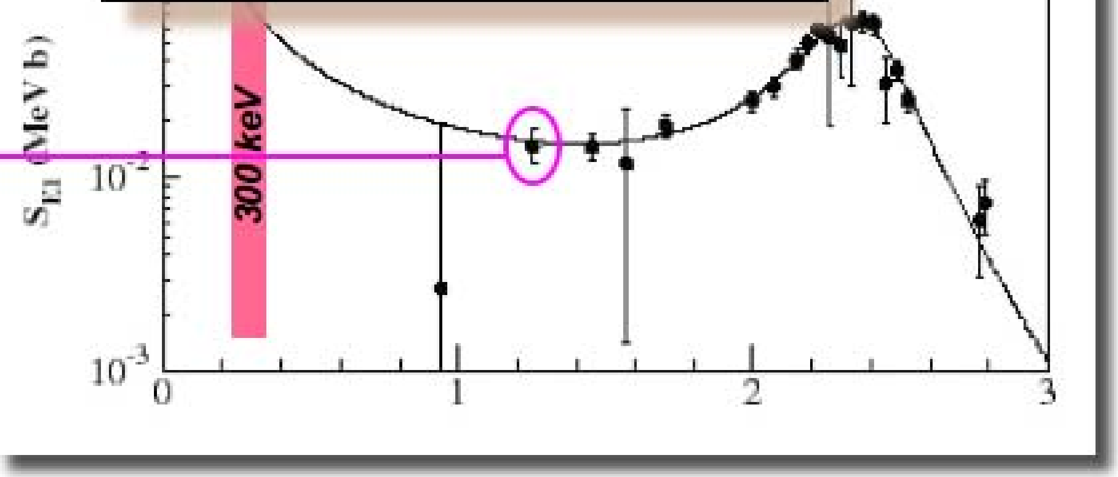
The $^{12}C/^{16}O$ ratio substantially affects the subsequent evolution of the star:
    Size of Fe core
    Supernova?

Influence of subthreshold states → substantial uncertainties in extrapolation

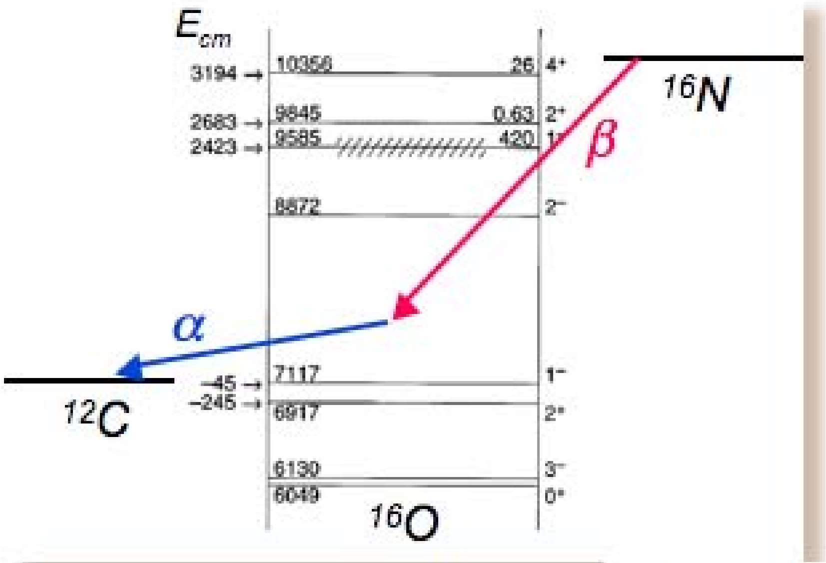


New Stuttgart measurements: improvement?

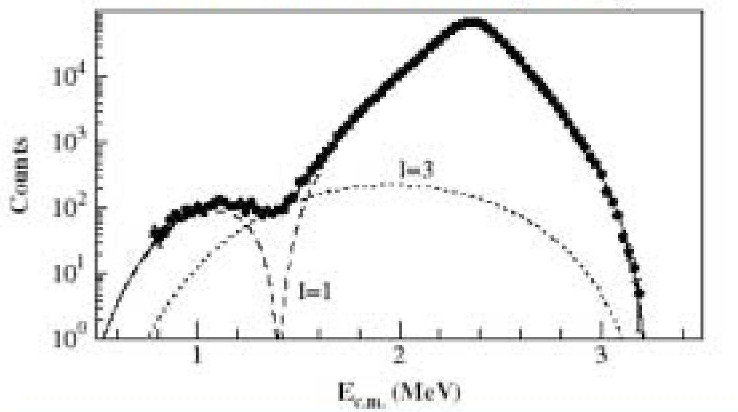
PRL (2001)



