Nuclear Astrophysics

2x50 minutes for $(13.7\pm0.13)\times10^{9}$ 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

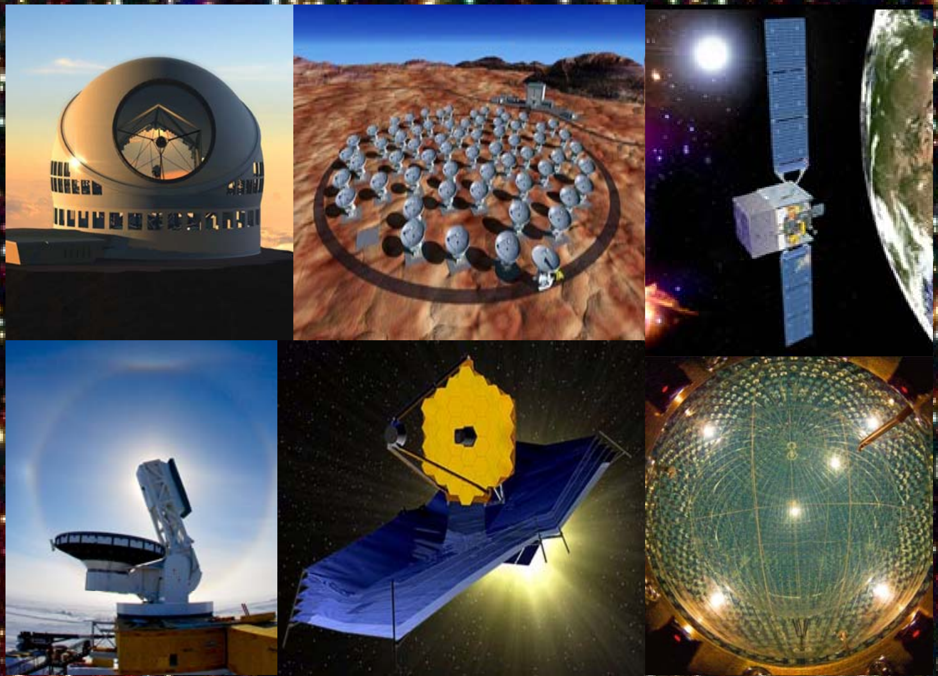
B^2FH:

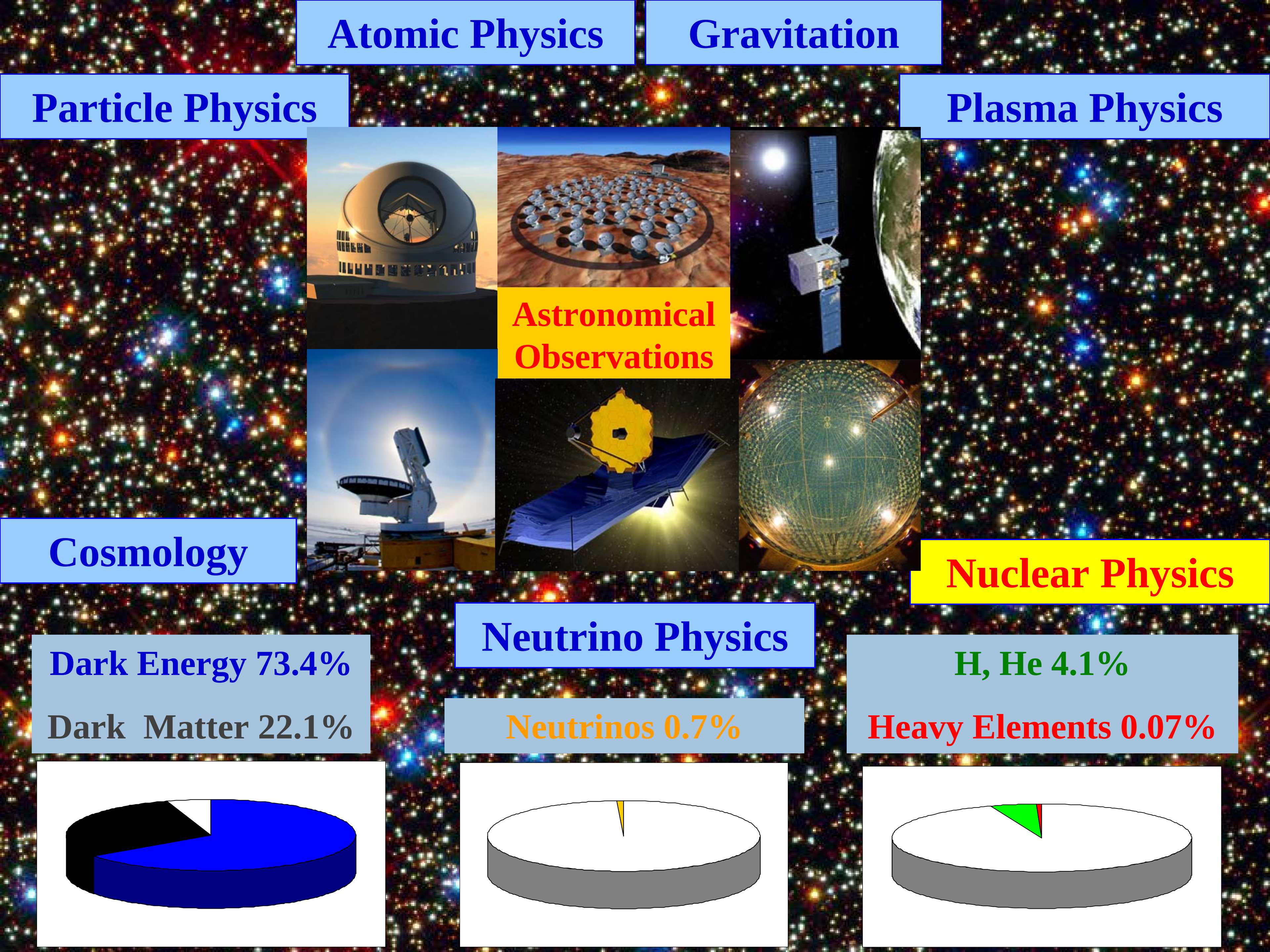
Burbidge,Burbidge,Fowler, Hoyle: Rev. Mod. Phys. 29, 15(1957)

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
Neutrino Physics
Dark Energy 73.4%
Dark Matter 22.1%
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:

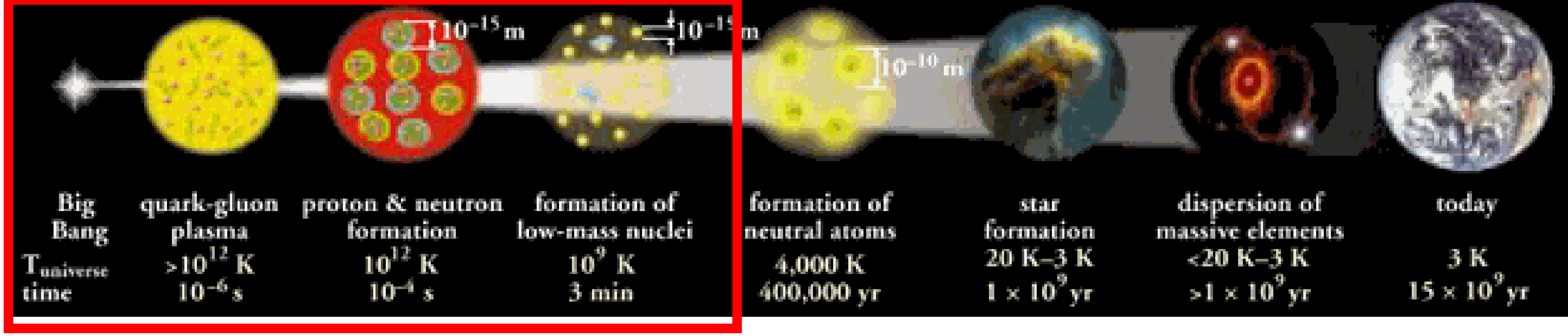
- Understanding the birth and death of stars
- Understanding the energy that powers the stars
- Understanding the formation of the elements

Nuclear Astrophysics - Challenges:

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

Frontiers:

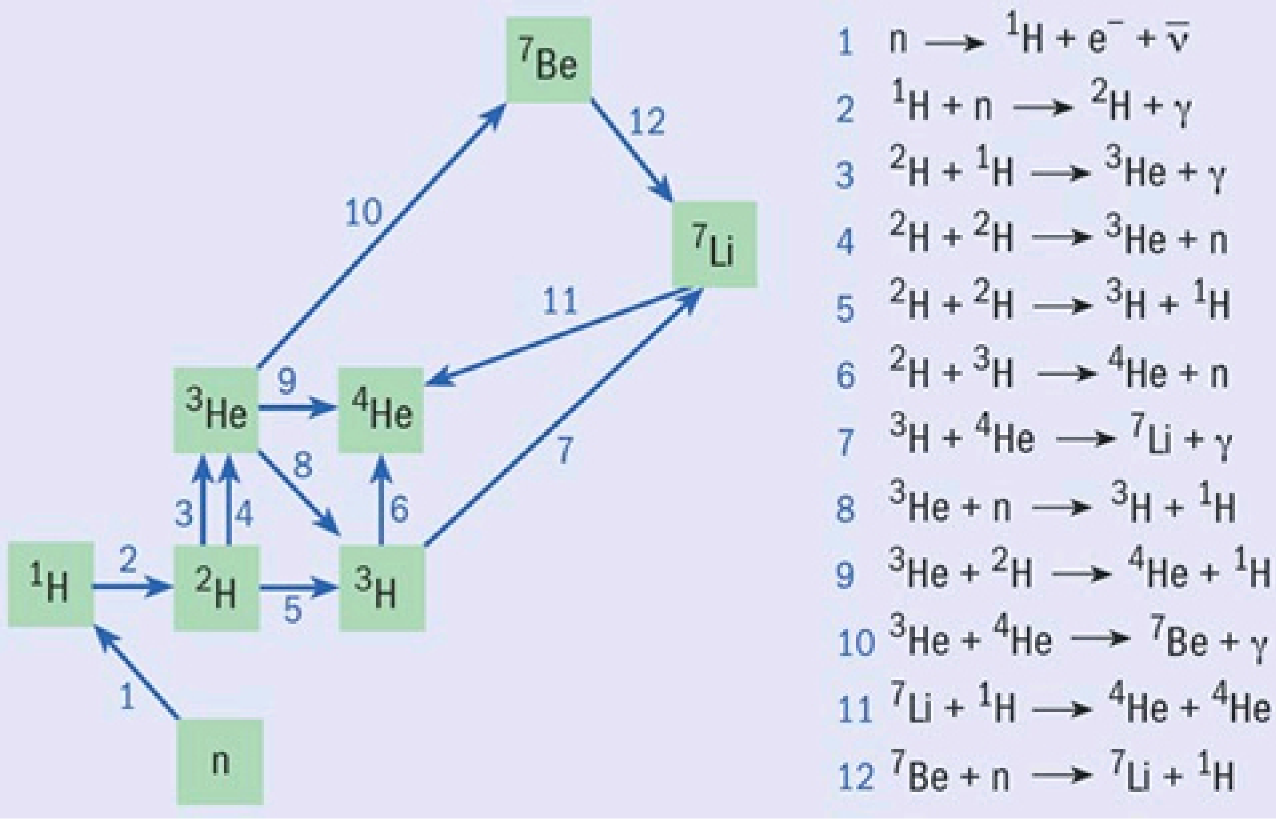
- High-current accelerators
- Underground laboratories
- Gas targets
- Radioactive ion beams
- High efficiency detectors

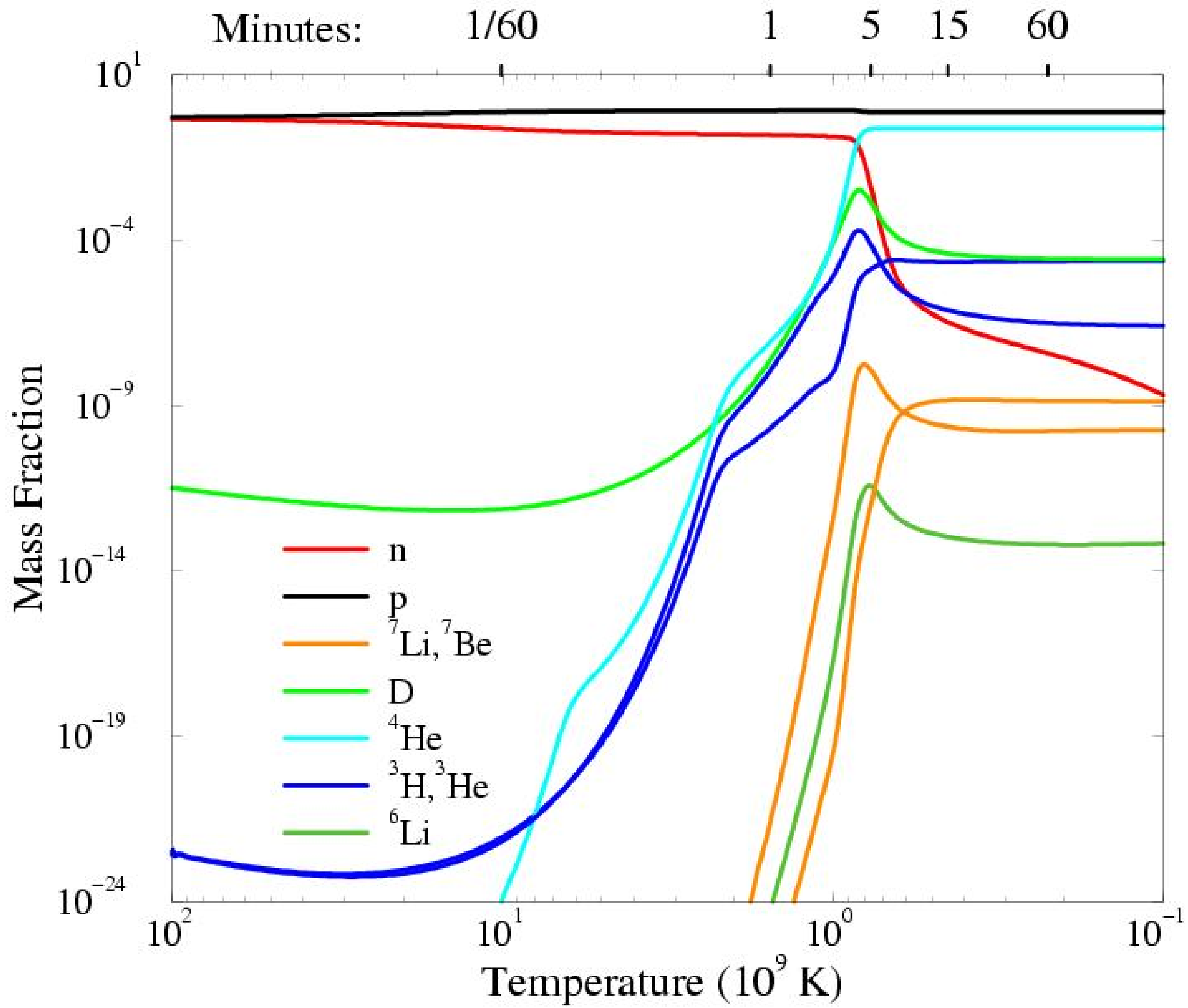


$T \sim 10^9$ K,

$\Delta t \sim 3$ min

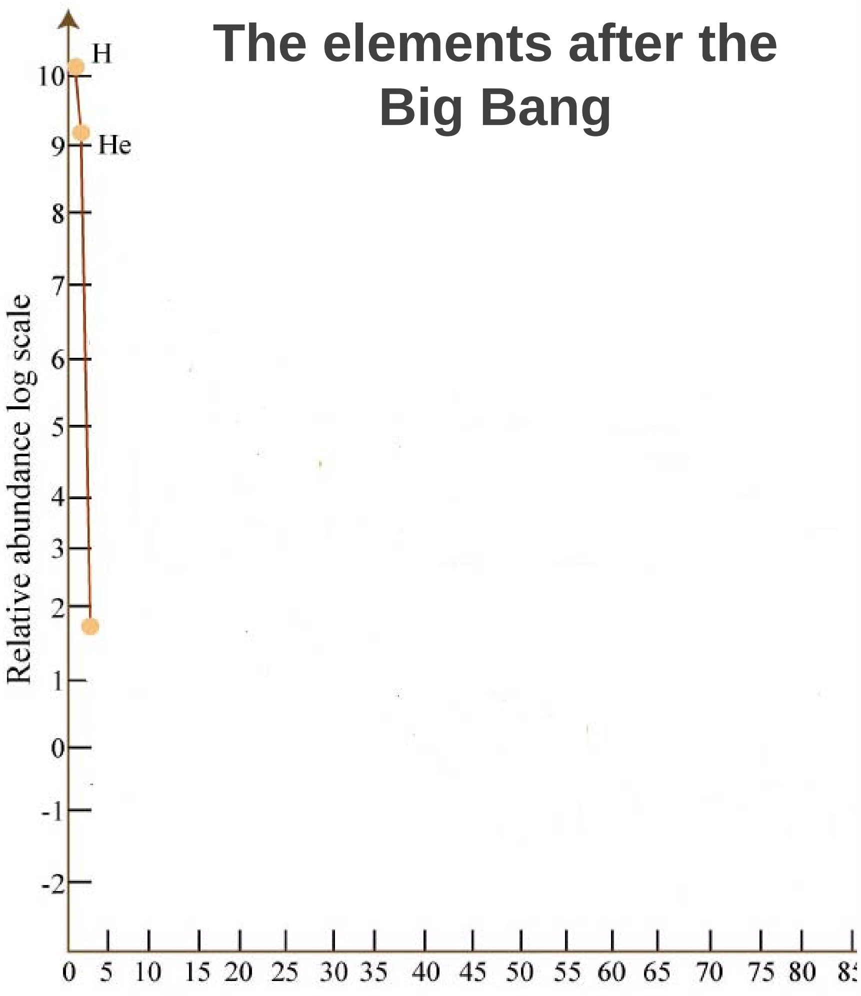
^{1}H	0.75
^{2}H	2.5×10^{-5}
^{3}He	4×10^{-5}
^{4}He	0.23
^{7}Li	5×10^{-9}

