

Nuclear Astrophysics

**2x50 minutes for $(13.7 \pm 0.13) \times 10^9$ years
(a ratio of 1.39×10^{-14} !)**

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Outline

- **Why astrophysics?**
- **The life of a star**
- **Astrophysical jargon:**
 - Big Bang nucleosynthesis, Jeans criterion, quiescent and explosive burning, reaction rate, Gamow window, S-factor, resonance strength,..
- **Examples**
 - (p, γ) reaction in X-ray bursts
 - n-rich nuclei and the r-process

Literature

C. Rolfs & W. Rodney:

Cauldrons in the Cosmos, University of Chicago Press, 1988

C. Iliadis:

Nuclear Physics of Stars, Wiley 2007

I. Thompson and F. Nunes

Nuclear Reactions for Astrophysics, Cambridge Univ. Press 2009

B²FH:

Burbidge, Burbidge, Fowler, Hoyle: Rev. Mod. Phys. 29, 15(1957)

Annual Review of Nuclear and Particle Physics

Annual Review of Astronomy and Astrophysics

What is astrophysics? Why astrophysics? Forefront science



Atomic Physics

Gravitation

Particle Physics

Plasma Physics



Astronomical Observations

Cosmology

Nuclear Physics

Dark Energy 73.4%

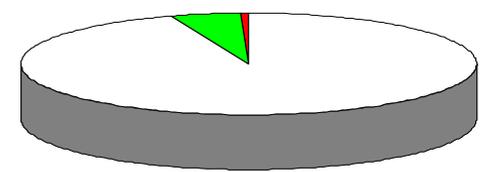
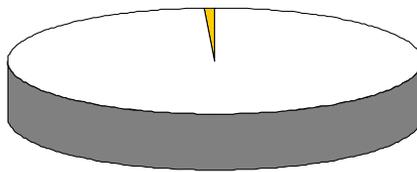
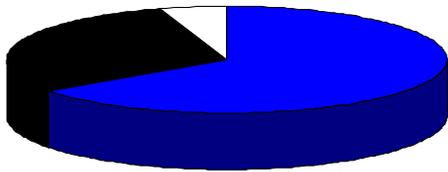
Dark Matter 22.1%

Neutrino Physics

Neutrinos 0.7%

H, He 4.1%

Heavy Elements 0.07%



Whatever stars do, they do it to the extreme

	Lab/Earth	Stars
gravitation	9.81 m/sec ²	Black hole
magnetic field	91.4 T	10-100x10 ⁹ T
Acc. energy	7x10 ¹² eV	10 ²⁰ eV
density	22.5 g/cm ³	10 ¹³ g/cm ³
ν -flux	10 ²⁰ ν /sec	10 ⁵⁸ ν in ~ 1 s

Nuclear Astrophysics – goals:

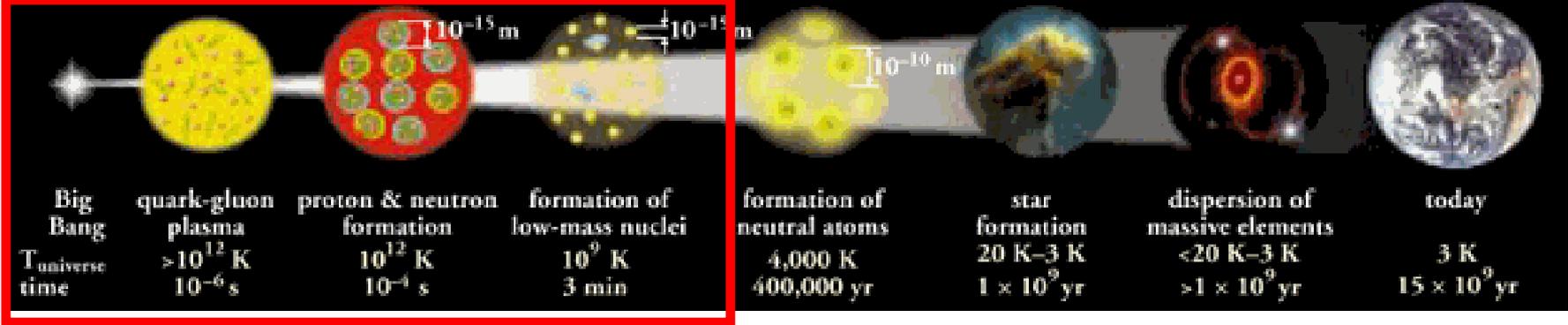
- Understanding the birth and death of stars
- Understanding the energy that powers the stars
- Understanding the formation of the elements

Nuclear Astrophysics - Challenges:

- Extremely small cross sections
- backgrounds
- Reactions involving unstable nuclei

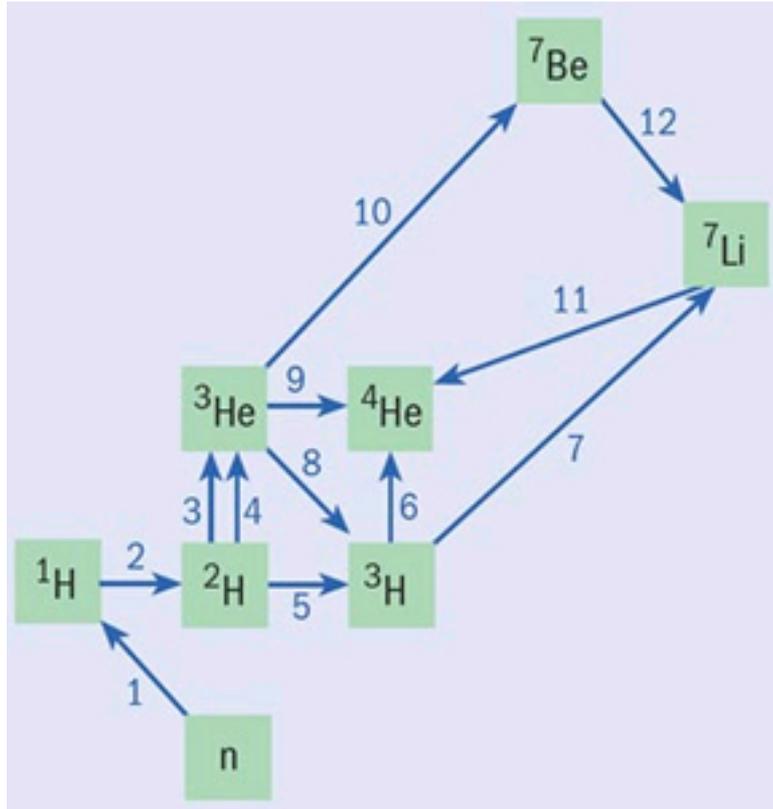
Frontiers:

- High-current accelerators
- Underground laboratories
- Gas targets
- Radioactive ion beams
- High efficiency detectors

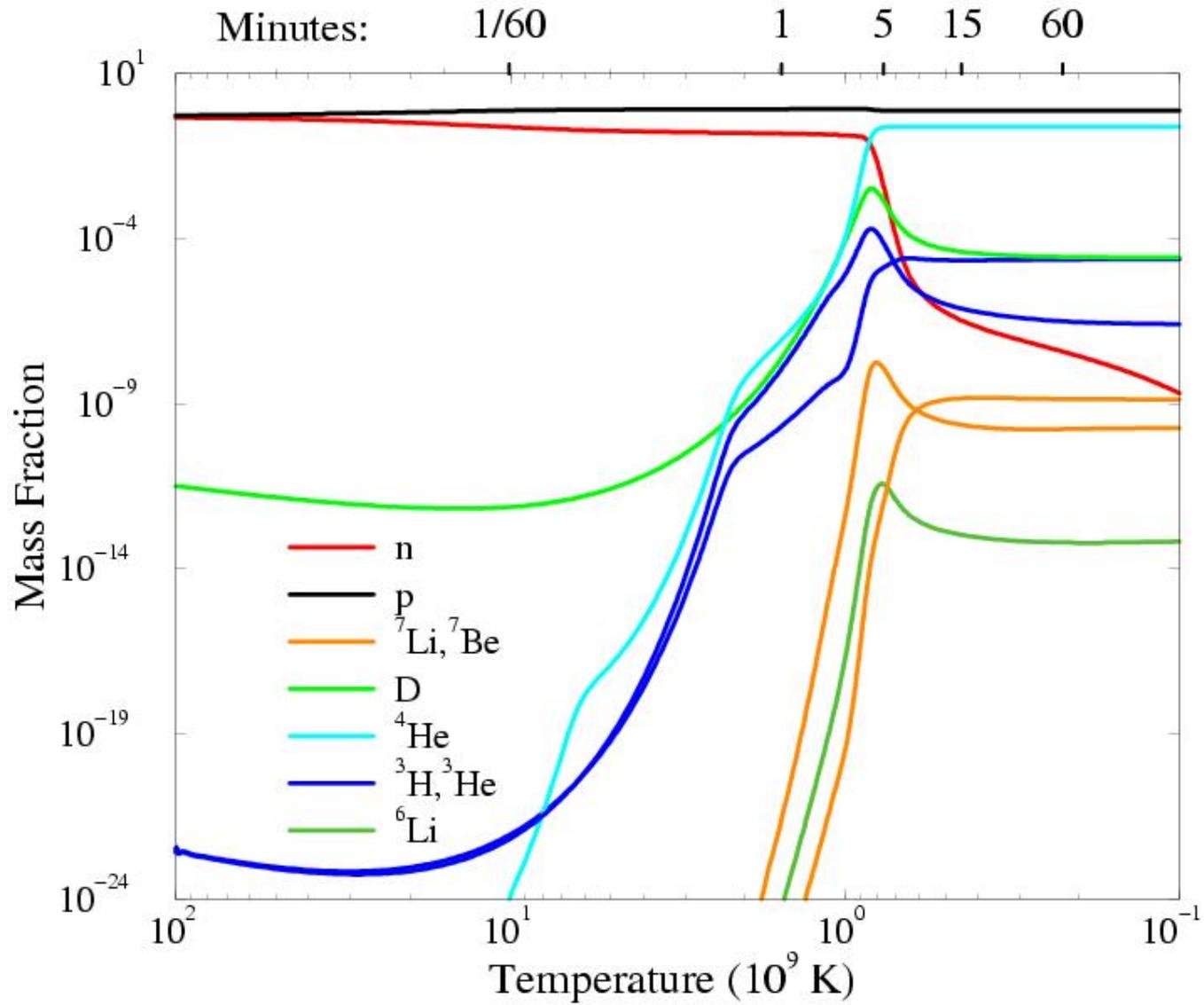


$T \sim 10^9$ K,
 $\Delta t \sim 3$ min

^1H	0.75
^2H	2.5×10^{-5}
^3He	4×10^{-5}
^4He	0.23
^7Li	5×10^{-9}



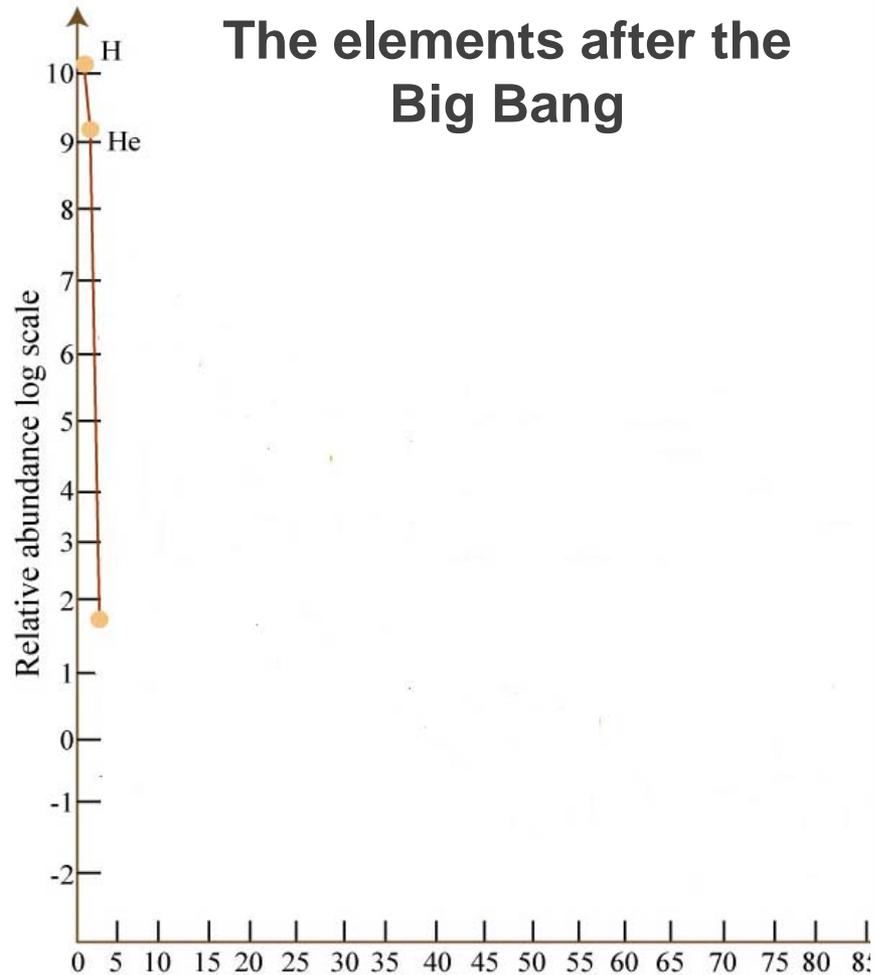
- 1 $n \rightarrow ^1\text{H} + e^- + \bar{\nu}$
- 2 $^1\text{H} + n \rightarrow ^2\text{H} + \gamma$
- 3 $^2\text{H} + ^1\text{H} \rightarrow ^3\text{He} + \gamma$
- 4 $^2\text{H} + ^2\text{H} \rightarrow ^3\text{He} + n$
- 5 $^2\text{H} + ^2\text{H} \rightarrow ^3\text{H} + ^1\text{H}$
- 6 $^2\text{H} + ^3\text{H} \rightarrow ^4\text{He} + n$
- 7 $^3\text{H} + ^4\text{He} \rightarrow ^7\text{Li} + \gamma$
- 8 $^3\text{He} + n \rightarrow ^3\text{H} + ^1\text{H}$
- 9 $^3\text{He} + ^2\text{H} \rightarrow ^4\text{He} + ^1\text{H}$
- 10 $^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma$
- 11 $^7\text{Li} + ^1\text{H} \rightarrow ^4\text{He} + ^4\text{He}$
- 12 $^7\text{Be} + n \rightarrow ^7\text{Li} + ^1\text{H}$



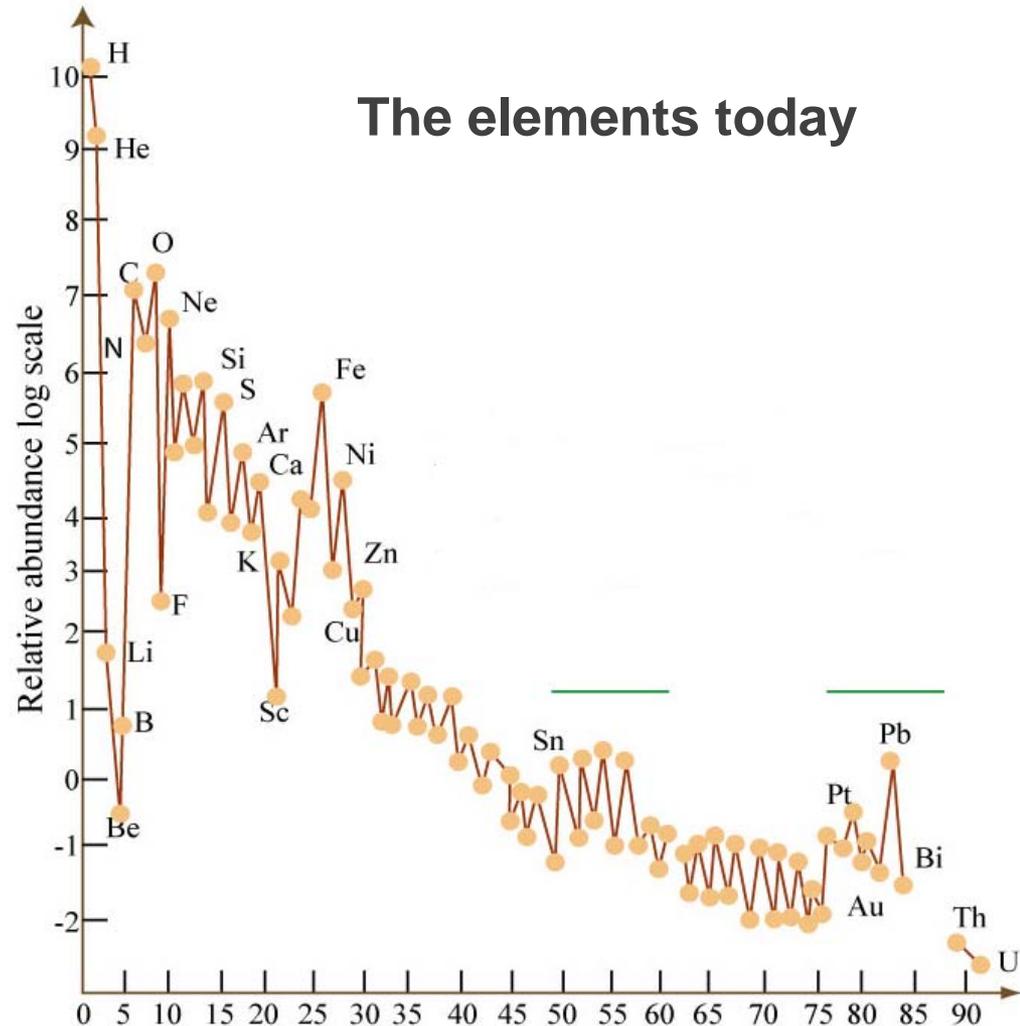
Burles, Nollett, Turner, ApJ

What the stars did for us

The elements after the Big Bang



The elements today



Virial theorem: $2K + U = 0$

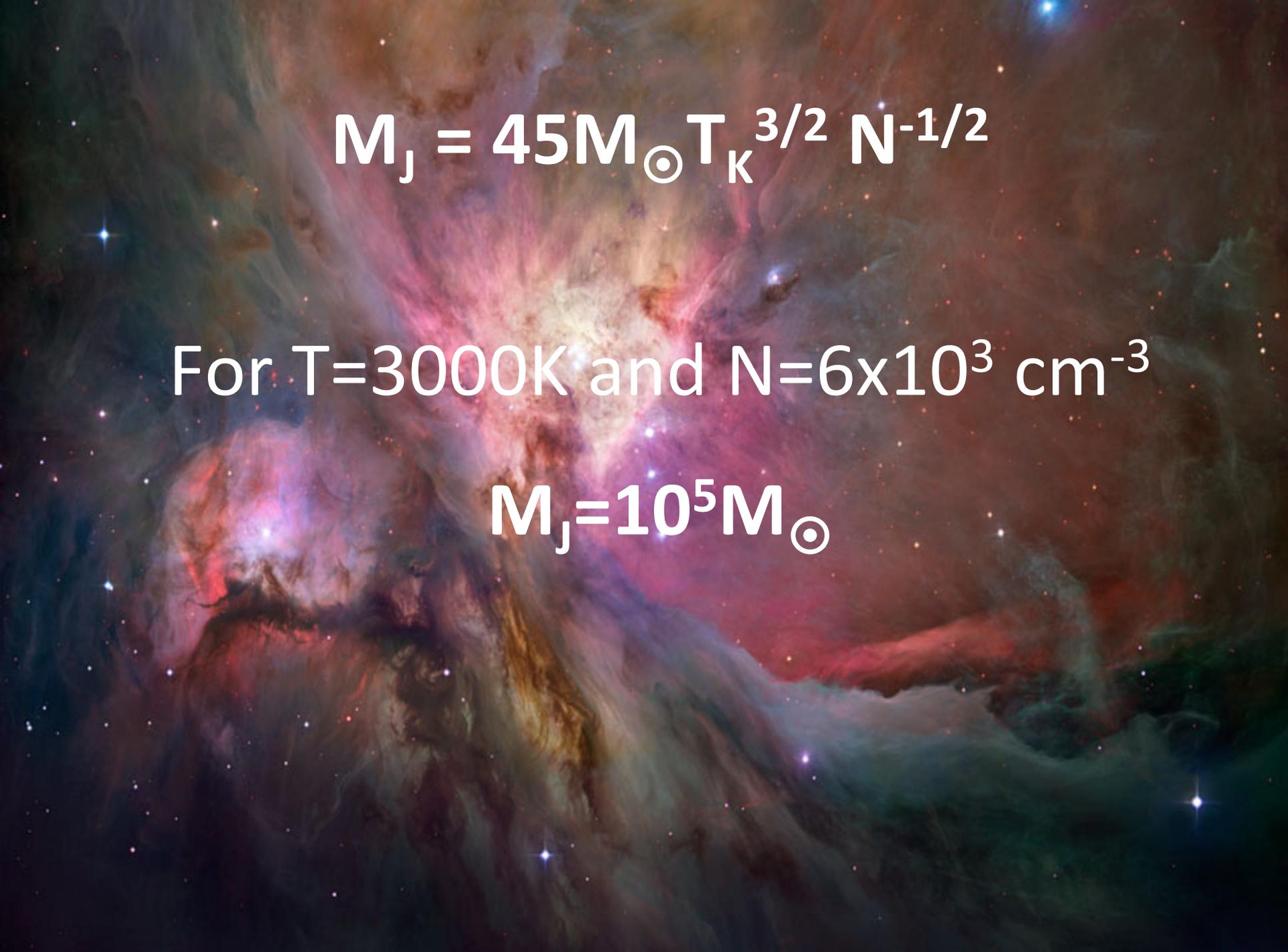
Collapse: $2K < -U$

$$K = \frac{3}{2} NkT \quad N = \frac{M_C}{\mu \cdot m_H} \quad U = -\frac{3}{5} \frac{GM_C^2}{R_C}$$

$$\frac{3M_C kT}{\mu \cdot m_H} < \frac{3}{5} \frac{GM_C^2}{R_C} \quad R_C = \left(\frac{3M_C}{4\pi\rho_C} \right)^{1/3}$$

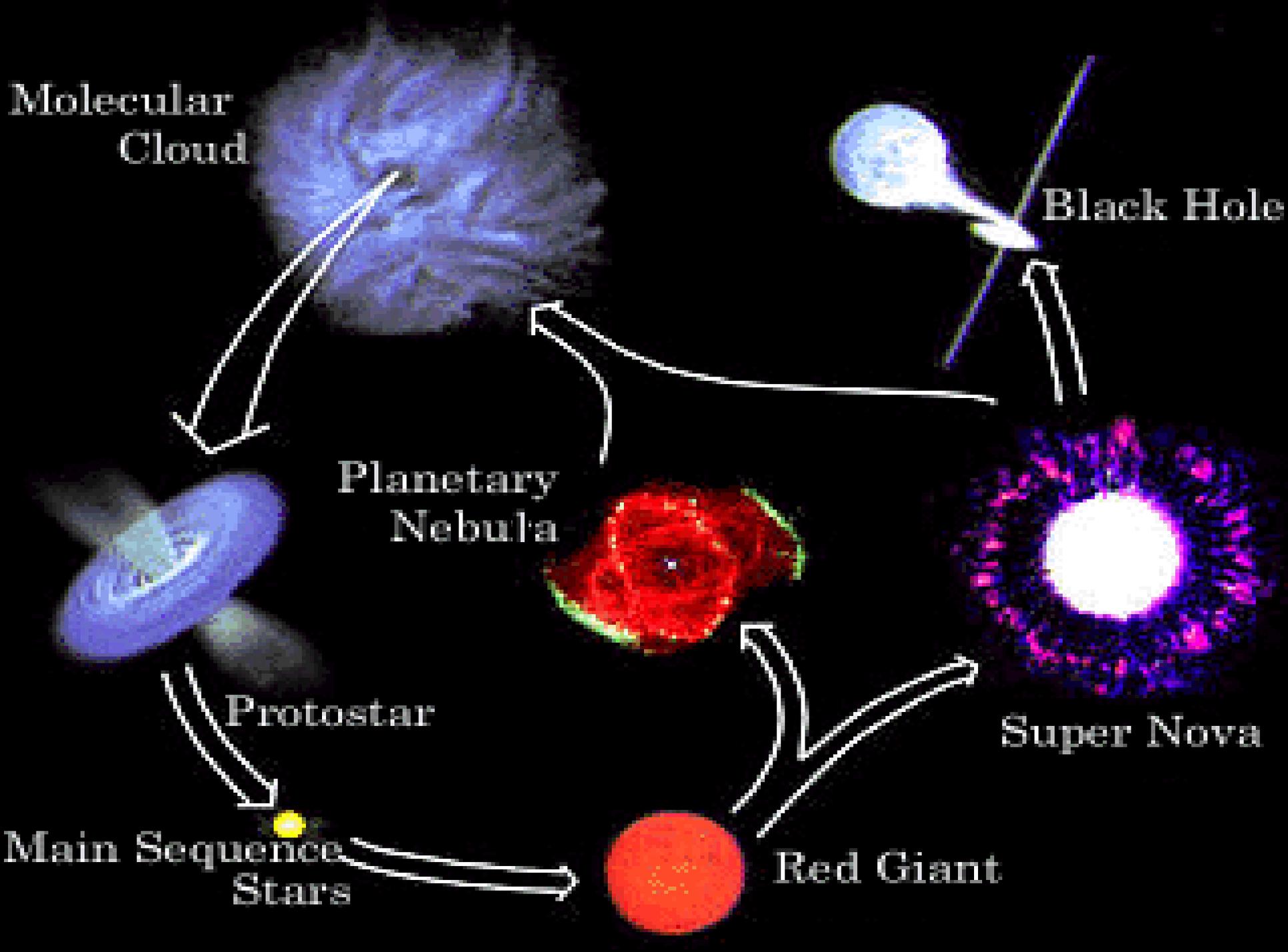
$$M_J > \left(\frac{5kT}{G\mu \cdot m_H} \right)^{3/2} \left(\frac{3}{4\pi\rho_C} \right)^{1/2}$$

Jeans criterion (1902)


$$M_j = 45M_{\odot} T_K^{3/2} N^{-1/2}$$

For $T=3000\text{K}$ and $N=6 \times 10^3 \text{ cm}^{-3}$

$$M_j = 10^5 M_{\odot}$$



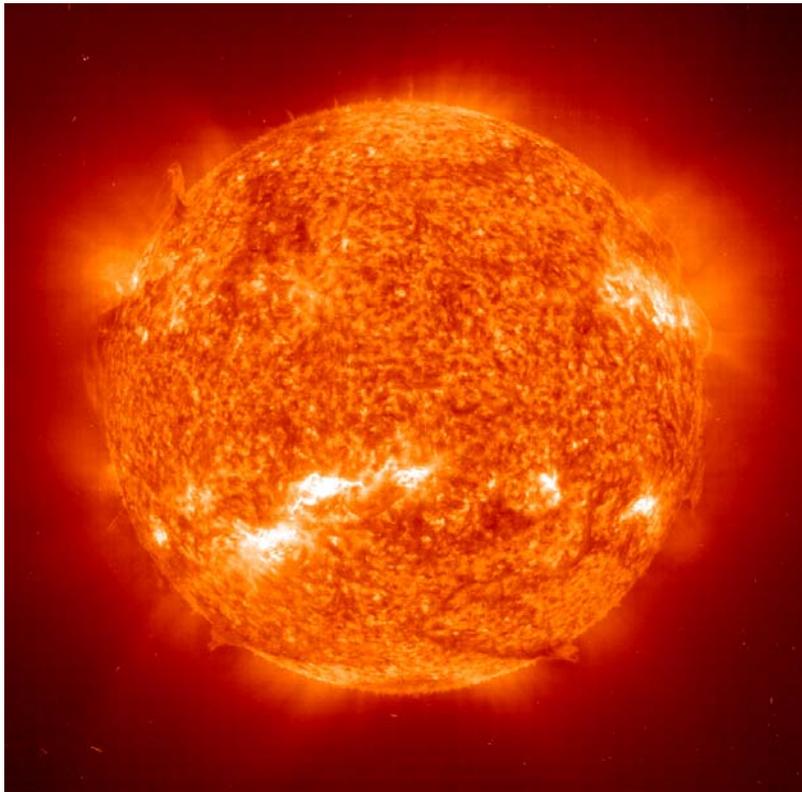
Two paths to 'cook' the elements in stars:

Slowly (quiescent)

~(10^9 years)

Example : the sun

hydrogen \rightarrow helium



Fast (explosive)

~(a few seconds)

Example:Supernova

iron \rightarrow heavy elements

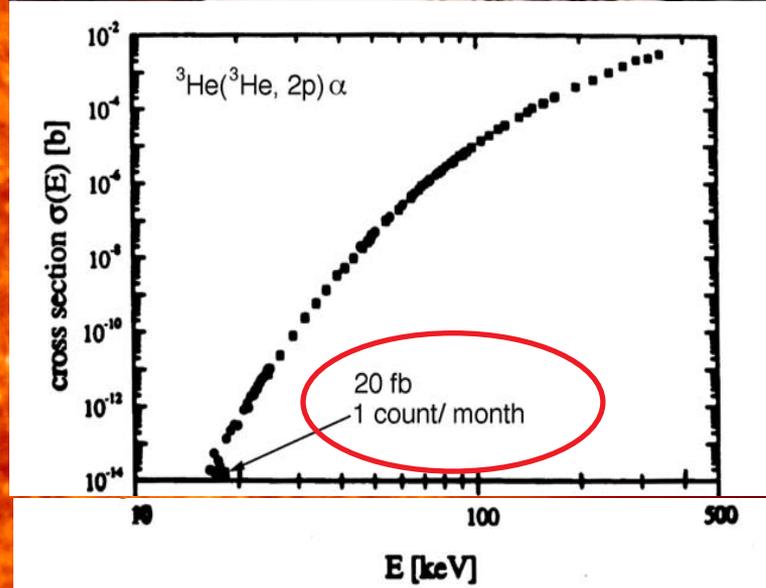
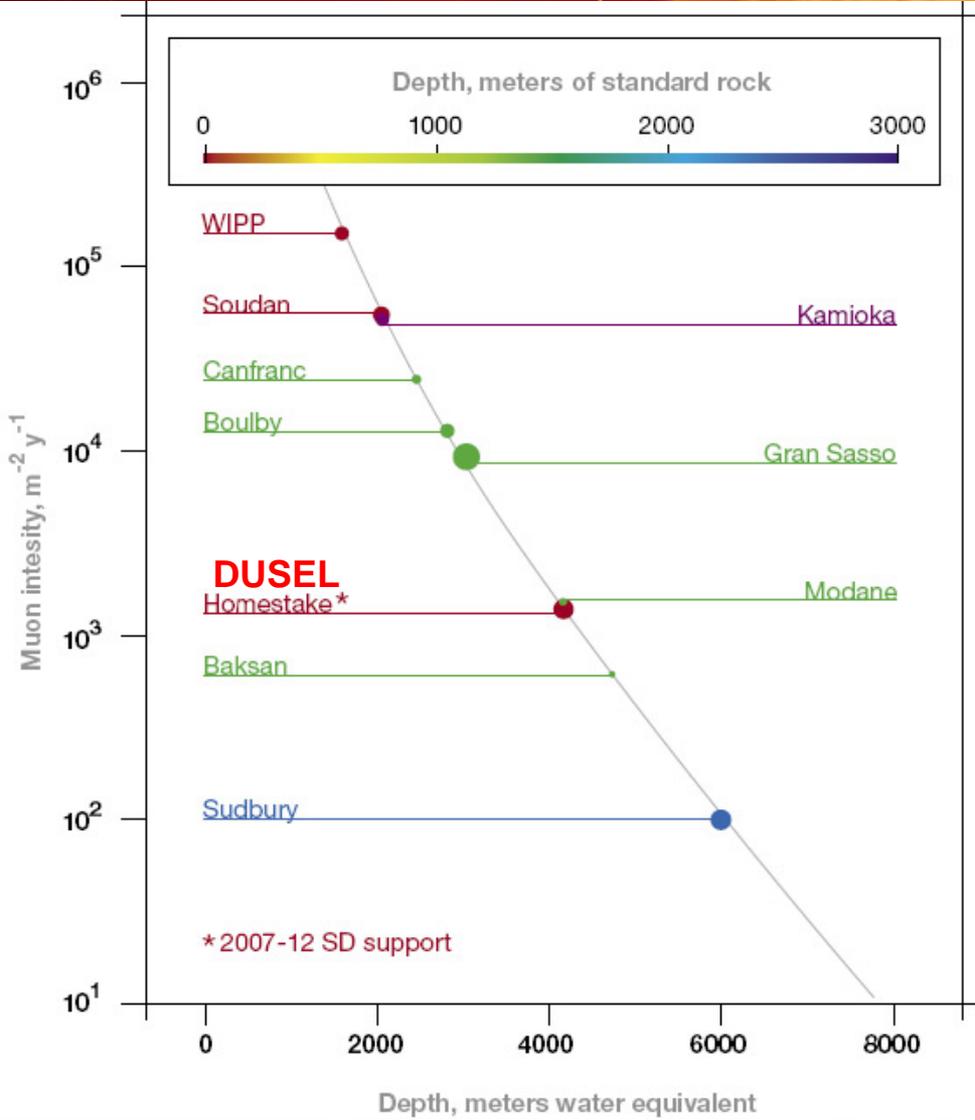