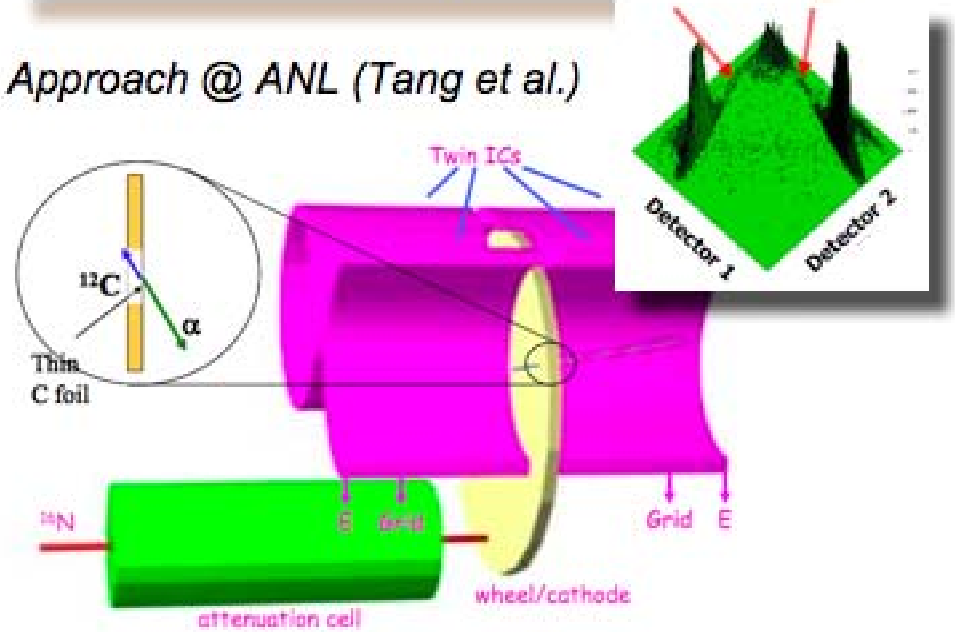
$^{12}C(\alpha,\gamma)^{16}O$ - via ^{16}N β decay



Azuma et al. PRC **50** (1994)

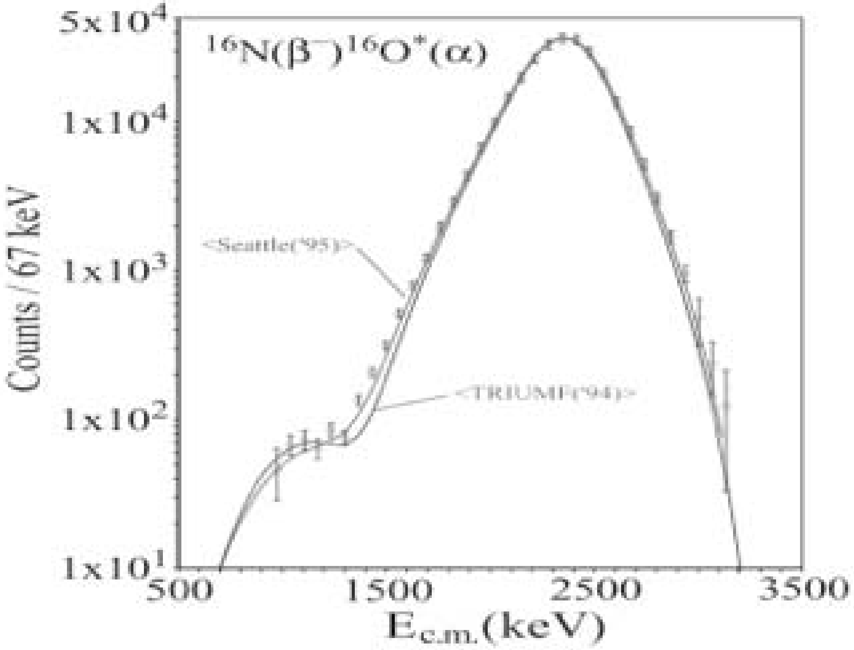


Approach @ ANL (Tang et al.)

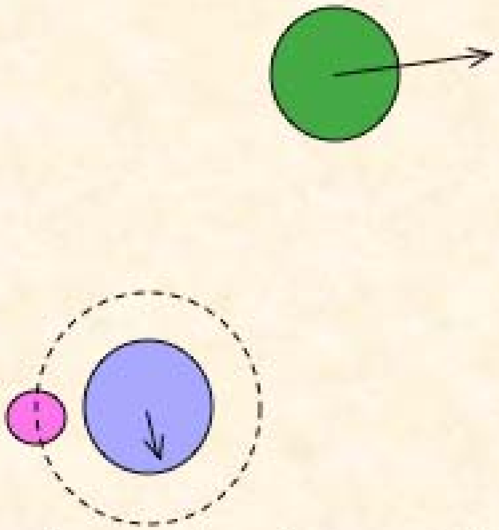


New WNSL Measurement

France et al.. PRC **75** (2007) 065802.