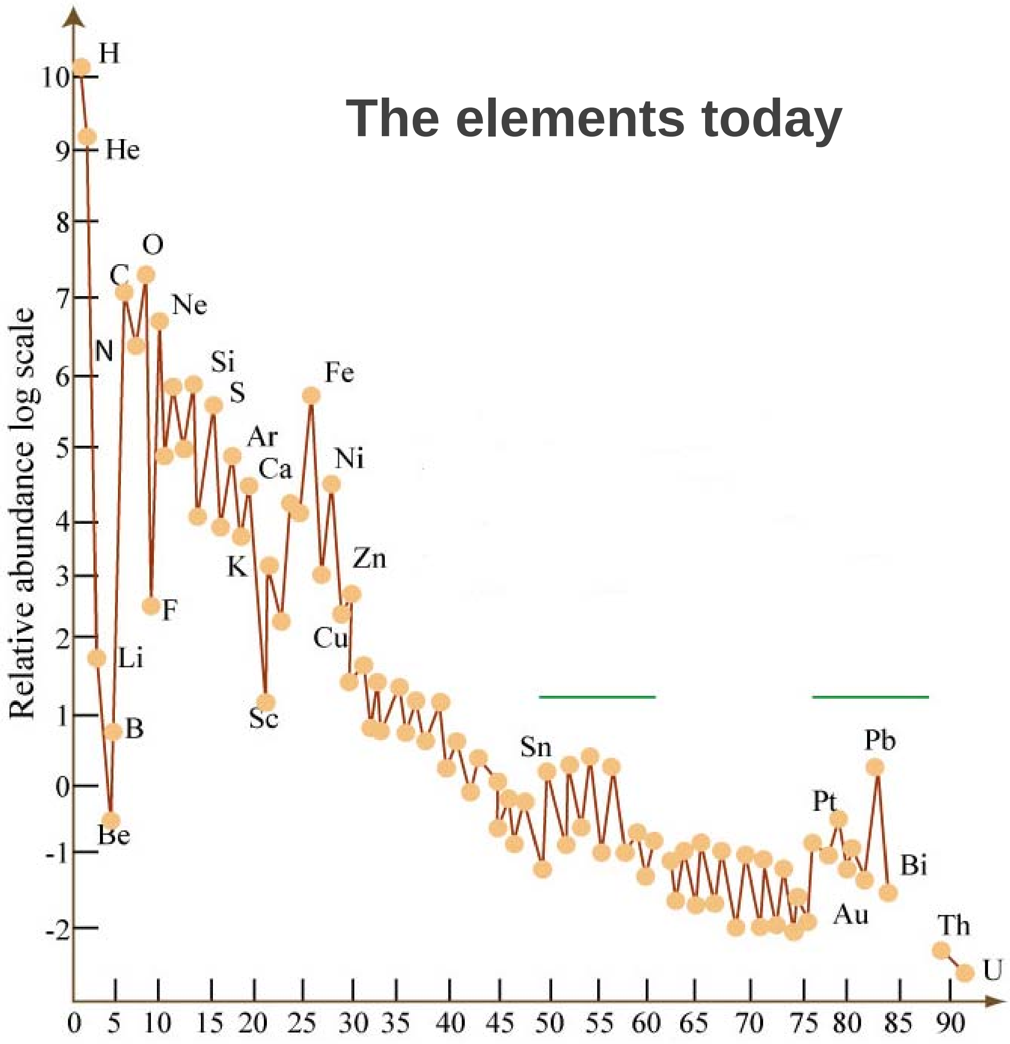




Burles, Nollett, Turner, ApJ

What the stars did for us





Virial theorem: 2K + U = 0

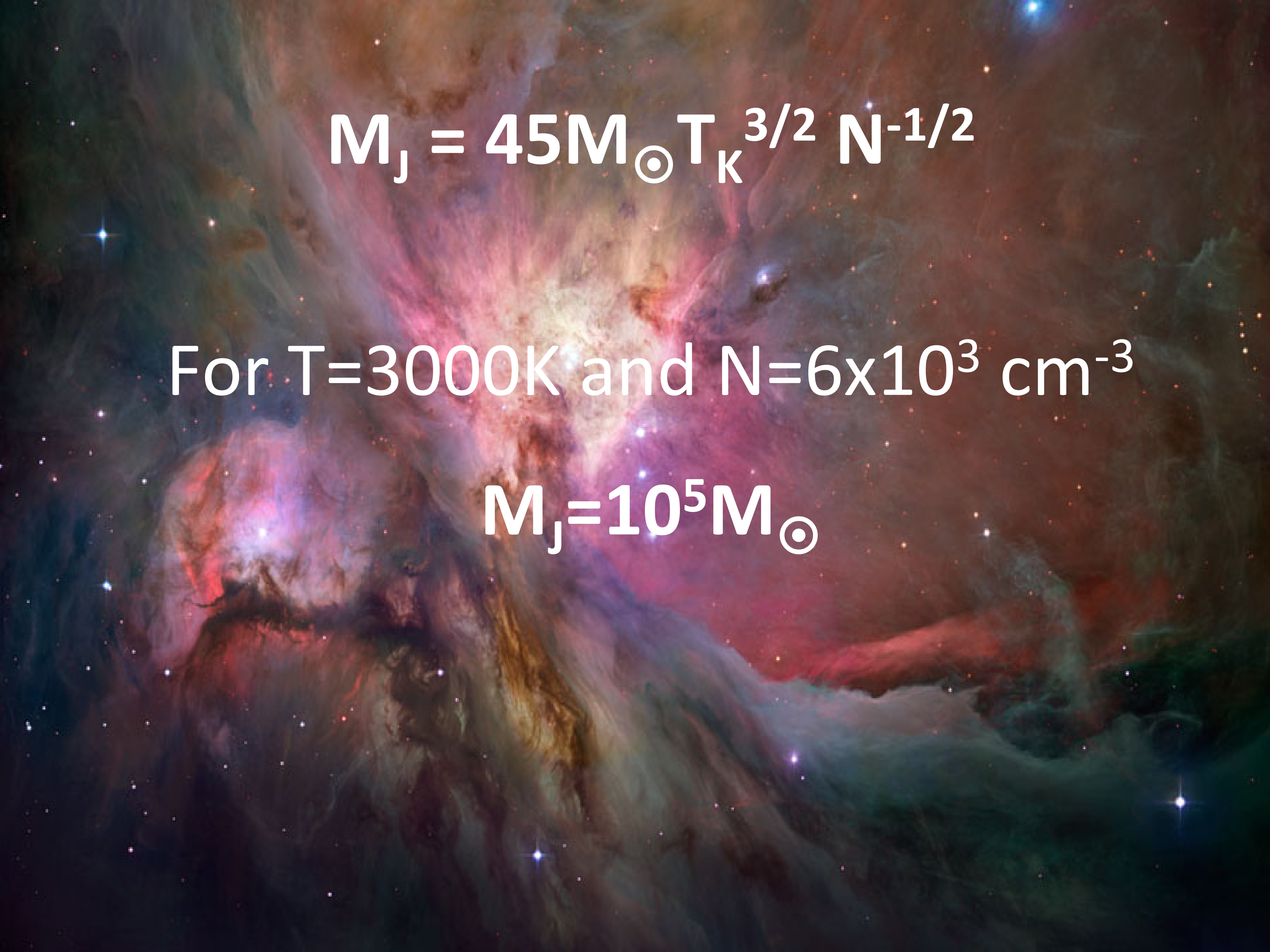
Collapse: 2K < -U

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

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

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

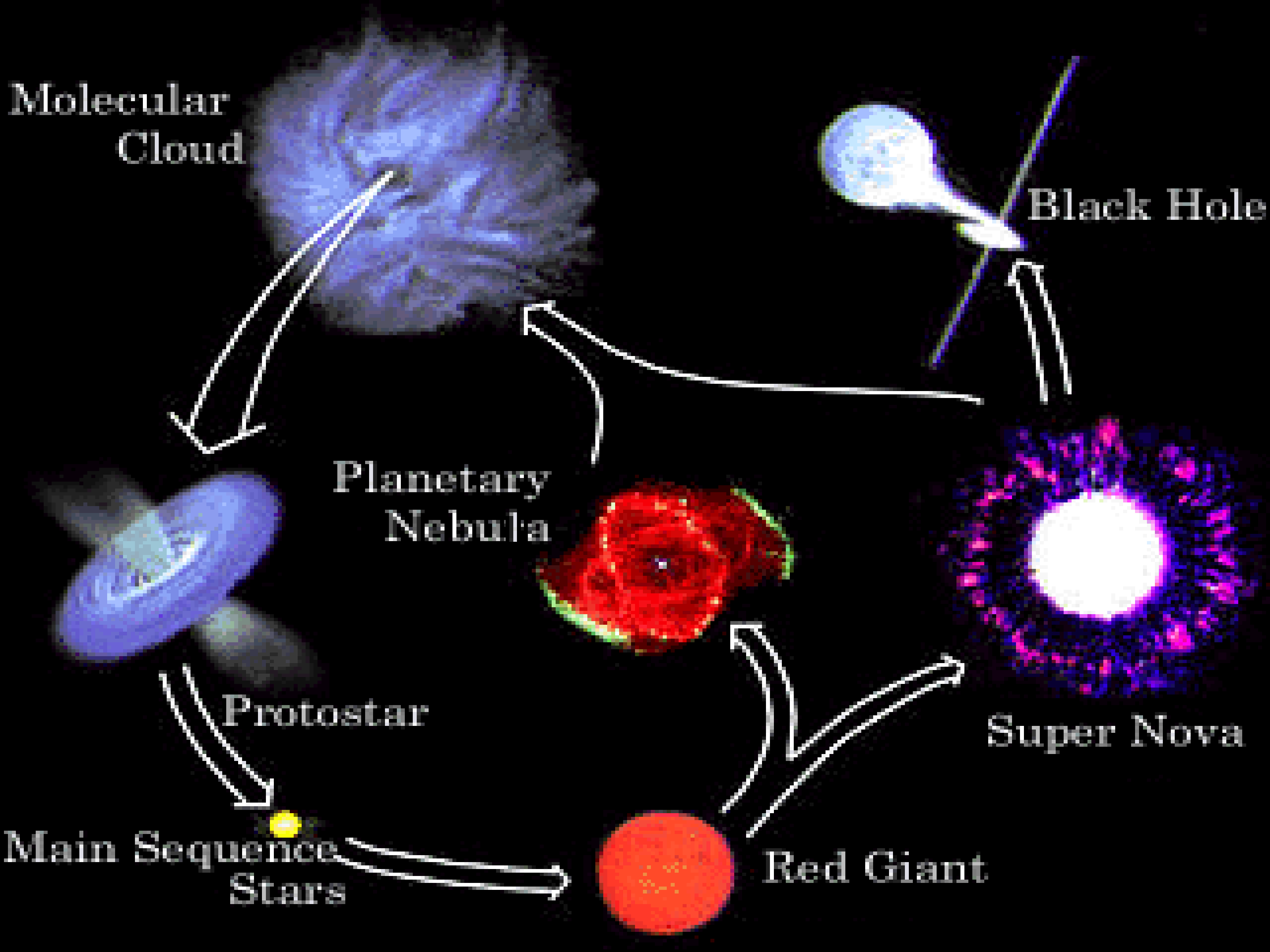
Jeans criterion (1902)



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

For $T = 3000K$ and $N = 6x10^3\ cm^{-3}$

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


Molecular
Cloud
Black Hole
Planetary
Nebula
Protostar
Super Nova
Main Sequence
Stars
Red Giant

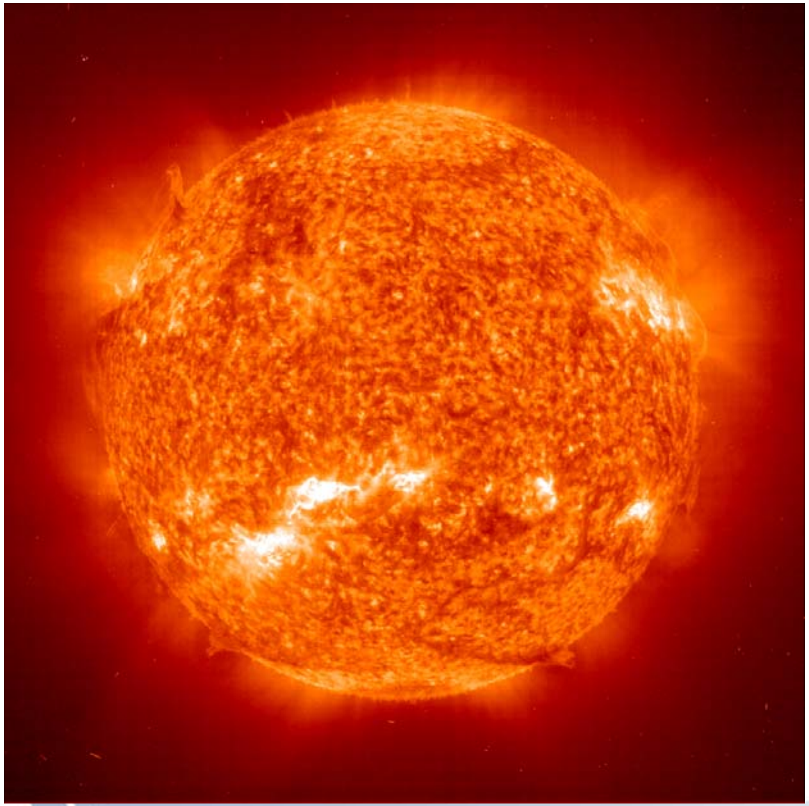
Two paths to 'cook' the elements in stars:

Slowly (quiescent)

~(10^9 years)

Example : the sun

hydrogen → helium



Fast (explosive)

~(a few seconds)