Experiments with stable beams and targets:

provide data for BB nucleo-synthesis and quiescent burning scenarios

Need:

- High beam intensities
- thick targets, that can tolerate the beams
- low backgrounds
- long runs



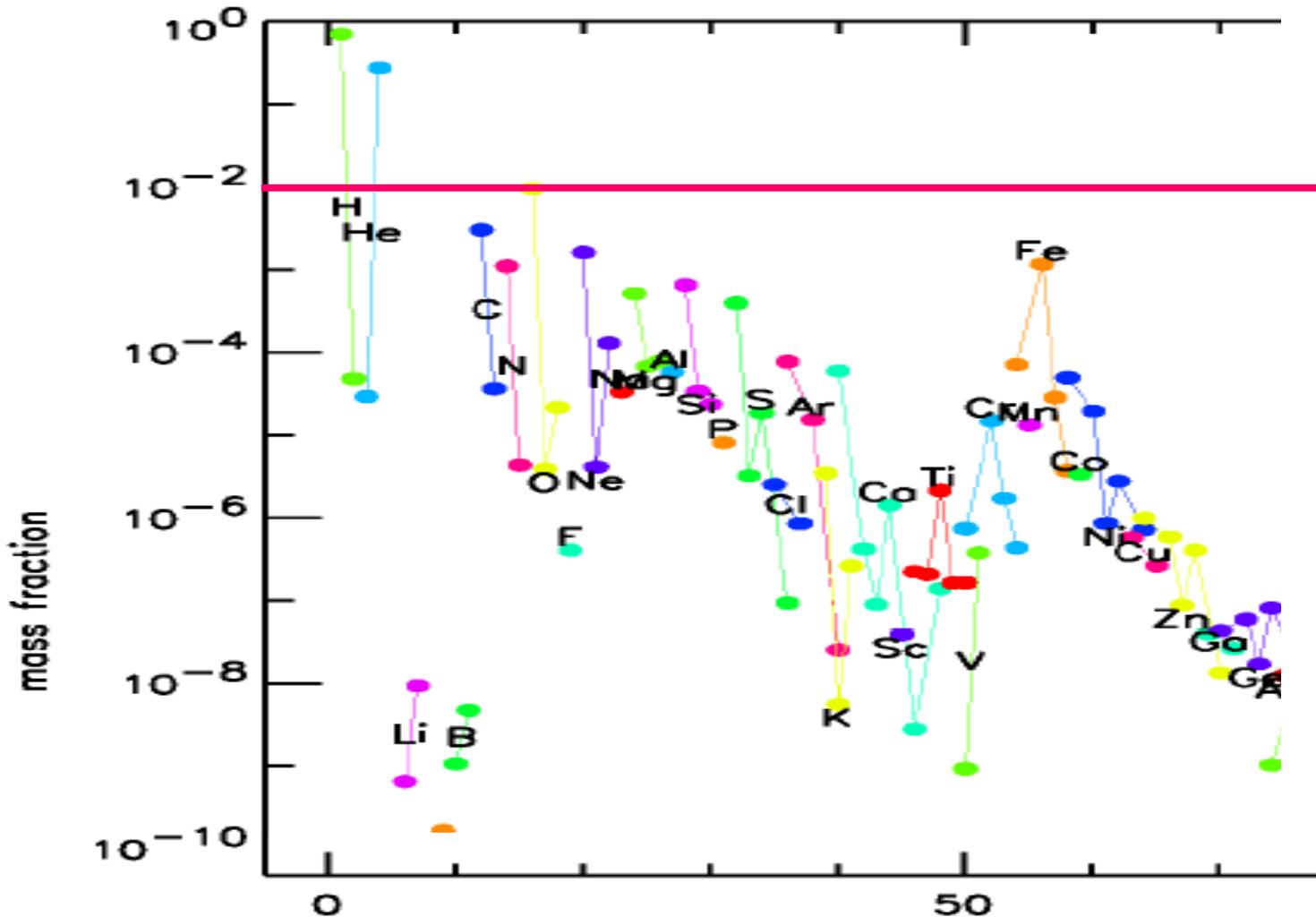
Experiments with radioactive beams:

provide data for explosive burning scenarios:

Need:

- Beams of unstable nuclei (low intensities, contaminants)
- thick targets (to compensate for the intensity)
- long runs

Targets for experiments with radioactive beams: controlled by stellar abundance pattern



Most reactions induced by:

p, α

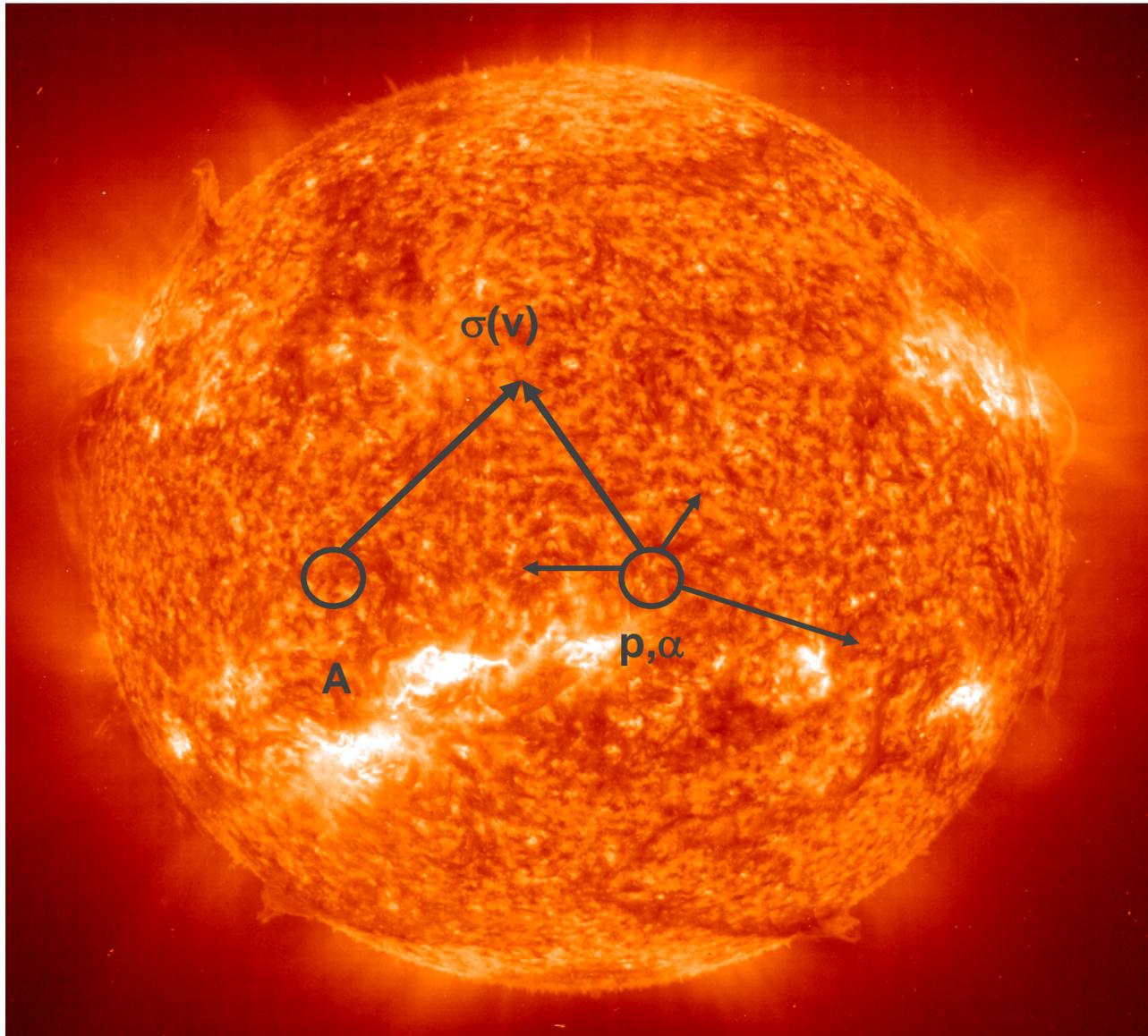
$(^{16}\text{O}, ^{12}\text{C}, n)$



Critical reactions in nuclear astrophysics

- (p,γ) (novae, rp-process)
- (α,γ) (red giants)
- (α,p) (rp-process)
- $^{12}\text{C} + ^{12}\text{C}$ fusion (supernovae)
- (n,γ) (r-process, s-process)
- GT transitions (supernovae)
- (α,n) (s-process, red giants)
- (p,α) (novae)
- $(\gamma,p), (\gamma,n), (\gamma,\alpha)$ (p-process)

In Nature:



In the laboratory:



Reactions between Charged Particles

(astrophysical reaction rate, Gamow window, S-factor, resonance strength)

Example: $^{12}\text{C}(p,\gamma)^{13}\text{N}$

N_c : ^{12}C particles/cm³

N_p : protons/cm³

v : relative velocity between C and p

Astrophys. reaction rate: $r = N_c \cdot N_p \cdot v \cdot \sigma_{p\gamma}(v)$

Particle densities N_i :

$$\rho = N_i \mu \quad \mu = \text{weight of a particle}$$

$$\rho = N_i A / N_A \quad N_A: \text{Avogadro's Number}$$

$$N_i = \rho N_A / A$$

Or, for a multiparticle gas with X_i as a mass fraction:

$$N_i = \rho N_A / A X_i$$

Example: particle density in the center of the sun:

$$\rho \sim 150 \text{ g/cm}^3$$

$$X_i = 0.73$$

$$N_p = 6.6 \cdot 10^{25} \text{ particles/cm}^3$$

In normal stellar matter (not in neutron stars)

$$\phi_i(v_i) = 4\pi v_i^2 \left(\frac{m}{2\pi kT} \right)^{3/2} \exp\left(-\frac{mv^2}{2kT}\right) \text{ (Maxwellian)}$$

$$\langle \sigma v \rangle = \iint \phi(v_1) \phi(v_2) \sigma(v_{\text{rel}}) v_{\text{rel}} dv_1 dv_2$$

$$v_1 = V + m_2 / (m_1 + m_2) v \quad V : \text{center-of-mass velocity}$$

$$v_2 = V - m_1 / (m_1 + m_2) v \quad v : \text{relative velocity } (v_1 - v_2)$$

$$\langle \sigma v \rangle = \iint \Phi(V) \phi(v) v \sigma(v) dv dV$$

Where:

$$\Phi(V) = 4\pi V^2 \left(\frac{M}{2\pi kT} \right)^{3/2} \exp(-MV^2/(2kT))$$

$$M = m_1 + m_2$$

$$\phi(v) = 4\pi v^2 \left(\frac{\mu}{2\pi kT} \right)^{3/2} \exp(-\mu v^2/(2kT))$$

$$\mu = m_1 m_2 / (m_1 + m_2)$$

$$\langle \sigma v \rangle = \int \phi(v) v \sigma(v) dv$$

$$\text{Because } \int \Phi(V) dV = 1$$

$$\langle \sigma v \rangle = 4\pi \left(\frac{\mu}{2\pi kT} \right)^{3/2} \int v^3 \sigma(v) \exp\left(-\frac{\mu v^2}{2kT}\right) dv$$

or

$$\langle \sigma v \rangle = \left(\frac{8}{\pi \mu} \right)^{1/2} \left(\frac{1}{kT} \right)^{3/2} \int \sigma(E) E \exp\left(-\frac{E}{kT}\right) dE$$

Some useful expressions:

$$R_{12} = N_1 N_2 \langle \sigma \cdot v \rangle$$

Reactions/(cm³ sec) in a plasma consisting of N₁ and N₂ particles/cm³

$$E_{12} = R_{12} \cdot Q_{12}$$

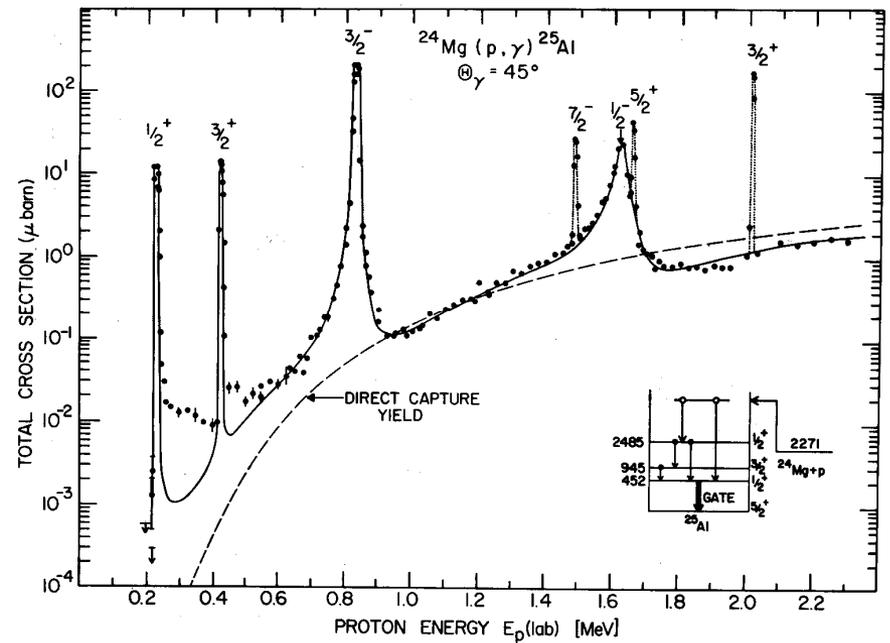
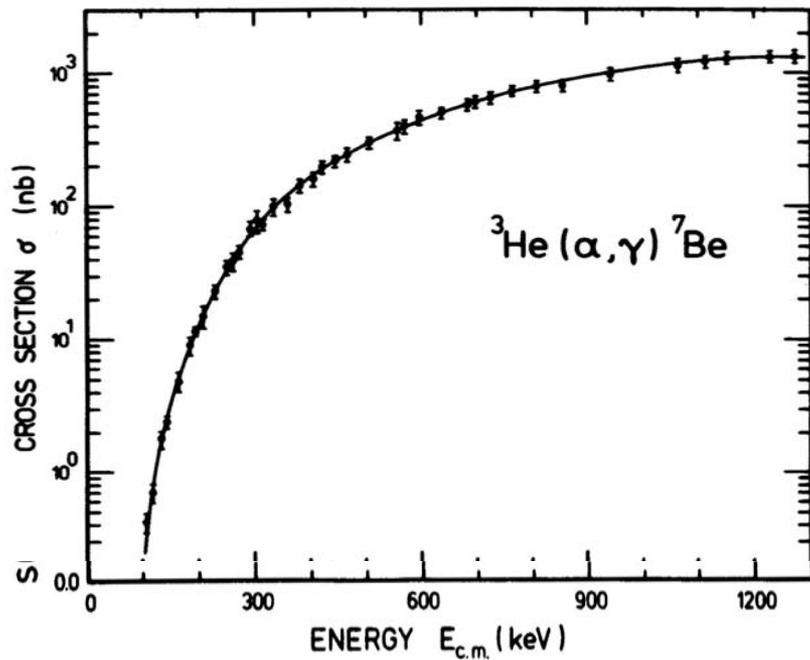
Rate of energy release (MeV/(cm³ sec))

$$\tau(1) = \frac{1}{N_2 \langle \sigma \cdot v \rangle}$$

Life time (sec) of particle 1 in a plasma consisting of N₂ particles/cm³

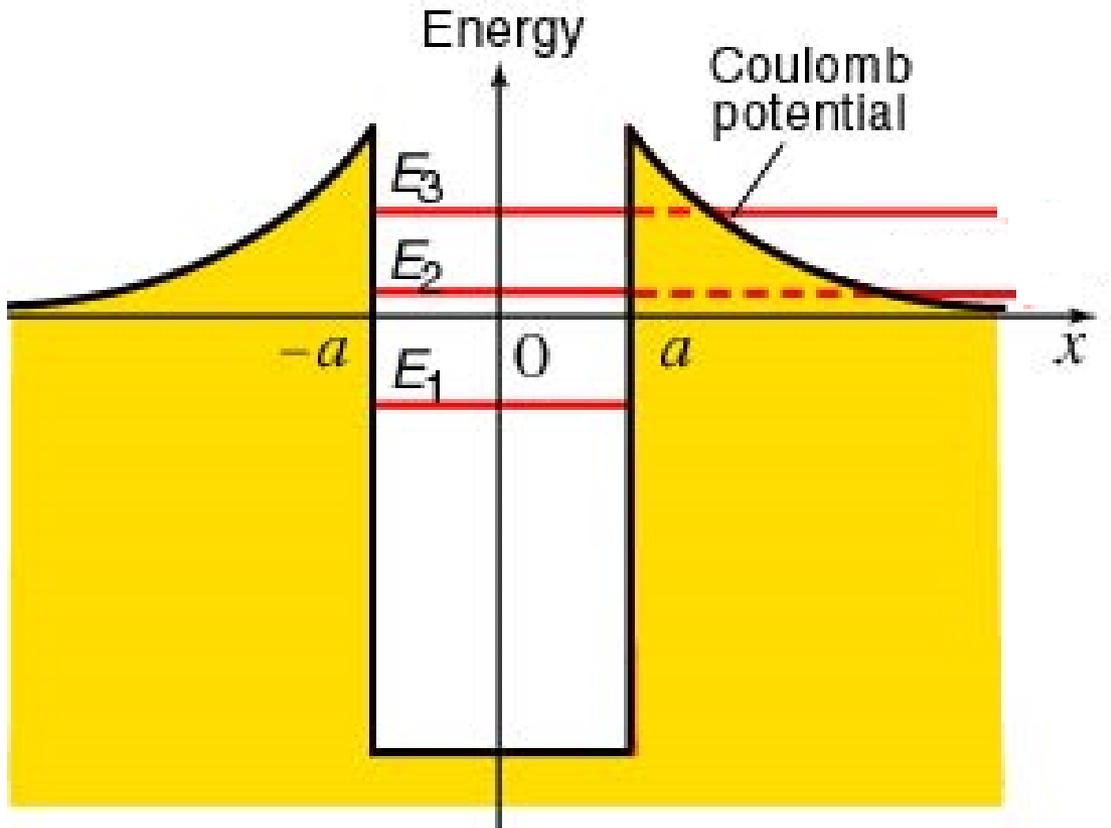
Need to measure $\sigma(v)$ (or $\sigma(E)$)

Need $\sigma(E)$:



Non-resonant cross sections

resonant cross sections



Probability of tunneling through the Coulomb barrier:

$$P \sim \exp(-2\pi\eta); \quad 2\pi\eta = 31.29 * Z_1 Z_2 (\mu/E_{cm})^{1/2}; \quad \mu \text{ in amu, } E \text{ in keV}$$

2.1 Non-resonant Reactions:

$$\sigma = \pi/k^2 \sum_l (2l + 1) |T_l|^2$$

at low energies only $l=0$ collisions contribute:

$$\sigma = \pi/k^2 |T_0|^2 = \pi/k^2 \frac{1}{F_o^2 + G_o^2} \quad (\text{F,G:Coulomb functions})$$

With asymptotic values (Abramowitz-Stegun):

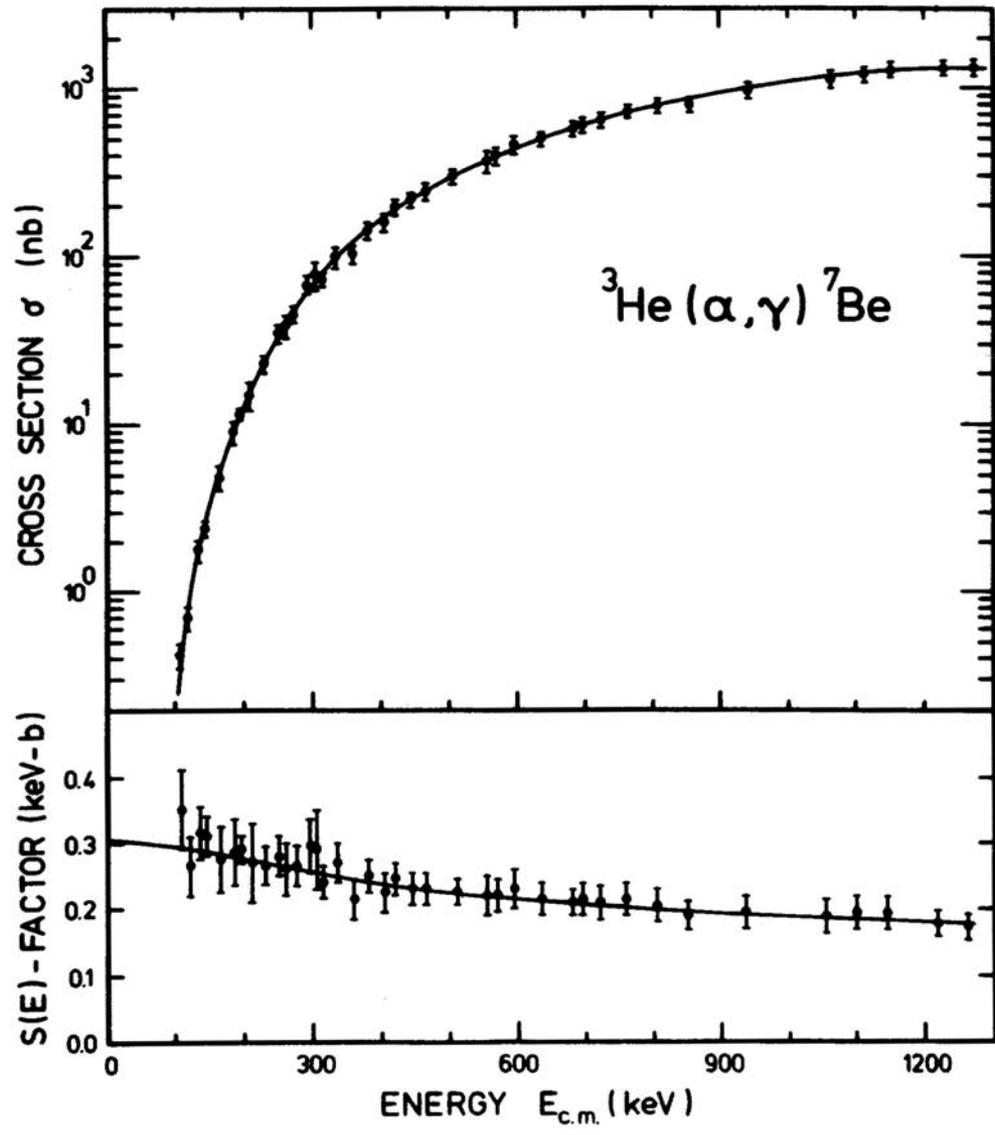
$$\sigma \sim 1/E \exp(-2\pi\eta)$$

Where $\eta = Z_1 Z_2 e^2 / (\hbar v)$ Sommerfeld parameter

To eliminate the strong energy dependence, one takes out the trivial factors : $e^{-2\pi\eta}/E$ and defines a new parameter S (**S-Factor**) which contains the ‘non-trivial’ energy dependence:

$$\sigma = S(E)/E e^{(-2\pi\eta)}$$

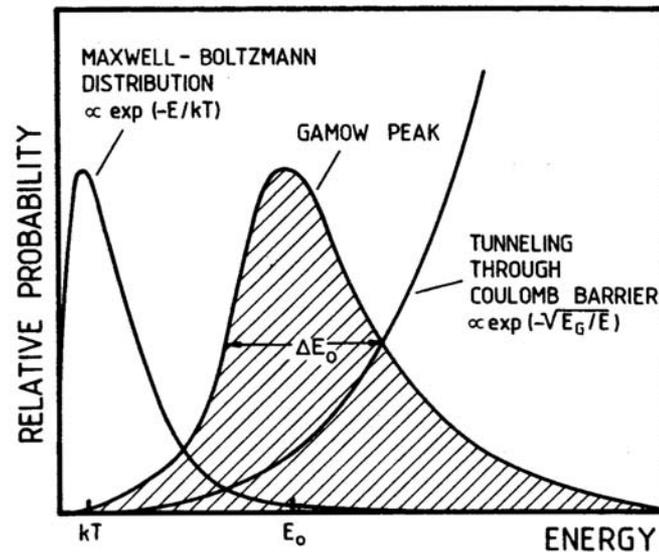
$$S(E) = \sigma E e^{(2\pi\eta)}$$



With $S(E)$ one can rewrite $\langle \sigma v \rangle$:

$$\langle \sigma v \rangle = \left(\frac{8}{\pi \mu} \right)^{1/2} \left(\frac{1}{kT} \right)^{3/2} \int S(E) \exp(-E/kT - b/E^{1/2}) dE$$

argument of the exponent:



Maximum of the argument at E_0 :

$$E_0 = (bkT/2)^{2/3} \text{ with } b = (2\mu)^{1/2} \pi e^2 Z_1 Z_2 / \hbar$$

or

$$E_0 = 1.22 (Z_1^2 Z_2^2 \mu T_6^2)^{1/3} \text{ [keV]}$$

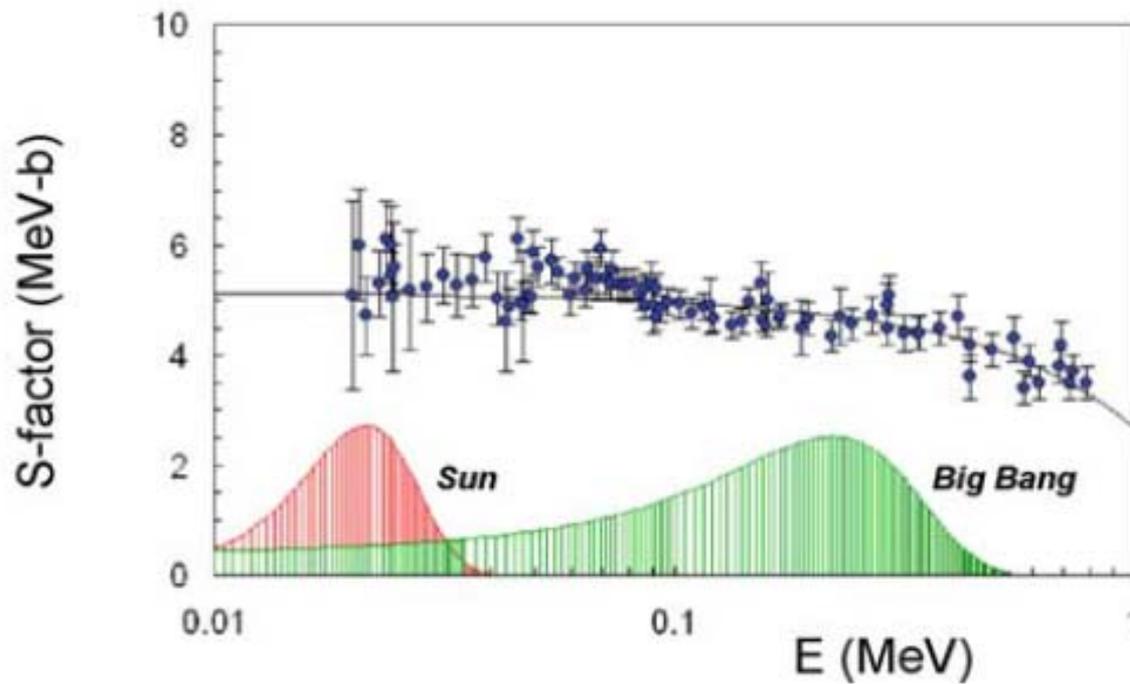
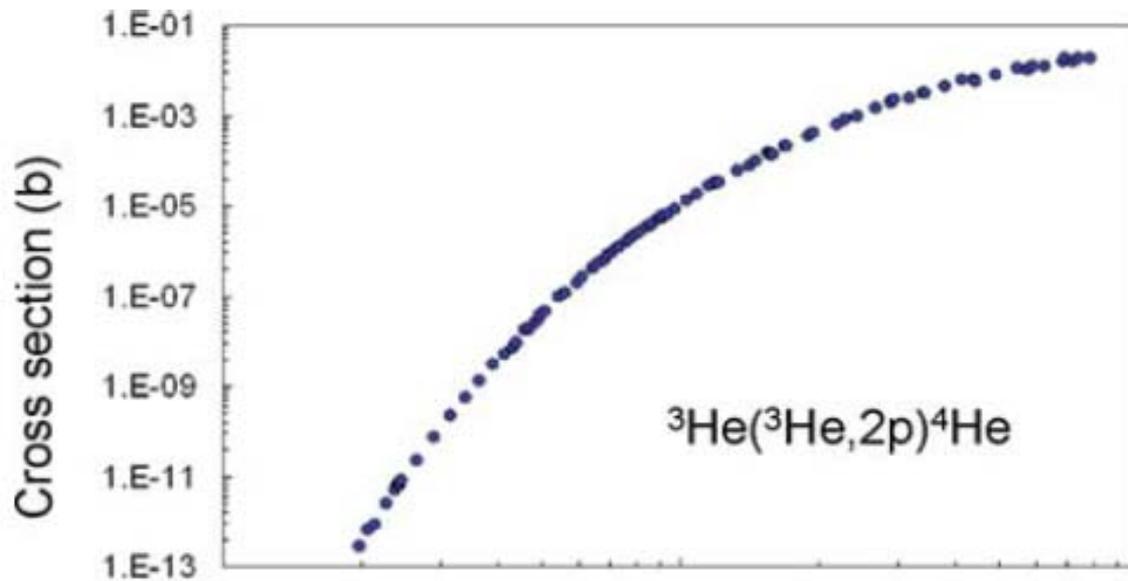
Gamow peak