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



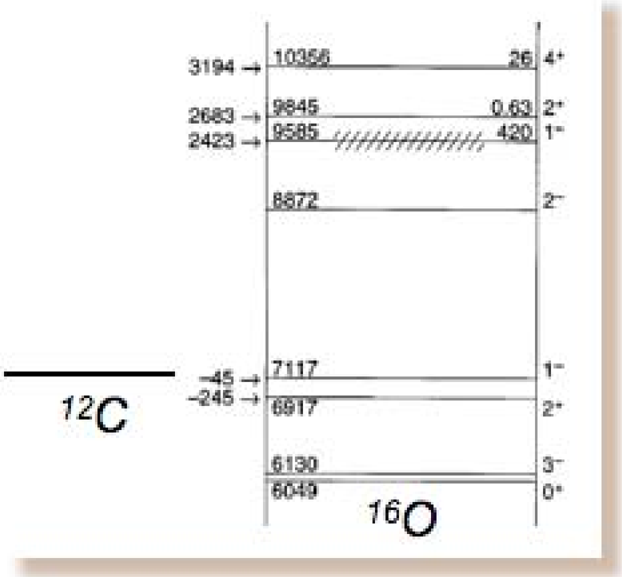
A nucleon or “cluster” of nucleons (no internal degrees of freedom) is transferred from one nucleus to another.

- ➢ The core nuclei are unperturbed.

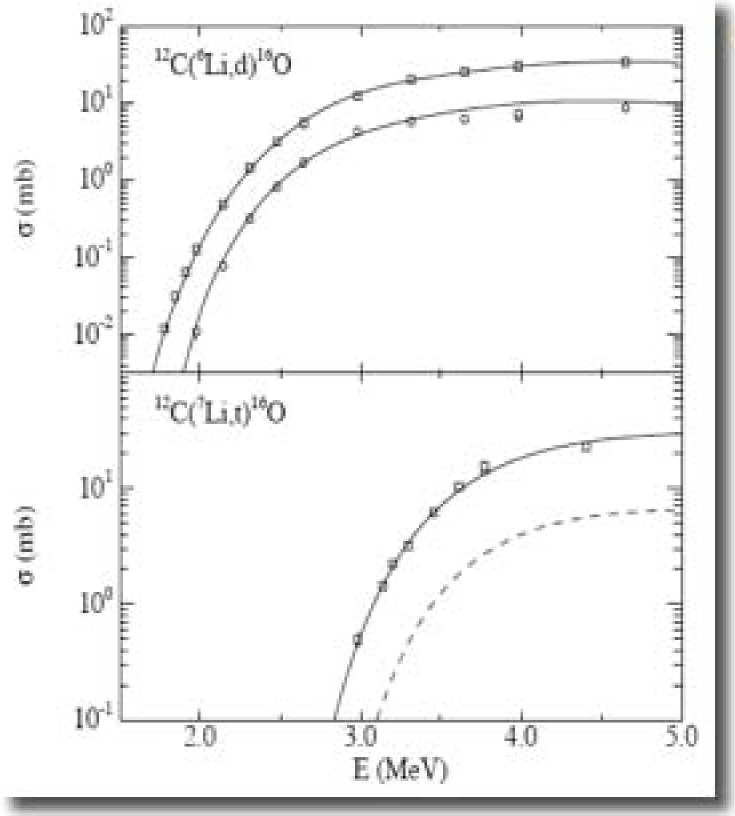
$$\sigma_{exp}=S_1S_2\sigma_{DWBA} \qquad \sigma_{DWBA} \sim \left|\langle\chi_\beta\psi_\beta|\vartheta|\chi_\alpha\psi_\alpha\rangle\right|^2 \qquad \psi \rightarrow C\frac{W(r)}{r}$$

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

SubCoulomb α transfer
to subthreshold states



Brune et al. PRL ***83*** *(1999)*



6.92 (2^+)

7.12 (1^-)