Example:Supernova

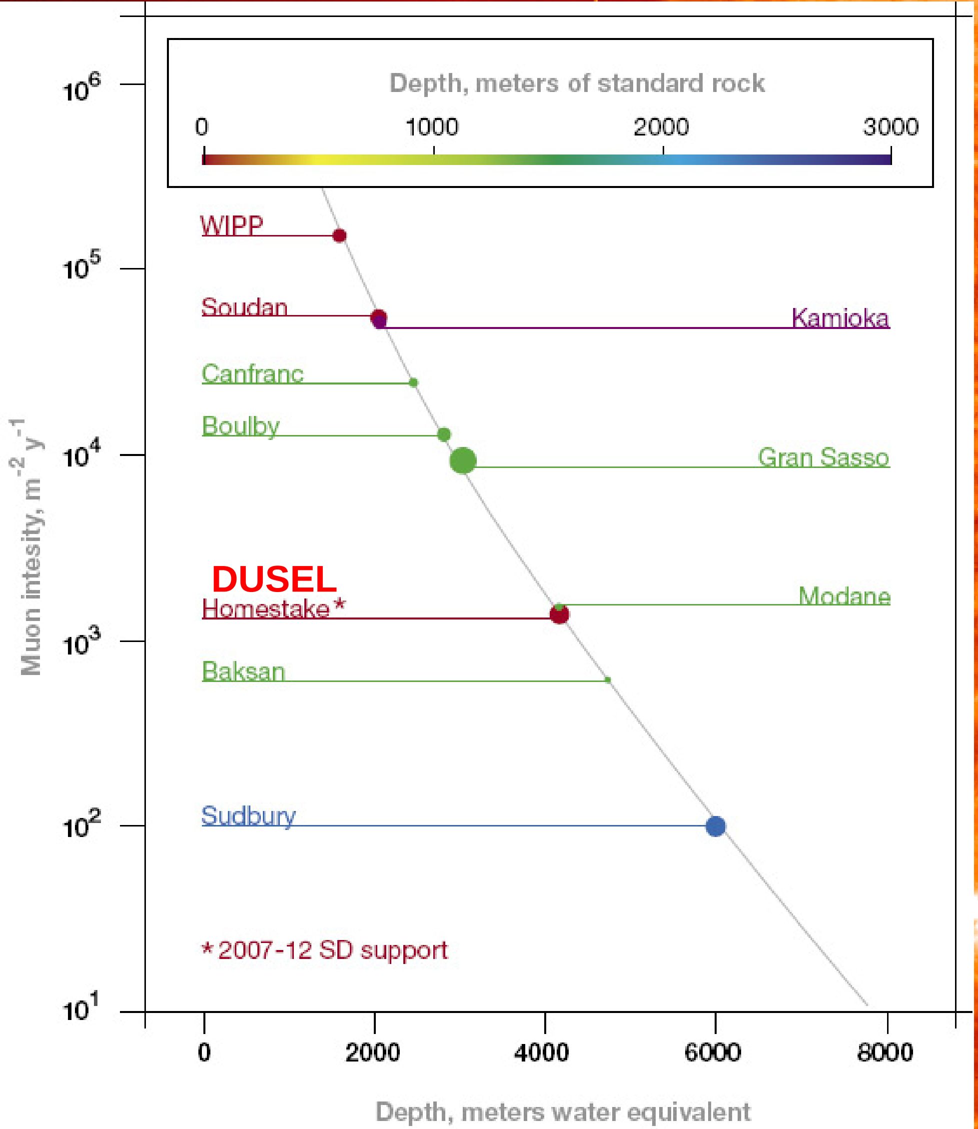
iron → heavy elements

Experiments with stable beams and targets:

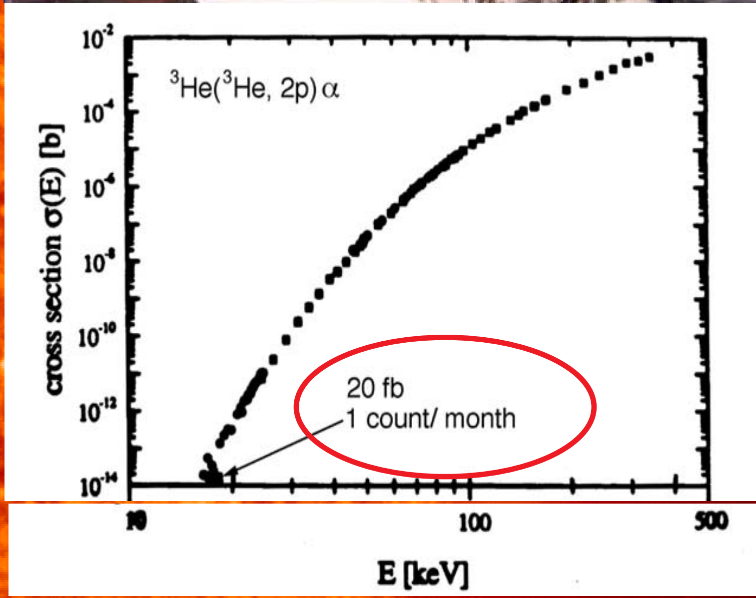
provide data for BB nucleo-synthesis and quiescent burning scenarios

Need:

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


Depth, meters of standard rock
0
1000
2000
3000
WIPP
Soudan
Kamioka
Canfranc
Boulby
Gran Sasso
DUSEL
Homestake*
Modane
Baksan
Sudbury
*2007-12 SD support
Muon intesity, m-2 y-1
10^6
10^5
10^4
10^3
10^2
10^1
0
2000
4000
6000
8000
Depth, meters water equivalent


LUNA Gran Sasso


3He(3He, 2p)α
cross section σ(E) [b]
20 fb
1 count/ month
10
100
500
E [keV]

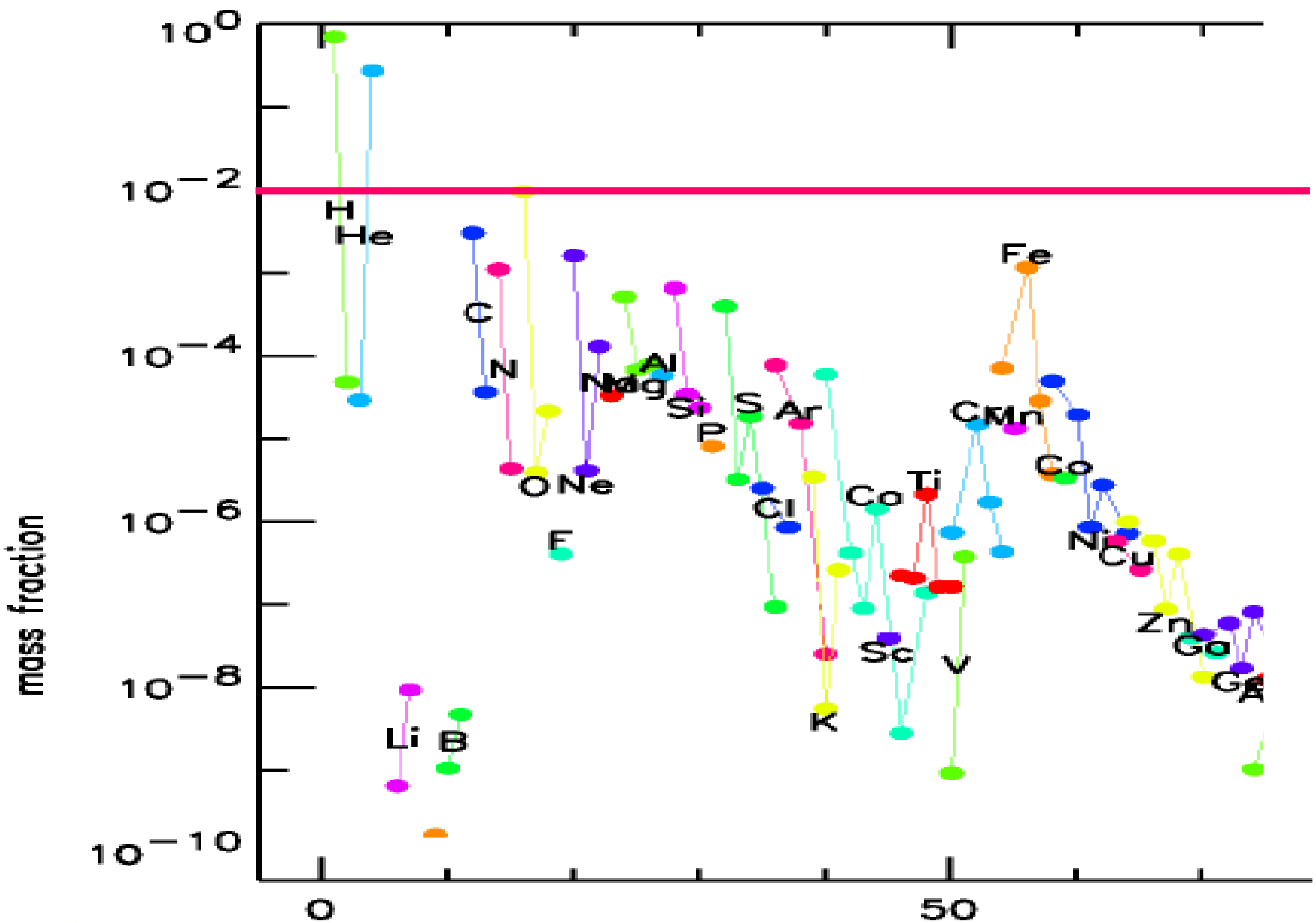
Experiments with radioactive beams:

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:

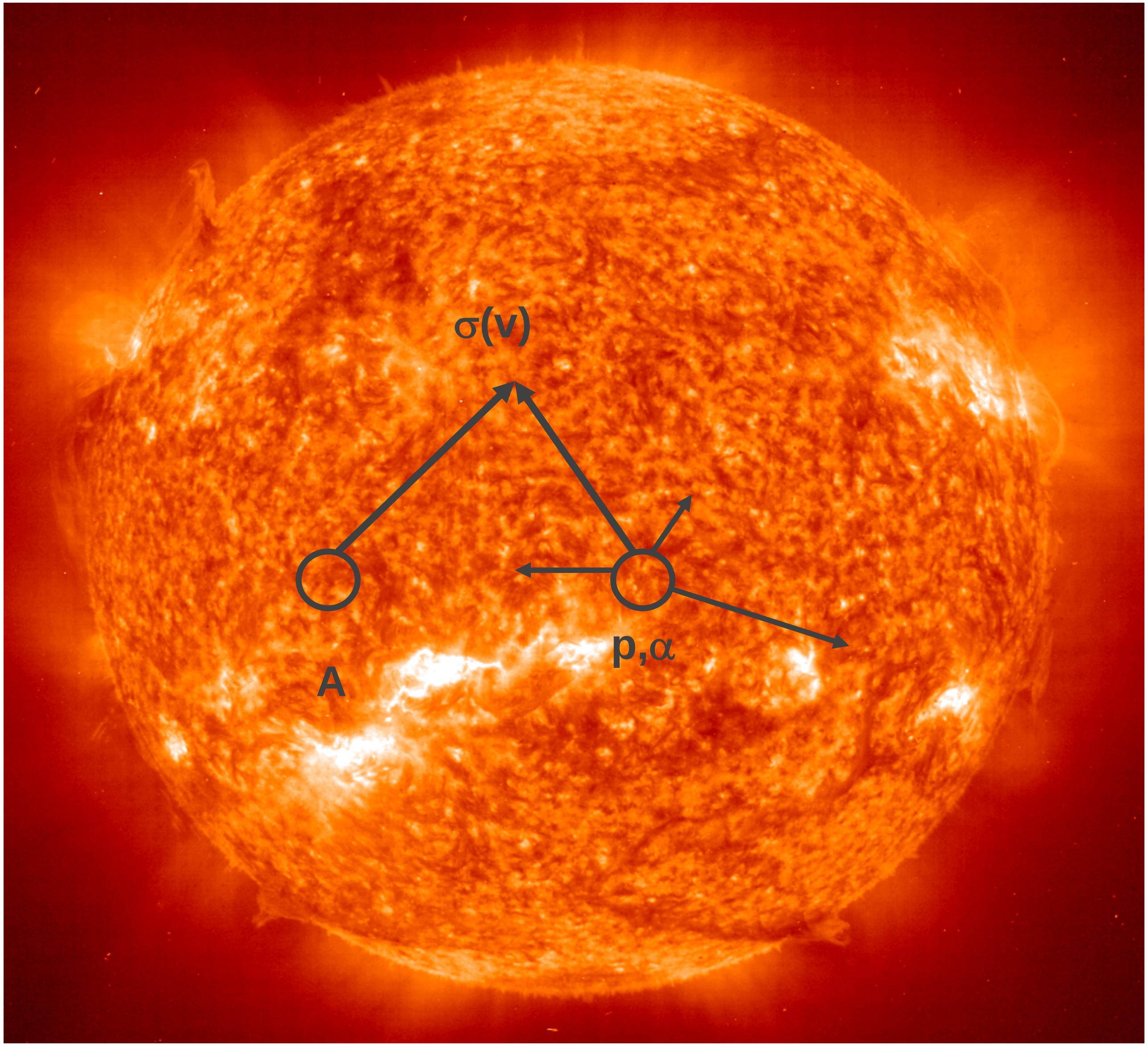
p,α

(^{16}O,^{12}C, n)

Critical reactions in nuclear astrophysics

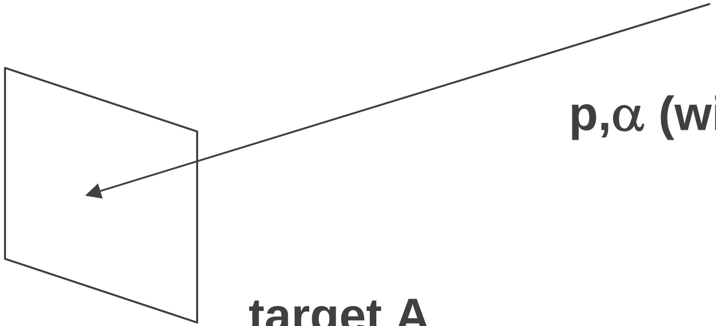
(p,γ)	(novae, rp-process)
(α,γ)	(red giants)
(α,p)	(rp-process)
$^{12}C + {}^{12}C$ fusion	(supernovae)
(n,γ)	(r-process, s-process)
GT transitions	(supernovae)
(α,n)	(s-process, red giants)
(p,α)	(novae)
(γ,p), (γ,n), (γ,α)	(p-process)

In Nature:



v: Maxwellian distribution

In the laboratory:



p,α (with velocity v_o)

$\sigma(v_o)$

target A

Reactions between Charged Particles

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

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

N_c: ^{12}C particles/cm^3

N_p: protons/cm^3

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:

$\rho = N_i \mu$ μ= weight of a particle

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

ρ ~150 g/cm^3

X_i=0.73

N_p=6.6 10^{25} particles/cm^3

In normal stellar matter (not in neutron stars)

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

$<\sigma v>=\iint \phi(v_1)\phi(v_2)\sigma(v_{rel})v_{rel}\, dv_1 dv_2$

$v_1=V + m_2/(m_1+m_2)v$ V : center-of-mass velocity

$v_2=V - m_1/(m_1+m_2)v$ v : relative velocity (v_1-v_2)

$<\sigma v>=\iint \Phi(V)\phi(v)\, v\, \sigma(v)\, dv\, dV$

Where:

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

$M=m_1+m_2$

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

$\mu=m_1m_2/(m_1+m_2)$

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

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:

$$R_{12} = N_1 N_2 < \sigma \cdot v >$$

Reactions/(cm^3 sec) in a plasma consisting of N_1 and N_2 particles/cm^3

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

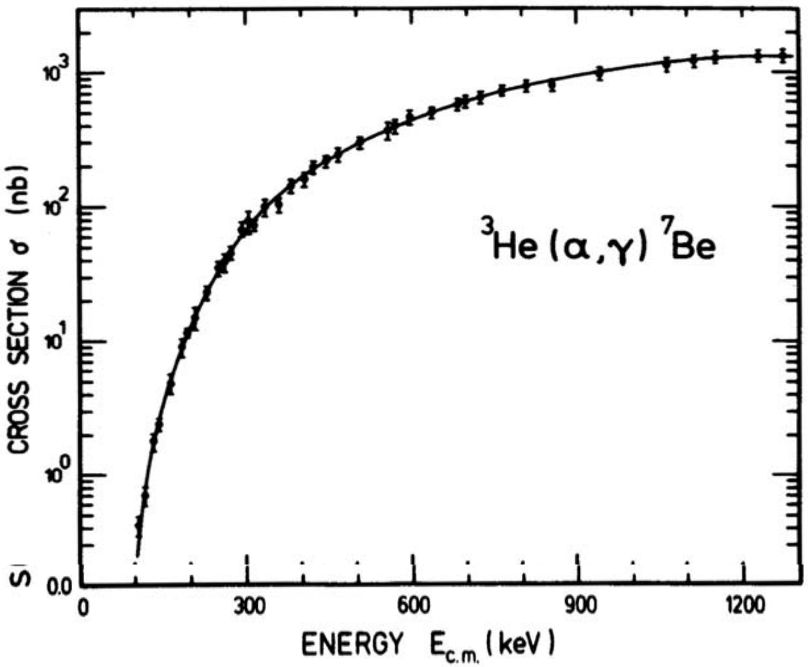
Rate of energy release (MeV/(cm^3 sec)