T_6 : temperature in 10^6 K

Example of Gamow window values

$$T_6 = 15 \text{ K} \quad T = 15 \times 10^6 \text{ K}$$

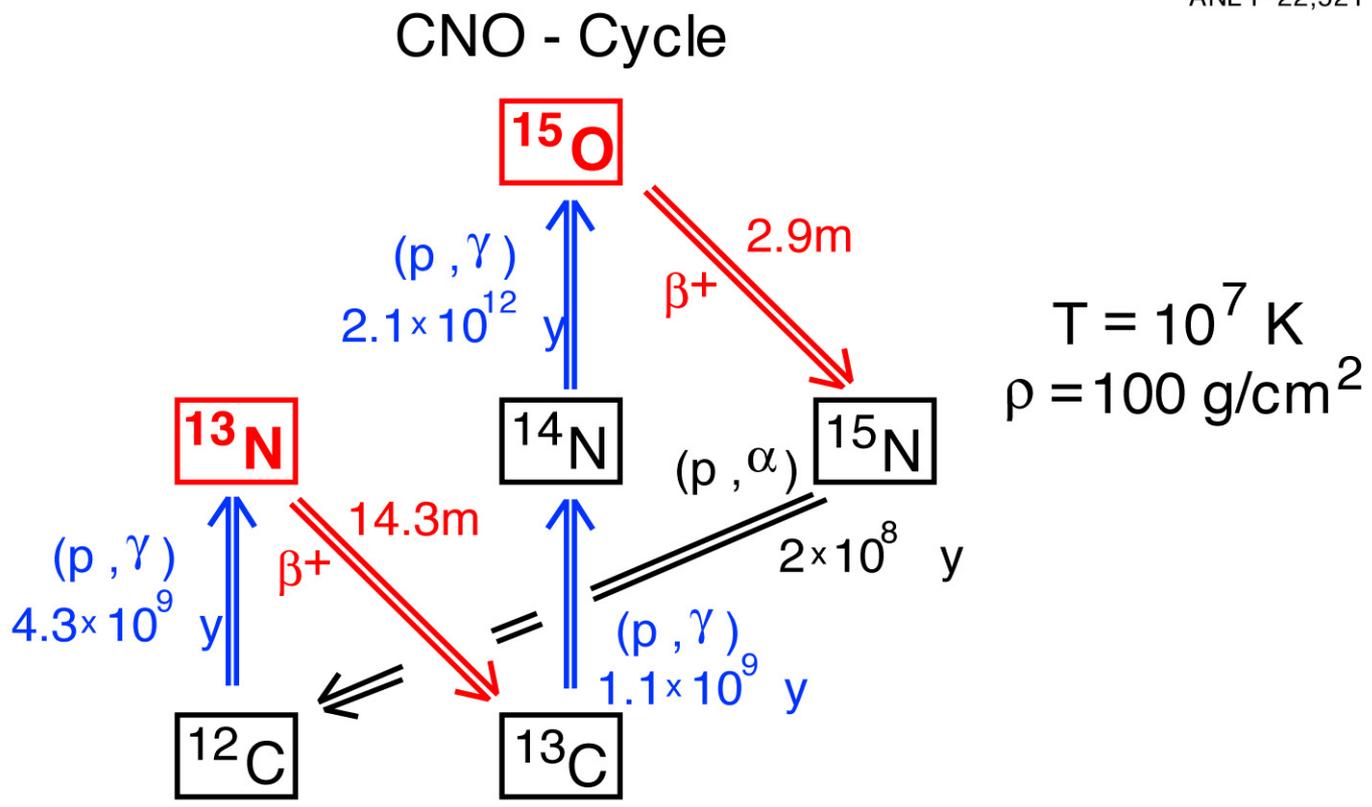
System	E_0 [keV]	Δ [keV]	τ
${}^3\text{He} + {}^3\text{He}$	21	12.1	49.7
$p + {}^{12}\text{C}$	24	12.8	55.4
$\alpha + {}^{12}\text{C}$	56	19.6	130.2
${}^{16}\text{O} + {}^{16}\text{O}$	237	40.4	550.9



From C. Angulo

Example: reactions in the CNO cycle

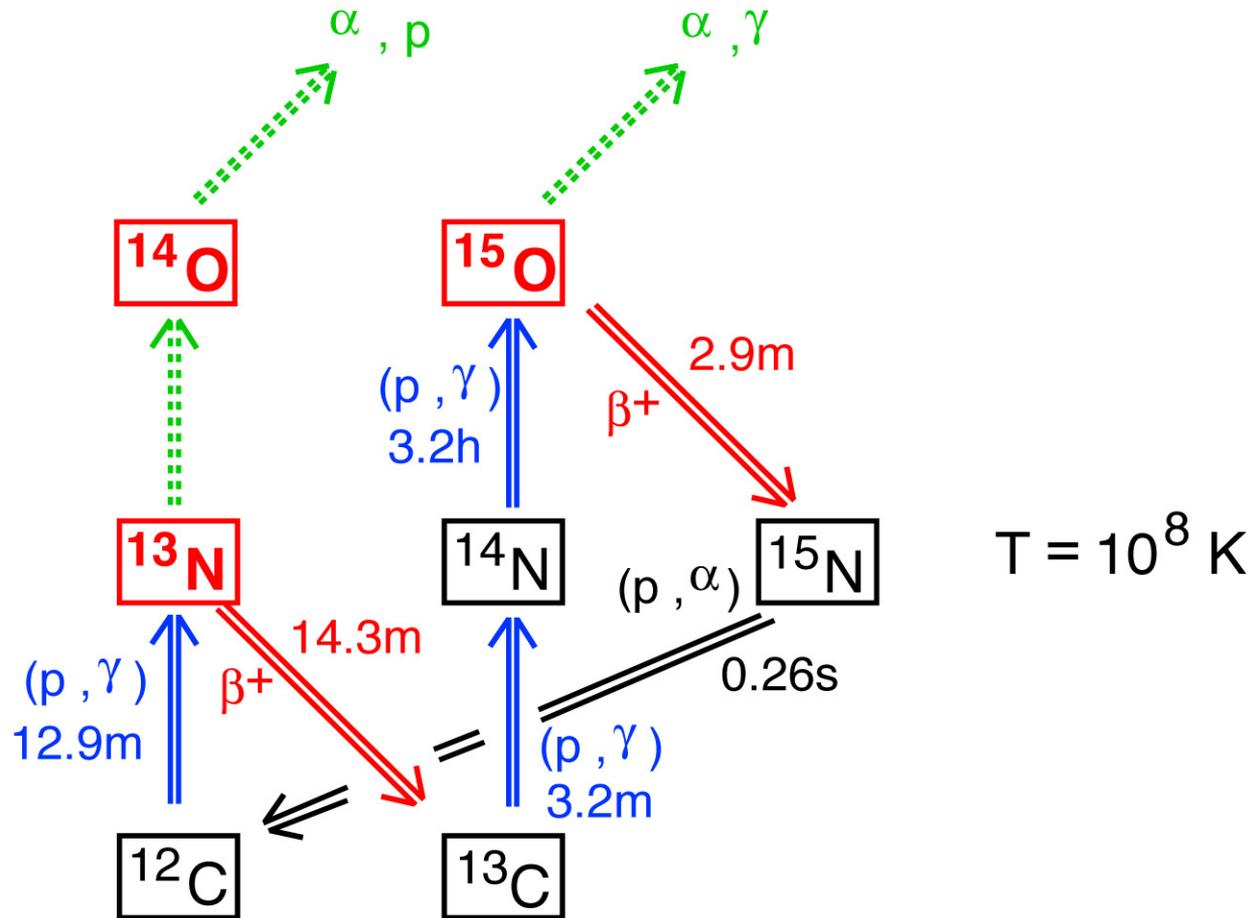
ANL-P-22,521



reaction times long compared to τ_β

→ Nuclear reactions occur on stable nuclei

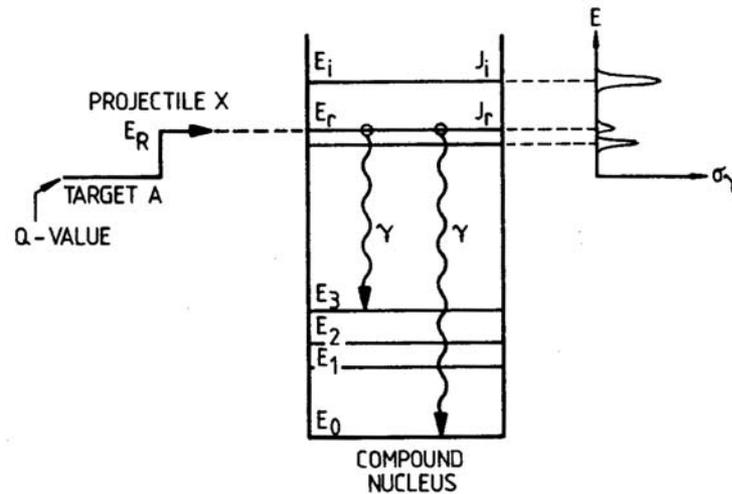
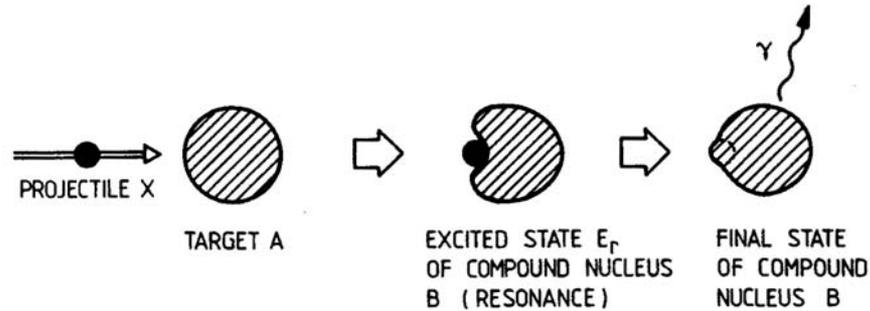
Increasing the temperature by a factor of 10:



Reaction times are comparable to decay times.

→ unstable nuclei become part of the reaction network

2.2 Resonance Reactions



$\sigma_{\text{resonance}}$: Breit-Wigner shape

$$\sigma_{i \rightarrow f} = \frac{\pi}{k^2} \frac{2J + 1}{(2J_1 + 1)(2J_2 + 1)} \frac{\Gamma_i \Gamma_f}{(E - E_r)^2 + (\Gamma/2)^2}$$

J : spin of the resonance

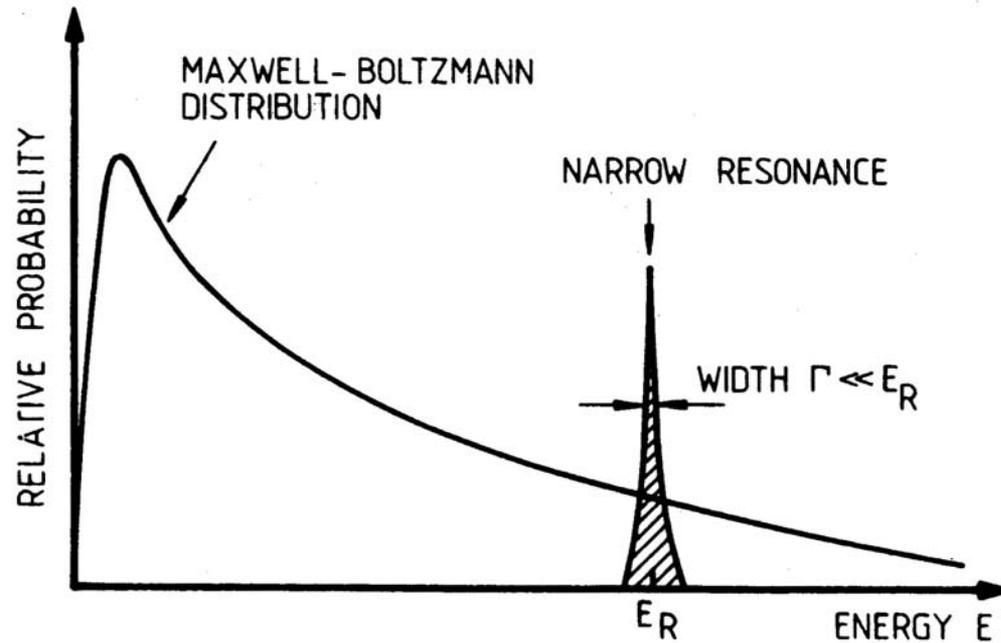
$J_{1,2}$: spin of the particles in the entrance channel

k : wave number

$\Gamma_{i,f}$: widths (decay probabilities) in the entrance or exit channel

E_r : resonance energy

Γ : total width ($\Gamma_i + \Gamma_f + \dots$)



$$\langle \sigma v \rangle = \left(\frac{8}{\pi \mu} \right)^{1/2} \left(\frac{1}{kT} \right)^{3/2} \int \sigma_{\text{BW}} E \exp(-E/kT) dE$$

$$\langle \sigma v \rangle = \left(\frac{8}{\pi \mu} \right)^{1/2} \left(\frac{1}{kT} \right)^{3/2} E_r \exp(-E_r/kT) \int \sigma_{\text{BW}}(E) dE$$

$$\int \sigma_{\text{BW}}(E) dE = \frac{\pi}{k^2} \omega \Gamma_i \Gamma_f \pi / (\Gamma/2)$$

$$= 2\pi^2/k^2 \frac{\omega \Gamma_i \Gamma_f}{\Gamma} =$$

$$= 2\pi^2/k^2 \omega \gamma$$

$\omega \gamma$: resonance strength

$$\langle \sigma v \rangle = \left(\frac{2\pi}{\mu kT} \right)^{3/2} \hbar^2 \omega \gamma \exp(-E_r/kT)$$

For several non-overlapping resonances:

$$\langle \sigma v \rangle = \left(\frac{2\pi}{\mu kT} \right)^{3/2} \hbar^2 \sum \omega \gamma_i \exp(-E_i/kT)$$

High rates for:

1. Large $\omega \gamma$
2. low resonance energies E_i

What are the important levels in the compound nucleus (^{18}Ne)? Example: $^{14}\text{O}(\alpha, p)^{17}\text{F}$

spin-parity selection rules, e.g.

$$^{14}\text{O} + \alpha: \quad 0^+, 1^-, 2^+, 3^-, \dots$$

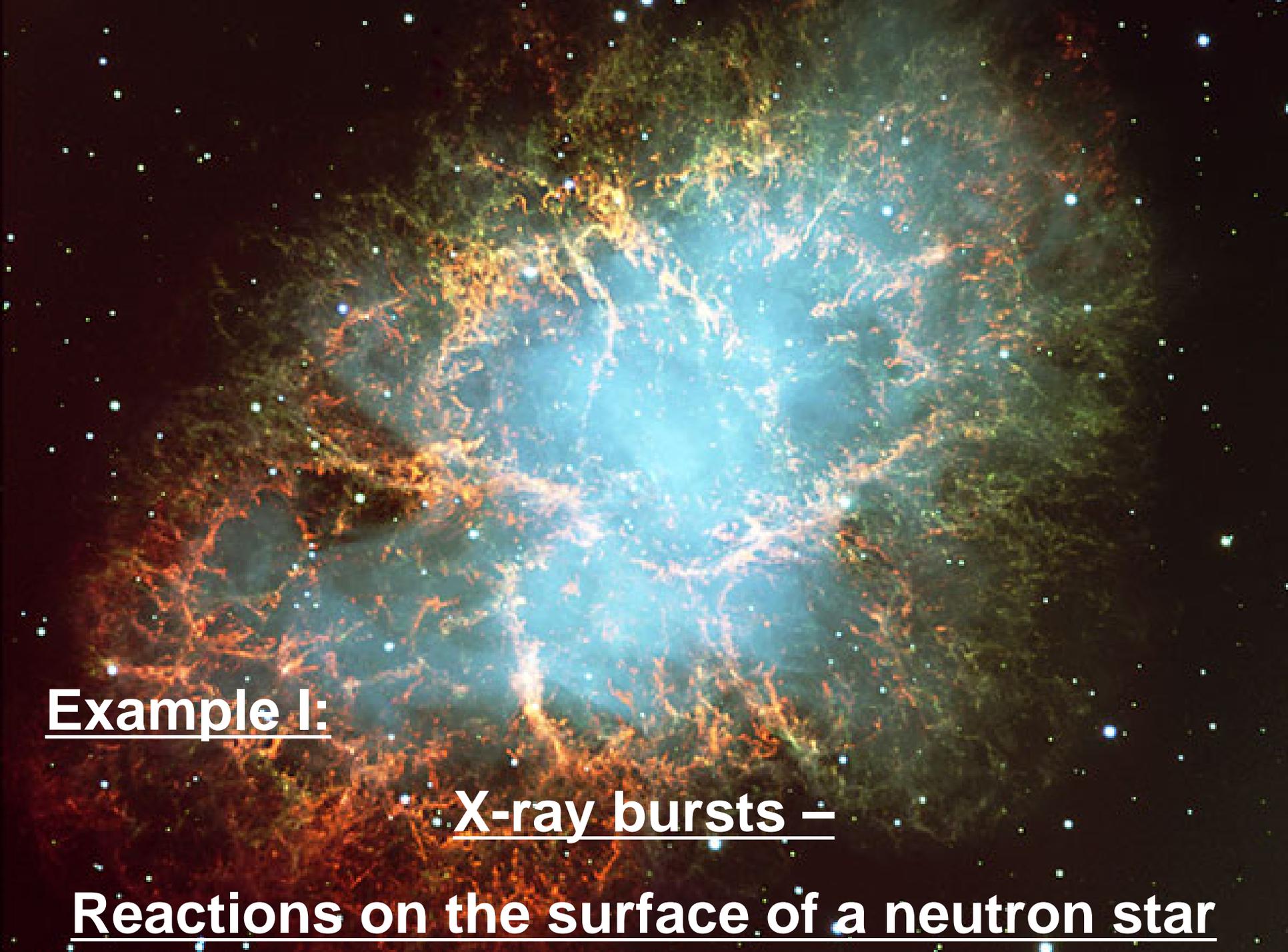
$$^{17}\text{F}(5/2^+) + p(1/2^+): \quad 2^+, 3^+, 1^-, 2^-, \dots$$

Angular momentum barrier:

$$V_{\text{int}} = Z_1 Z_2 e^2 / R + \hbar^2 l(l+1) / (2\mu R^2)$$

→ tunneling inhibited for higher l

preference for $l=0$ transitions



Example I:

X-ray bursts –

Reactions on the surface of a neutron star

X-ray bursts

KS 1731-260

D=23 kly



accumulation rate

$\sim 10^{-8}-10^{-10} M_{\odot}/y$

(50-0.5 kg/cm²/s)

~ 200 MeV/u

normal H, He star

period: hours-100d

distance $\sim 10^{-3}-1$ AU

donor star

accretion disk

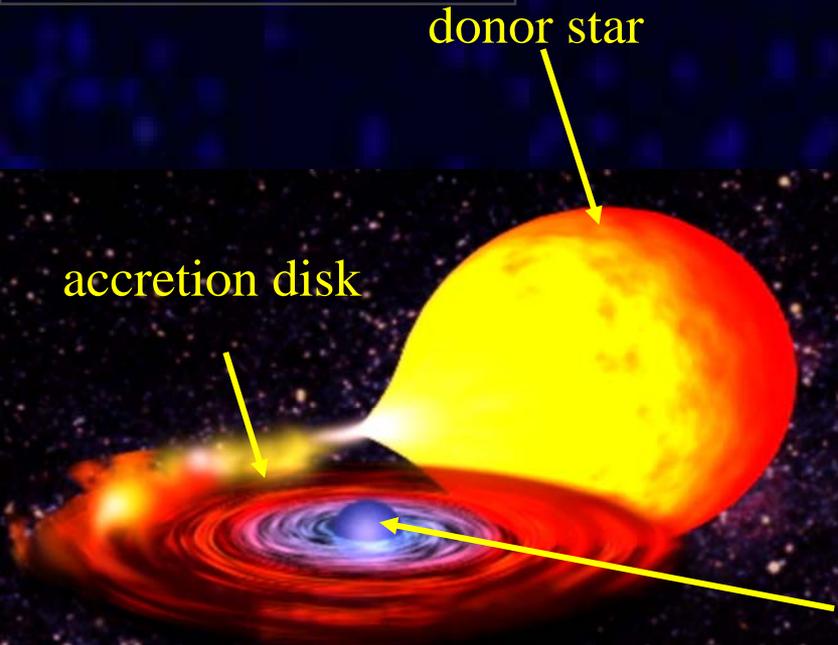
neutron star

$\sim 1.5 M_{\odot}$

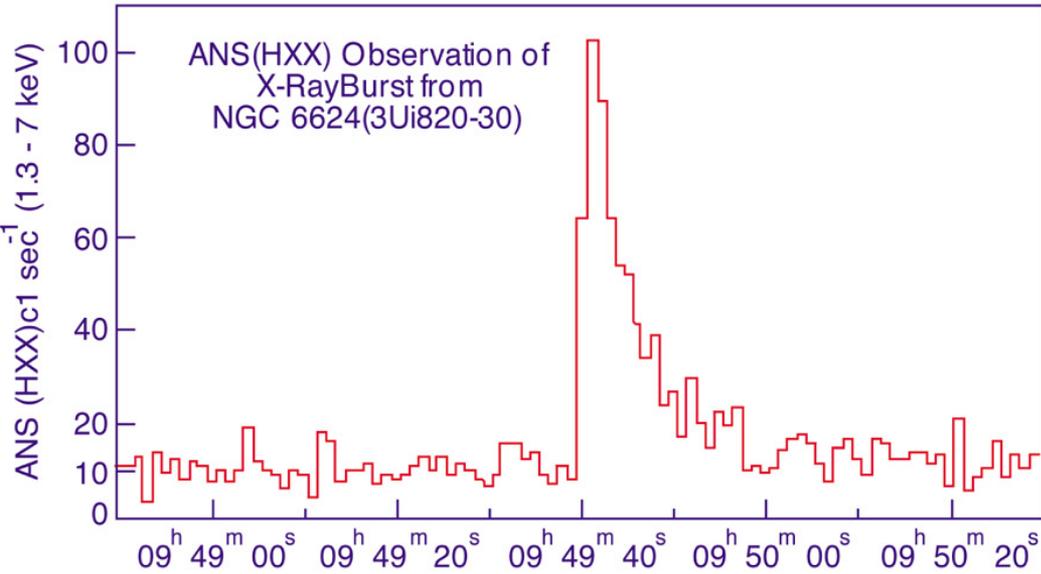
radius ~ 10 km

$\rho \sim 10^{6-14}$ g/cm³

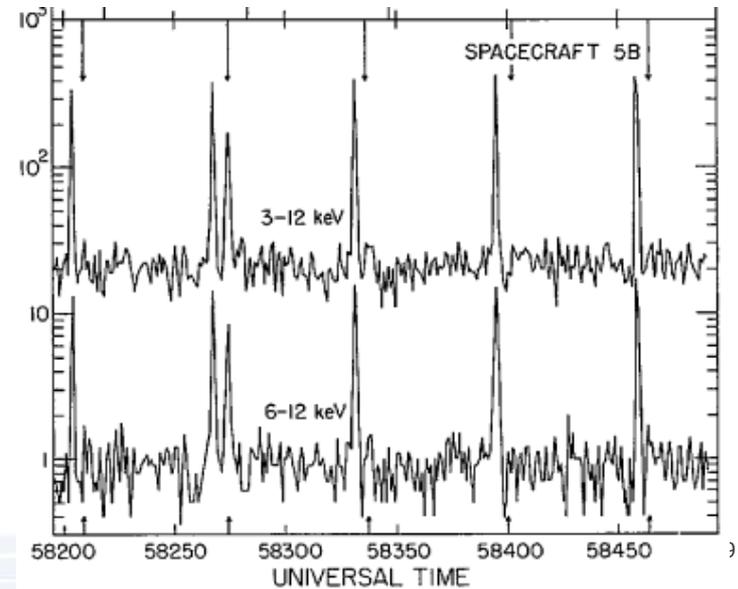
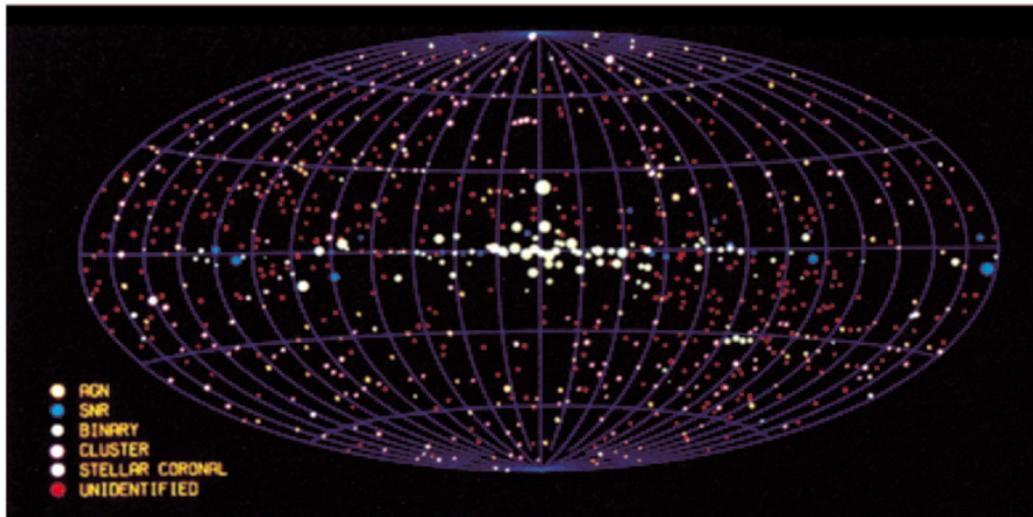
T $\sim 10^7$ K



X-ray Bursts



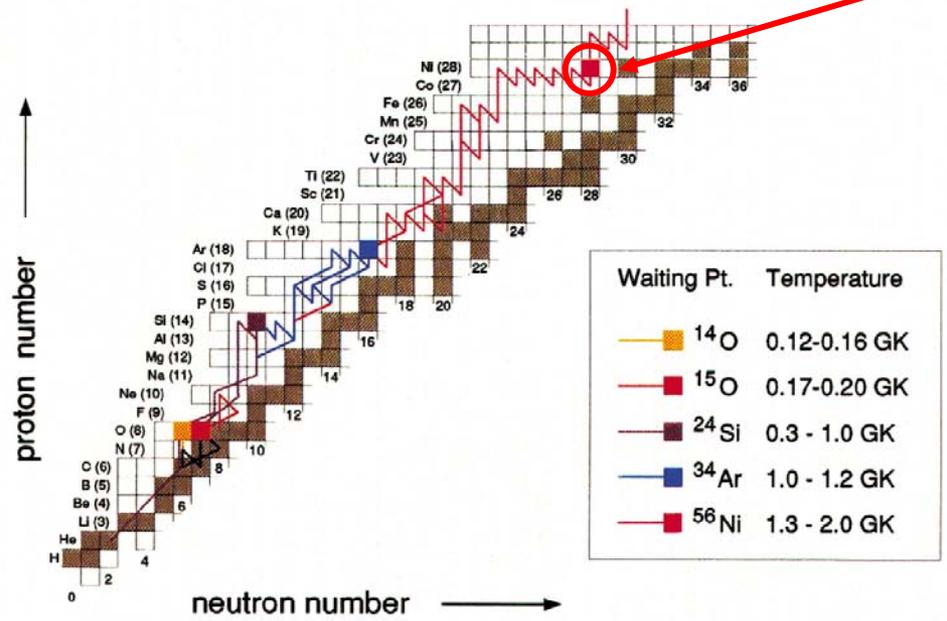
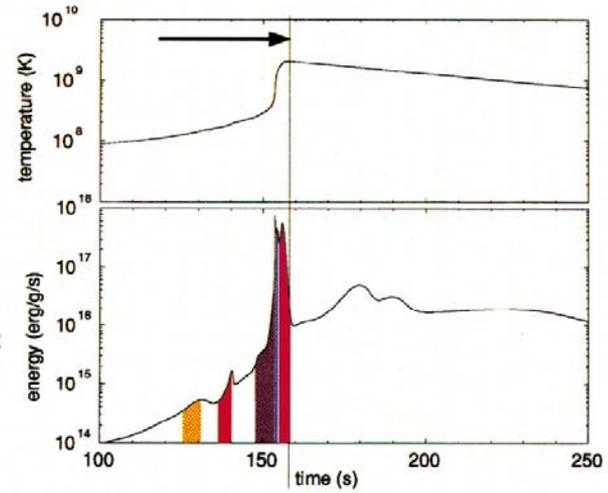
- ~repetition rate hours-days
- duration of ~10 sec
- $E=10^{38}$ erg/s (sun 10^{33} erg/s)



Network calculations for x-ray bursts

● temperature:

● energy production:



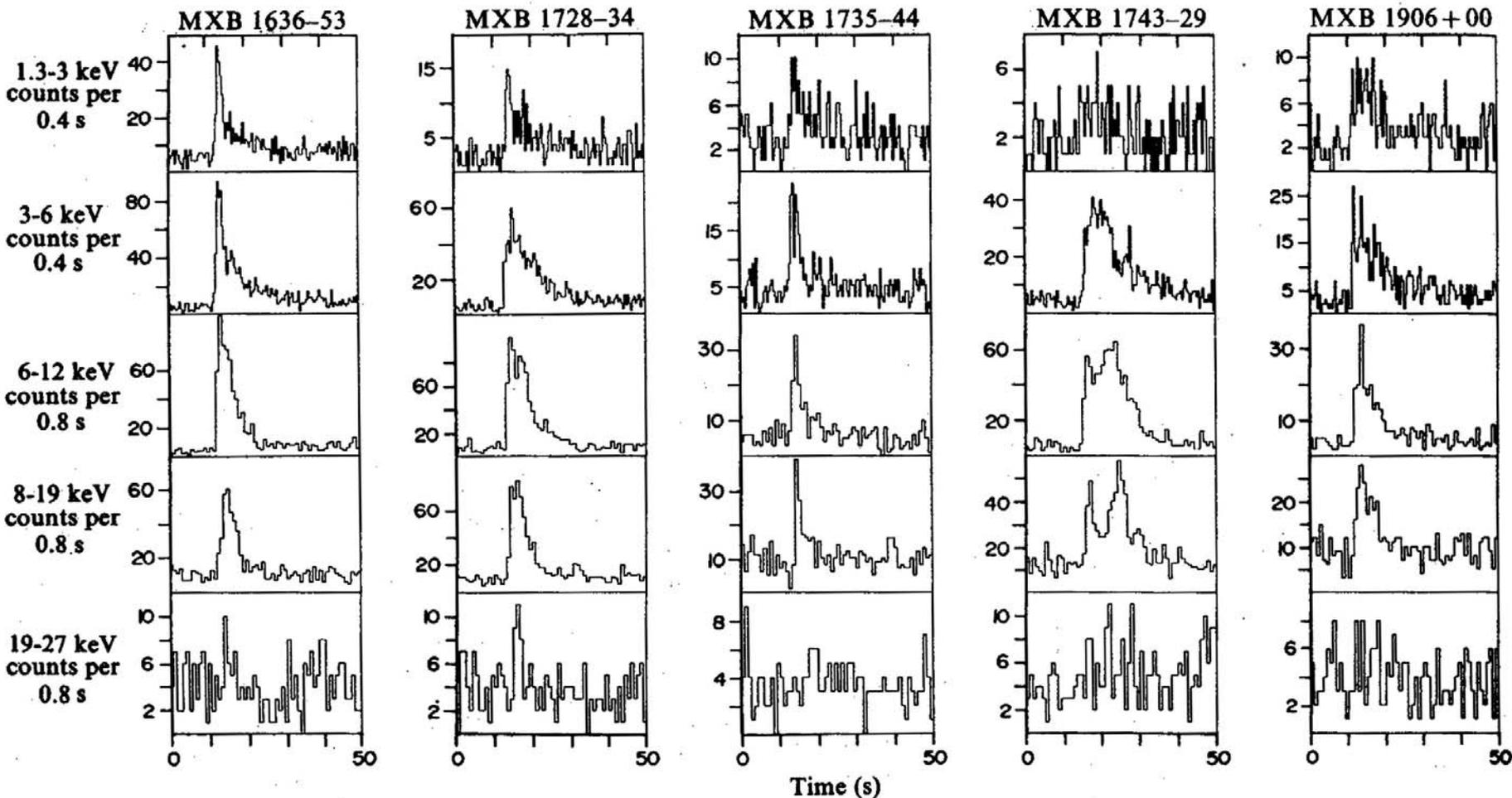
$\sigma \sim \mu\text{b}$

$T_{1/2}(^{56}\text{Ni})=6.1\text{d}$

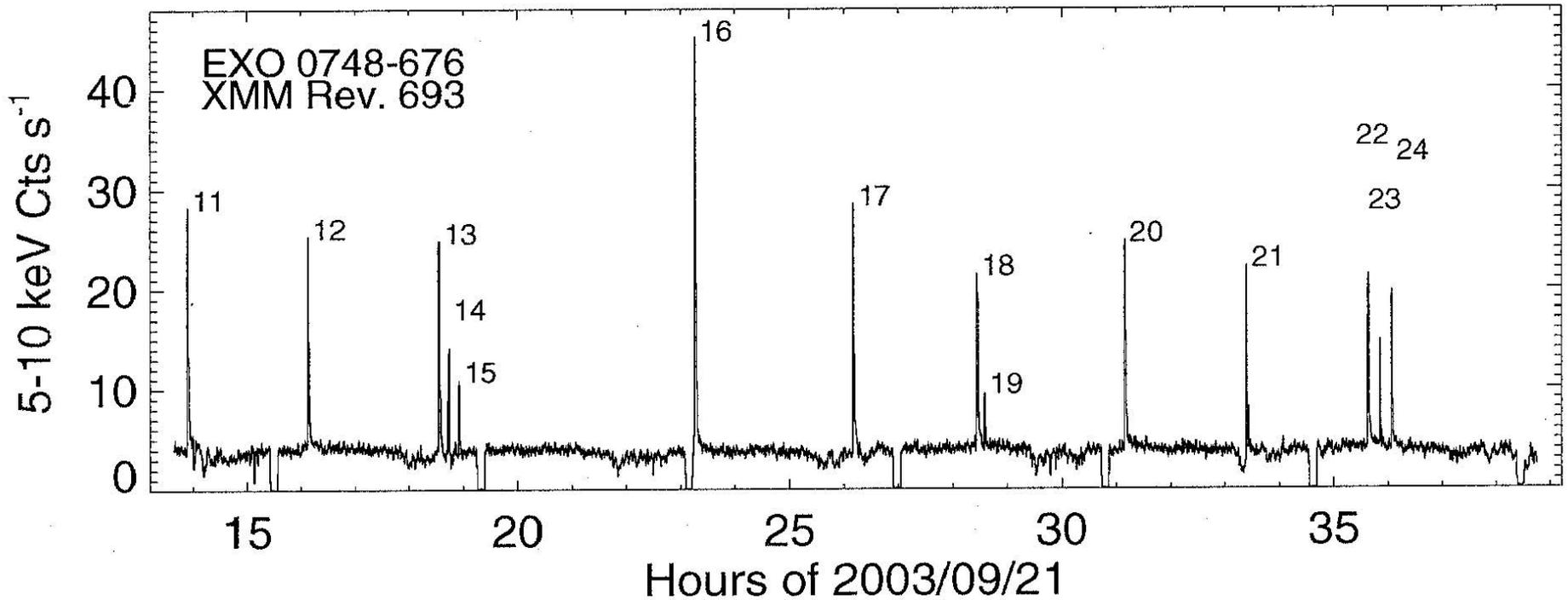
Waiting Pt.	Temperature
14O	0.12-0.16 GK
15O	0.17-0.20 GK
24Si	0.3 - 1.0 GK
34Ar	1.0 - 1.2 GK
56Ni	1.3 - 2.0 GK

What are the observables?

a) Time dependence of the luminosity



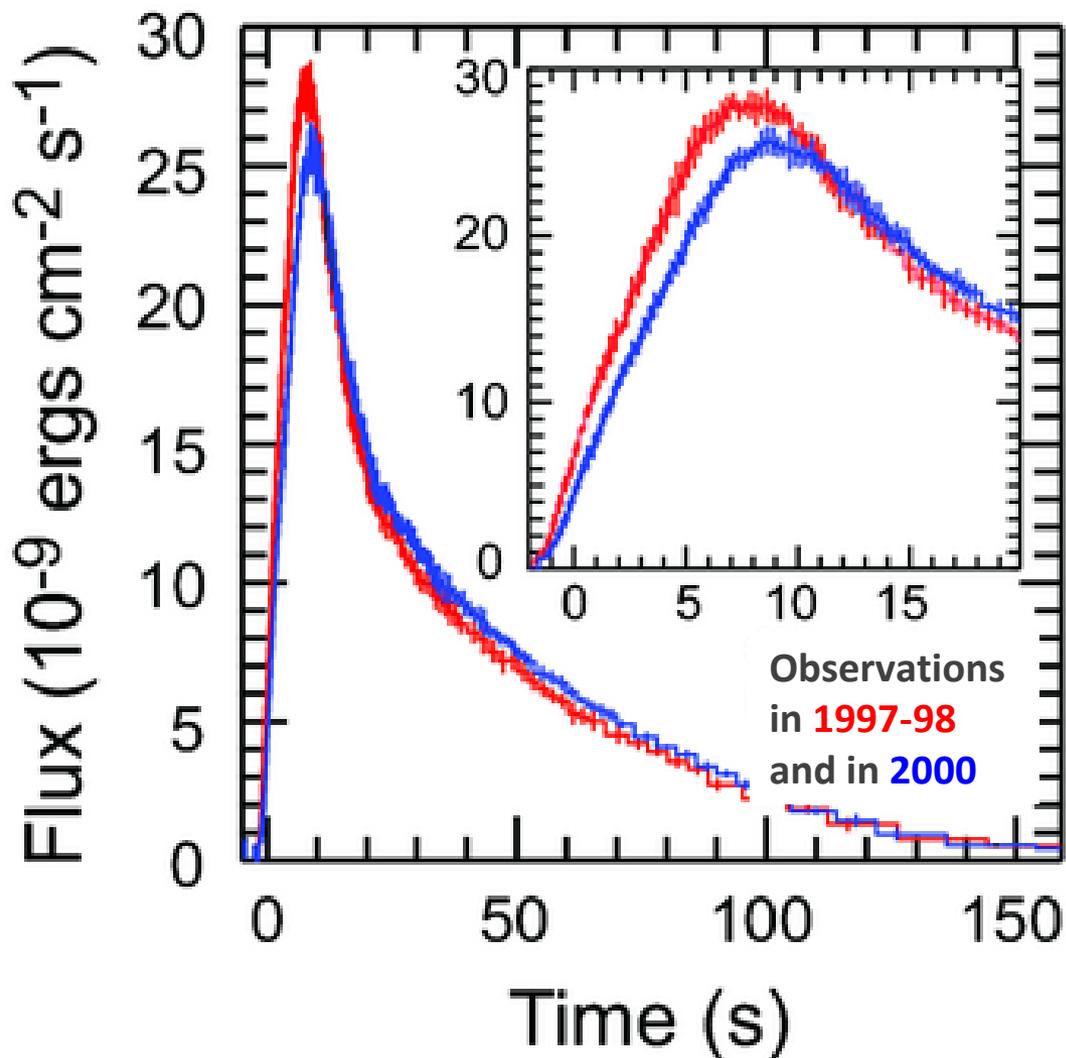
Observables cnt'd: multiplets



L. Boirin et al.,
A&A 2007

Observables cnt'd:

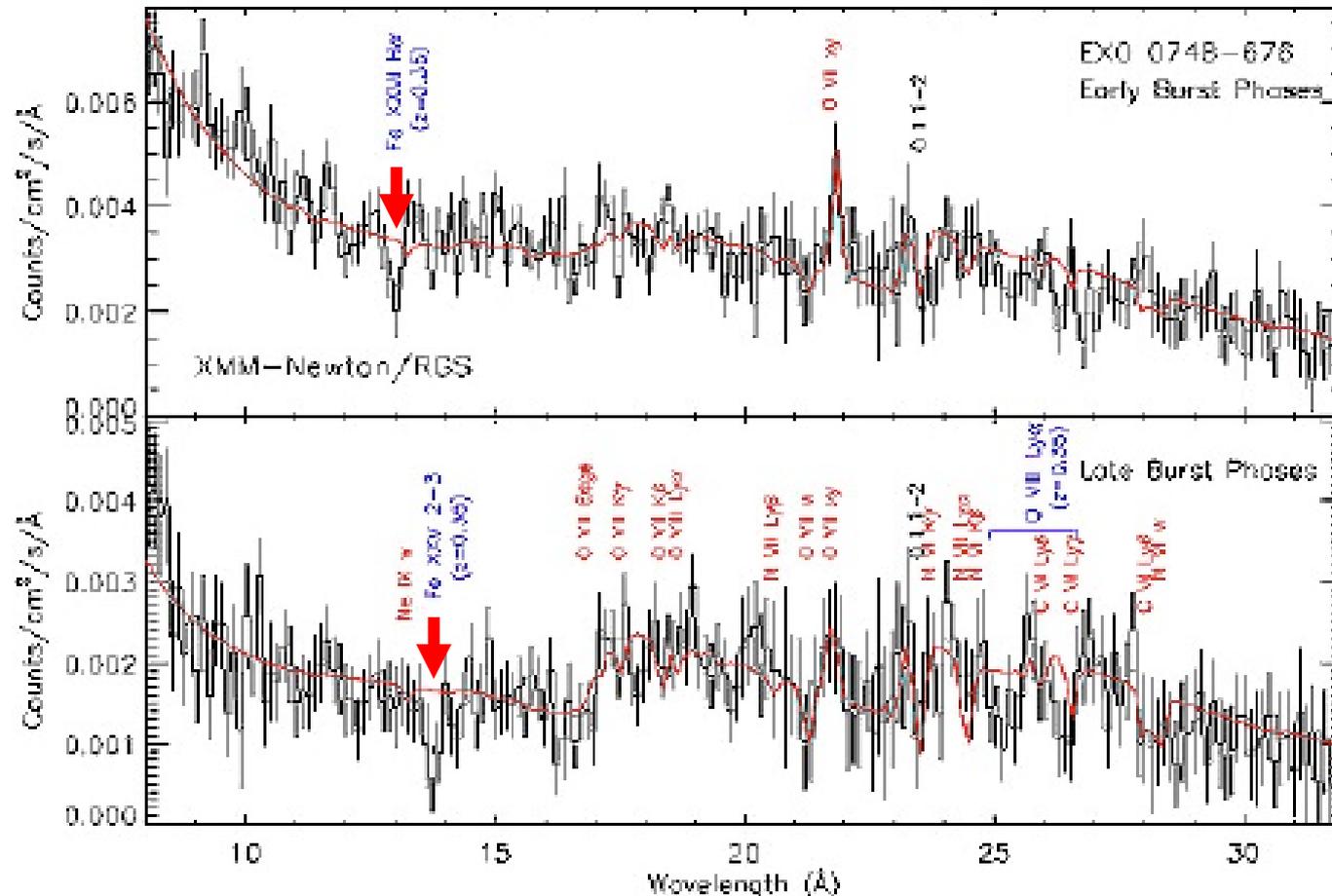
'aging' effects in X-ray bursts



Galloway et al.,
ApJ 601,466(2004)

Observables cnt'd:

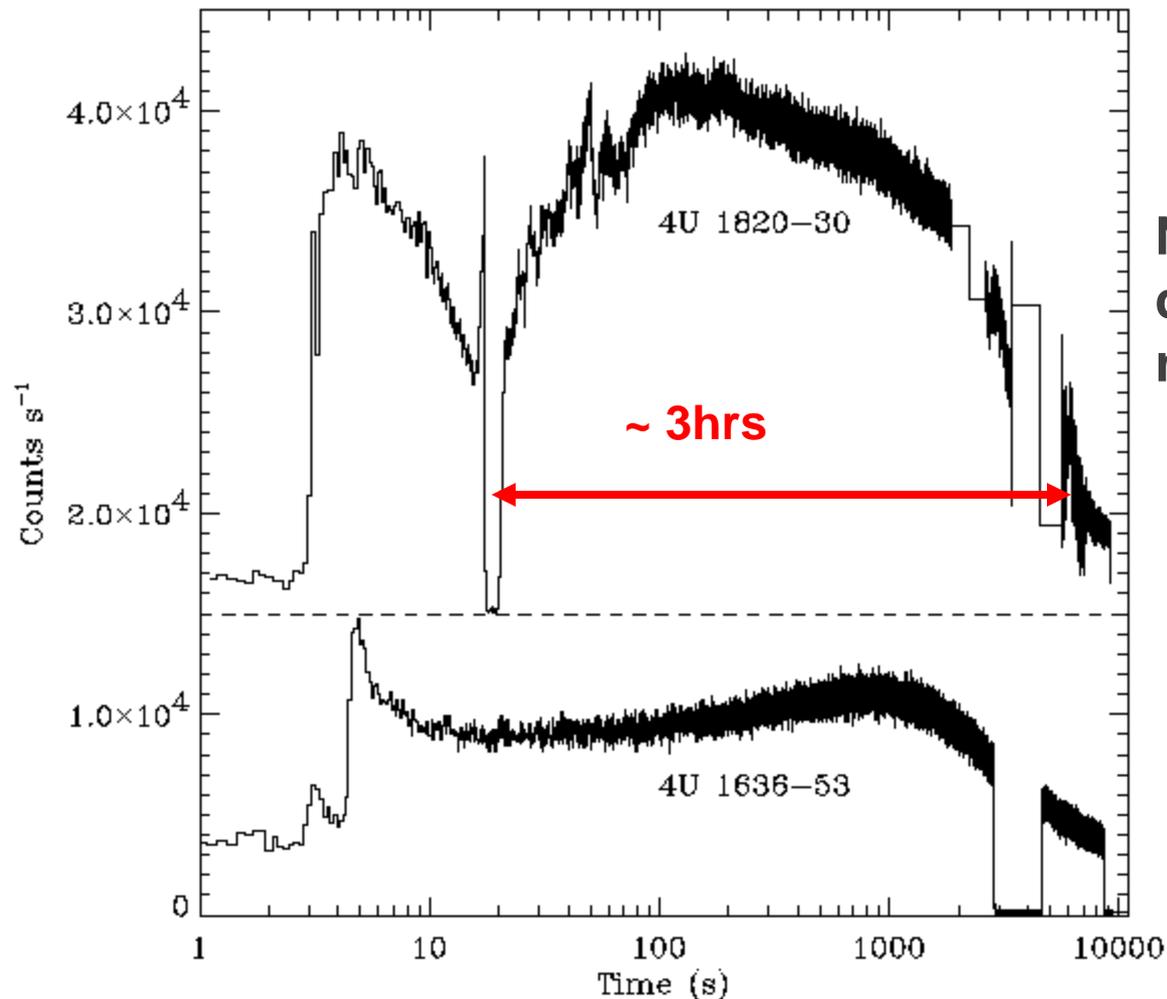
Energy shift of Fe-absorption line (ionization)



Cottam et al. (2002) - Strong gravitational redshifts!
Nature 420, 51

Observables cnt'd:

Long ('super') bursts

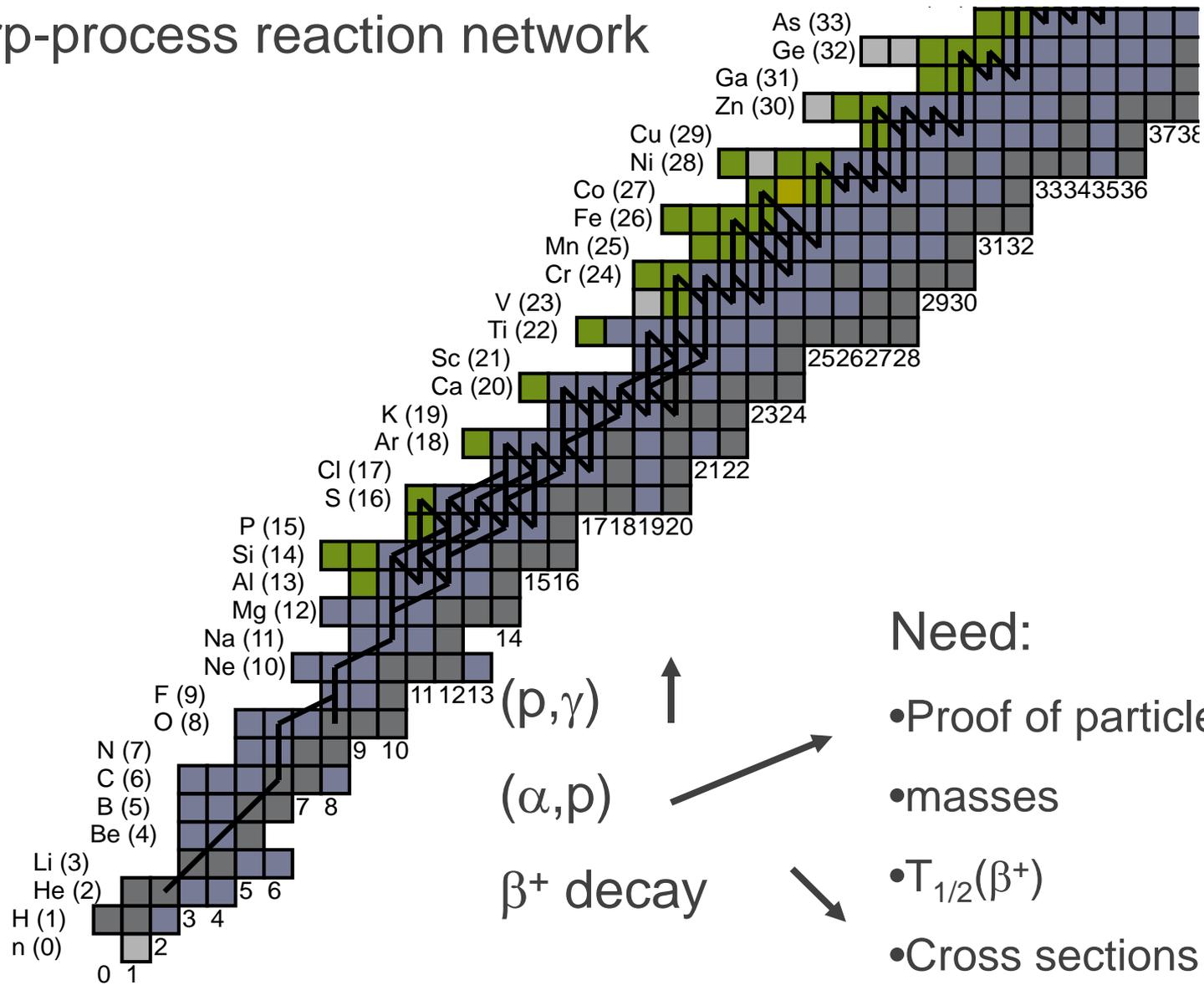


**Nuclear reactions
deeper inside the
neutron star**

**Strohmayer & Brown
ApJ 566, 1045(2002)**

X-ray bursts and Nuclear Physics

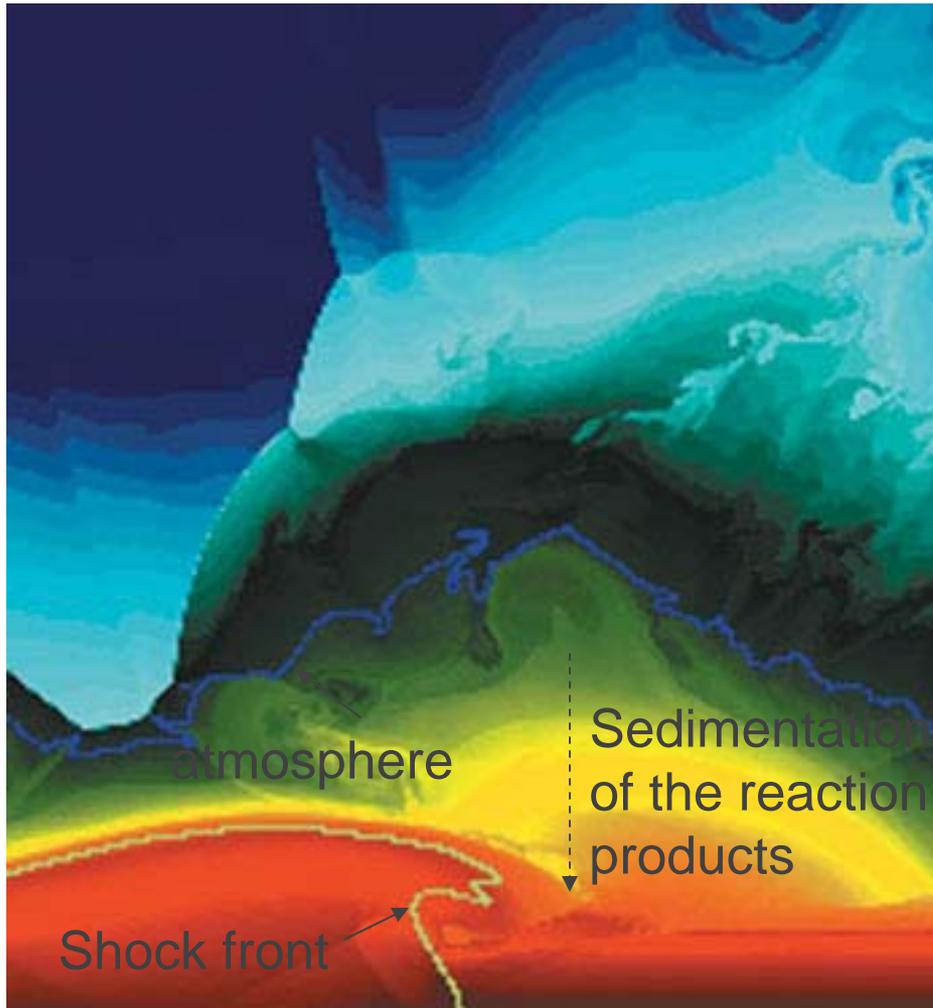
Typical rp-process reaction network



Need:

- Proof of particle stability
- masses
- $T_{1/2}(\beta^+)$
- Cross sections

Theoretical treatment of X-ray bursts

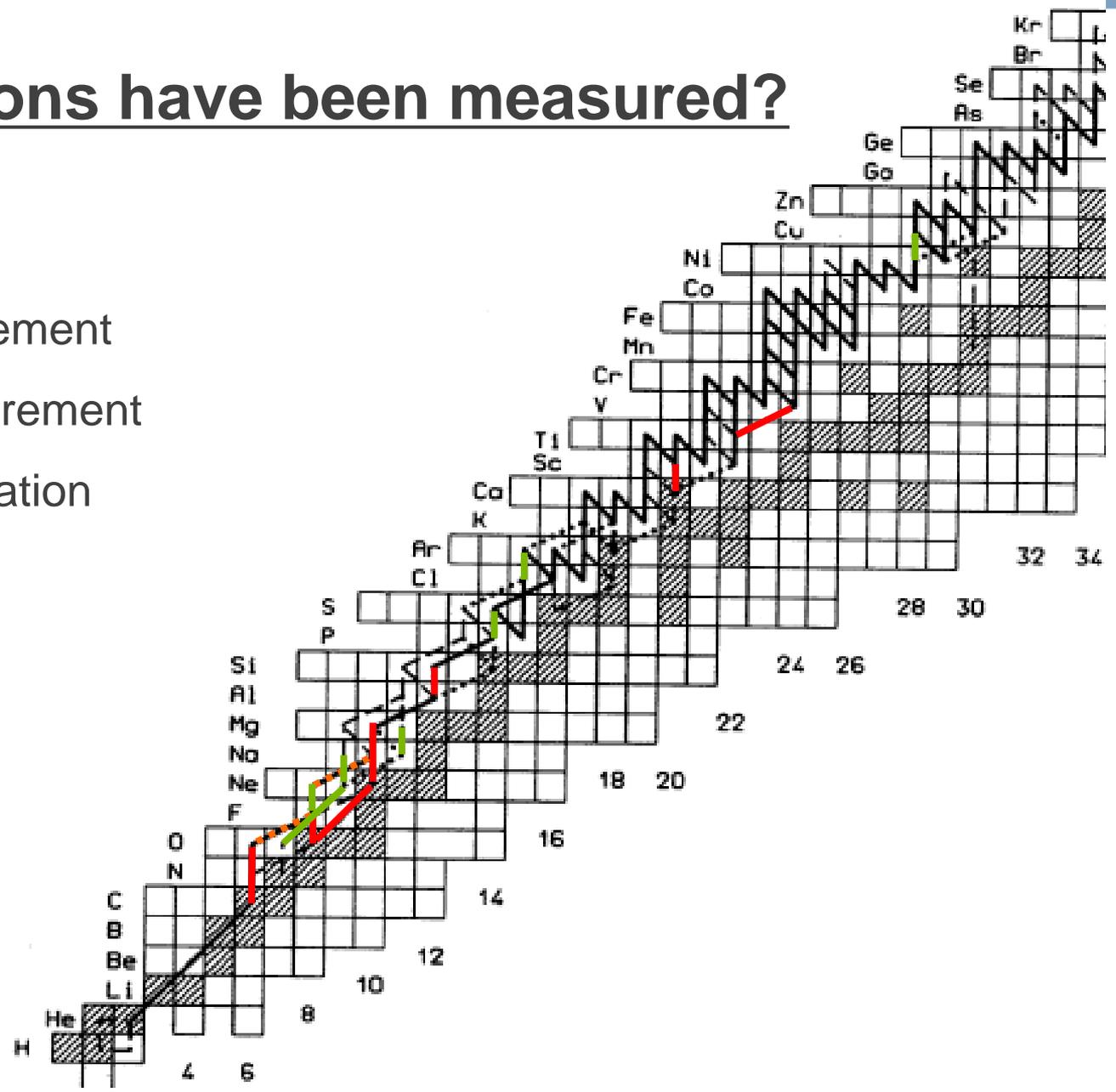


FLASH Center ANL

- $E_{gr}/mc^2 = GM_{NS}/(R_{NS}c^2) \sim 0.2$
- Relativistic treatment
- Three-dimensional
- Rotations
- Turbulences
- Sedimentation
- ‘Ashes’ (e.g. ^{12}C) can burn as well
- Magnetic fields

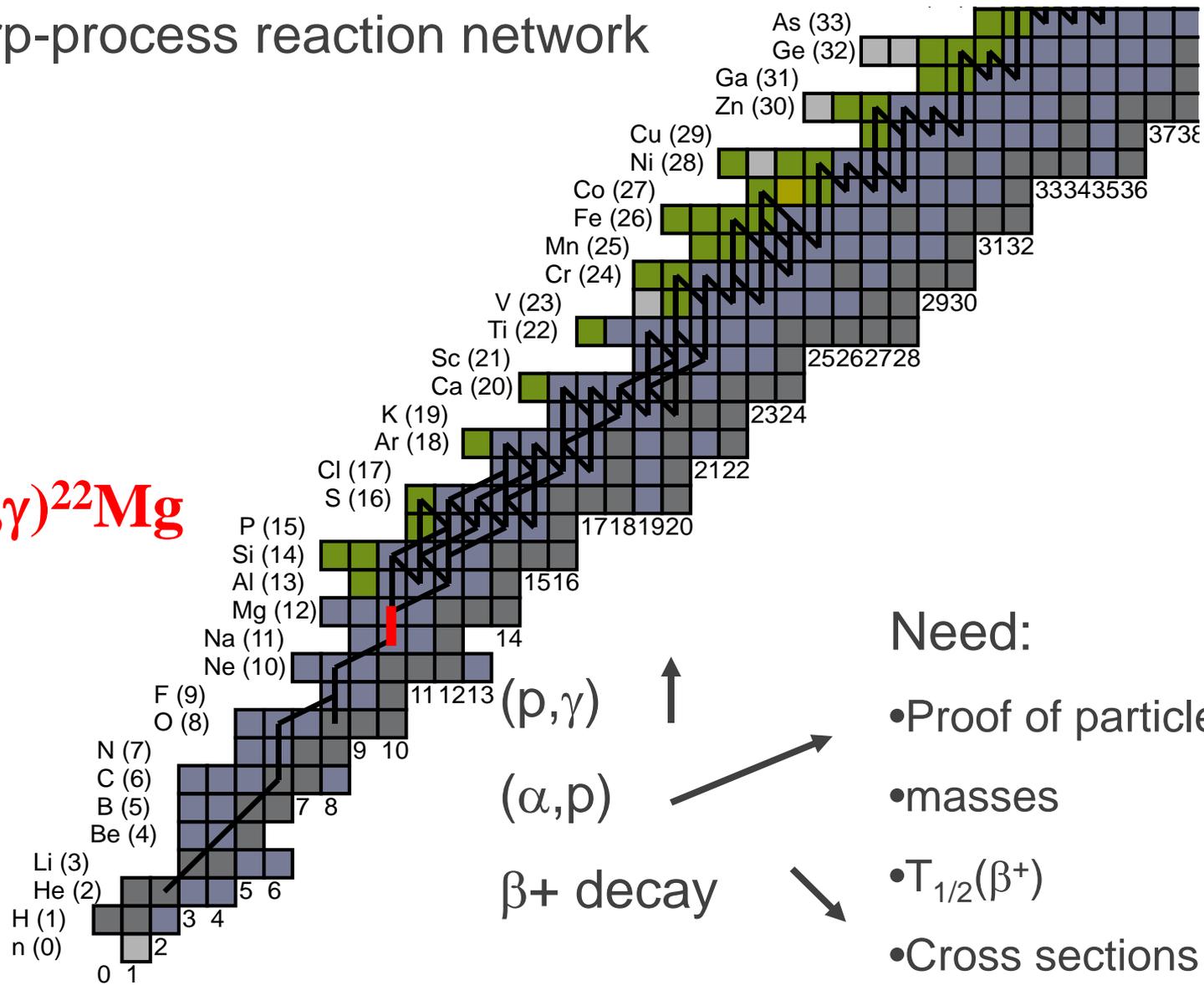
Which reactions have been measured?