DWBA

$C^2(2^+)=(1.3\pm0.2)\times10^{10}\ fm^{-1}$

$C^2(1^-)=(4.3\pm0.8)\times10^{28}\ fm^{-1}$

w/ ^{16}N β decay

$$S_{E2}(300keV)=42^{+16}_{-23}keV\cdot b$$

$$S_{E1}(300keV)=101\pm17keV\cdot b$$

Neutron sources in AGB Stars

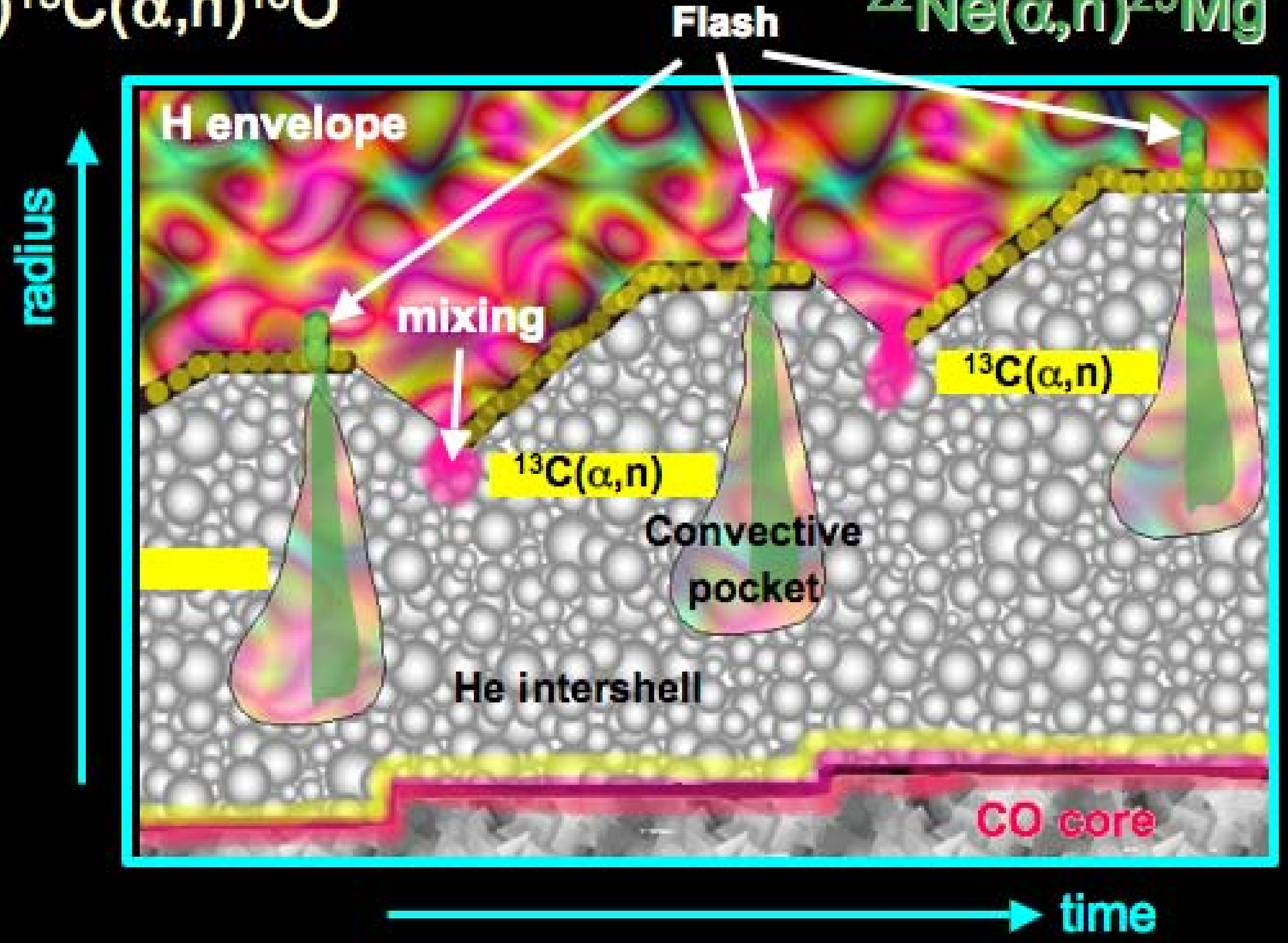
Stars are thermally unstable: mixing, convection, mass loss