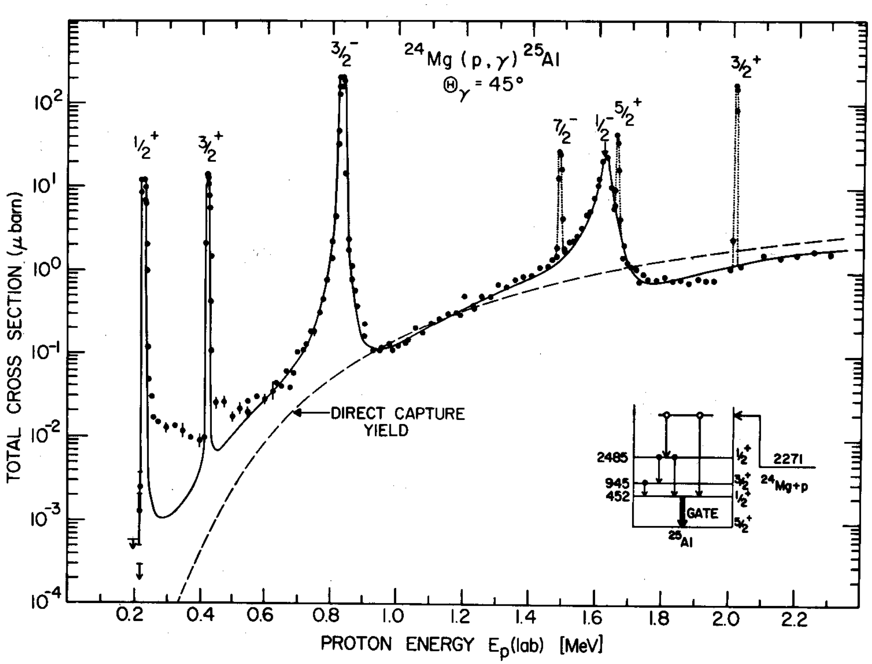
$$\tau(1) = \frac{1}{N_2 < \sigma \cdot v >}$$

Life time (sec) of particle 1 in a plasma consisting of N_2 particles/cm^3

Need to measure σ(v) (or σ(E))

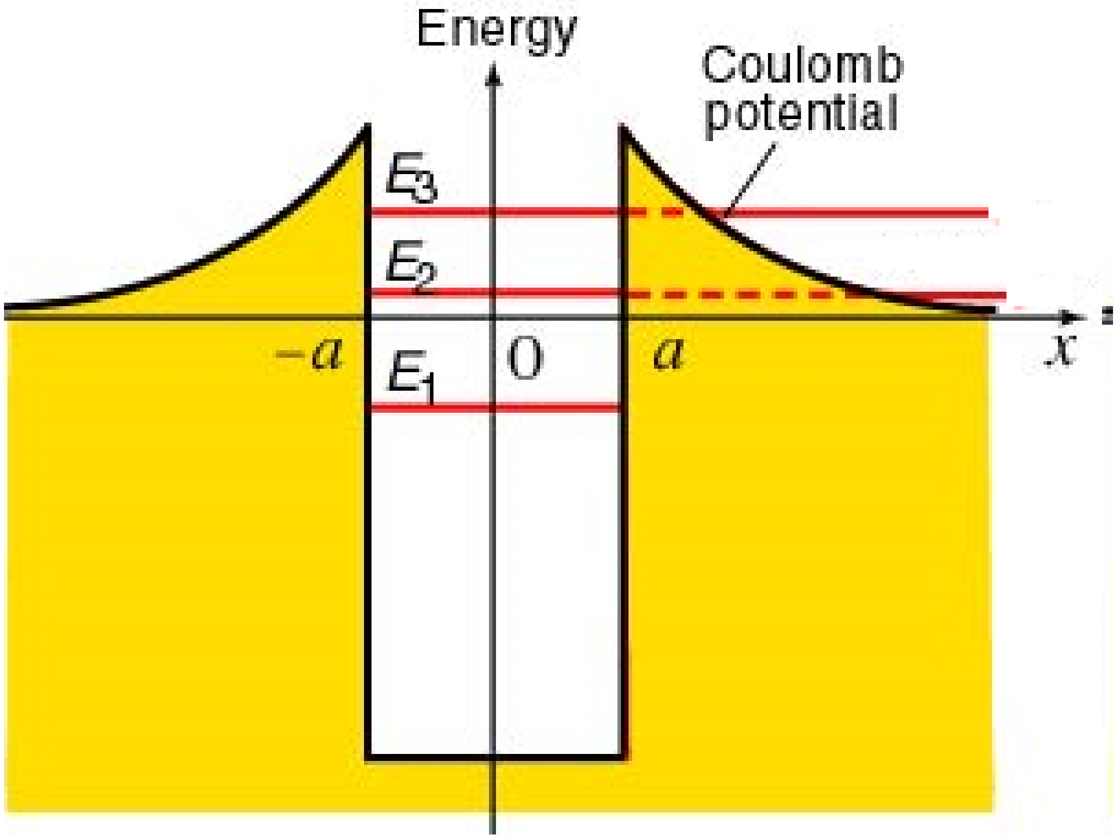
Need σ(E):





Non-resonant cross sections

resonant cross sections



Probability of tunneling through the Coulomb barrier:

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

2.1 Non-resonant Reactions:

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

at low energies only l=0 collisions contribute:

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

With asymptotic values (Abramowitz-Stegun):

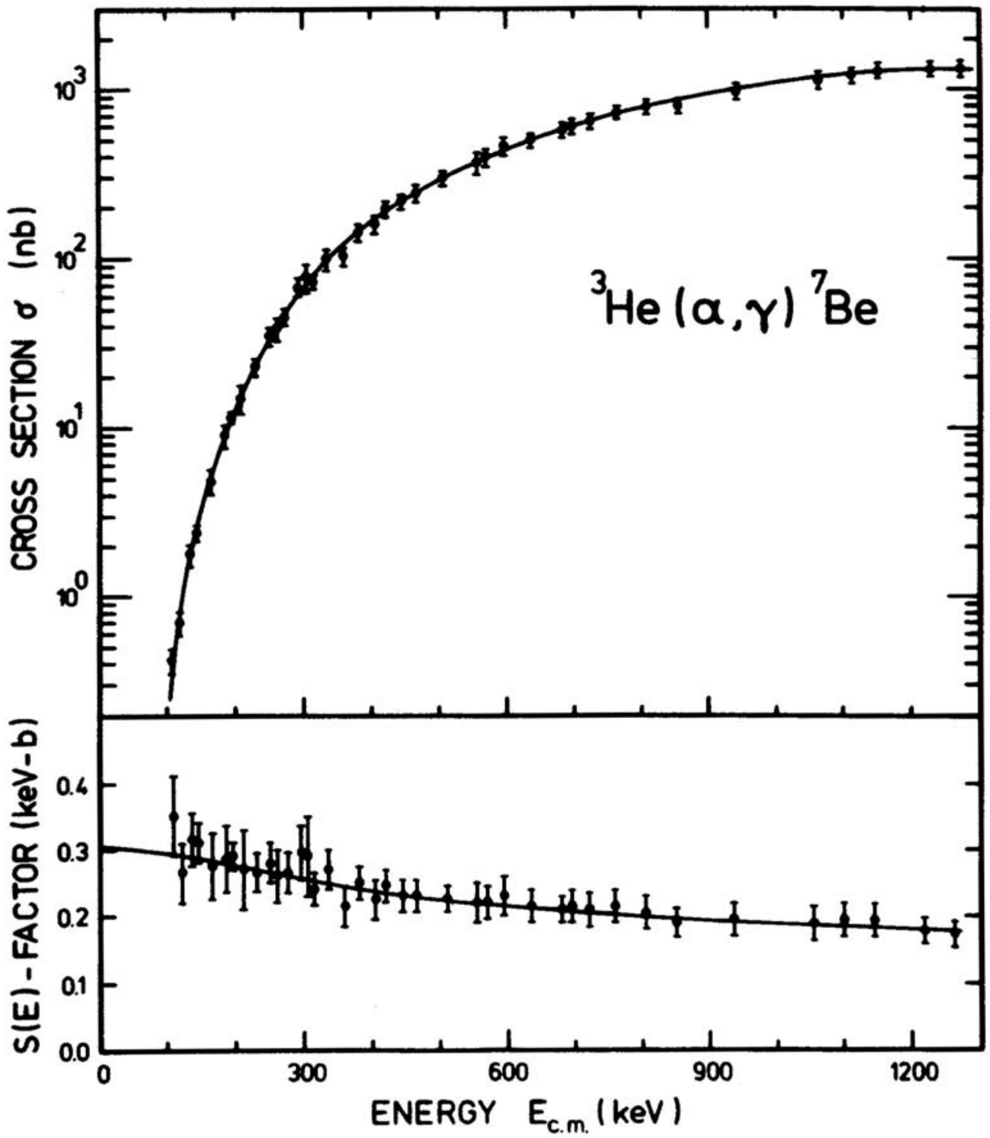
$\sigma \sim 1/E \exp(-2\pi\eta)$

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:

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

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

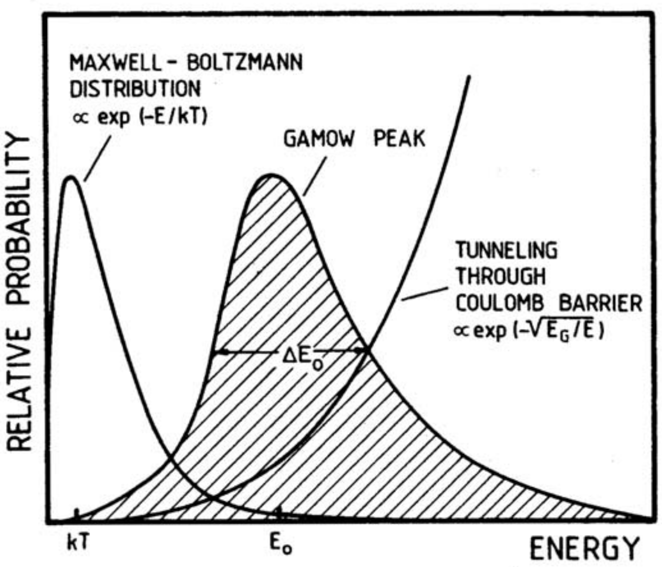


CROSS SECTION σ (nb)
10^3
10^2
10^1
10^0
$^3He(\alpha,\gamma)^7Be$
S(E) - FACTOR (keV-b)
0.4
0.3
0.2
0.1
0.0
0
300
600
900
1200
ENERGY $E_{c.m.}$ (keV)

With S(E) one can rewrite <σv>:

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

argument of the exponent:



Maximum of the argument at E_0:

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

or

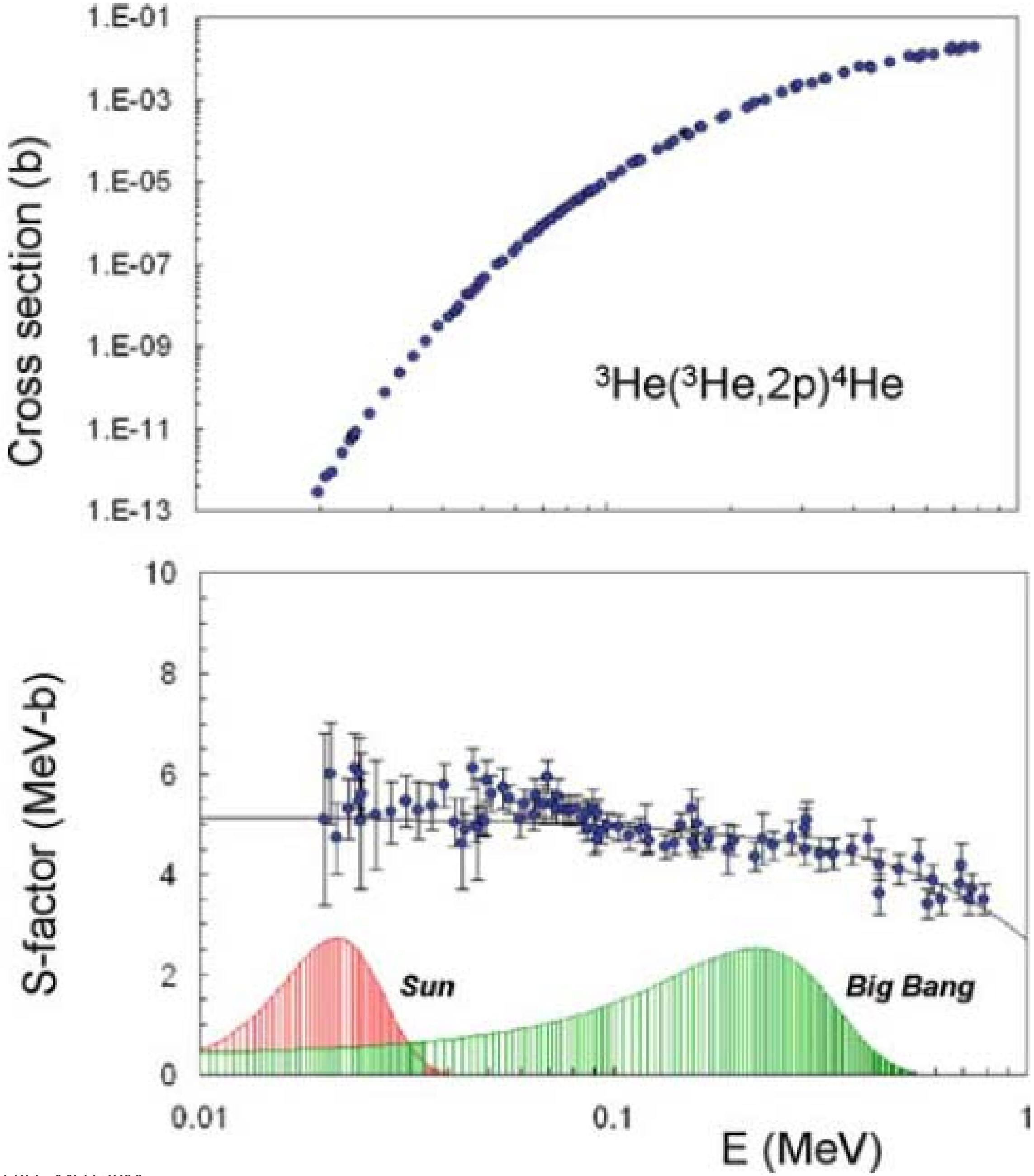
$E_0=1.22(Z_1^2 Z_2^2 \mu T_6^2)^{1/3}$ [keV] **Gamow peak**