- █ Direct measurement
- █ Indirect measurement
- █ Under investigation



X-ray bursts and Nuclear Physics

Typical rp-process reaction network



Need:

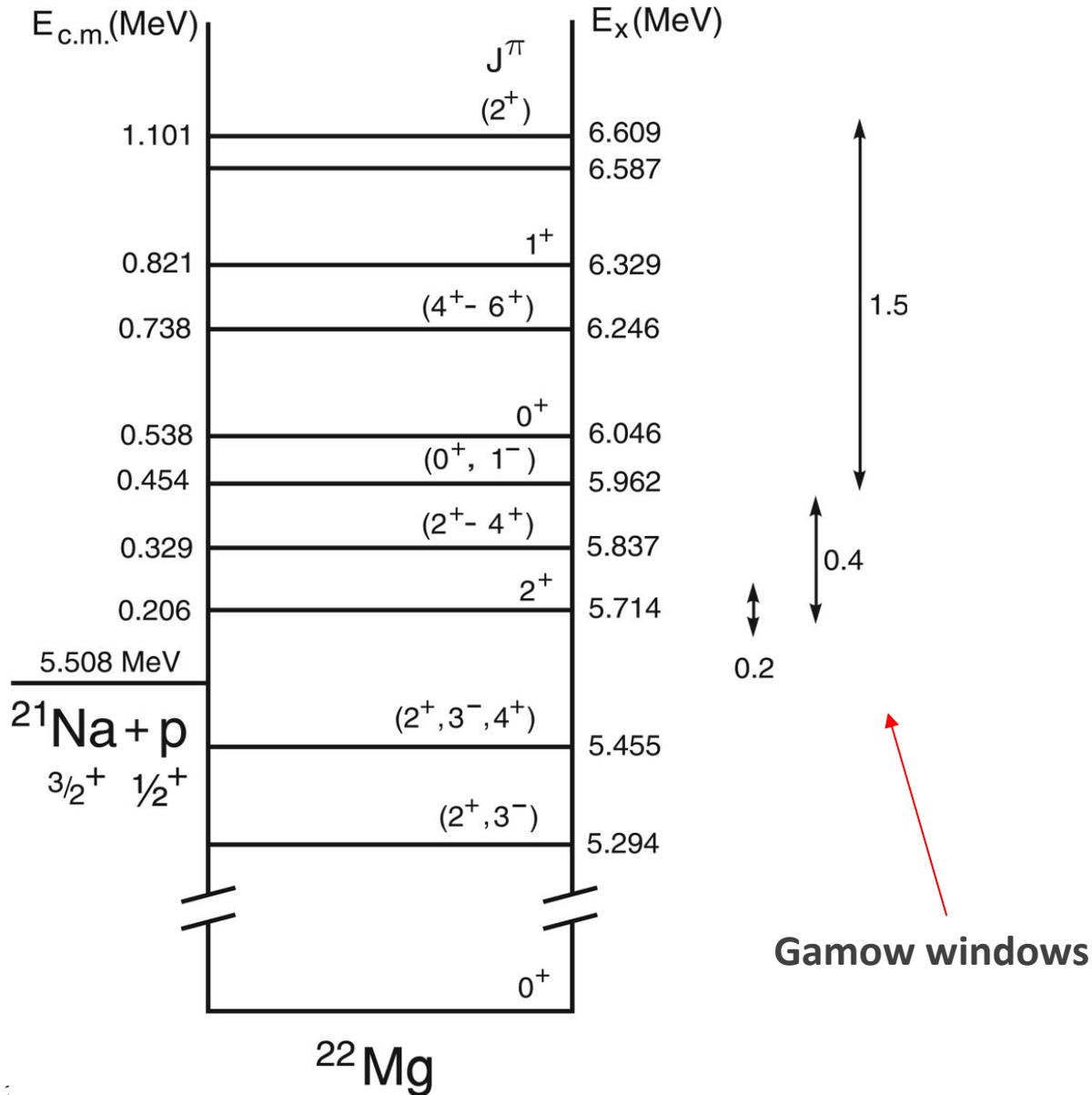
- Proof of particle stability
- masses
- $T_{1/2}(\beta^+)$
- Cross sections

(p,γ) reactions

- Center of activities with radioactive beams
- Mainly resonant
- Example $^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$ (TRIUMF)

S. Bishop et al. PRL90, 162501(2003)

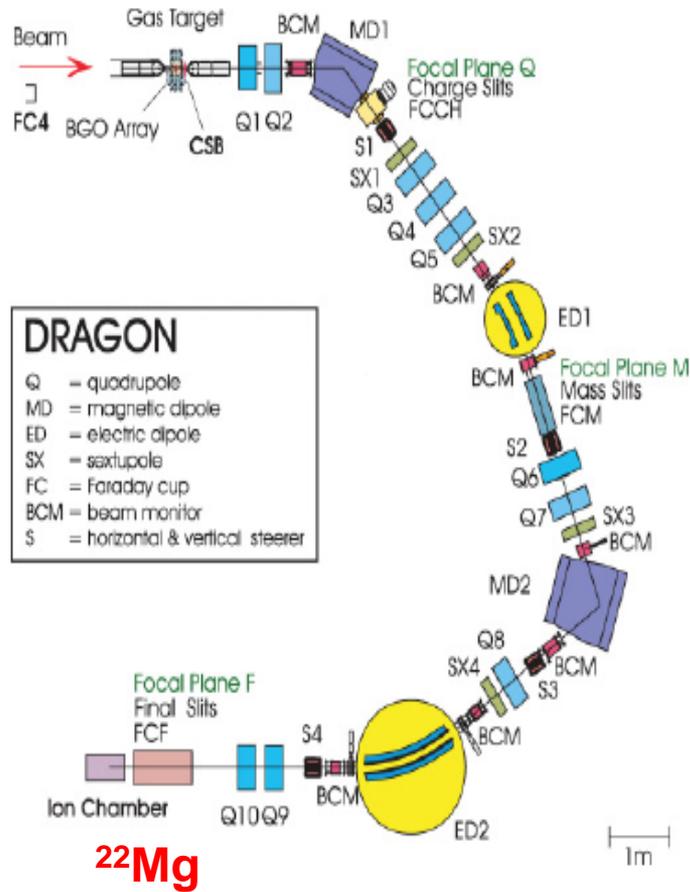
J. d'Auria et al. PRC69, 065803(2004)



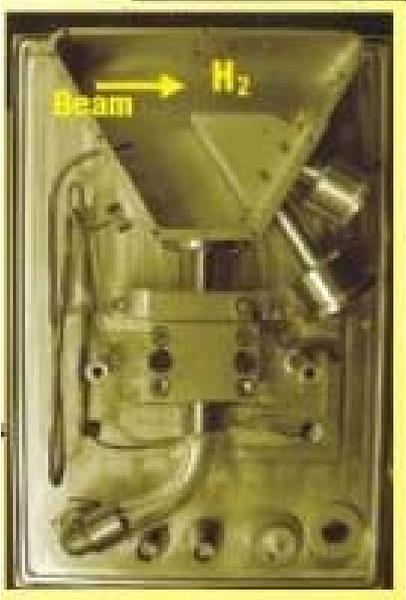
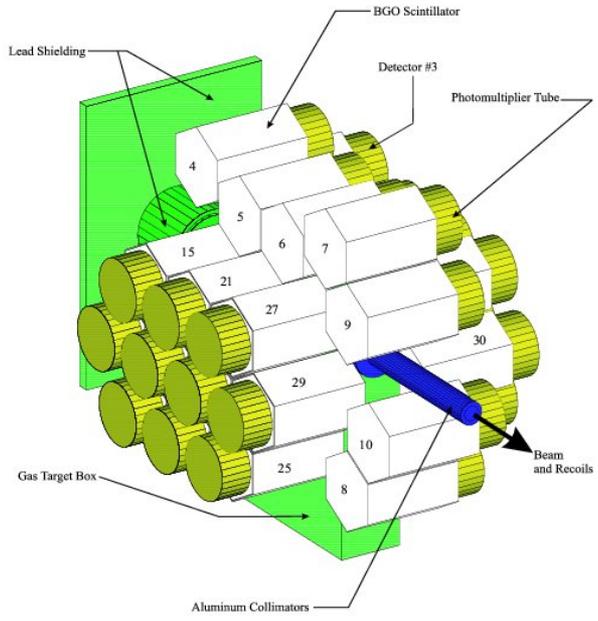
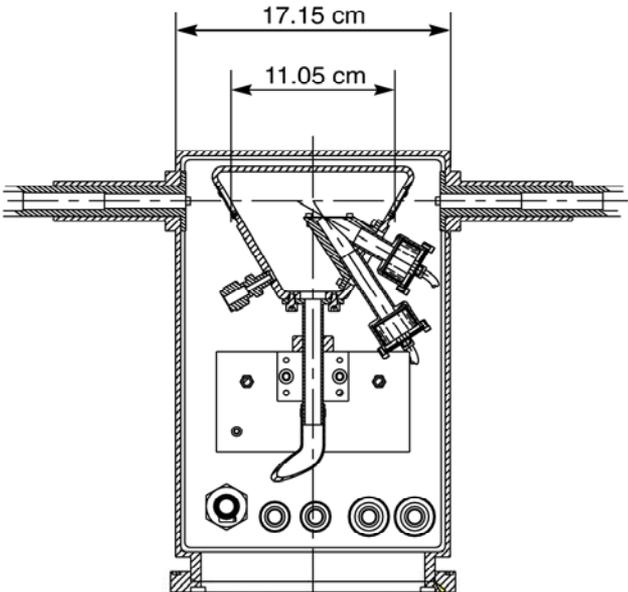
Need 200-900 keV ^{21}Na ($T_{1/2}=22.8$ s) beams and hydrogen gas target

Reaction studied as: $p(^{21}\text{Na}, ^{22}\text{Mg})\gamma$

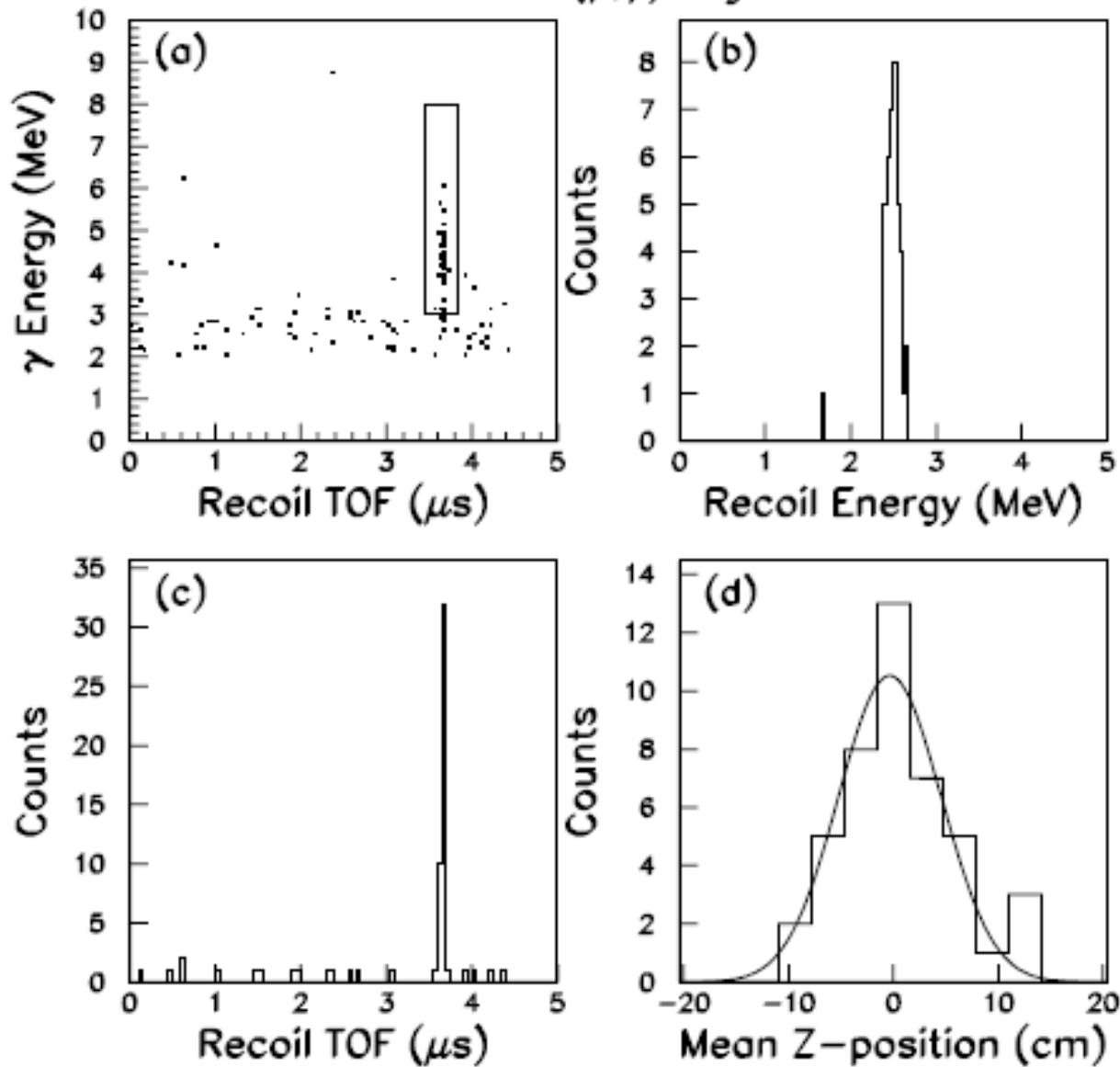
^{21}Na γ

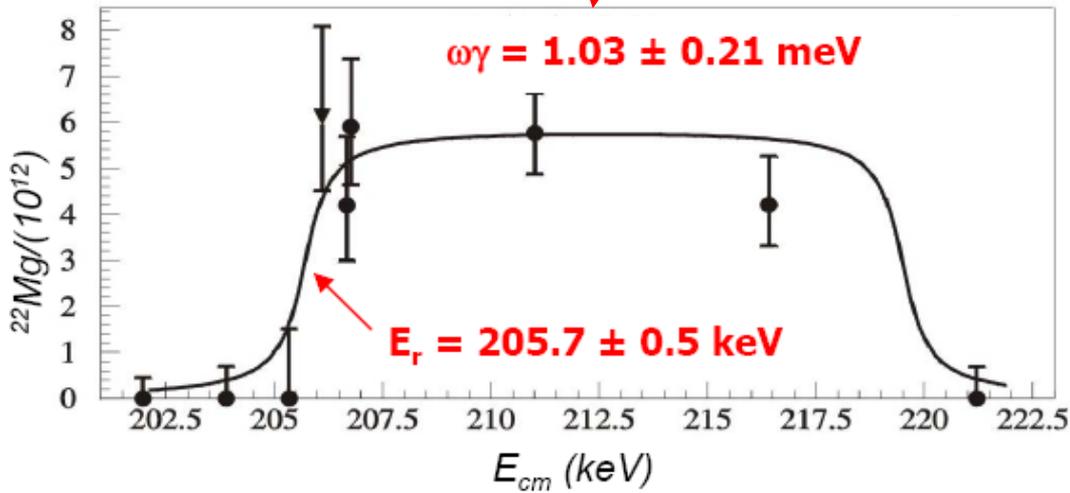
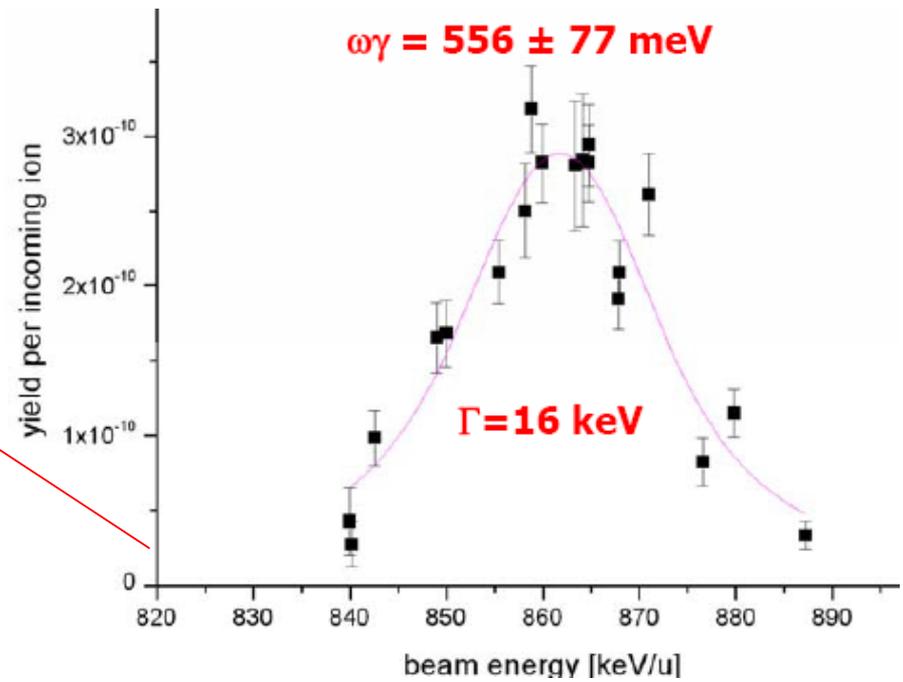
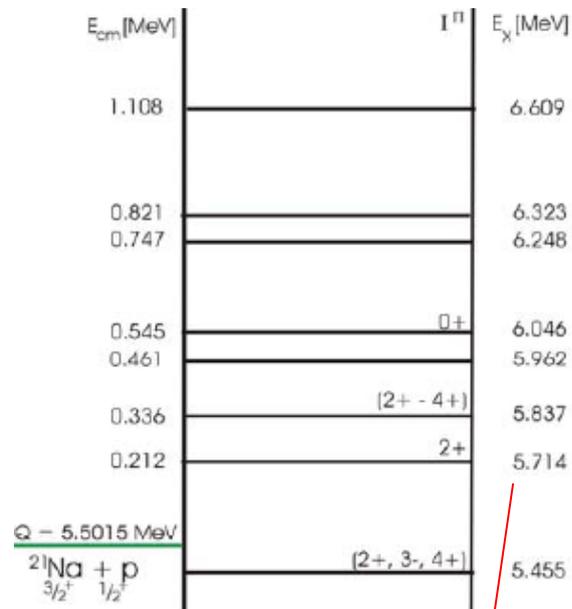


Beam

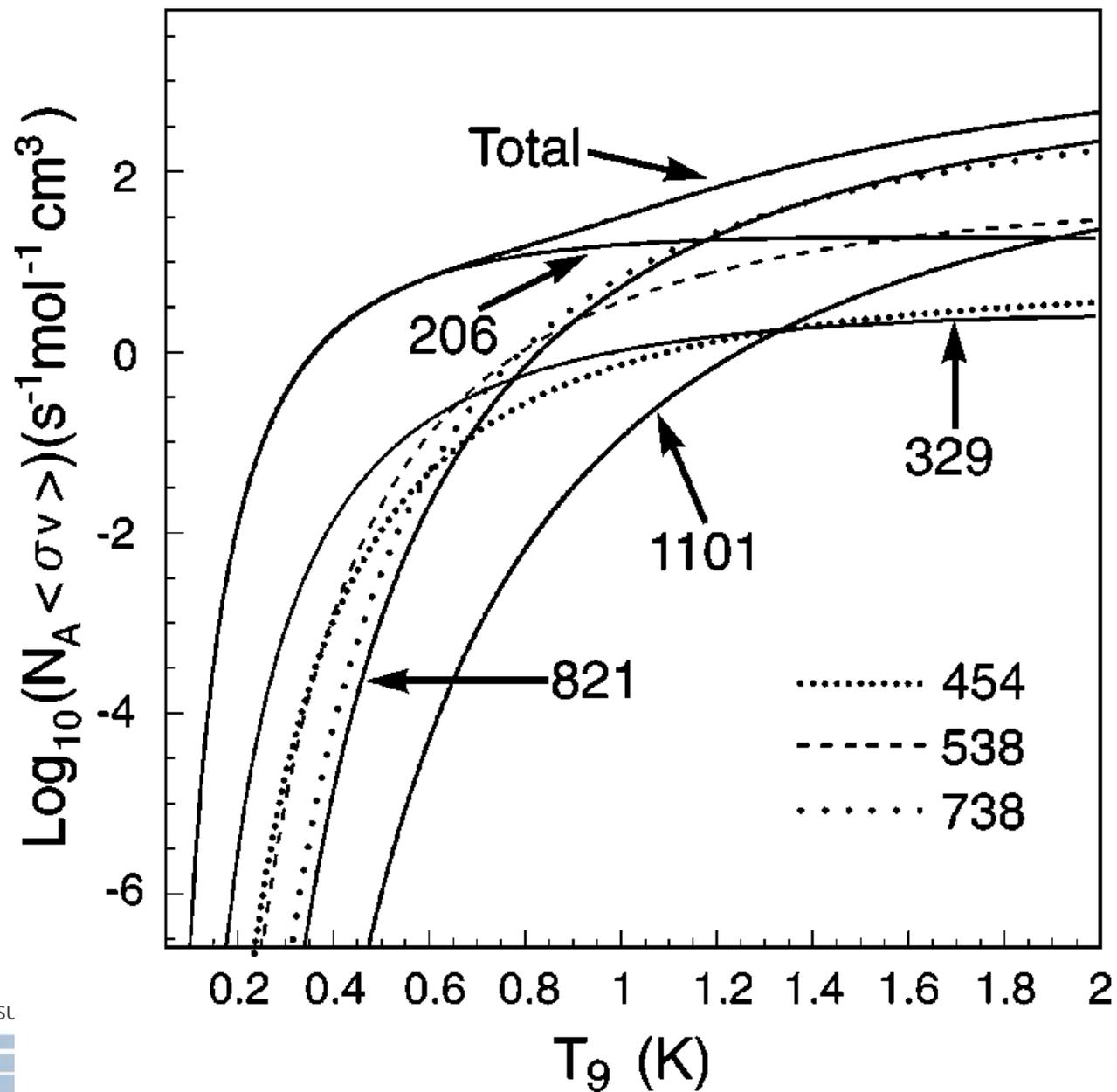


$^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$





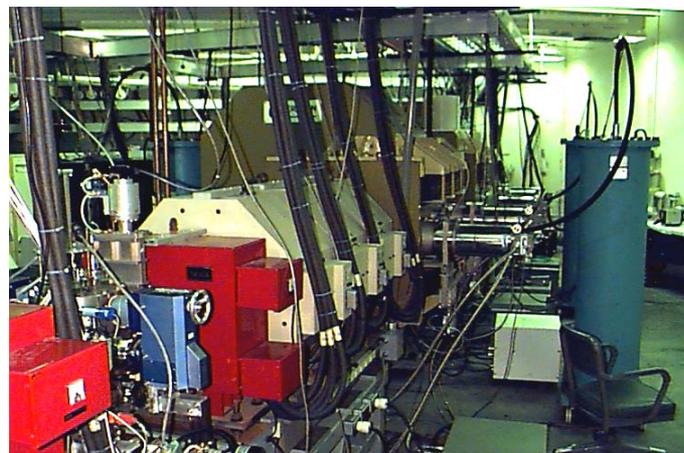
Conversion from cross section to reaction rate



Other Recoil Separators for Astrophysics



DRAGON at TRIUMF ISAC
Used to measure $^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$



DRS at ORNL HRIBF
Used to measure $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$

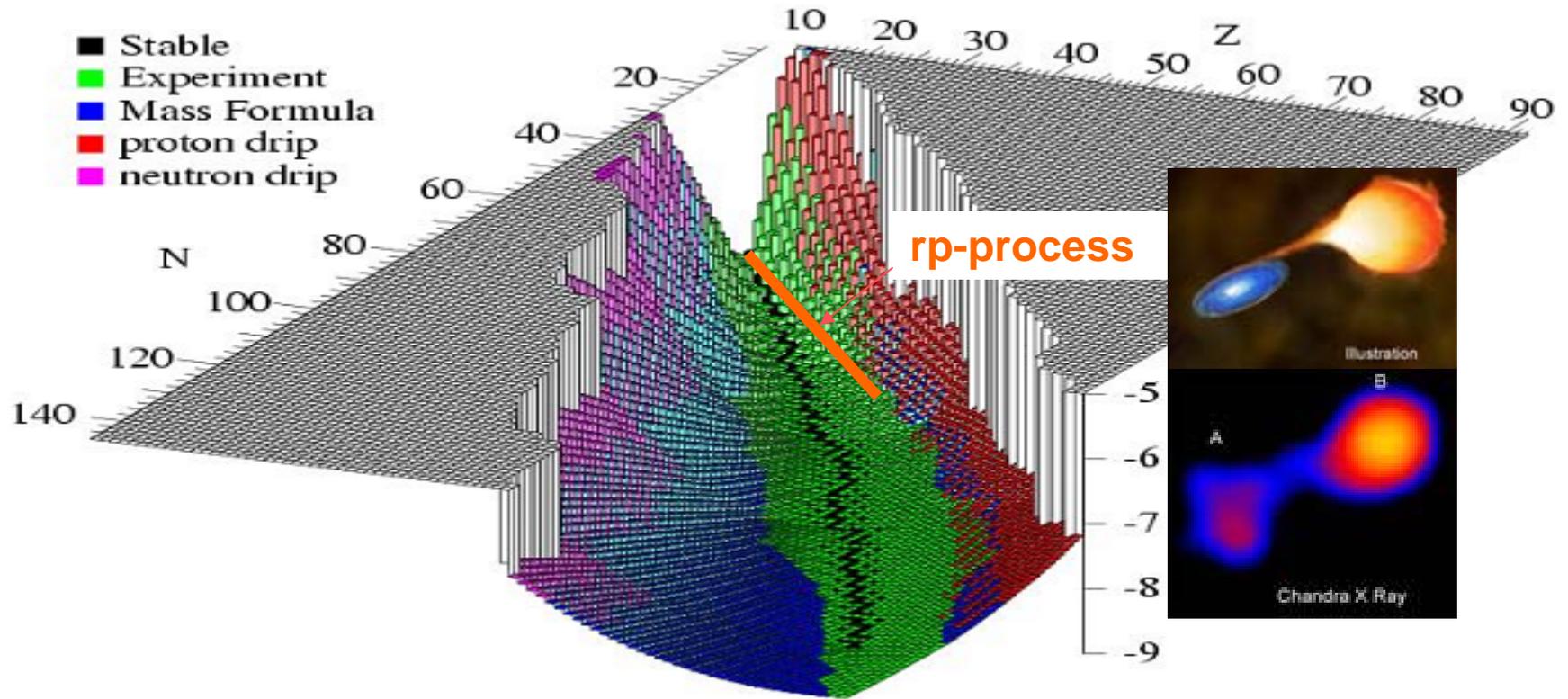


ARES at Louvain-la-Neuve
Used to measure $^{19}\text{Ne}(p,\gamma)^{20}\text{Na}$



FMA at ANL ATLAS
Used to measure $^{18}\text{F}(p,\gamma)^{19}\text{Ne}$

Nuclei involved in Astrophysics



Example 2:

Nucleosynthesis beyond ^{56}Fe :

(r and s-processes)

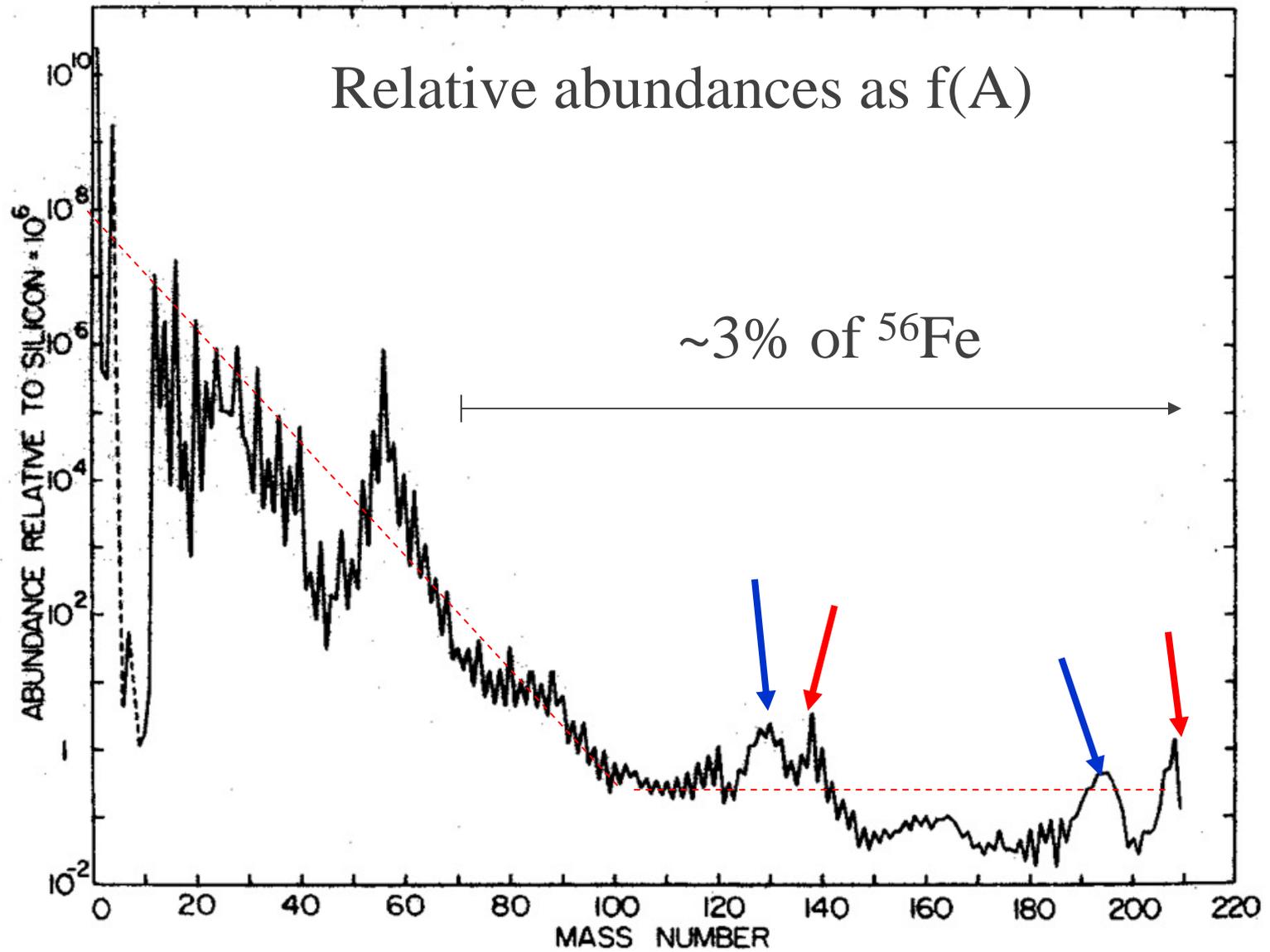
Coulomb barrier too high for charged-particle reactions

→ reactions involving neutrons

from the mass distributions: at least two processes

slow neutron capture (s-process)

rapid neutron capture (r-process)



Where does nature produce neutrons in stars?