$^{12}C(p,\gamma)^{13}N(\beta\nu)^{13}C(\alpha,n)^{16}O$

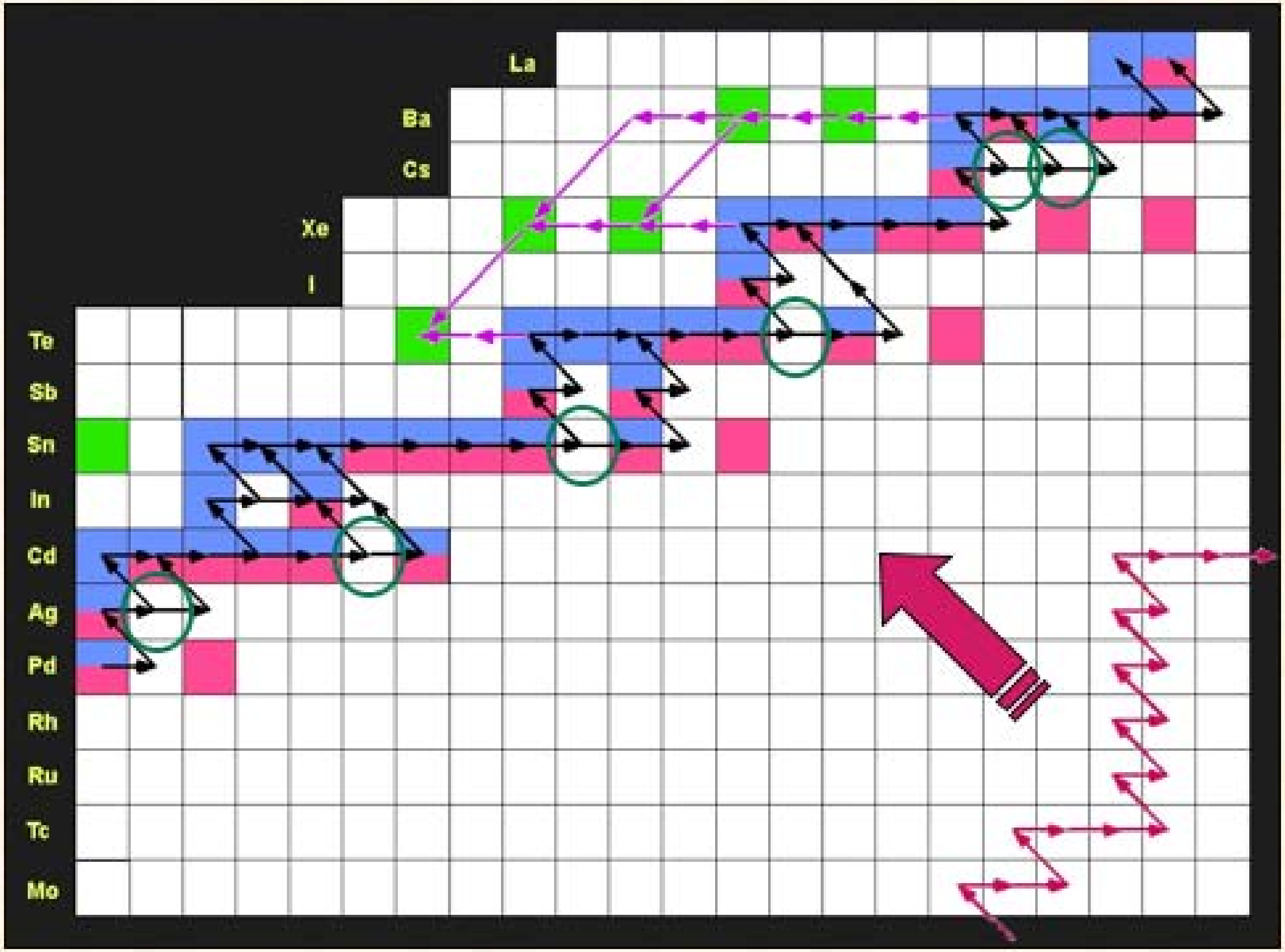
$^{22}Ne(\alpha,n)^{25}Mg$

convective
envelope
driven off

→ CO core
(white dwarf)



Synthesis of heavy elements



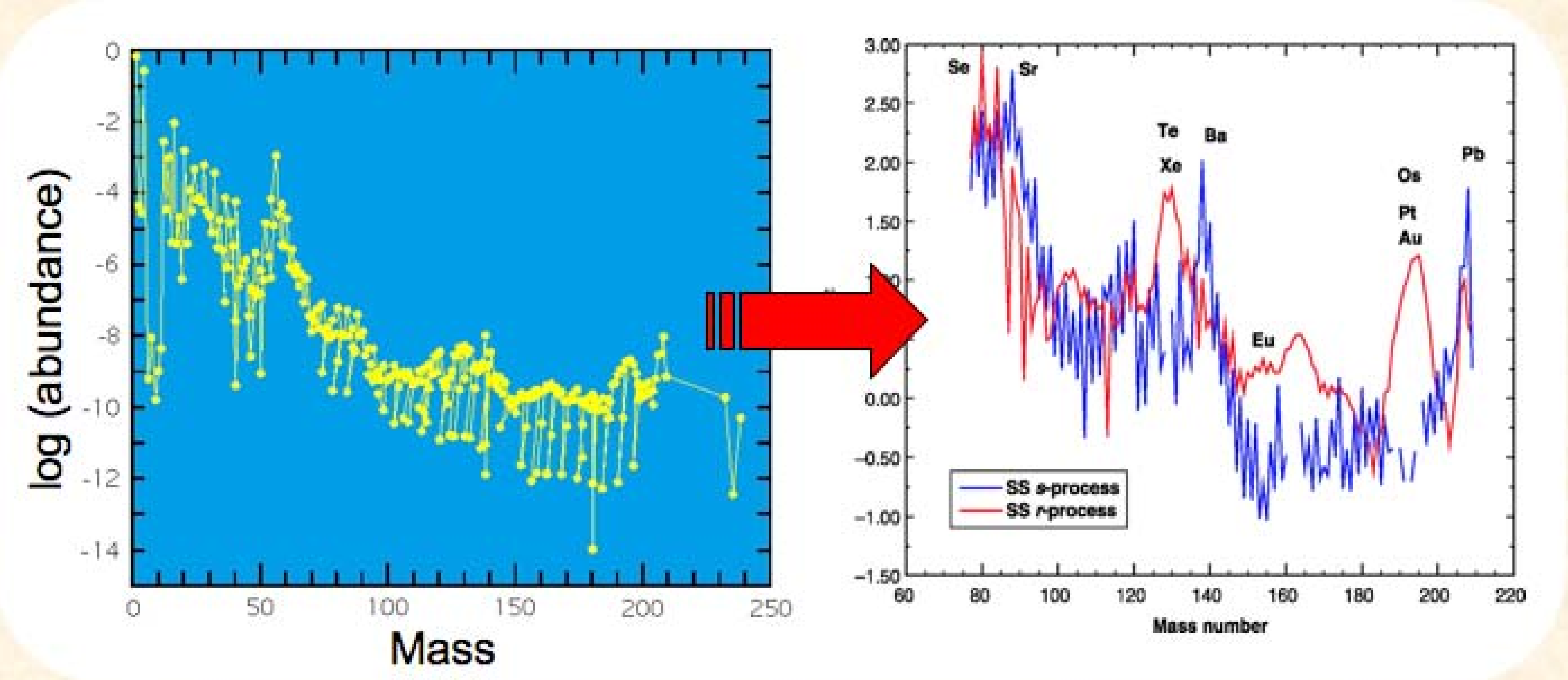
- s process
  - ~ 80% of isotopes
  - (n,γ) rates needed
  - Branch points crucial
- r process
  - ~ 70% of isotopes
  - Far from stability
  - See supernovae
- p process
  - ~ 10% of isotopes
  - Very low abundance
  - Secondary process
  - Neglected here

$$\sigma(n,\gamma) \sim \frac{1}{v} \Rightarrow \langle \sigma v \rangle \sim \mathit{constant} \quad \text{(s-wave)}$$