T_6: temperature in 10^6 K

Example of Gamow window values

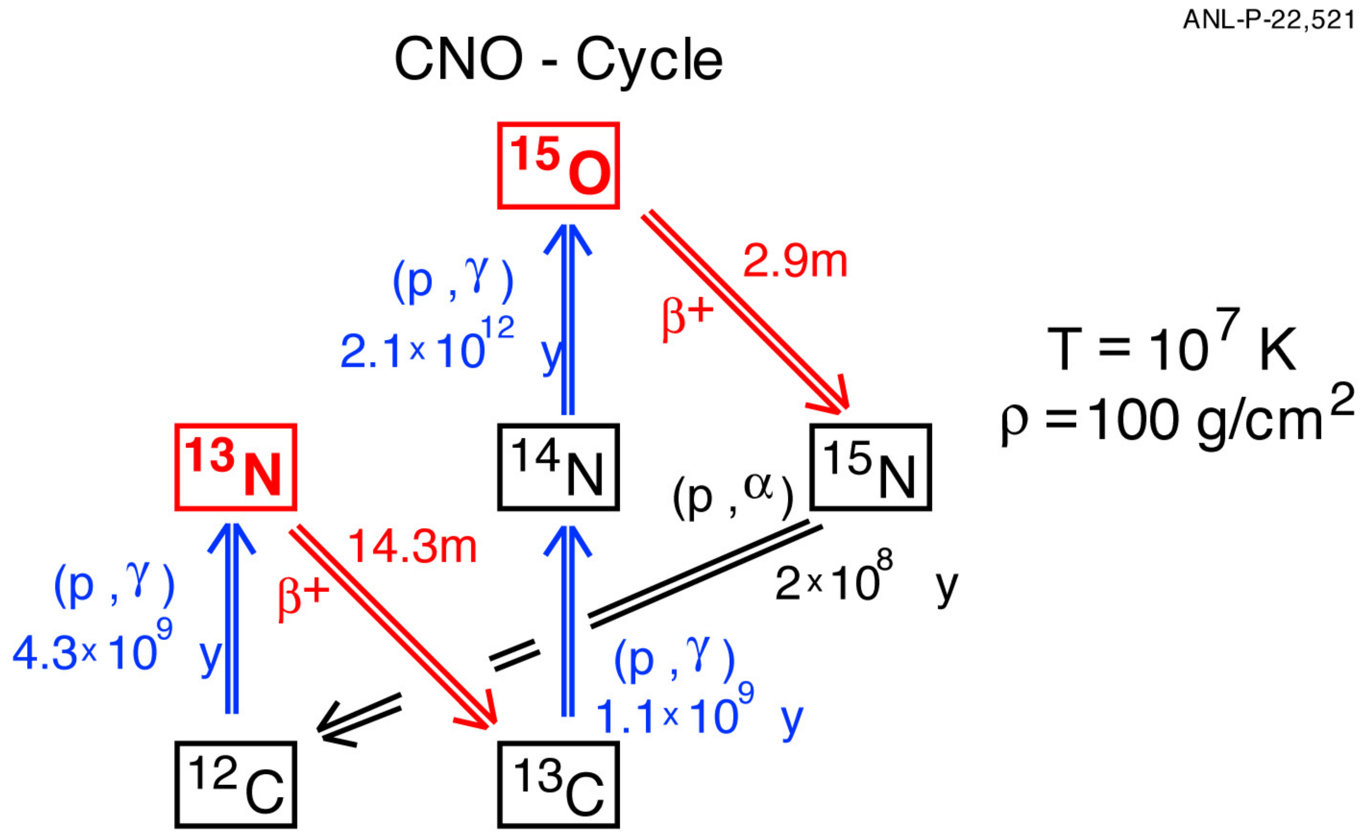
T_6=15 K T=15x10^6 K

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



From C. Angulo

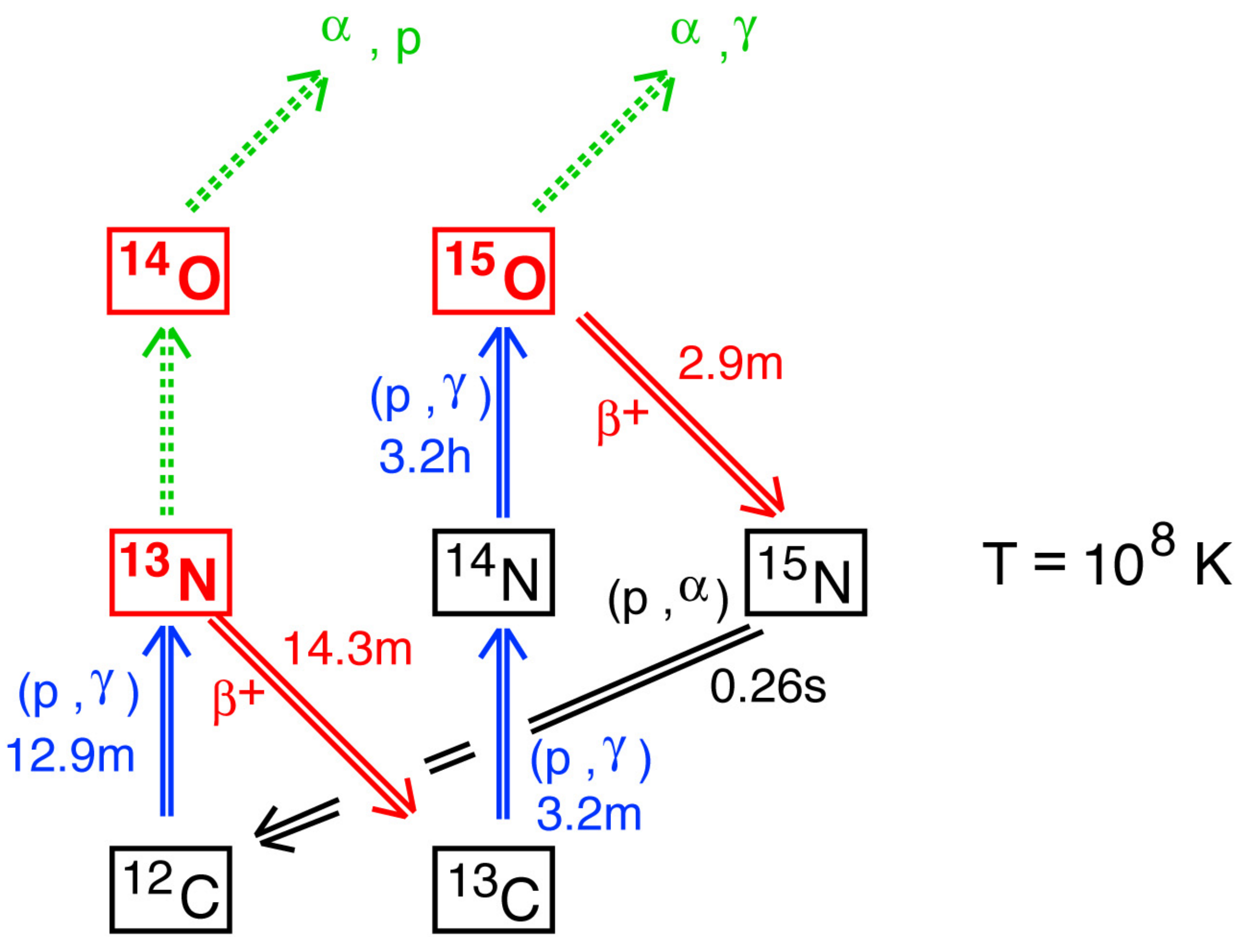
Example: reactions in the CNO cycle



reaction times long compared to τ_β

→Nuclear reactions occur on stable nuclei

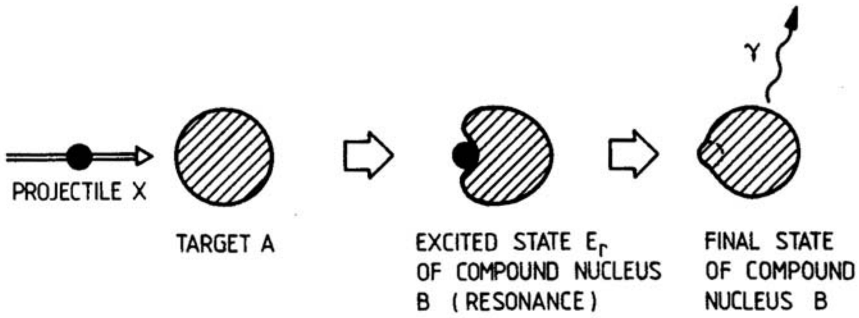
Increasing the temperature by a factor of 10:

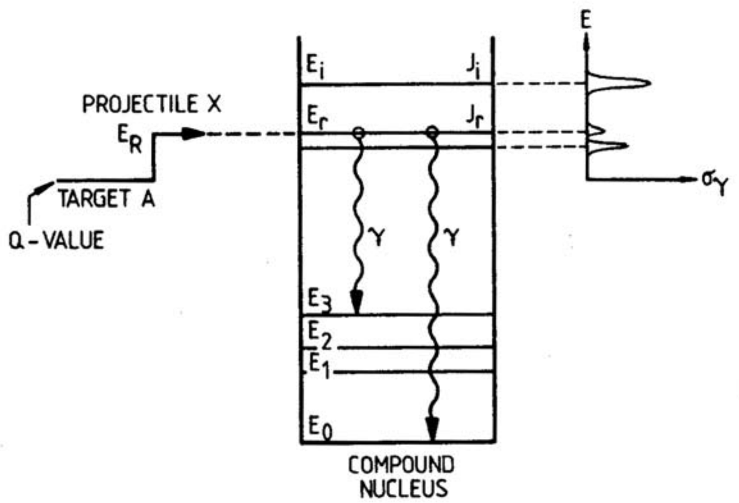


Reaction times are comparable to decay times.

→ unstable nuclei become part of the reaction network

2.2 Resonance Reactions





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

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

J: spin of the resonance

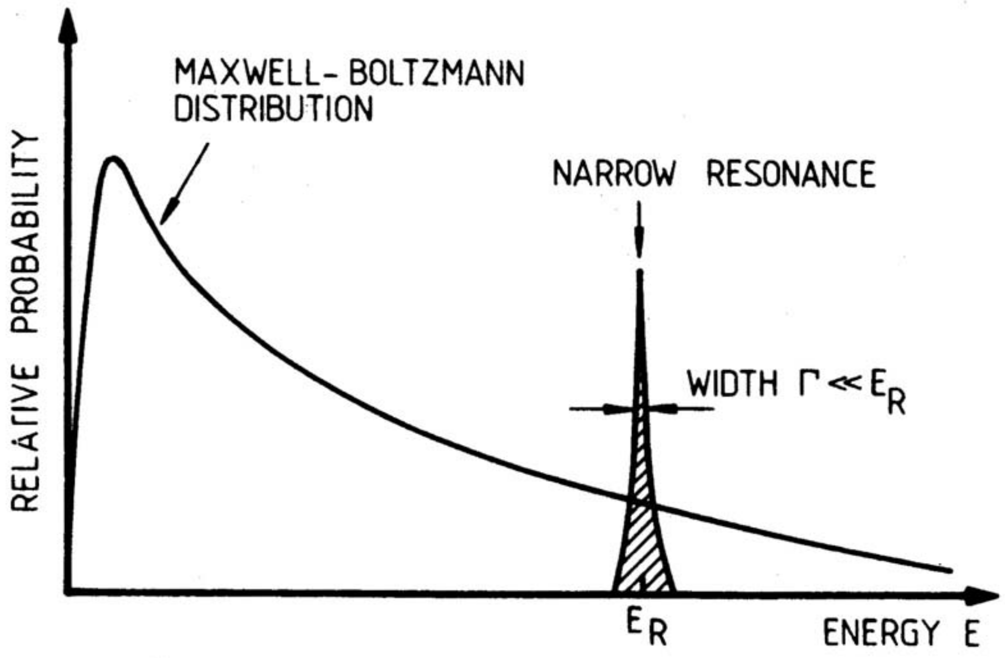
$J_{1,2}$: spin of the particles in the entrance channel

k: wave number

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

E_r: resonance energy

Γ: total width (Γ_i+Γ_f+..)



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

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

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

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

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

$\omega\gamma$: resonance strength

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

For several non-overlapping resonances:

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

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: $^{14}O(\alpha,p)^{17}F$

spin-parity selection rules, e.g.

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

$^{17}F(5/2^+) + p(1/2^+)$: $2^+, 3^+, 1^-, 2^-$,..

Angular momentum barrier:

$$V_{int}=Z_1Z_2e^2/R + \hbar^2\, l(l+1)/(2\mu R^2)$$

→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

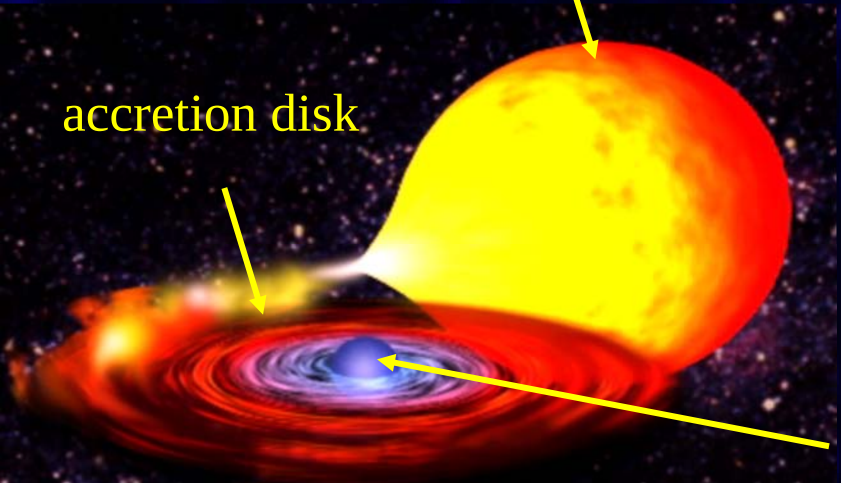
distance~ 10^{-3}– 1AU

$\sim 1.5\ M_\odot$

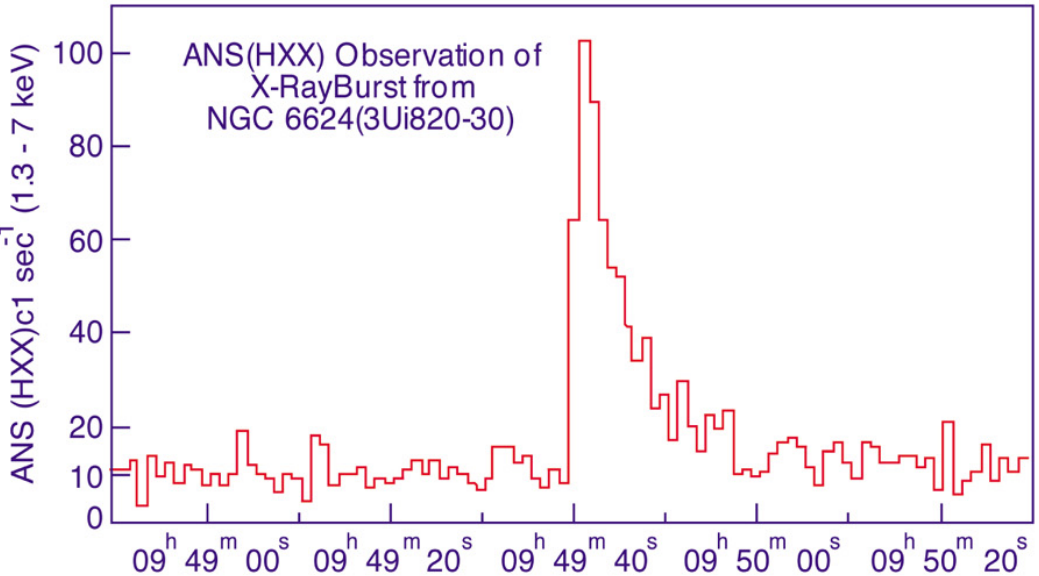
radius ~ 10 km

$\rho \sim 10^{6\text{-}14}$ g/cm^3

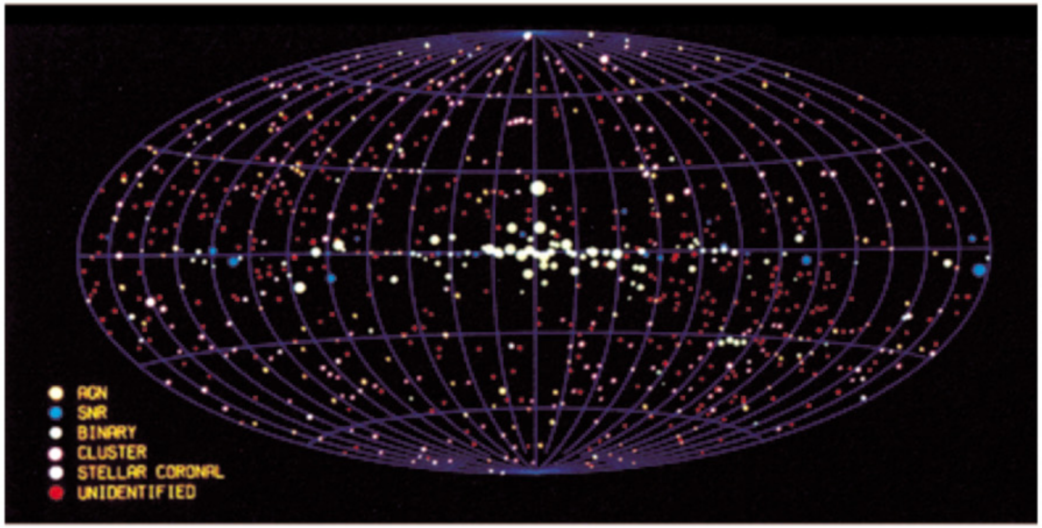
T ~ 10^7 K

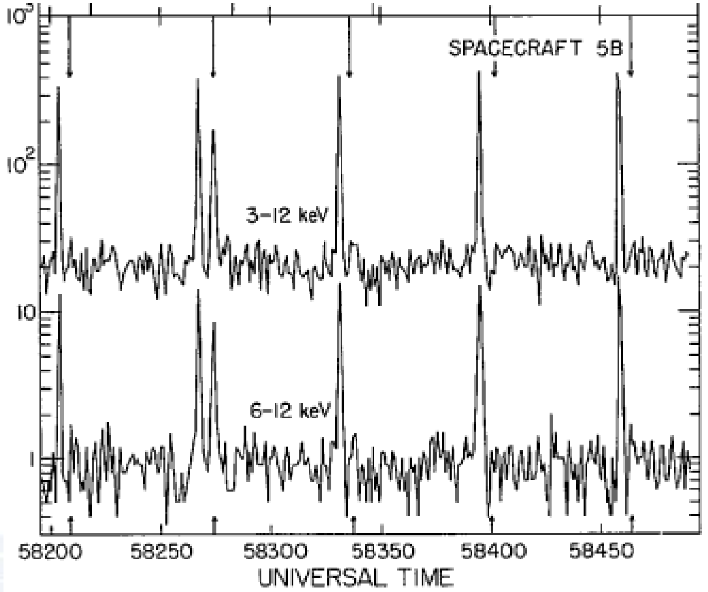


X-ray Bursts

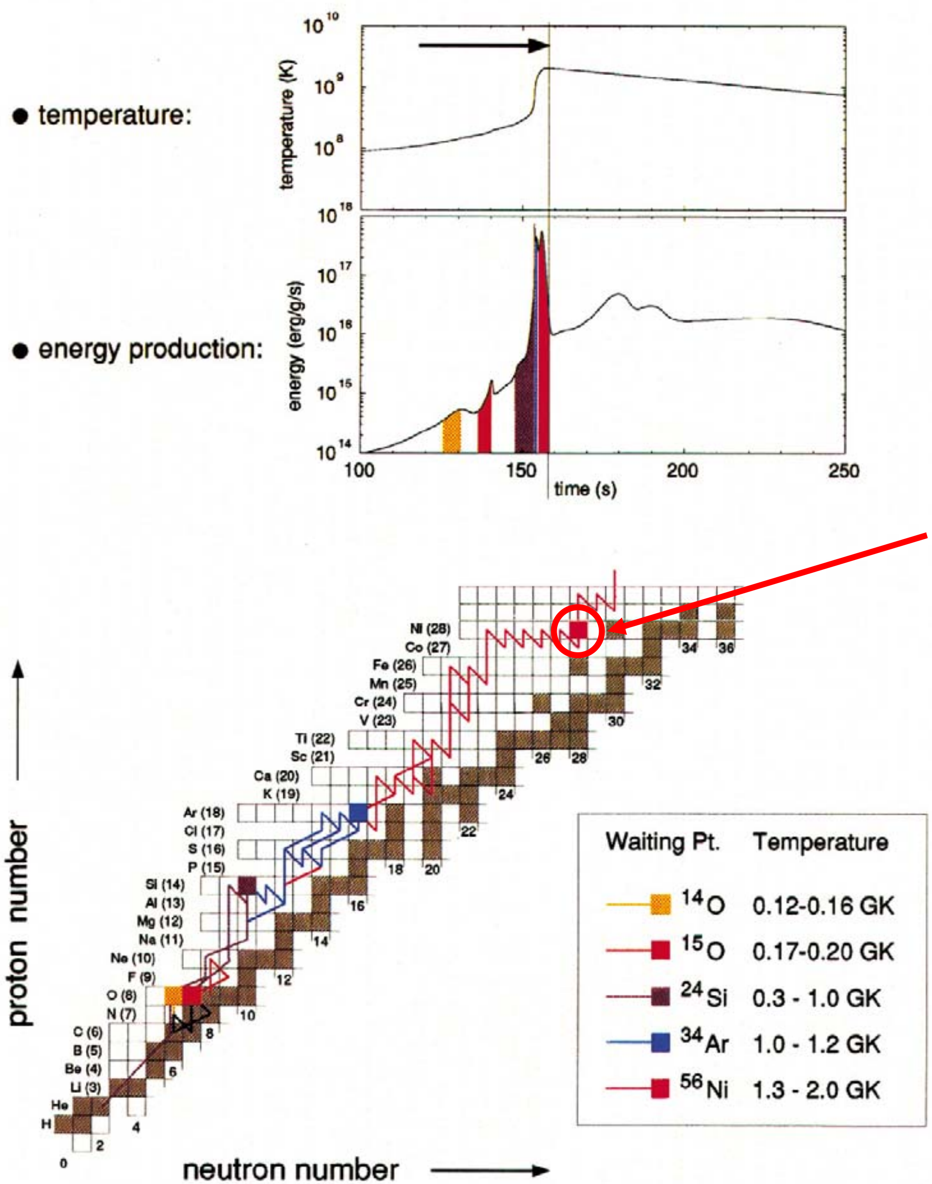


- ~repetition rate hours-days
- duration of ~10 sec
- E=10^{38} erg/s (sun 10^{33} erg/s)





Network calculations for x-ray bursts



M. Wiescher et al.

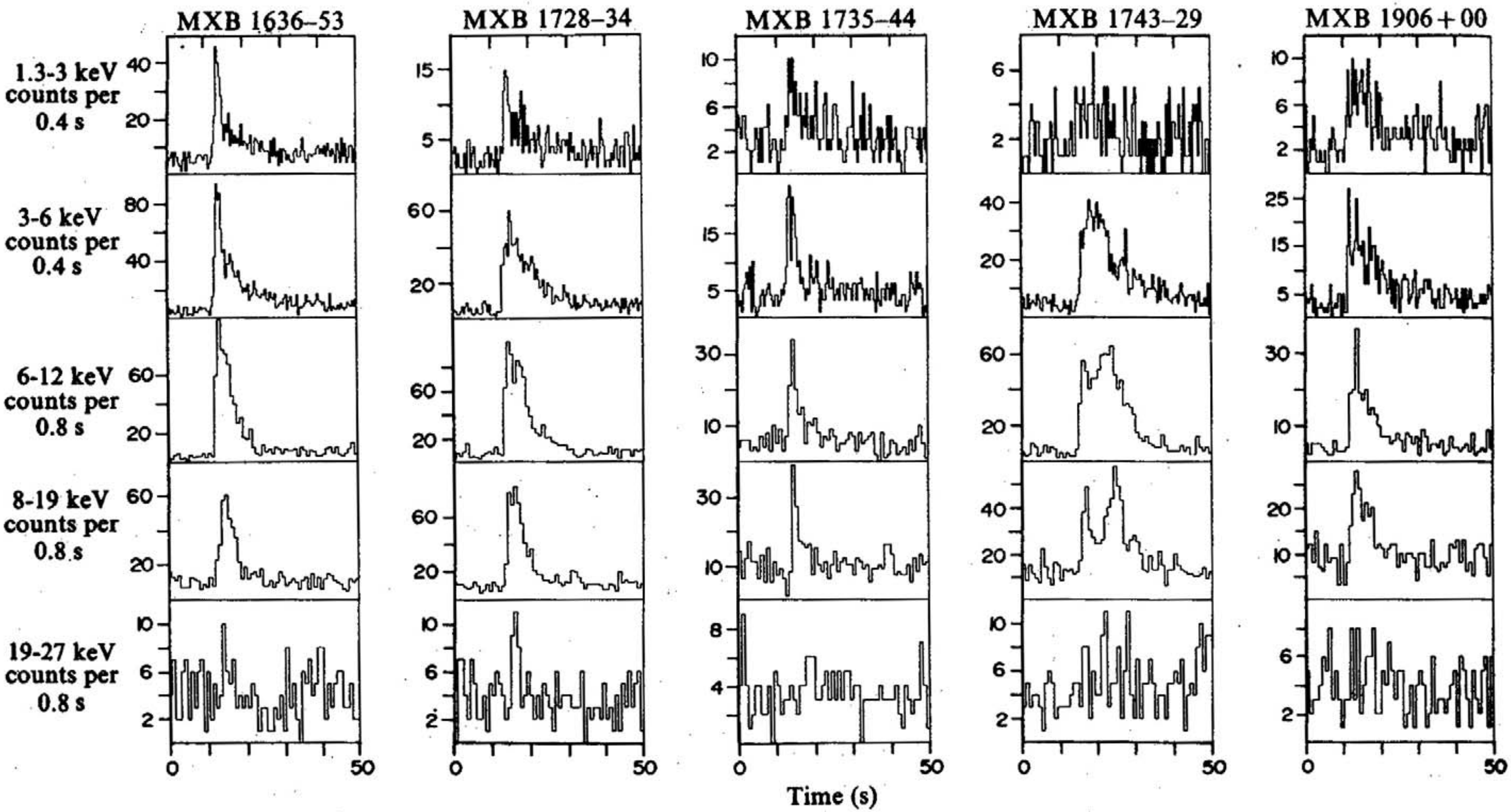
^{56}Ni(p,γ)^{57}Cu

$\sigma \sim \mu$b

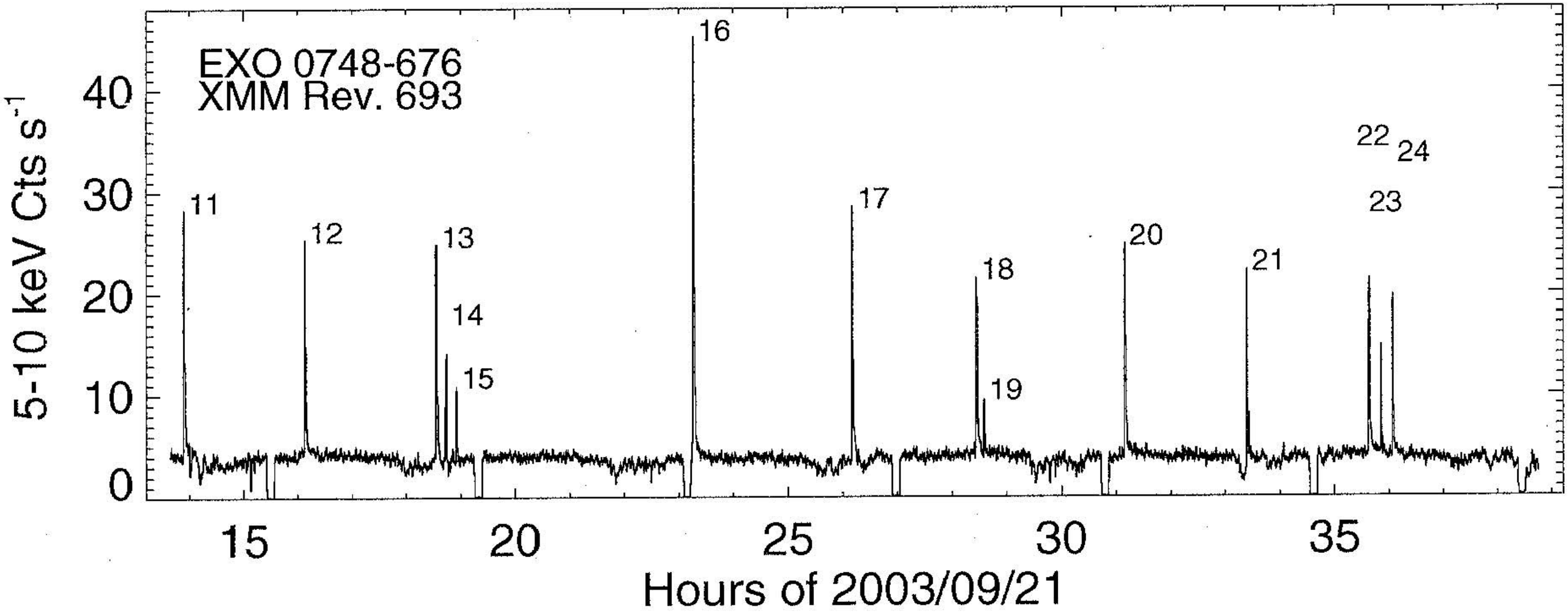
$T_{1/2}(^{56}$Ni$)=6.1$d

What are the observables?

a) Time dependence of the luminosity



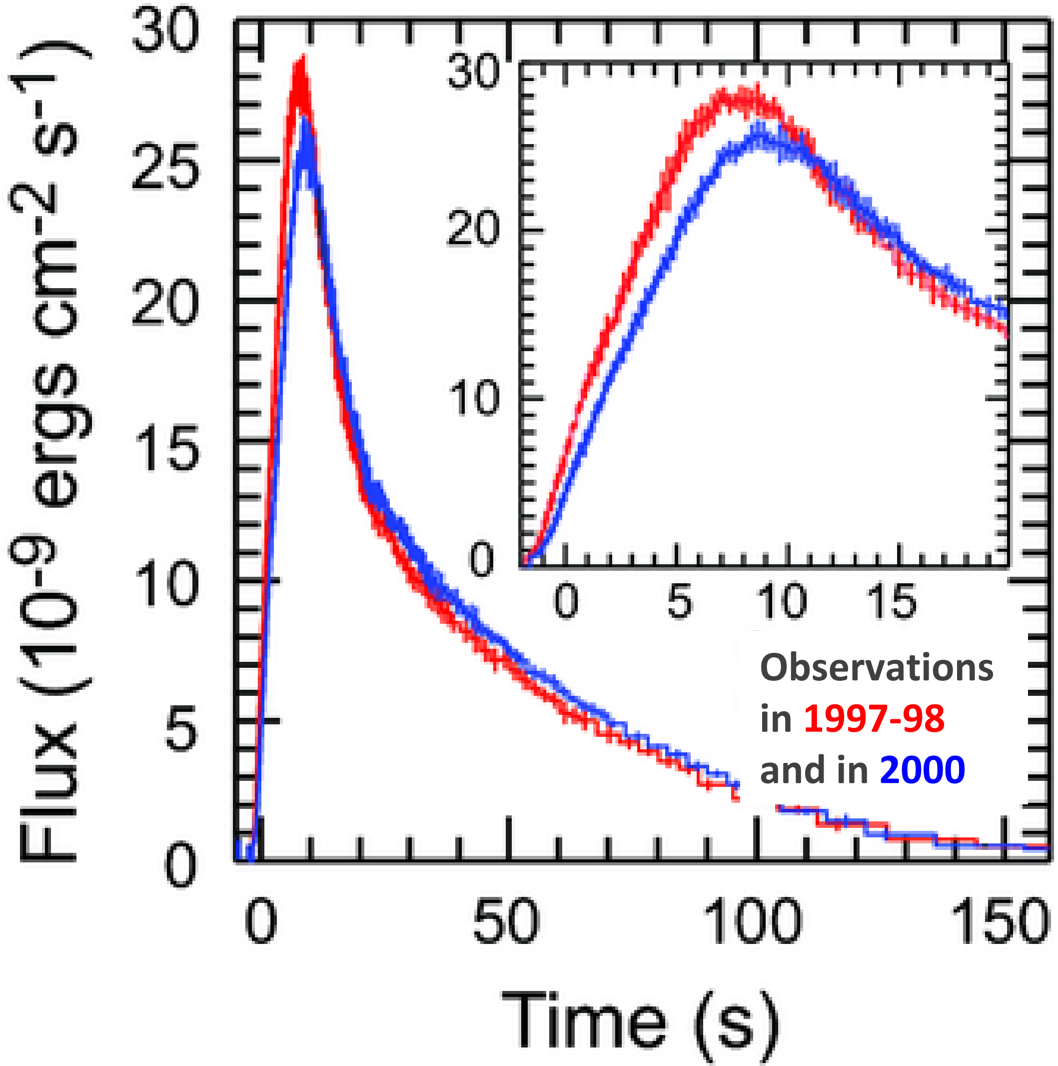
Observables cnt'd:
multiplets



L. Boirin et al.,

A&A 2007

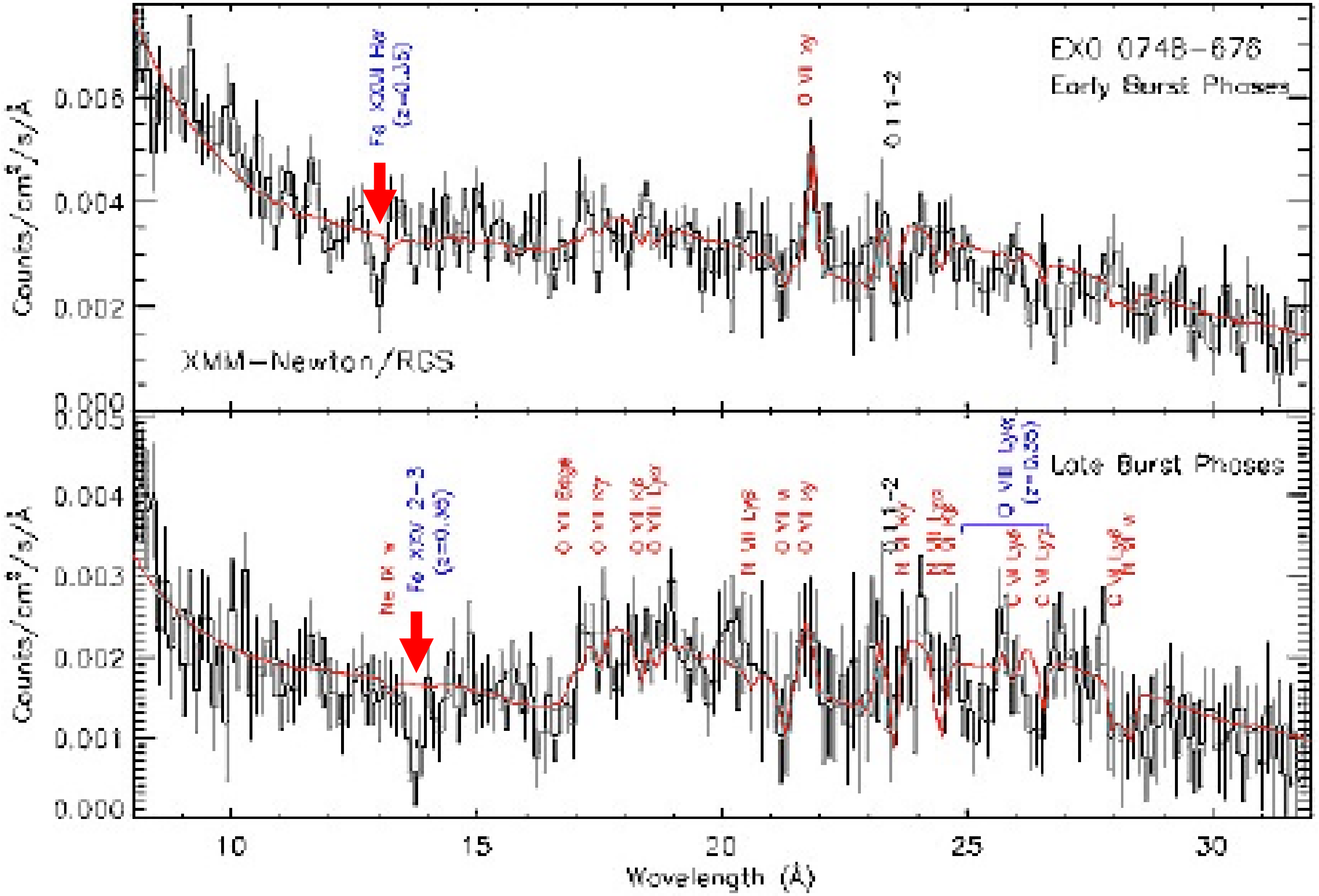
Observables cnt'd:
'aging' effects in X-ray bursts