Charged-particle reactions

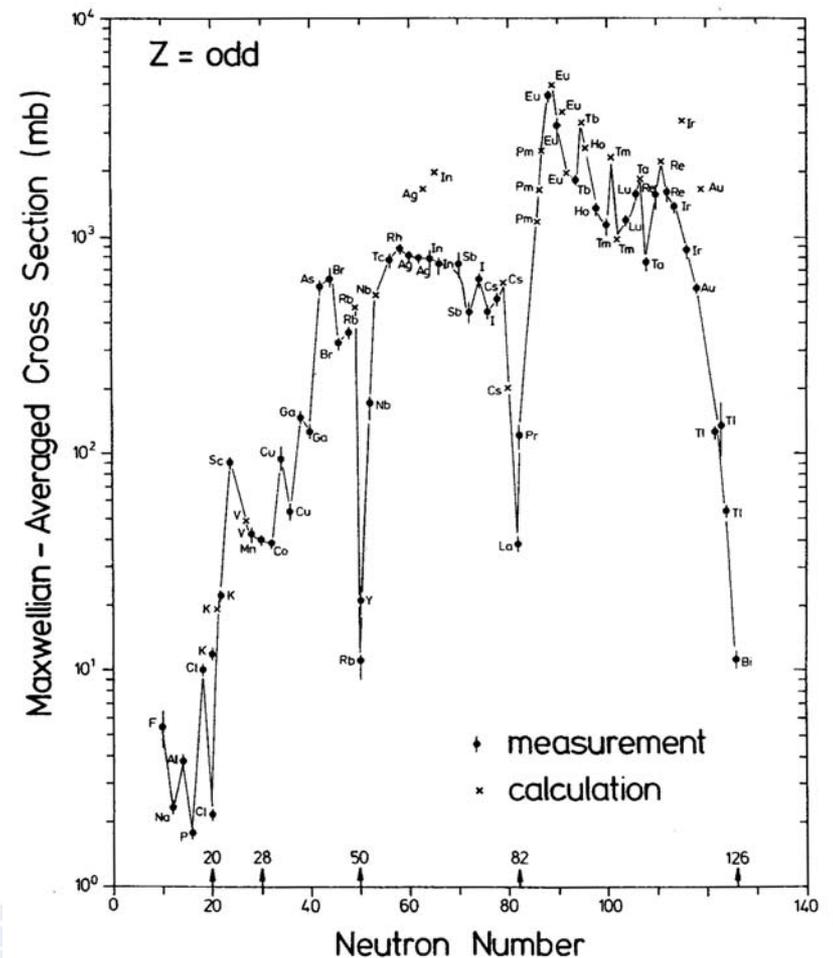
$^{13}\text{C}(\alpha,n)^{16}\text{O}$ $Q=2.216$ MeV (but $^{12}\text{C}(\alpha,n)^{15}\text{O}$ $Q=-8.508$)

$^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$ $Q=-0.480$ MeV

Cross sections for neutron capture reactions are usually quite large.

(100-5000 mb)

Shell effects!

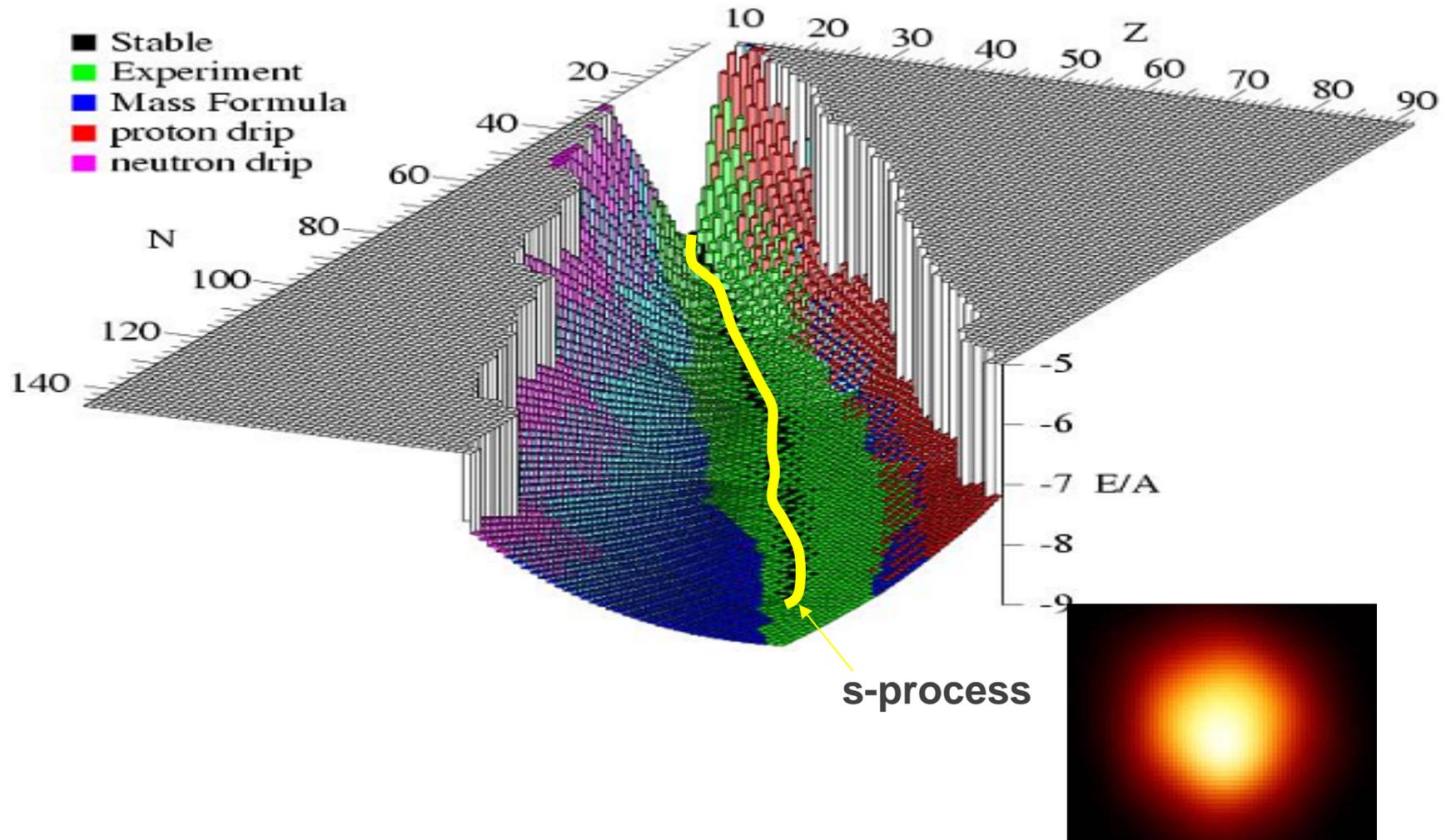


		38		37		36		35		34		33		32		31		30		29		28		27		26		25		24		23		22		21		20		19		18		17		16		15		14		13		12		11		10		9		8		7		6		5		4		3		2		1																					
		Rb 85,4678		Kr 83,80		Kr 69		Kr 70		Kr 71		Kr 72		Kr 73		Kr 74		Kr 75		Kr 76		Kr 77		Kr 78		Kr 79		Kr 80		Kr 81		Kr 82		Kr 83		Kr 84		Kr 85		Kr 86		Kr 87		Kr 88		Kr 89		Kr 90		Kr 91		Kr 92		Kr 93		Kr 94		Kr 95		Kr 96		Kr 97		Kr 98		Kr 99		Kr 100																													
K 53 30 ms		K 54 10 ms		Br 79,904		Br 69		Br 70		Br 71		Br 72		Br 73		Br 74		Br 75		Br 76		Br 77		Br 78		Br 79		Br 80		Br 81		Br 82		Br 83		Br 84		Br 85		Br 86		Br 87		Br 88		Br 89		Br 90		Br 91		Br 92		Br 93		Br 94		Br 95		Br 96		Br 97		Br 98		Br 99		Br 100																													
Se 78,96		Se 65 ?		Se 66		Se 67		Se 68		Se 69		Se 70		Se 71		Se 72		Se 73		Se 74		Se 75		Se 76		Se 77		Se 78		Se 79		Se 80		Se 81		Se 82		Se 83		Se 84		Se 85		Se 86		Se 87		Se 88		Se 89		Se 90		Se 91		Se 92		Se 93		Se 94		Se 95		Se 96		Se 97		Se 98		Se 99		Se 100																									
As 74,92159		As 64		As 65		As 66		As 67		As 68		As 69		As 70		As 71		As 72		As 73		As 74		As 75		As 76		As 77		As 78		As 79		As 80		As 81		As 82		As 83		As 84		As 85		As 86		As 87		As 88		As 89		As 90		As 91		As 92		As 93		As 94		As 95		As 96		As 97		As 98		As 99		As 100																							
Ge 72,61		Ge 61 40 ms		Ge 62		Ge 63 95 ms		Ge 64 64 s		Ge 65 31 s		Ge 66 2,3 h		Ge 67 18,7 m		Ge 68 270,82 d		Ge 69 39,0 h		Ge 70 21,23		Ge 71 11,43 d		Ge 72 27,66		Ge 73 7,73		Ge 74 35,94		Ge 75 47 s		Ge 76 7,44		Ge 77 53 s		Ge 78 11,3 h		Ge 79 1,53 · 10 ²¹ a		Ge 80 53 s		Ge 81 11,3 h		Ge 82 1,53 · 10 ²¹ a		Ge 83 53 s		Ge 84 11,3 h		Ge 85 1,53 · 10 ²¹ a		Ge 86 53 s		Ge 87 11,3 h		Ge 88 1,53 · 10 ²¹ a		Ge 89 53 s		Ge 90 11,3 h		Ge 91 1,53 · 10 ²¹ a		Ge 92 53 s		Ge 93 11,3 h		Ge 94 1,53 · 10 ²¹ a		Ge 95 53 s		Ge 96 11,3 h		Ge 97 1,53 · 10 ²¹ a		Ge 98 53 s		Ge 99 11,3 h		Ge 100 1,53 · 10 ²¹ a																	
Ga 69,723		Ga 60		Ga 61 0,15 s		Ga 62 116 ms		Ga 63 31,4 s		Ga 64 2,61 m		Ga 65 15 m		Ga 66 9,4 h		Ga 67 78,3 h		Ga 68 67,63 m		Ga 69 60,108		Ga 70 21,15 m		Ga 71 39,892		Ga 72 14,1 h		Ga 73 4,86 h		Ga 74 9,5 s		Ga 75 8,1 m		Ga 76 2,1 m		Ga 77 32,6 s		Ga 78 9,5 s		Ga 79 8,1 m		Ga 80 32,6 s		Ga 81 9,5 s		Ga 82 8,1 m		Ga 83 32,6 s		Ga 84 9,5 s		Ga 85 8,1 m		Ga 86 32,6 s		Ga 87 9,5 s		Ga 88 8,1 m		Ga 89 32,6 s		Ga 90 9,5 s		Ga 91 8,1 m		Ga 92 32,6 s		Ga 93 9,5 s		Ga 94 8,1 m		Ga 95 32,6 s		Ga 96 9,5 s		Ga 97 8,1 m		Ga 98 32,6 s		Ga 99 9,5 s		Ga 100 8,1 m															
Zn 58 ?		Zn 59 182 ms		Zn 60 2,4 m		Zn 61 1,5 m		Zn 62 9,13 h		Zn 63 38,1 m		Zn 64 48,6		Zn 65 244,3 d		Zn 66 27,9		Zn 67 4,1		Zn 68 18,8		Zn 69 13,8 h		Zn 70 0,6		Zn 71 3,9 h		Zn 72 46,5 h		Zn 73 5,8 s		Zn 74 23,5 s		Zn 75 96 s		Zn 76 10,2 s		Zn 77 96 s		Zn 78 10,2 s		Zn 79 96 s		Zn 80 10,2 s		Zn 81 96 s		Zn 82 10,2 s		Zn 83 96 s		Zn 84 10,2 s		Zn 85 96 s		Zn 86 10,2 s		Zn 87 96 s		Zn 88 10,2 s		Zn 89 96 s		Zn 90 10,2 s		Zn 91 96 s		Zn 92 10,2 s		Zn 93 96 s		Zn 94 10,2 s		Zn 95 96 s		Zn 96 10,2 s		Zn 97 96 s		Zn 98 10,2 s		Zn 99 96 s		Zn 100 10,2 s													
Cu 57 199 ms		Cu 58 3,20 s		Cu 59 82 s		Cu 60 23 m		Cu 61 3,4 h		Cu 62 9,74 m		Cu 63 69,17		Cu 64 12,700 h		Cu 65 30,83		Cu 66 5,1 m		Cu 67 61,9 h		Cu 68 3,8 m		Cu 69 3,0 m		Cu 70 42 s		Cu 71 19,5 s		Cu 72 6,6 s		Cu 73 3,9 s		Cu 74 1,59 s		Cu 75 1,59 s		Cu 76 1,59 s		Cu 77 1,59 s		Cu 78 1,59 s		Cu 79 1,59 s		Cu 80 1,59 s		Cu 81 1,59 s		Cu 82 1,59 s		Cu 83 1,59 s		Cu 84 1,59 s		Cu 85 1,59 s		Cu 86 1,59 s		Cu 87 1,59 s		Cu 88 1,59 s		Cu 89 1,59 s		Cu 90 1,59 s		Cu 91 1,59 s		Cu 92 1,59 s		Cu 93 1,59 s		Cu 94 1,59 s		Cu 95 1,59 s		Cu 96 1,59 s		Cu 97 1,59 s		Cu 98 1,59 s		Cu 99 1,59 s		Cu 100 1,59 s											
Ni 56 6,075 d		Ni 57 36,0 h		Ni 58 68,077		Ni 59 7,5 · 10 ⁴ a		Ni 60 26,2 d		Ni 61 1,67 s		Ni 62 634		Ni 63 90 a		Ni 64 0,926		Ni 65 2,52 h		Ni 66 54,6 h		Ni 67 21 s		Ni 68 19 s		Ni 69 11,4 s		Ni 70 1,86 s		Ni 71 2,06 s		Ni 72 0,90 s		Ni 73 0,90 s		Ni 74 0,90 s		Ni 75 0,90 s		Ni 76 0,90 s		Ni 77 0,90 s		Ni 78 0,90 s		Ni 79 0,90 s		Ni 80 0,90 s		Ni 81 0,90 s		Ni 82 0,90 s		Ni 83 0,90 s		Ni 84 0,90 s		Ni 85 0,90 s		Ni 86 0,90 s		Ni 87 0,90 s		Ni 88 0,90 s		Ni 89 0,90 s		Ni 90 0,90 s		Ni 91 0,90 s		Ni 92 0,90 s		Ni 93 0,90 s		Ni 94 0,90 s		Ni 95 0,90 s		Ni 96 0,90 s		Ni 97 0,90 s		Ni 98 0,90 s		Ni 99 0,90 s		Ni 100 0,90 s									
Co 55 17,54 h		Co 56 77,26 d		Co 57 271,79 d		Co 58 8,94 h		Co 59 70,86 d		Co 60 10,3 s		Co 61 1,65 h		Co 62 14,0 m		Co 63 1,5 m		Co 64 0,3 s		Co 65 1,14 s		Co 66 0,23 s		Co 67 0,42 s		Co 68 0,18 s		Co 69 0,27 s		Co 70 0,19 s		Co 71 0,20 s		Co 72 0,15 s		Co 73 0,15 s		Co 74 0,15 s		Co 75 0,15 s		Co 76 0,15 s		Co 77 0,15 s		Co 78 0,15 s		Co 79 0,15 s		Co 80 0,15 s		Co 81 0,15 s		Co 82 0,15 s		Co 83 0,15 s		Co 84 0,15 s		Co 85 0,15 s		Co 86 0,15 s		Co 87 0,15 s		Co 88 0,15 s		Co 89 0,15 s		Co 90 0,15 s		Co 91 0,15 s		Co 92 0,15 s		Co 93 0,15 s		Co 94 0,15 s		Co 95 0,15 s		Co 96 0,15 s		Co 97 0,15 s		Co 98 0,15 s		Co 99 0,15 s		Co 100 0,15 s							
Fe 54 5,8		Fe 55 2,73 a		Fe 56 91,72		Fe 57 2,2		Fe 58 0,28		Fe 59 4,5 · 10 ³ d		Fe 60 1,5 · 10 ⁶ a		Fe 61 6,0 m		Fe 62 8,8		Fe 63 8,1		Fe 64 2,3 s		Fe 65 2,3 s		Fe 66 2,3 s		Fe 67 2,3 s		Fe 68 2,3 s		Fe 69 2,3 s		Fe 70 2,3 s		Fe 71 2,3 s		Fe 72 2,3 s		Fe 73 2,3 s		Fe 74 2,3 s		Fe 75 2,3 s		Fe 76 2,3 s		Fe 77 2,3 s		Fe 78 2,3 s		Fe 79 2,3 s		Fe 80 2,3 s		Fe 81 2,3 s		Fe 82 2,3 s		Fe 83 2,3 s		Fe 84 2,3 s		Fe 85 2,3 s		Fe 86 2,3 s		Fe 87 2,3 s		Fe 88 2,3 s		Fe 89 2,3 s		Fe 90 2,3 s		Fe 91 2,3 s		Fe 92 2,3 s		Fe 93 2,3 s		Fe 94 2,3 s		Fe 95 2,3 s		Fe 96 2,3 s		Fe 97 2,3 s		Fe 98 2,3 s		Fe 99 2,3 s		Fe 100 2,3 s					
Mn 53 3,7 · 10 ⁶ a		Mn 54 312,2 d		Mn 55 100		Mn 56 2,58 h		Mn 57 1,5 m		Mn 58 65,3 s		Mn 59 3,0 s		Mn 60 1,77 s		Mn 61 0,71 s		Mn 62 0,88 s		Mn 63 0,25 s		Mn 64 0,25 s		Mn 65 0,25 s		Mn 66 0,25 s		Mn 67 0,25 s		Mn 68 0,25 s		Mn 69 0,25 s		Mn 70 0,25 s		Mn 71 0,25 s		Mn 72 0,25 s		Mn 73 0,25 s		Mn 74 0,25 s		Mn 75 0,25 s		Mn 76 0,25 s		Mn 77 0,25 s		Mn 78 0,25 s		Mn 79 0,25 s		Mn 80 0,25 s		Mn 81 0,25 s		Mn 82 0,25 s		Mn 83 0,25 s		Mn 84 0,25 s		Mn 85 0,25 s		Mn 86 0,25 s		Mn 87 0,25 s		Mn 88 0,25 s		Mn 89 0,25 s		Mn 90 0,25 s		Mn 91 0,25 s		Mn 92 0,25 s		Mn 93 0,25 s		Mn 94 0,25 s		Mn 95 0,25 s		Mn 96 0,25 s		Mn 97 0,25 s		Mn 98 0,25 s		Mn 99 0,25 s		Mn 100 0,25 s			
Cr 52 83,789		Cr 53 9,501		Cr 54 2,365		Cr 55 3,50 m		Cr 56 5,9 m		Cr 57 21,1 s		Cr 58 7,0 s		Cr 59 0,74 s		Cr 60 0,57 s		Cr 61 0,57 s		Cr 62 0,57 s		Cr 63 0,57 s		Cr 64 0,57 s		Cr 65 0,57 s		Cr 66 0,57 s		Cr 67 0,57 s		Cr 68 0,57 s		Cr 69 0,57 s		Cr 70 0,57 s		Cr 71 0,57 s		Cr 72 0,57 s		Cr 73 0,57 s		Cr 74 0,57 s		Cr 75 0,57 s		Cr 76 0,57 s		Cr 77 0,57 s		Cr 78 0,57 s		Cr 79 0,57 s		Cr 80 0,57 s		Cr 81 0,57 s		Cr 82 0,57 s		Cr 83 0,57 s		Cr 84 0,57 s		Cr 85 0,57 s		Cr 86 0,57 s		Cr 87 0,57 s		Cr 88 0,57 s		Cr 89 0,57 s		Cr 90 0,57 s		Cr 91 0,57 s		Cr 92 0,57 s		Cr 93 0,57 s		Cr 94 0,57 s		Cr 95 0,57 s		Cr 96 0,57 s		Cr 97 0,57 s		Cr 98 0,57 s		Cr 99 0,57 s		Cr 100 0,57 s	

s-process

slow neutron capture process

Nuclei involved in Astrophysics



What neutron flux is needed?

Rate equation for a nucleus A with respect to n-capture:

$$dN_A(t) = -N_A(t)/\tau_A dt$$

$\frac{dN_A}{dt}$ is the rate at which A is converted into A+1,

i.e. $N_A N_n \langle \sigma v \rangle = -dN_A/dt$

$$\tau_A N_n = 1 / \langle \sigma v \rangle$$

$$\sigma_{n\gamma} \sim 1/v \rightarrow \langle \sigma v \rangle \sim \text{constant}$$

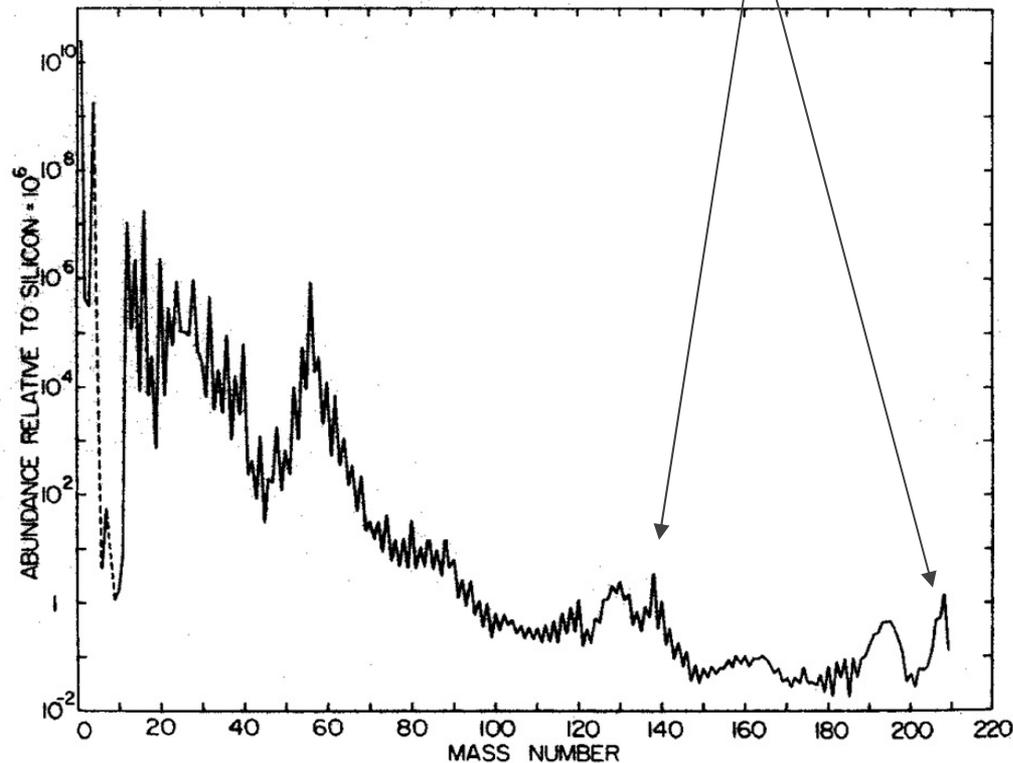
$$\sigma \sim 100 \text{ mb}, v \sim 10^8 \text{ cm/sec}$$

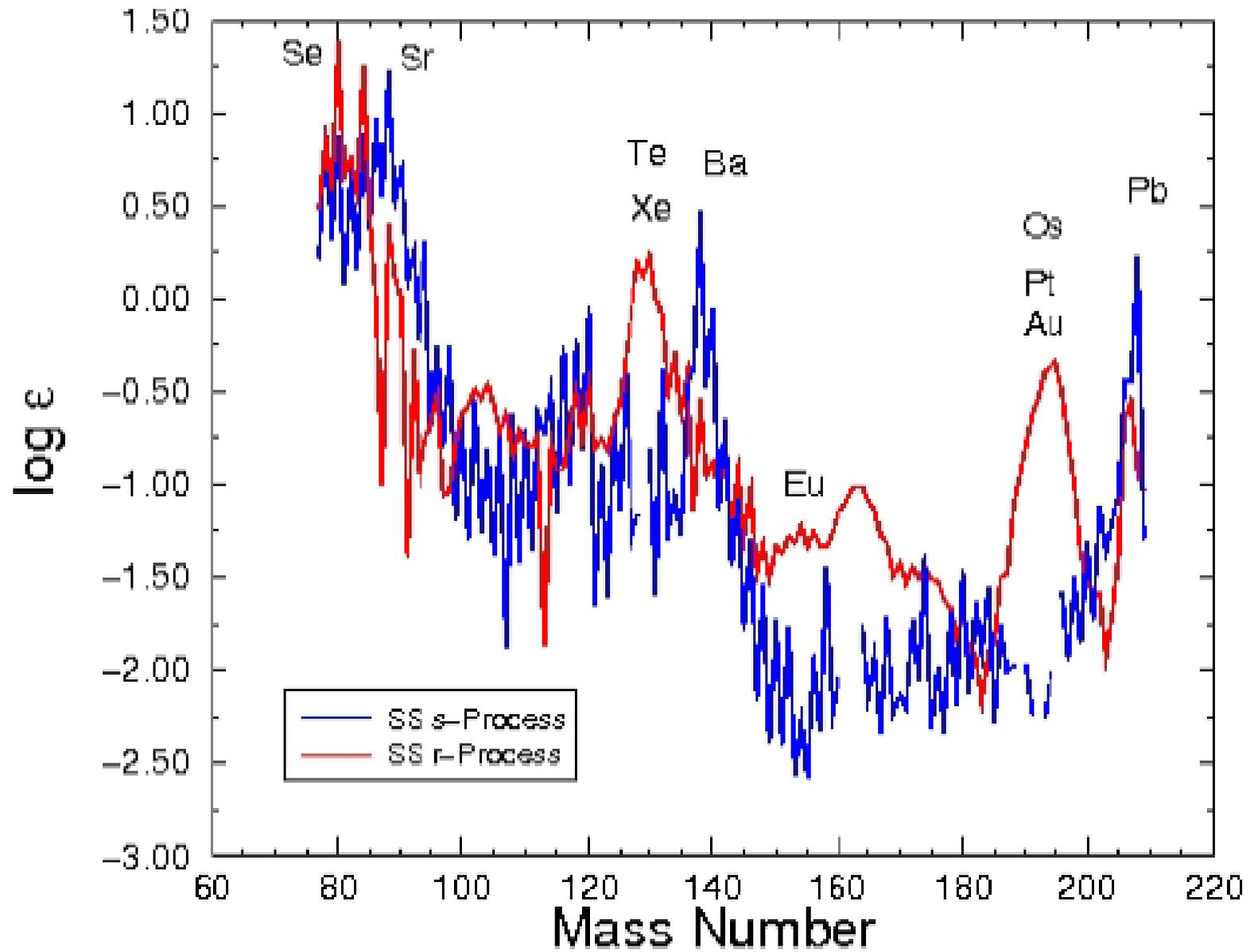
$$\tau N_n \sim 10^{17} \text{ s neutrons/cm}^3$$

To have capture times $< 10\text{y}$ ($=\pi \cdot 10^8 \text{ s}$)

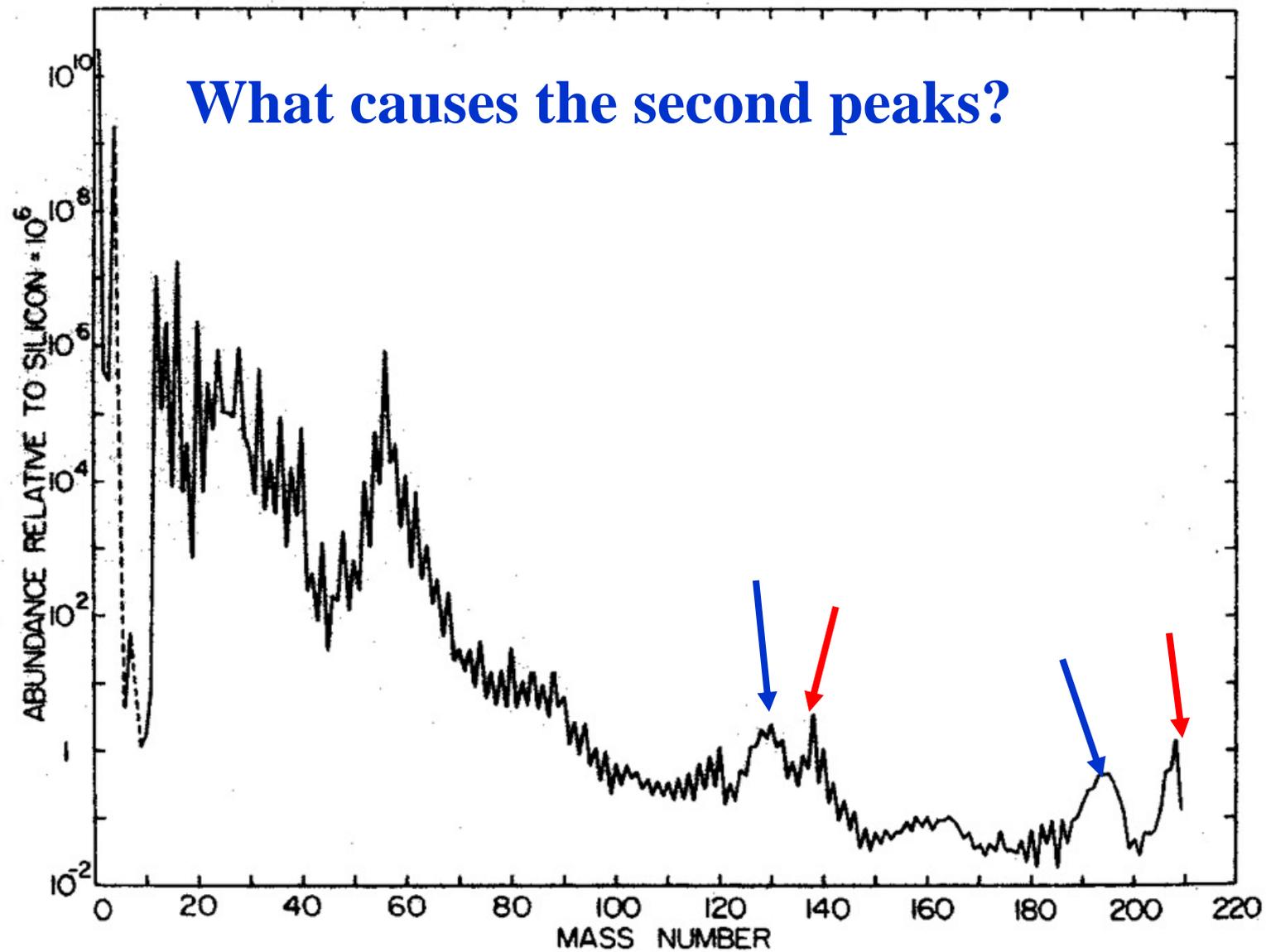
$$N_n > 3 \times 10^8 \text{ neutrons/cm}^3 \text{ (s-process)}$$

Nuclei with small $\sigma_{n\gamma}$ (e.g. closed shell nuclei) have a large τ and form a 'bottleneck' resulting in the s process abundance peaks.