Recipe for untangling r & s abundances

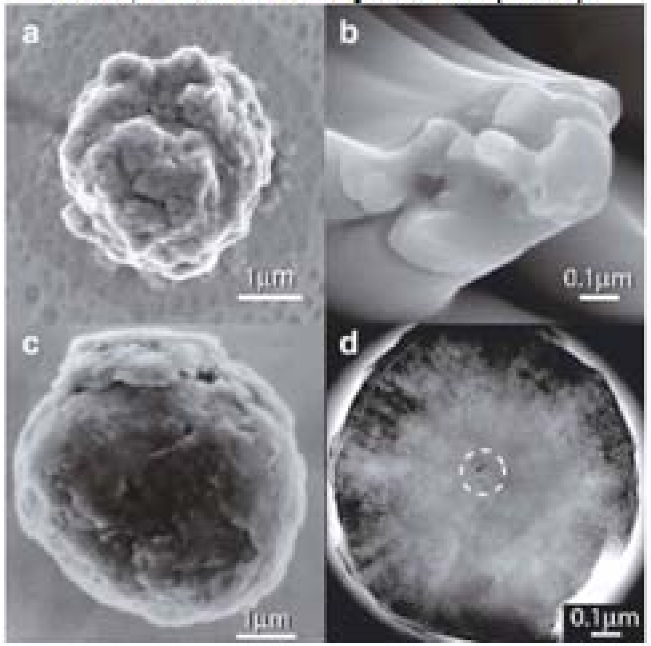
Calculate s process yields and ***fit to s only isotopes***

Subtract s abundances from solar system to get r abundances



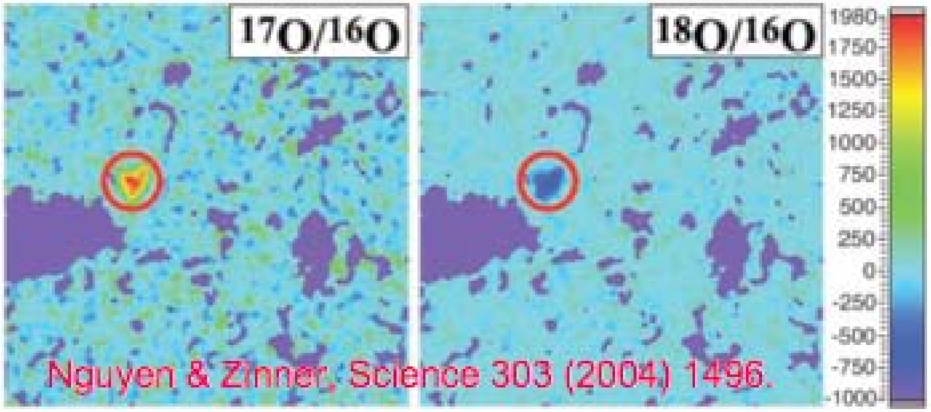
Stardust in a haystack

Nittler, Earth Planetary Sci Lett (2003)



Tiny grains isolated from meteorites

Unusual grains identified with SIMS

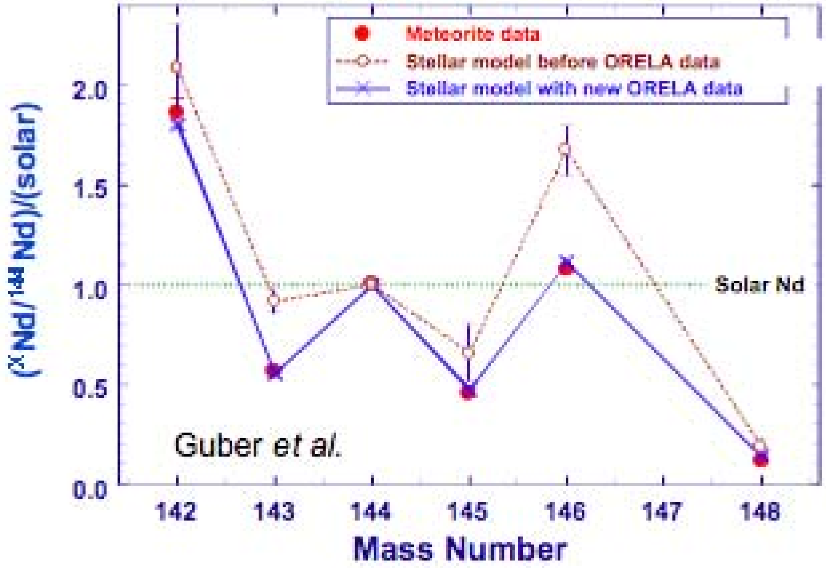


Nguyen & Zinner, Science 303 (2004) 1496.