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

Observables cnt'd:

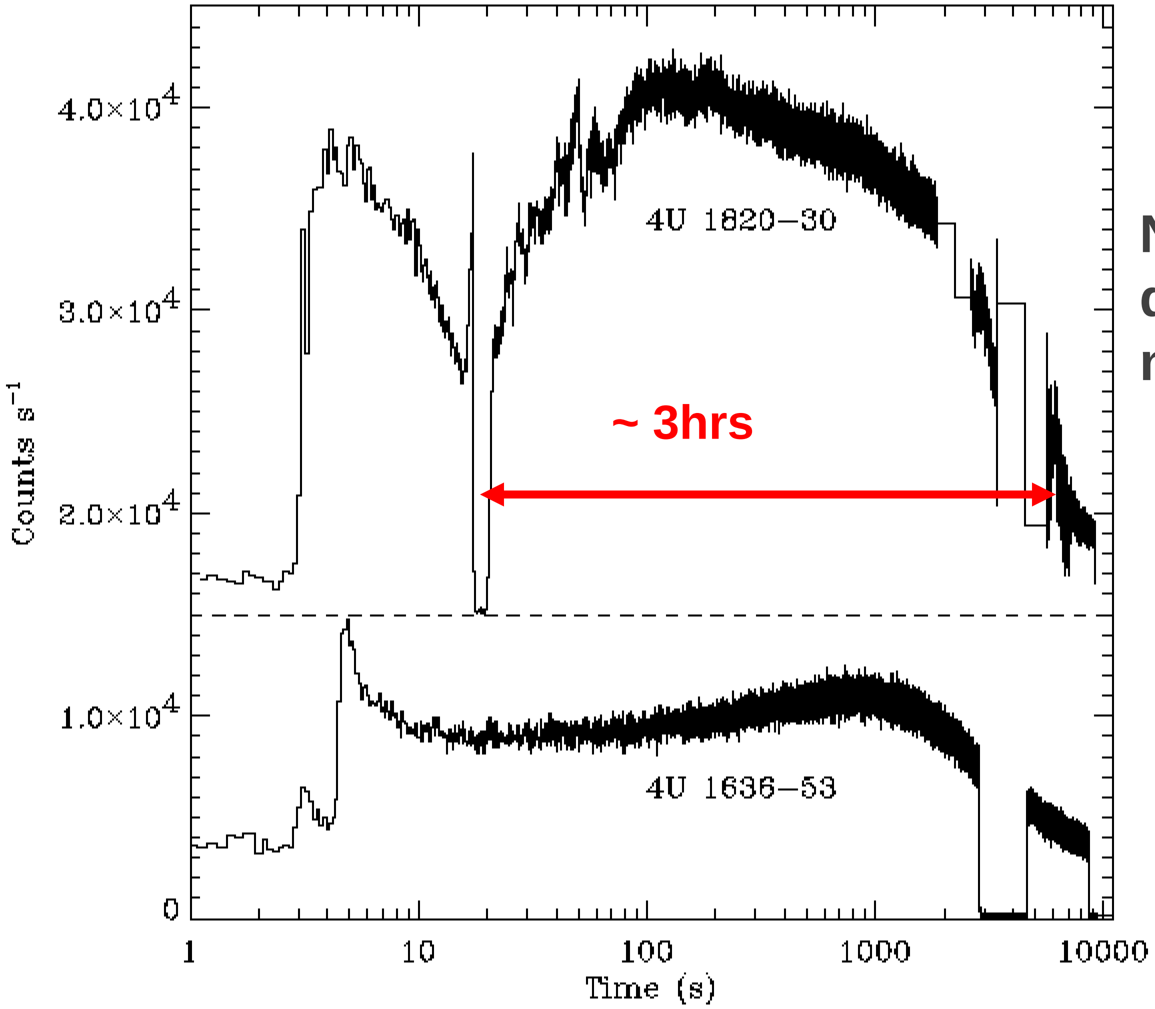
Energy shift of Fe-absorption line (ionization)



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

Observables cnt'd:

Long ('super') bursts

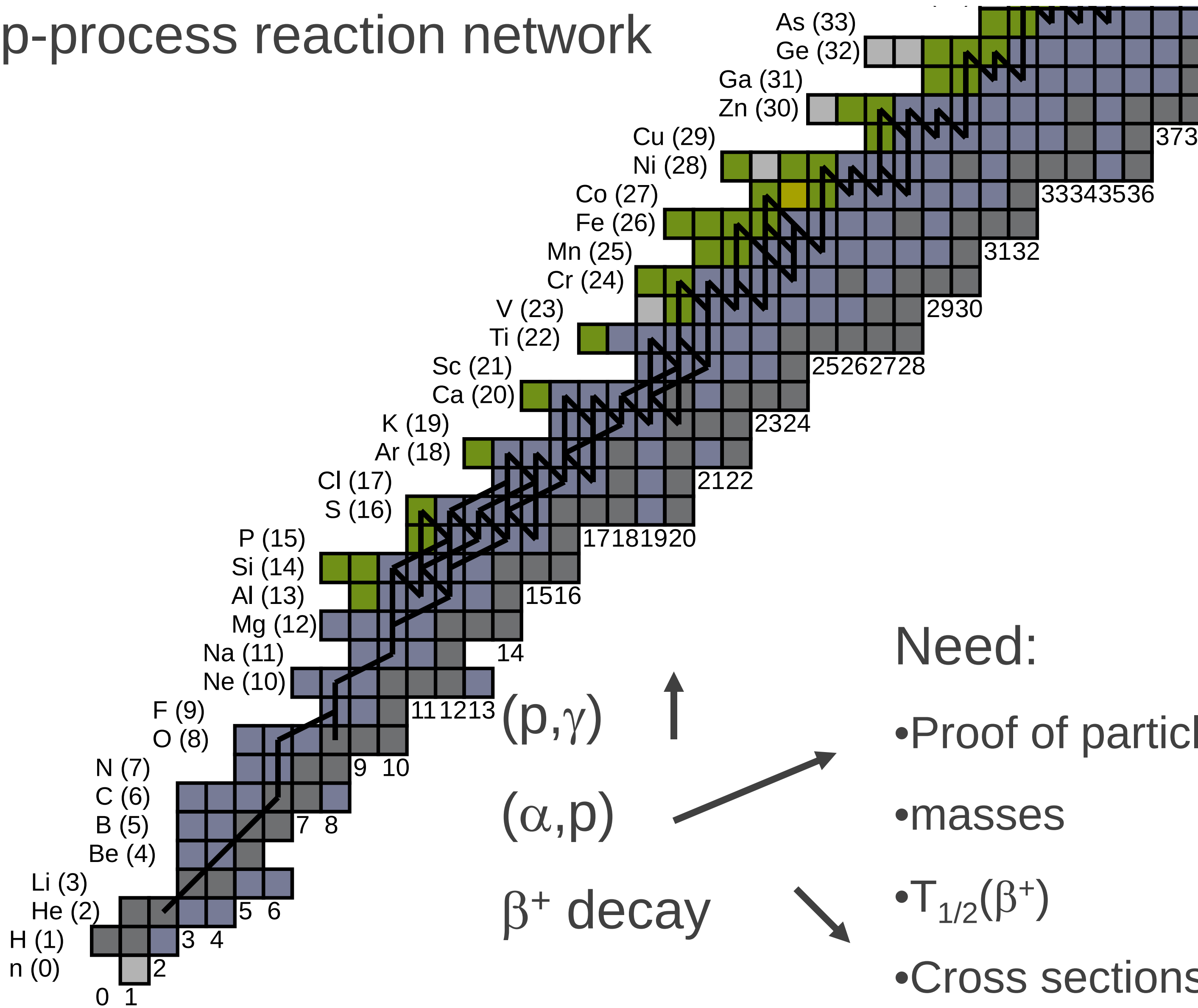


Nuclear reactions deeper inside the neutron star

Strohmayer & Brown ApJ 566, 1045(2002)

X-ray bursts and Nuclear Physics

Typical rp-process reaction network



(p,γ) ↑

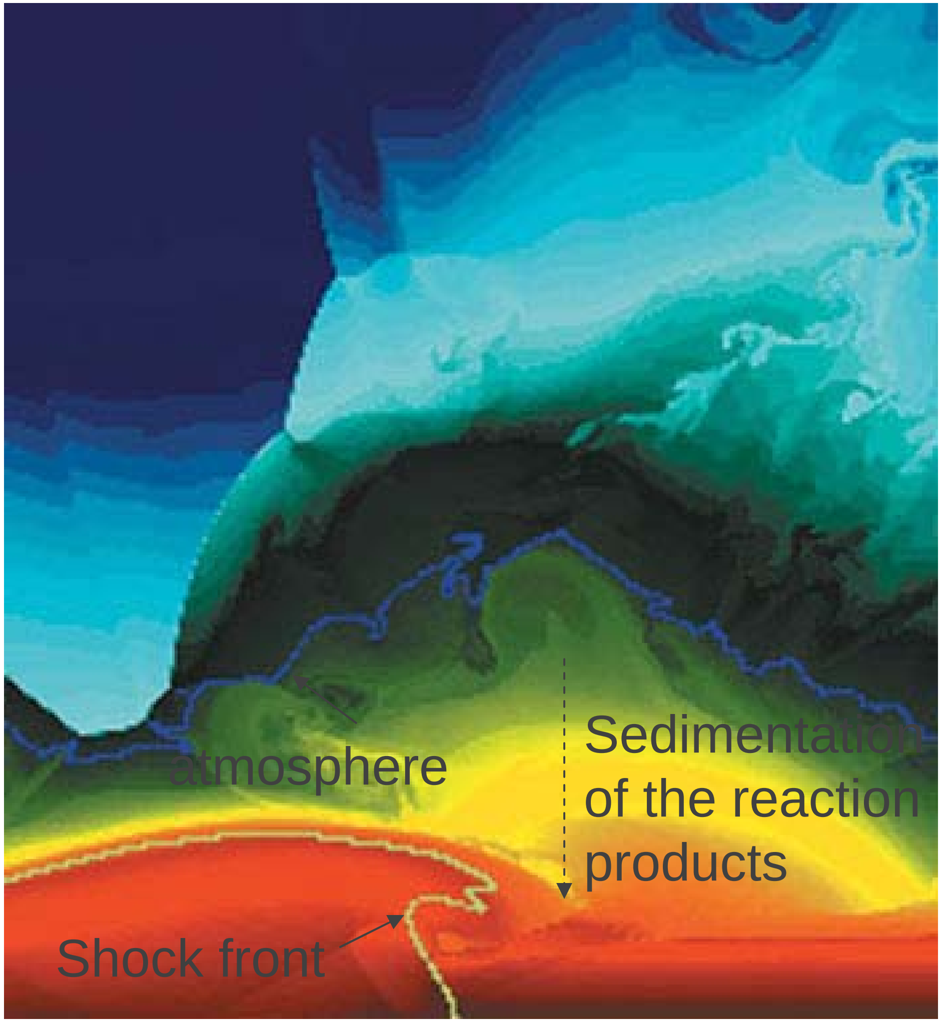
(α,p) ↗

β^+ decay ↘

Need:

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

Theoretical treatment of X-ray bursts



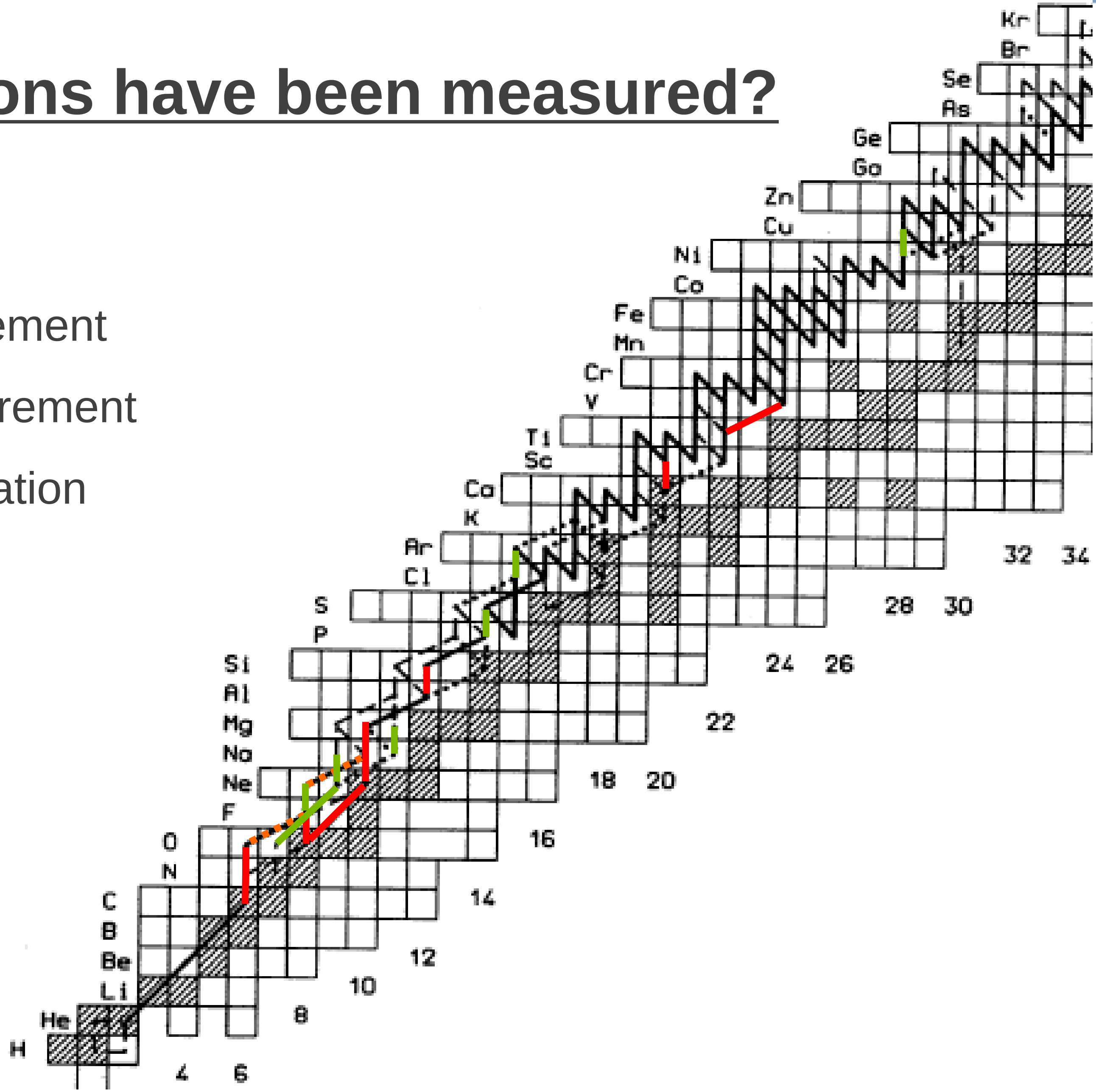
FLASH Center ANL

$E_{gr}/mc^2 = GM_{NS}/(R_{NS}c^2) \sim 0.2$

- Relativistic treatment
- Three-dimensional
- Rotations
- Turbulences
- Sedimentation
- 'Ashes' (e.g. ^{12}C) can burn as well
- Magnetic fields