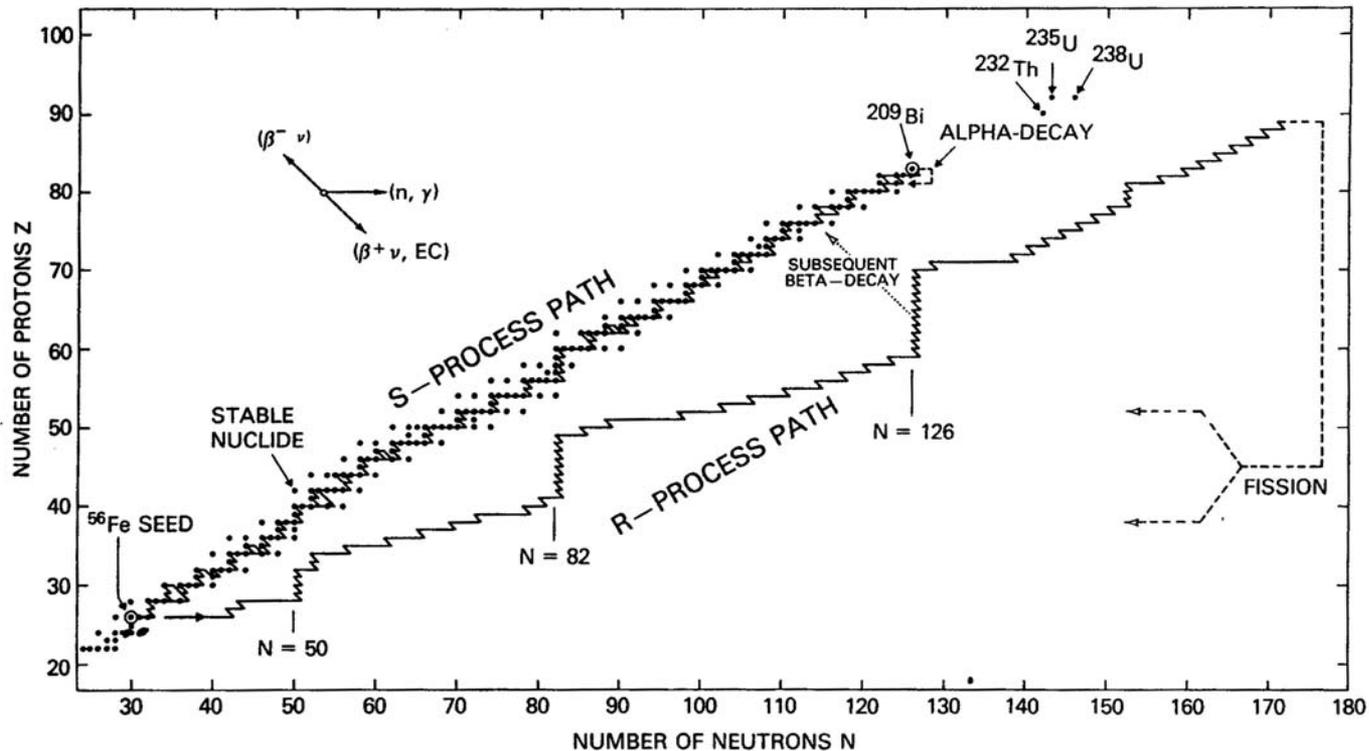




What causes the second peaks?



The other peaks in the abundance spectra are shifted downward in mass, but can be explained with a similar mechanism: **rapid capture of neutrons**.



		38		37		36		35		34		33		32		31		30		29		28		27		26		25		24		23		22		21		20		19		18		17		16		15		14		13		12		11		10		9		8		7		6		5		4		3		2		1	
		K 53 30 ms		K 54 10 ms		Rb 85,4678		Rb 74 65 ms		Rb 75 19 s		Rb 76 36,8 s		Rb 77 3,9 m		Rb 78 5,7 m 17,7 m		Rb 79 23,0 m		Rb 80 30 s		Rb 81 30,3 m 4,58 h		Rb 82 6,3 h 1,27 m		Kr 83,80		Kr 69		Kr 70		Kr 71 97 ms		Kr 72 17 s		Kr 73 26 s		Kr 74 11,5 m		Kr 75 4,5 m		Kr 76 14,6 h		Kr 77 1,24 h		Kr 78 0,35		Kr 79 50 s 34,9 h		Kr 80 2,25		Kr 81 13,1 s 2,3 10 ⁵ a		Kr 82																							
		Cl 51		Br 79,904		Br 69		Br 70 2,2 s 79 ms		Br 71 21,4 s		Br 72 10,9 s 1,3 m		Br 73 3,3 m		Br 74 46 m 25,4 m		Br 75 1,6 h		Br 76 1,32 s 16,0 h		Br 77 4,3 m 57,0 h		Br 78 6,46 m		Br 79 4,9 s 50,69		Br 80 4,42 h 17,6 m		Se 78,96		Se 65 ?		Se 66		Se 67 107 s		Se 68 35,5 s		Se 69 27,4 s		Se 70 41,1 m		Se 71 4,74 m		Se 72 8,5 d		Se 73 39 m 7,1 h		Se 74 0,89		Se 75 119,64 d		Se 76 9,36		Se 77 17,5 s 7,63		Se 78 23,78		Se 79 3,9 m ≤ 6,5 10 ⁴ a																	
		As 74,92159		As 64		As 65 0,19 s		As 66 96 ms		As 67 42,5 s		As 68 2,53 m		As 69 15,1 m		As 70 53 m		As 71 65,28 h		As 72 26,0 h		As 73 80,3 d		As 74 17,77 d		As 75 100		As 76 26,4 h		As 77 38,8 h		As 78 1,5 h		Ge 72,61		Ge 61 40 ms		Ge 62		Ge 63 95 ms		Ge 64 64 s		Ge 65 31 s		Ge 66 2,3 h		Ge 67 18,7 m		Ge 68 270,82 d		Ge 69 39,0 h		Ge 70 21,23		Ge 71 11,43 d		Ge 72 27,66		Ge 73 7,73		Ge 74 35,94		Ge 75 47 s 83 m		Ge 76 7,44		Ge 77 53 s 11,3 h									
		Ga 69,723		Ga 60		Ga 61 0,15 s		Ga 62 116 ms		Ga 63 31,4 s		Ga 64 2,62 m		Ga 65 15 m		Ga 66 9,4 h		Ga 67 78,3 h		Ga 68 67,63 m		Ga 69 60,108		Ga 70 21,15 m		Ga 71 39,892		Ga 72 14,1 h		Ga 73 4,86 h		Ga 74 2,1 m		Ga 75 2,1 m		Ga 76 32,6 s		Zn 58 ?		Zn 59 182 ms		Zn 60 2,4 m		Zn 61 1,5 m		Zn 62 9,13 h		Zn 63 38,1 m		Zn 64 48,6		Zn 65 244,3 d		Zn 66 27,9		Zn 67 4,1		Zn 68 18,8		Zn 69 13,8 h 56 m		Zn 70 0,6		Zn 71 3,9 h 2,4 m		Zn 72 46,5 h		Zn 73 5,8 s 23,5 s		Zn 74 96 s		Zn 75 10,2 s					
		Cu 57 199 ms		Cu 58 3,20 s		Cu 59 82 s		Cu 60 23 m		Cu 61 3,4 h		Cu 62 9,74 m		Cu 63 69,17		Cu 64 12,700 h		Cu 65 30,83		Cu 66 5,1 m		Cu 67 61,9 h		Cu 68 3,8 m 30 s		Cu 69 3,0 m		Cu 70 42 s 5 s		Cu 71 19,5 s		Cu 72 6,6 s		Cu 73 3,9 s		Cu 74 1,59 s		Ni 56 6,075 d		Ni 57 36,0 h		Ni 58 68,077		Ni 59 7,5 · 10 ⁴ s		Ni 60 26,2 s		Ni 61 1,67 s		Ni 62 634		Ni 63 90 a		Ni 64 0,926		Ni 65 2,52 h		Ni 66 54,6 h		Ni 67 21 s		Ni 68 19 s		Ni 69 11,4 s		Ni 70		Ni 71 1,86 s		Ni 72 2,06 s		Ni 73 0,90 s					
		Co 55 17,54 h		Co 56 77,26 d		Co 57 271,79 d		Co 58 8,94 h 70,86 d		Co 59 100		Co 60 10,5 s 5,272 a		Co 61 1,65 h		Co 62 14,0 m 1,5 m		Co 63 27,5 s		Co 64 0,3 s		Co 65 1,14 s		Co 66 0,23 s		Co 67 0,42 s		Co 68 0,18 s		Co 69 0,27 s		Co 70 0,19 s		Co 71 0,20 s		Co 72 0,15 s		Fe 54 5,8		Fe 55 2,73 a		Fe 56 91,72		Fe 57 2,2		Fe 58 0,28		Fe 59 4,5 503 d		Fe 60 1,5 · 10 ⁶ a		Fe 61 6,0 m		Fe 62 68 s		Fe 63 6,1 s		Fe 64 2,0 s		Fe 65 0,45 s		Fe 66		Fe 67		Fe 68 0,1 s		Fe 69									
		Mn 53 3,7 · 10 ⁶ a		Mn 54 312,2 d		Mn 55 100		Mn 56 2,58 h		Mn 57 1,5 m		Mn 58 65,3 s 3,0 s		Mn 59 7,1 s		Mn 60 1,71 s		Mn 61 0,88 s		Mn 62 0,25 s		Mn 63 0,25 s		Mn 64		Mn 65		Mn 66		Cr 52 83,789		Cr 53 9,501		Cr 54 2,365		Cr 55 3,50 m		Cr 56 5,9 m		Cr 57 21,1 s		Cr 58 7,0 s		Cr 59 0,74 s		Cr 60 0,6 s		Cr 61 0,6 s		Cr 62 0,6 s		Cr 63 0,6 s		Cr 64 0,6 s																							
		Cr 52 83,789		Cr 53 9,501		Cr 54 2,365		Cr 55 3,50 m		Cr 56 5,9 m		Cr 57 21,1 s		Cr 58 7,0 s		Cr 59 0,74 s		Cr 60 0,6 s		Cr 61 0,6 s		Cr 62 0,6 s		Cr 63 0,6 s		Cr 64 0,6 s		Cr 65 0,6 s		Cr 66 0,6 s		Cr 67 0,6 s		Cr 68 0,6 s		Cr 69 0,6 s		Cr 70 0,6 s		Cr 71 0,6 s		Cr 72 0,6 s		Cr 73 0,6 s		Cr 74 0,6 s		Cr 75 0,6 s		Cr 76 0,6 s		Cr 77 0,6 s		Cr 78 0,6 s		Cr 79 0,6 s		Cr 80 0,6 s		Cr 81 0,6 s		Cr 82 0,6 s															

s-process

r-process

rapid neutron capture process

44

42

For this to happen the n capture has to occur on a much faster time scale: $\tau_n \sim \text{ms}$

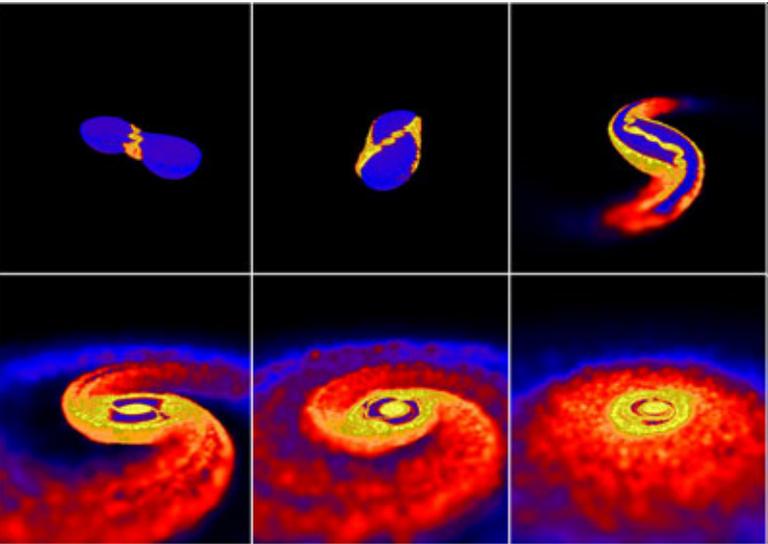
With $\tau N_n \sim 10^{17} \rightarrow$

$$N_n \sim 10^{20} \text{ n/cm}^3$$

At which astrophysical sites do we have these neutron densities?

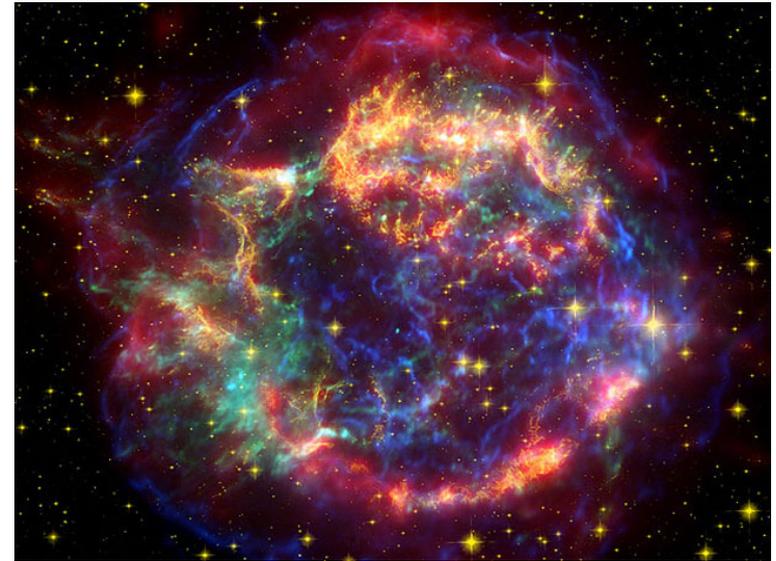
Where can we get these high neutron densities?

Neutron star mergers



Price and Rosswog

core-collapse supernovae



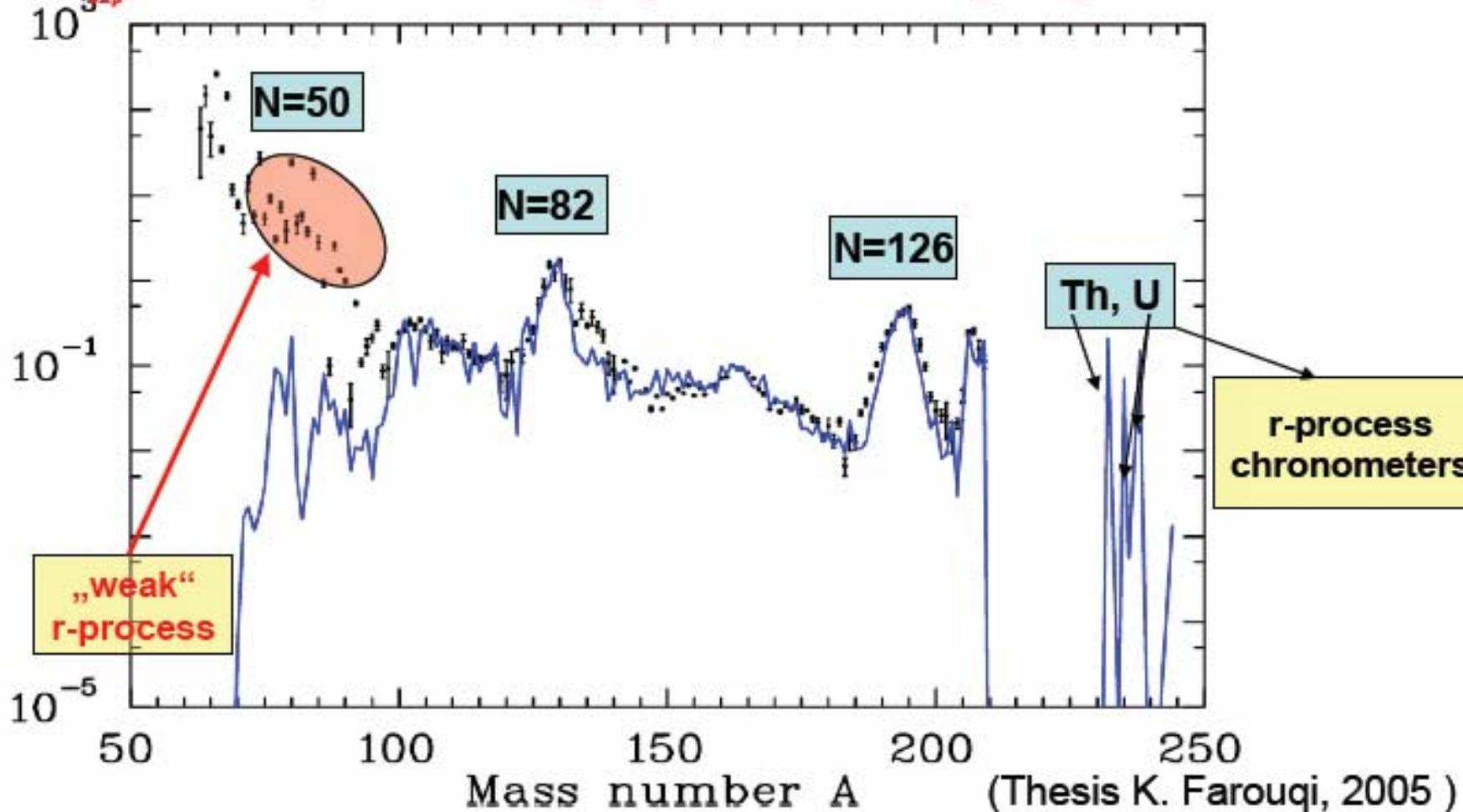
- Site of the r-process is unknown
- Properties of nuclei in the r-process path are unknown (half-lives, masses, n-capture cross sections..)

Superposition of 5 S-sequences to reproduce the $N_{r,\odot}$ pattern ($100 < A < 240$)

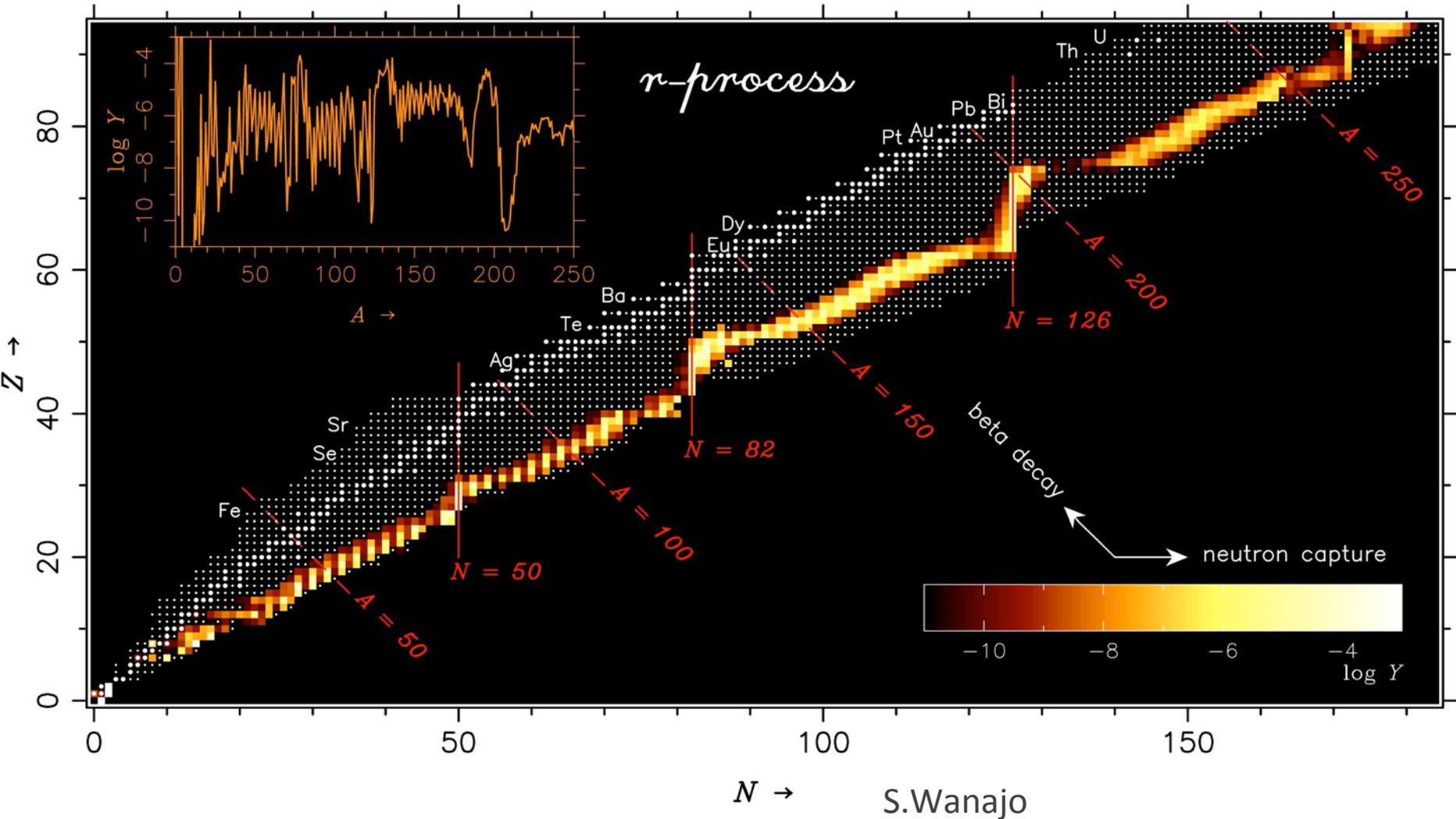
ETFSI-Q, NON-SMOKER rates, ADMC 2003, QRPA(GT+ff)

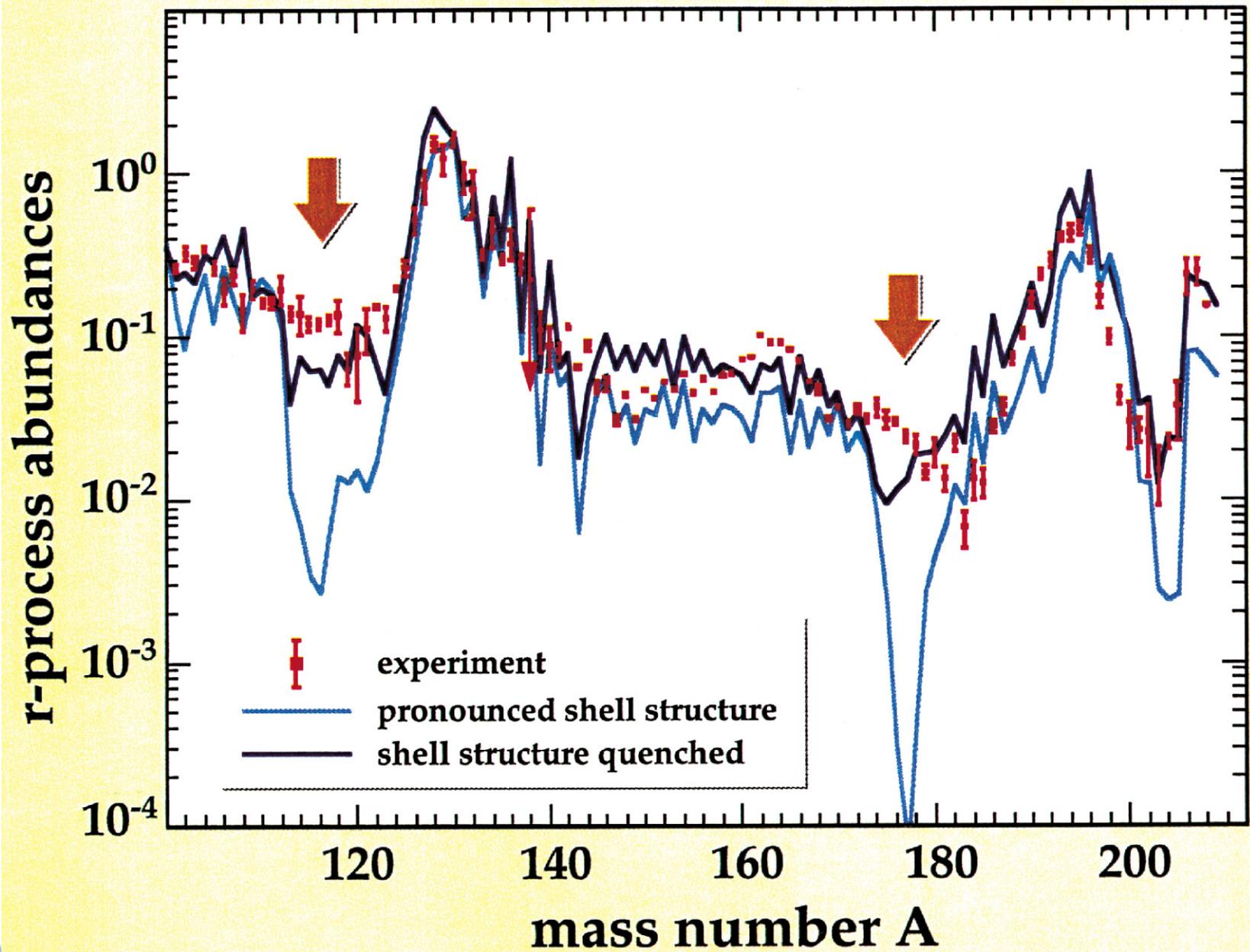
$V_{exp} = 7500$ Km/s, $Y_e = 0.45$, superposition of 5 entropy sequences

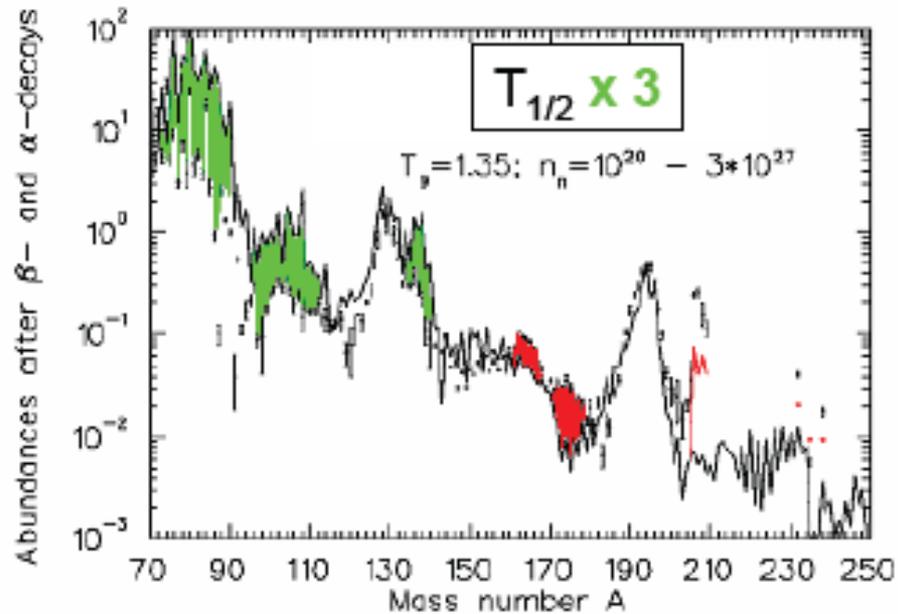
Abundance Y , $Y(\text{Si}) = 10^6$



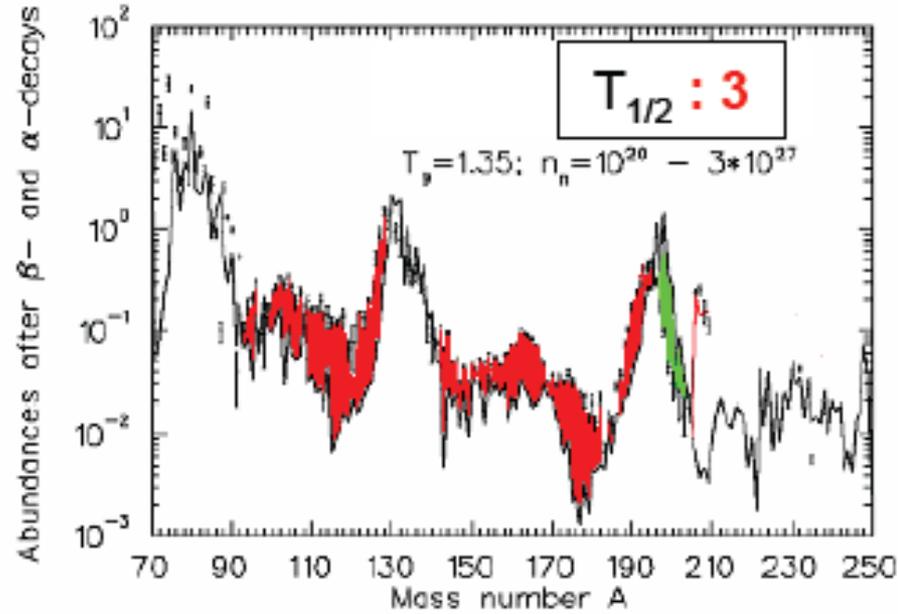
Basis for detailed astrophysical parameter studies