Some grains have preserved isotopic composition from solar environment

Relative abundances for isotopes of a given element from a single AGB star

Nd Isotope Ratios in SiC Grains



Guber *et al.*

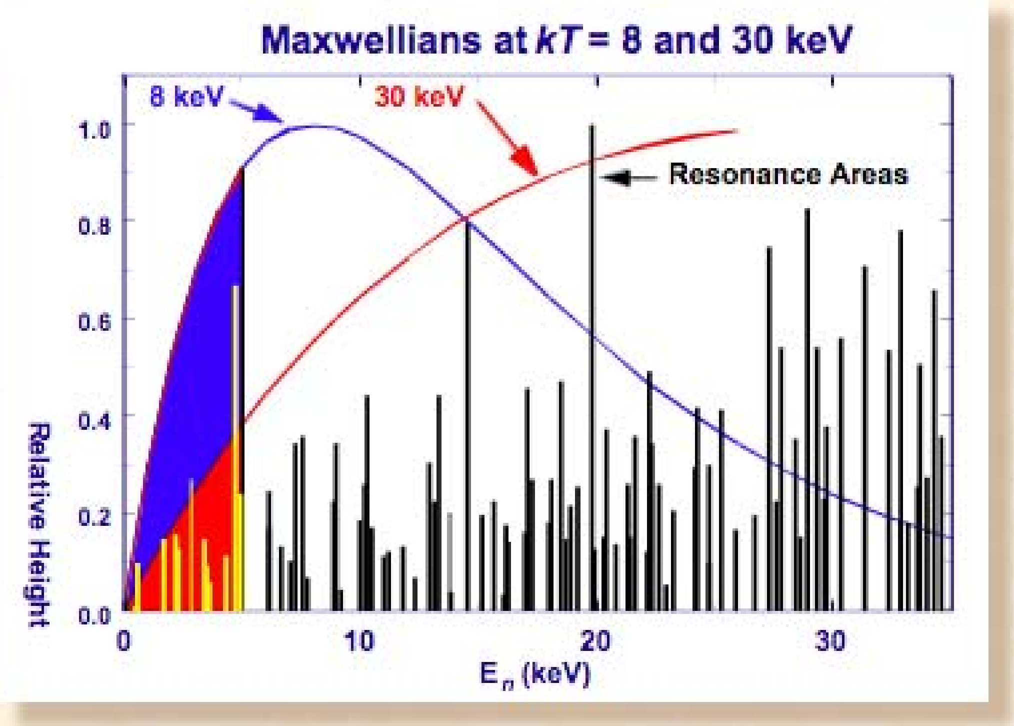
(n,γ) cross sections for the s process

ORELA

- Good data on most stable isotopes
- Spallation n sources
- TOF techniques
- Good energy resolution
- Often high level densities

Major outstanding issues

- Influence of low-energy levels on <σv> at low temp
- Effect of thermal excitations in stellar environment
- Branch point isotopes



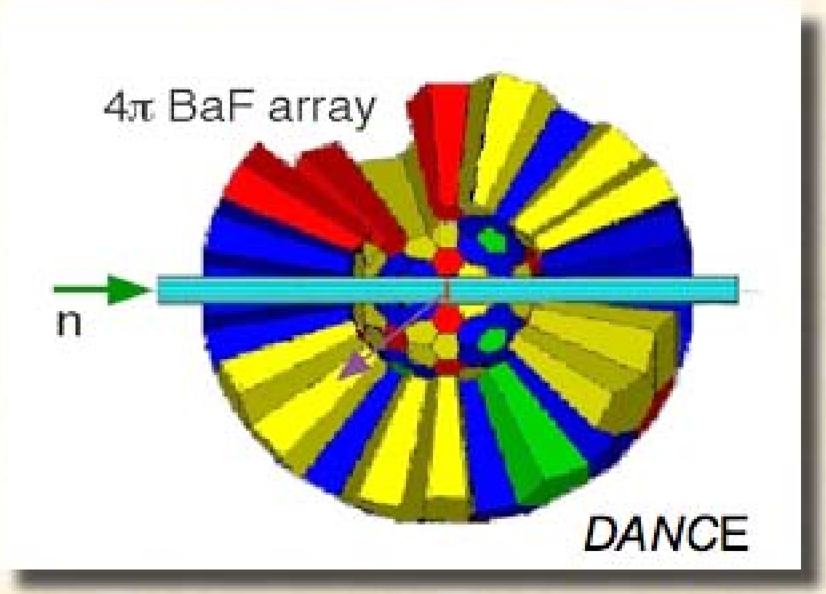
The new frontier

Source	***ORELA***	***Lujan***	***n TOF***	***SNS***
flight path (m)	40	20	180	20
resolution (ns/m)	0.2	6.2	0.05	18
power (kW)	8	64	45	2000
flux (n/s/cm^2)	2×10^4	5×10^6	3×10^5	2×10^8
FOM (n/s/cm^2)	5×10^5	6×10^9	5×10^8	9×10^{10}

Experiments now possible with samples of only ~ 10^{16} atoms/cm^2.