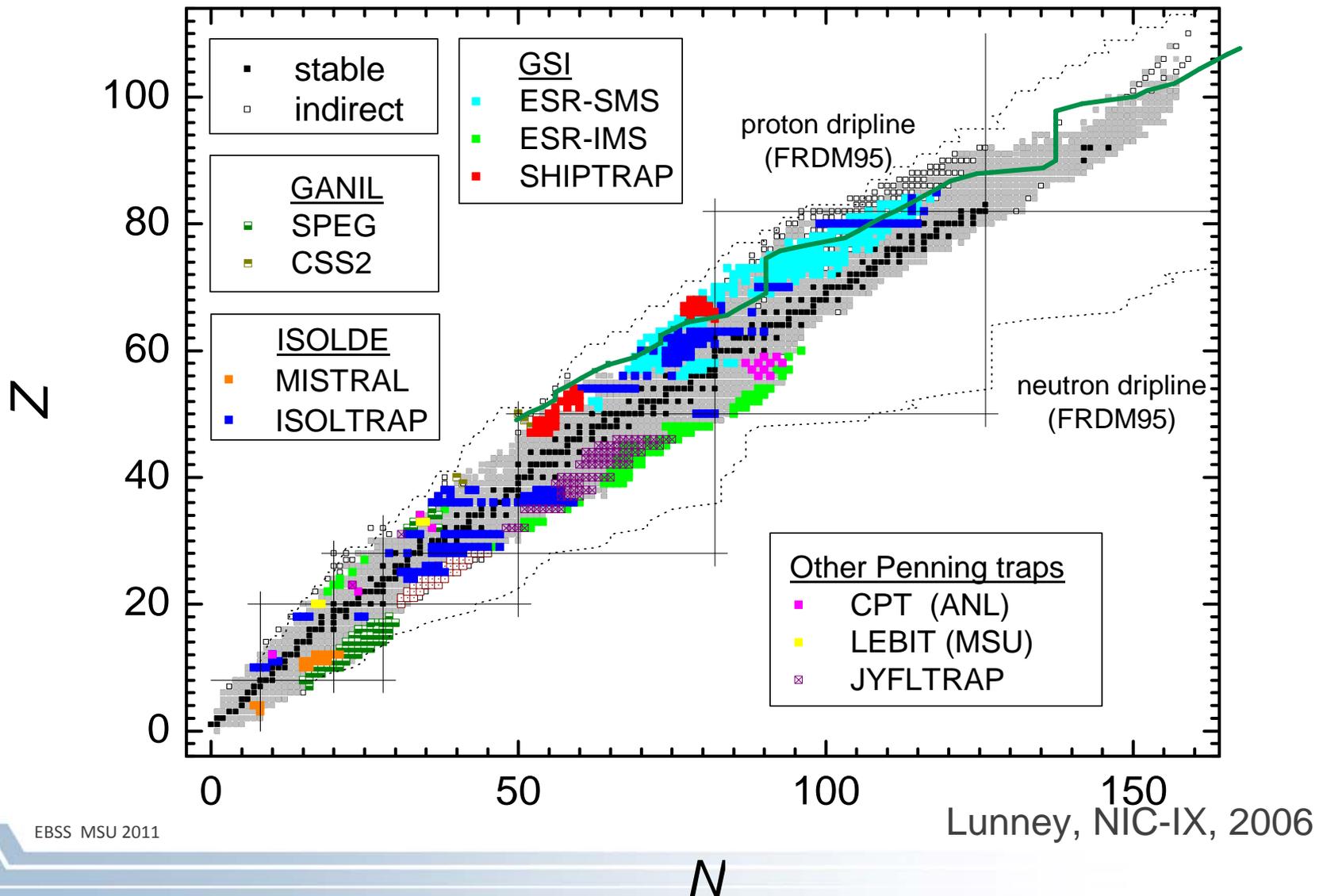


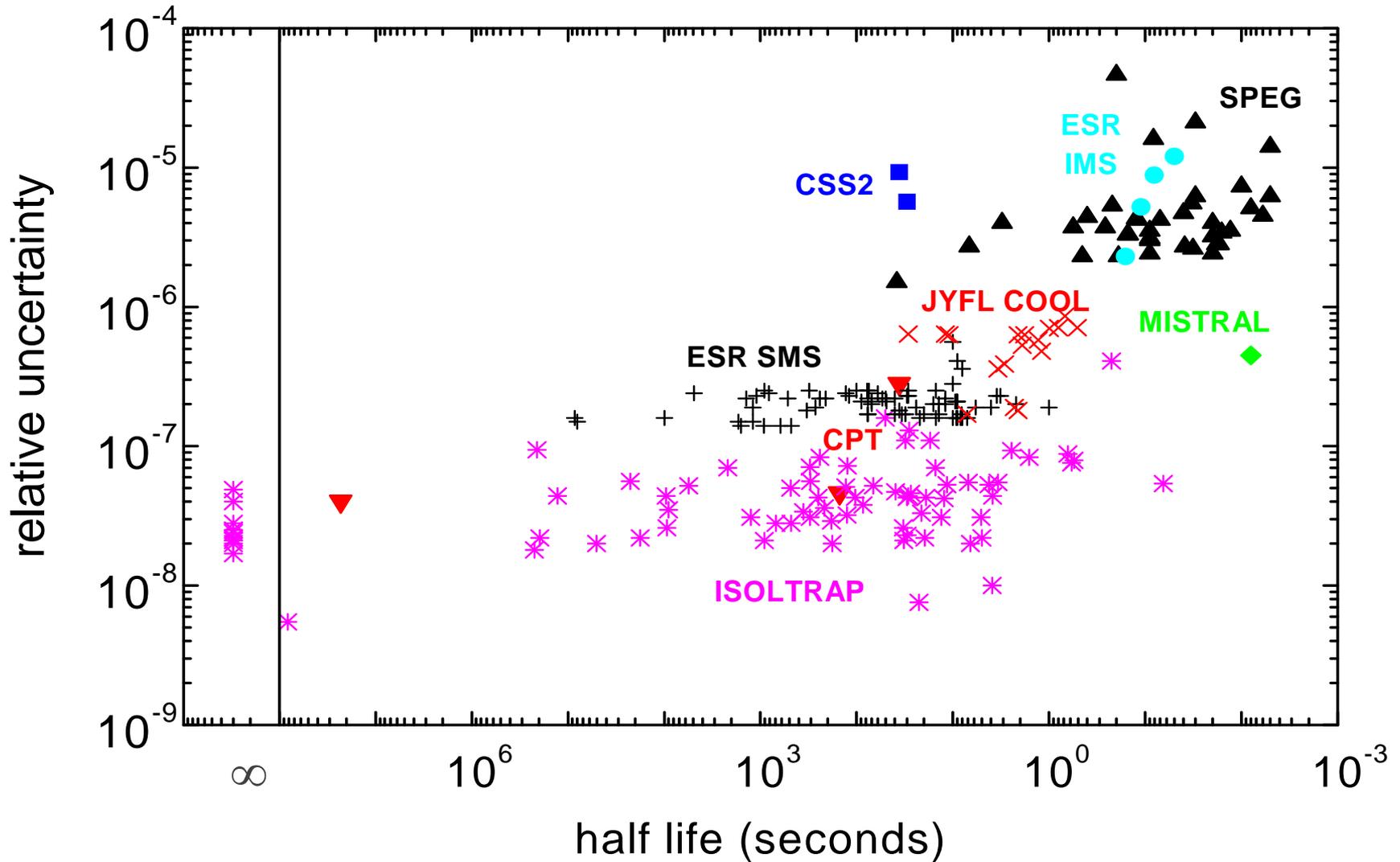
r-matter flow too **slow**



r-matter flow too **fast**

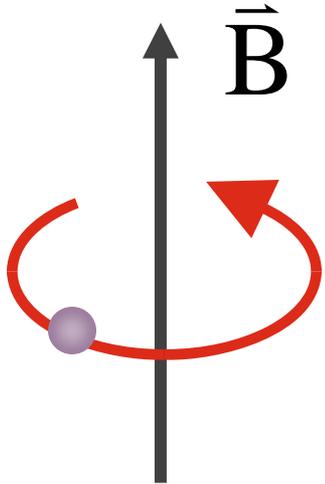
For the r-process path we need masses of neutron-rich nuclei





Most accurate mass measurements with Penning traps

How a Penning trap works -1

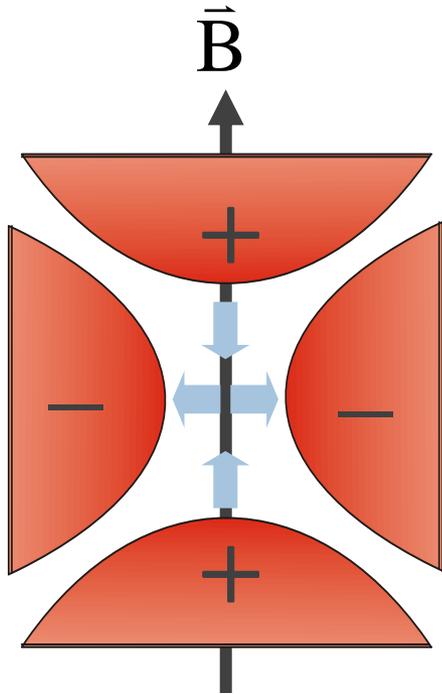


- constant axial magnetic field
- particle orbits in horizontal plane

$$\omega_c = \frac{qB}{m}$$

- free to escape axially

How a Penning trap works-2



Add an axial harmonic potential to confine particles:

$$V = \frac{V_o}{2d^2} \left(z^2 - \frac{r^2}{2} \right)$$

Motion of ions in a Penning trap

Solve for equations of motion:

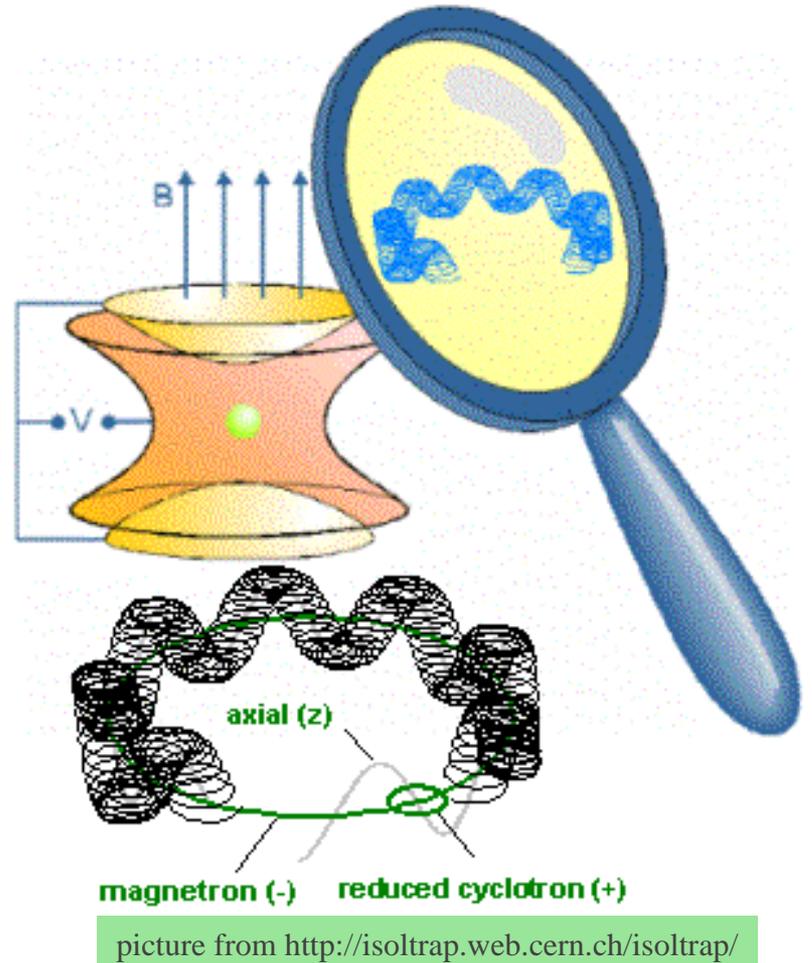
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

Axial oscillations:

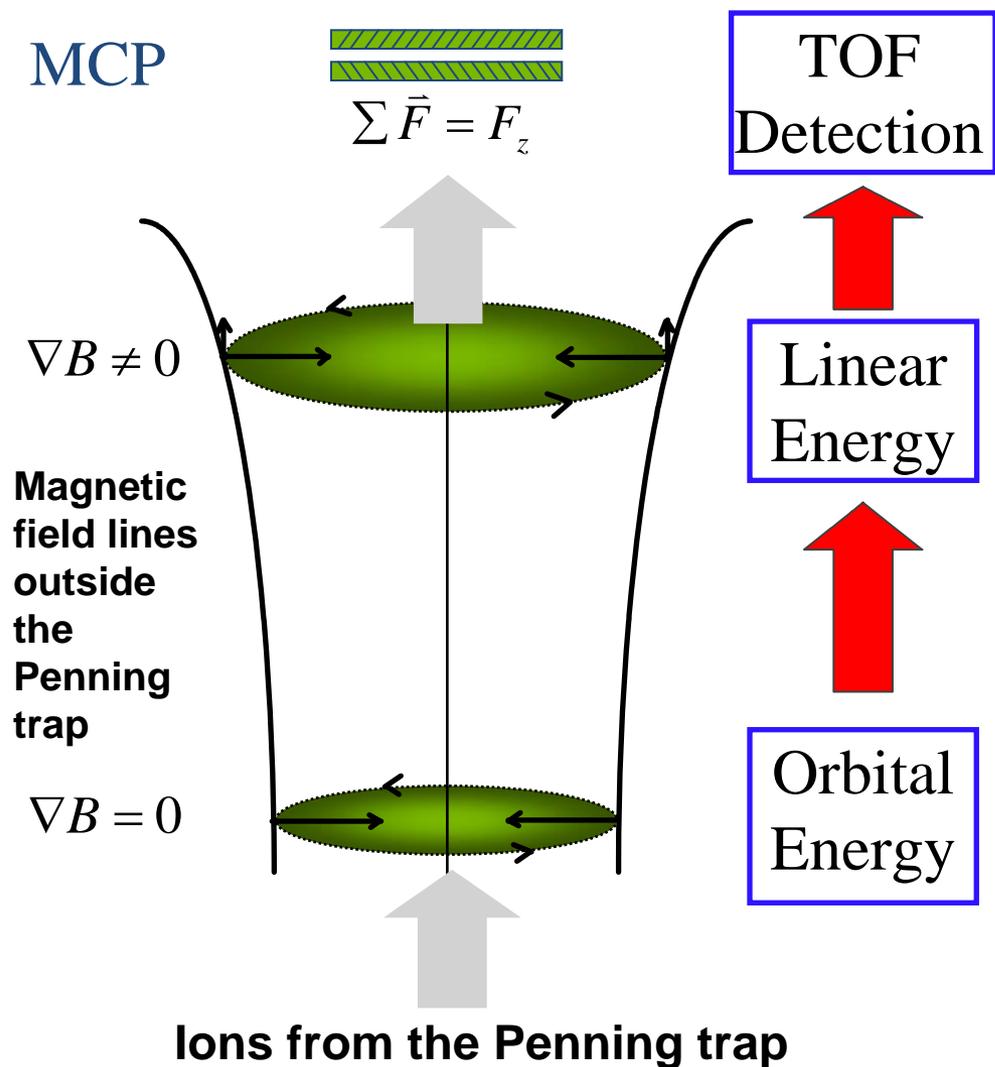
$$\omega_z = \sqrt{\frac{eV}{md^2}}$$

Radial motion:

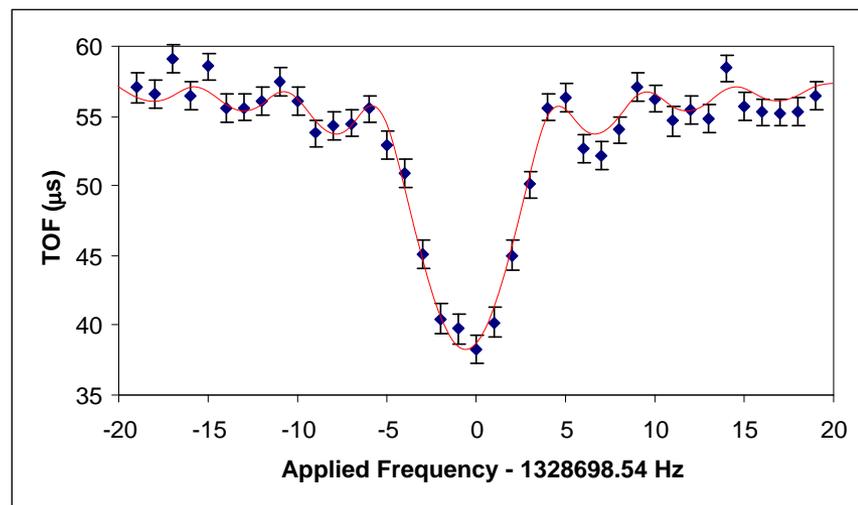
$$\omega_{\pm} = \frac{\omega_c}{2} \pm \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$



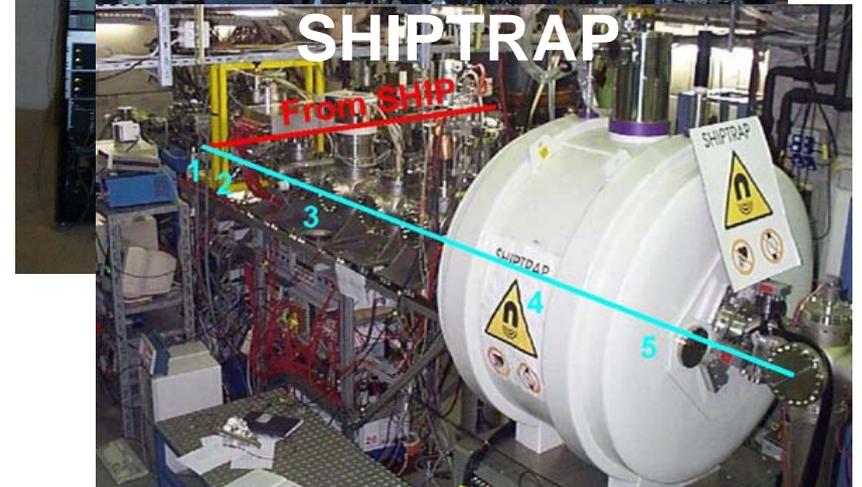
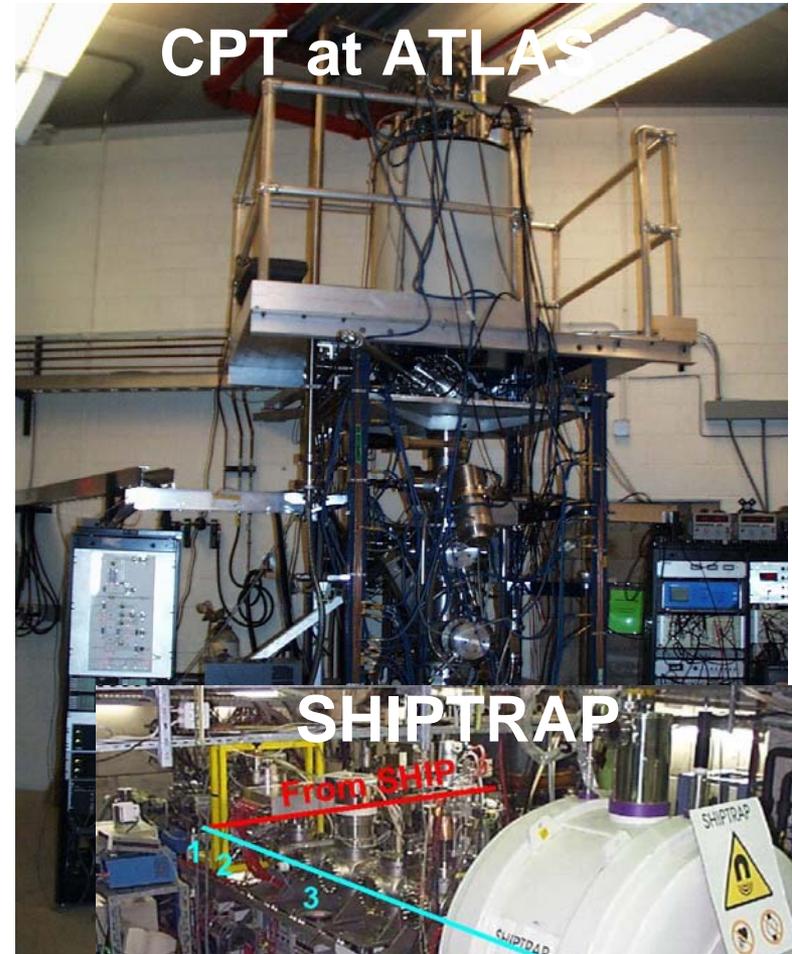
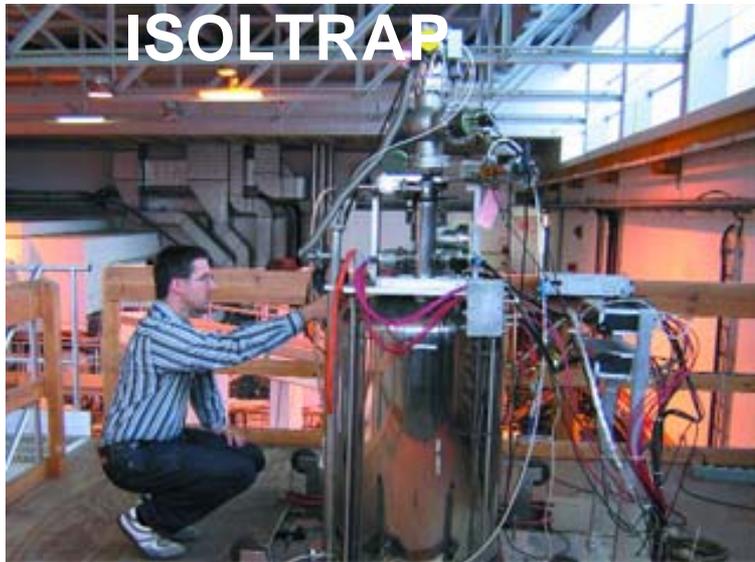
Penning trap mass spectrometry



Sample TOF spectrum

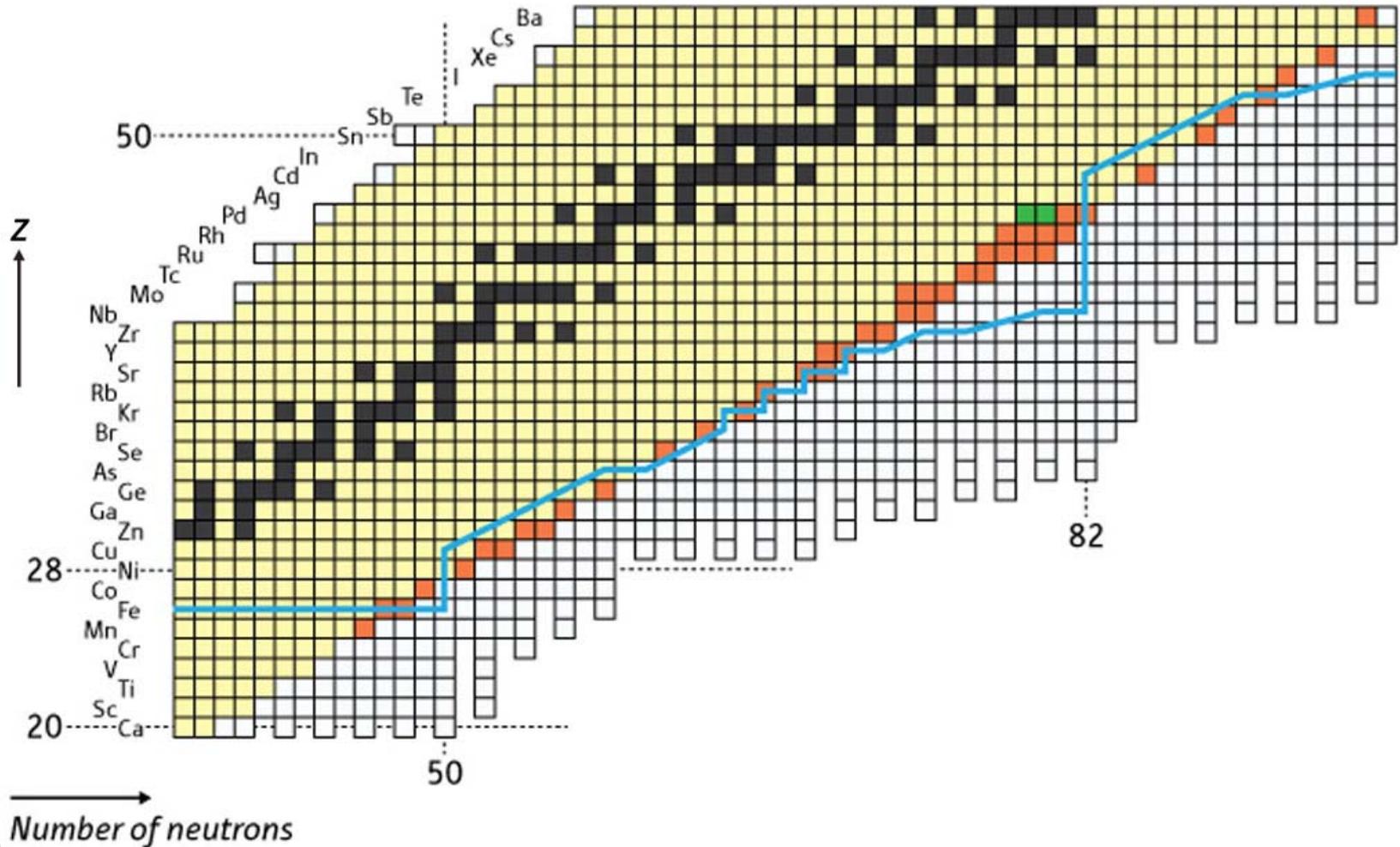


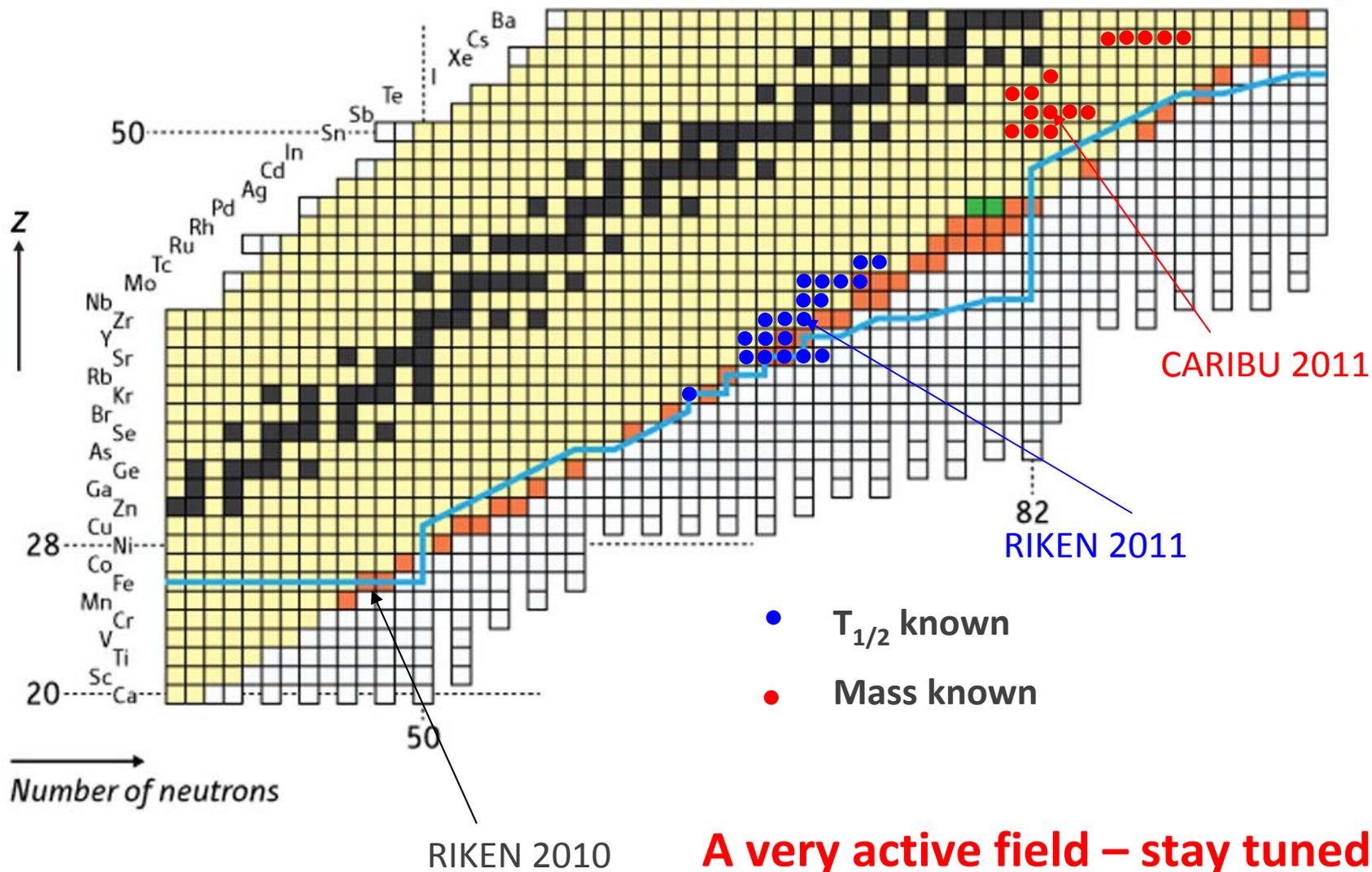
Penning traps



Need information of n-rich nuclei in the r-process path

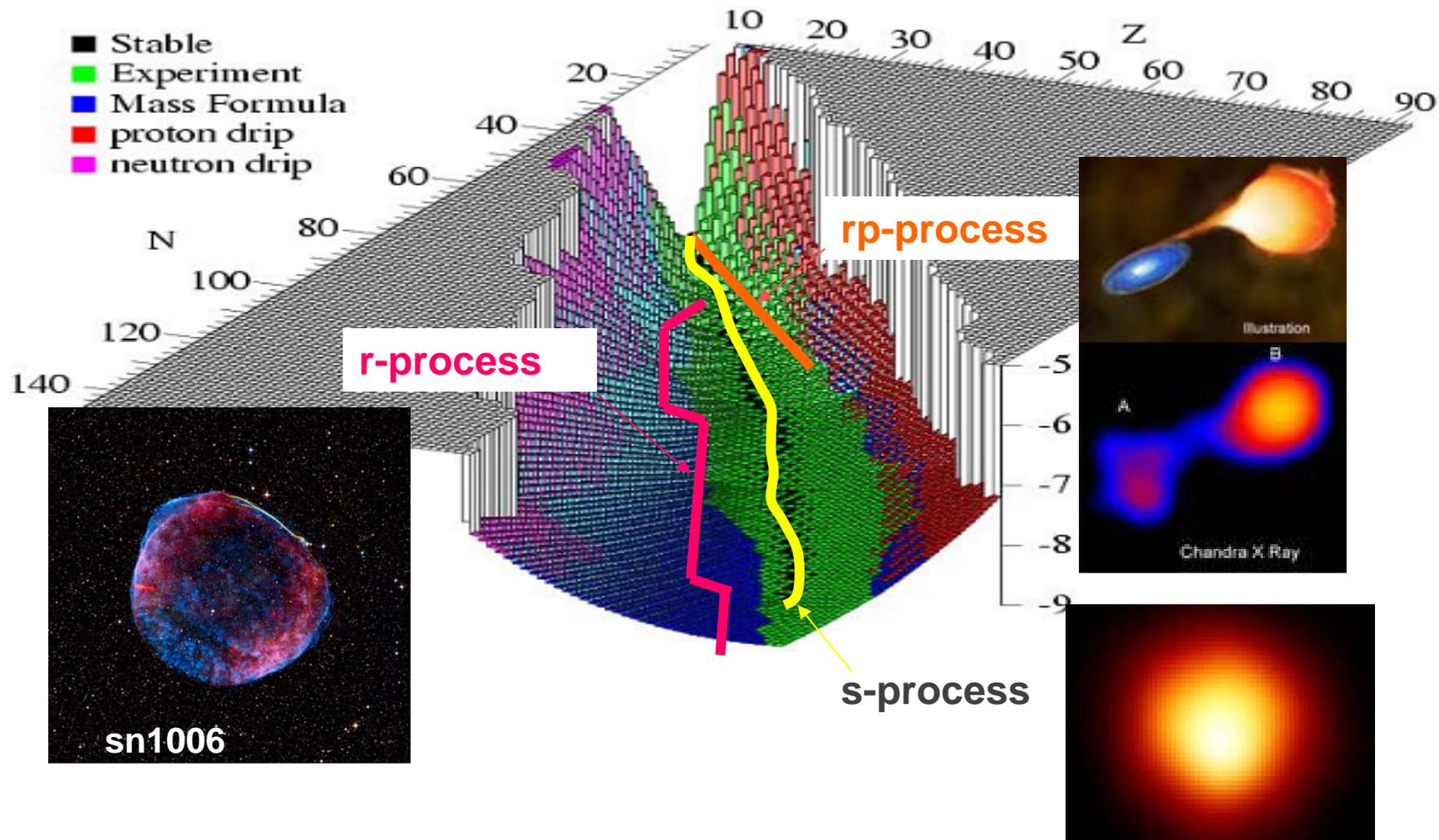
$T_{1/2}$, masses, n-capture rates





A very active field – stay tuned!

Nuclear Physics in Astrophysics





Thanks for listening 'til the bitter end.