High efficiency detector arrays

High segmentation to handle rate from radioactive sources



Important s process branch points

	status	*feasible*
^{63}Ni	🔴	🟢
^{79}Se	🔴	🟢
^{81}Kr	🔴	🟢
^{85}Kr	🔴	🟢
^{147}Nd	🔴	🔴
^{147}Pm	🟡	🟢
^{148}Pm	🔴	🔴
^{151}Sm	🟢	🟢
^{154}Eu	🔴	🔴
^{155}Eu	🟡	🟢
^{153}Gd	🔴	🟢
^{160}Tb	🔴	🔴
^{163}Ho	🟡	🟢
^{170}Tm	🔴	🟢
^{171}Tm	🟡	🟢
^{179}Ta	🔴	🟢
^{185}W	🔴	🟢
^{204}Tl	🔴	🟢

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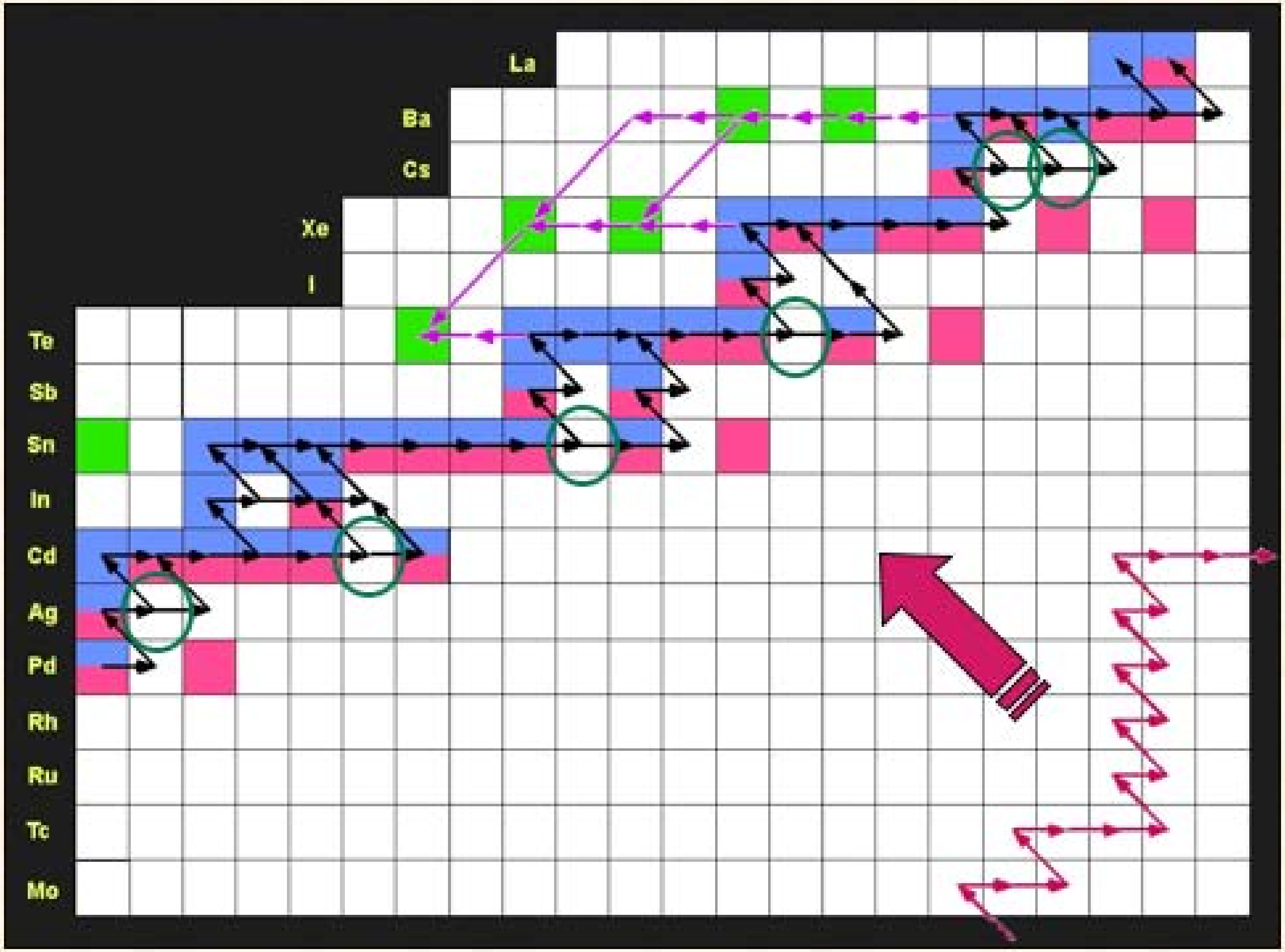

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  Branch points crucial

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