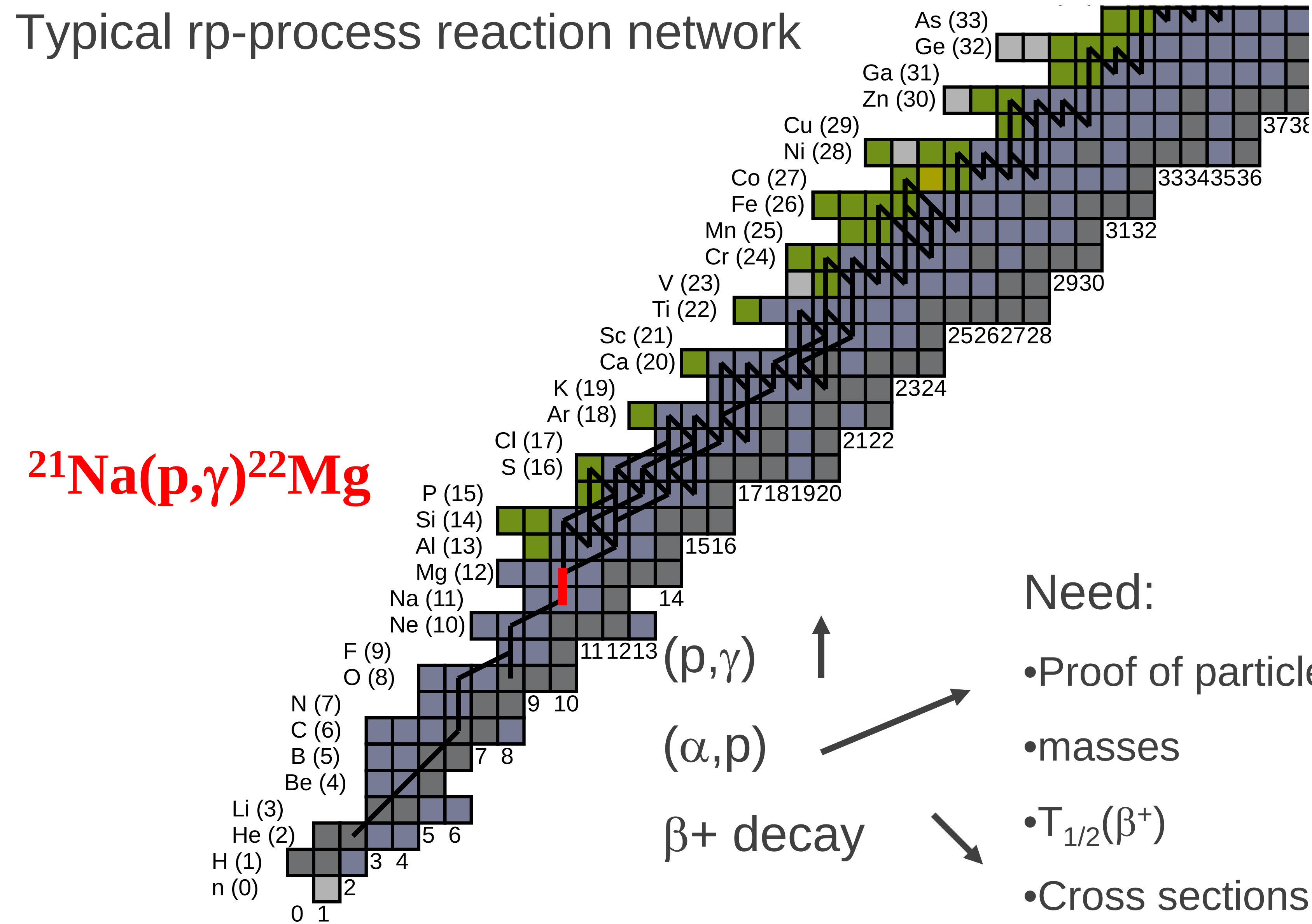
Which reactions have been measured?

- Direct measurement
- Indirect measurement
- Under investigation



X-ray bursts and Nuclear Physics

Typical rp-process reaction network



Need:

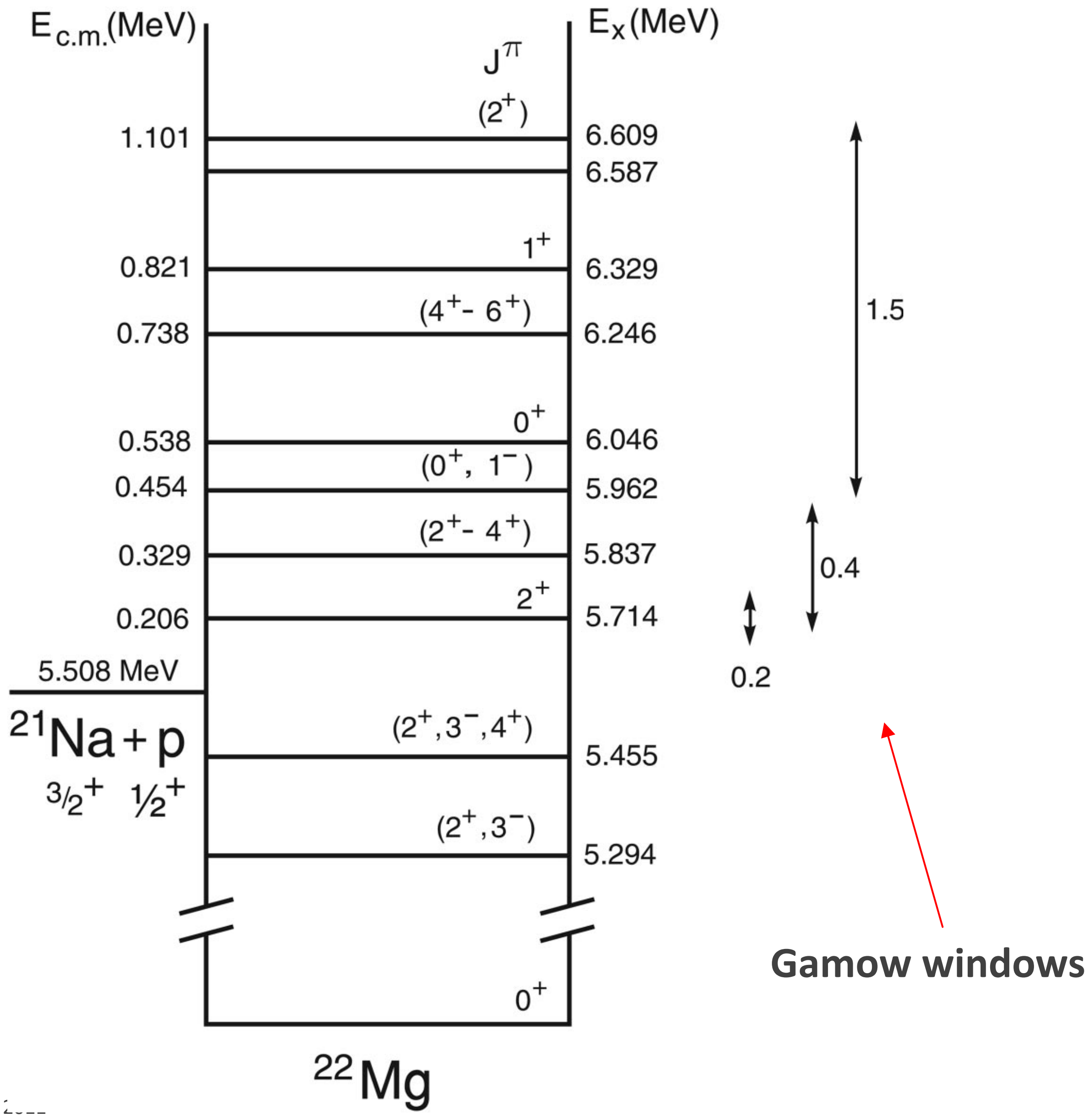
- Proof of particle stability
- masses
- $T_{1/2}(\beta^+)$
- Cross sections

(p,γ) reactions

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

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

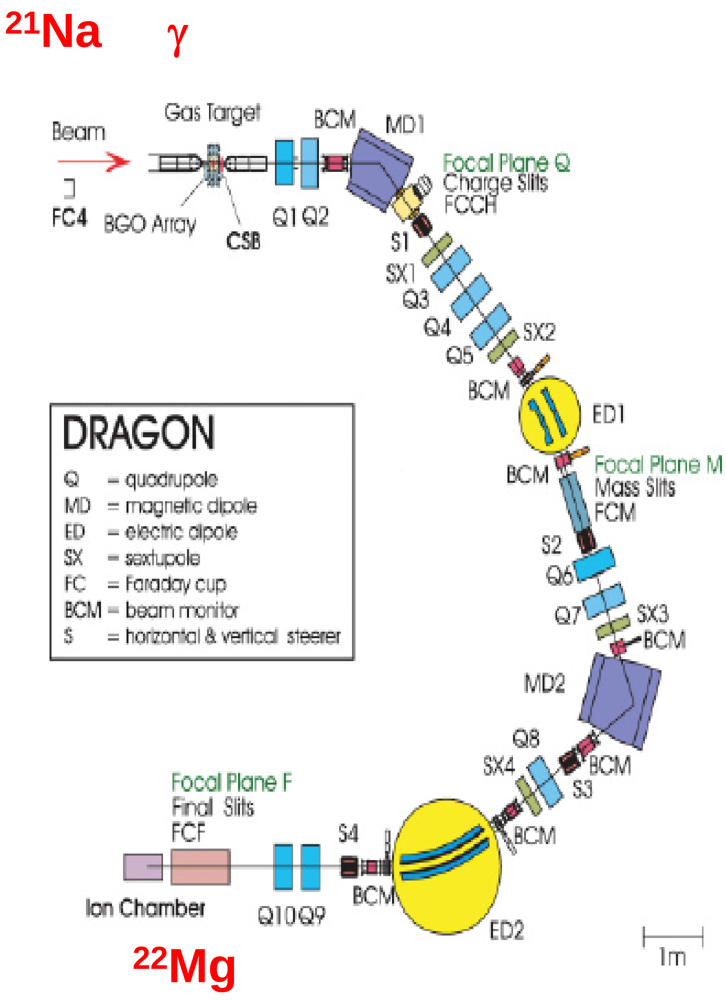
J. d'Auria et al. PRC69, 065803(2004)

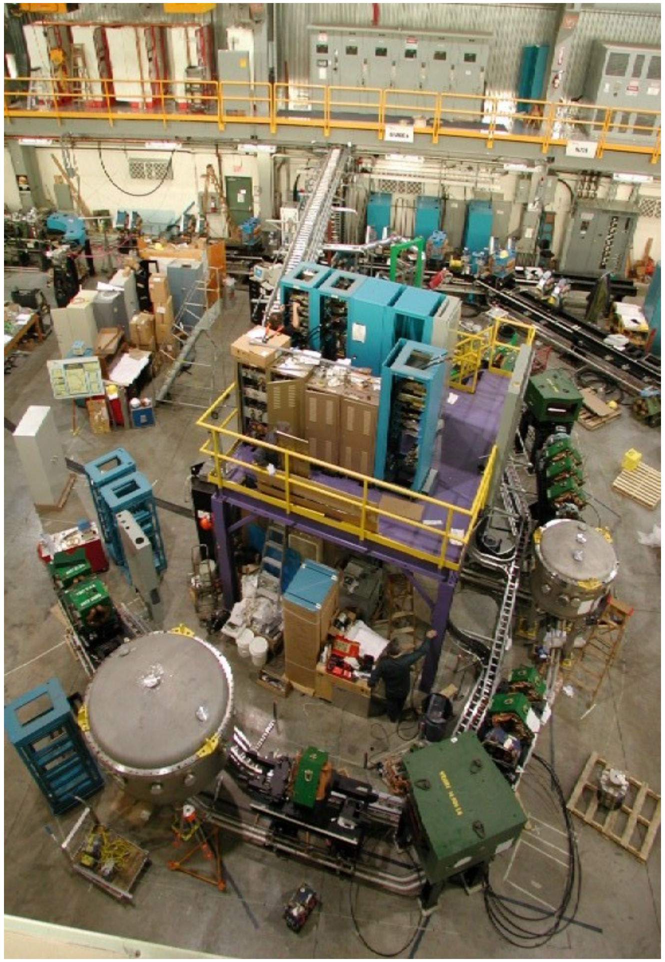


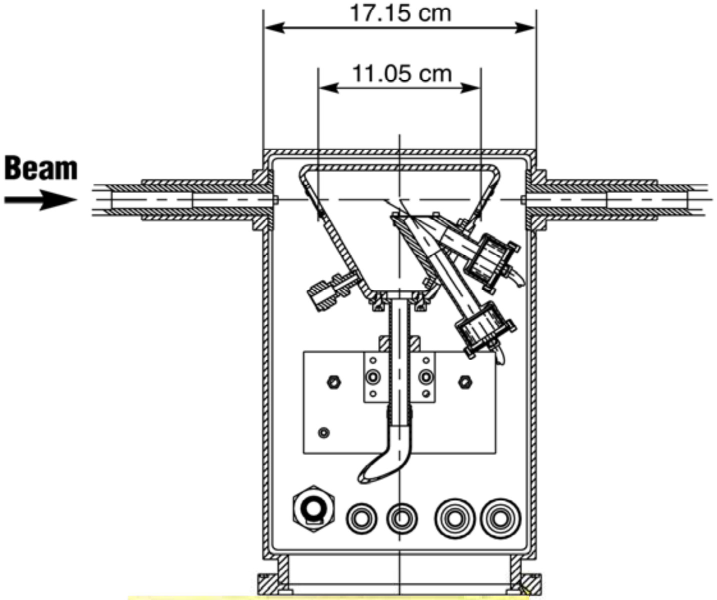
$E_{c.m.}$(MeV)
E_x(MeV)
J^π
(2^+)
1.101
6.609
6.587
1^+
0.821
6.329
$(4^+ - 6^+)$
0.738
6.246
0^+
0.538
6.046
$(0^+, 1^-)$
0.454
5.962
$(2^+ - 4^+)$
0.329
5.837
2^+
0.206
5.714
5.508 MeV
$^{21}Na + p$
$3/2^+$ $1/2^+$
$(2^+, 3^-, 4^+)$
5.455
$(2^+, 3^-)$
5.294
0^+
^{22}Mg
1.5
0.4
0.2
Gamow windows

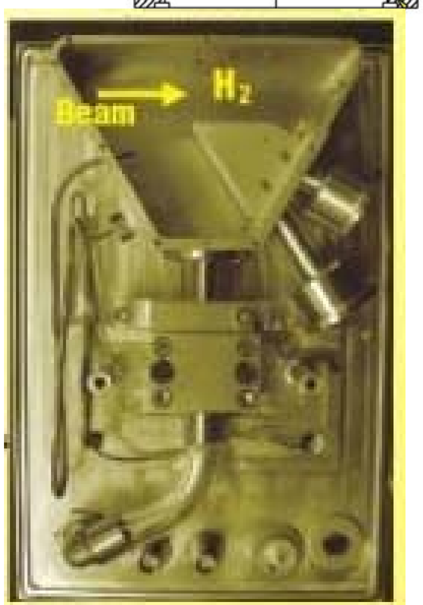
Need 200-900 keV ^{21}Na ($T_{1/2}$=22.8 s) beams and hydrogen gas target

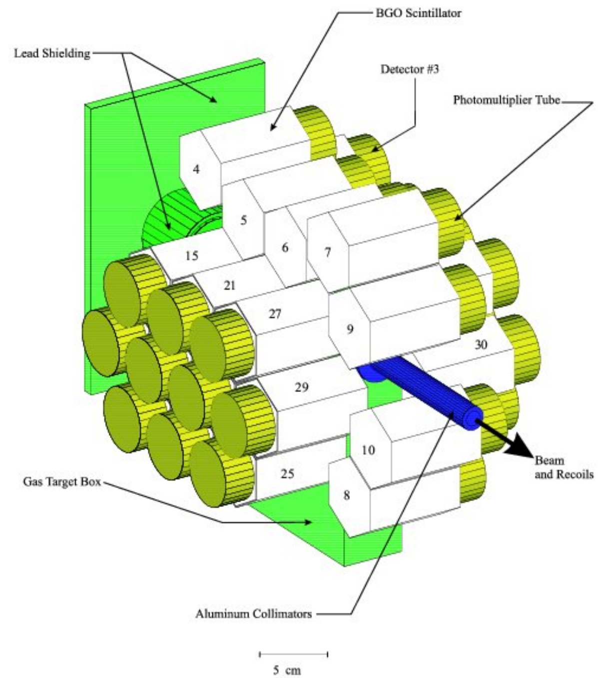
Reaction studied as: p(^{21}Na,^{22}Mg)γ

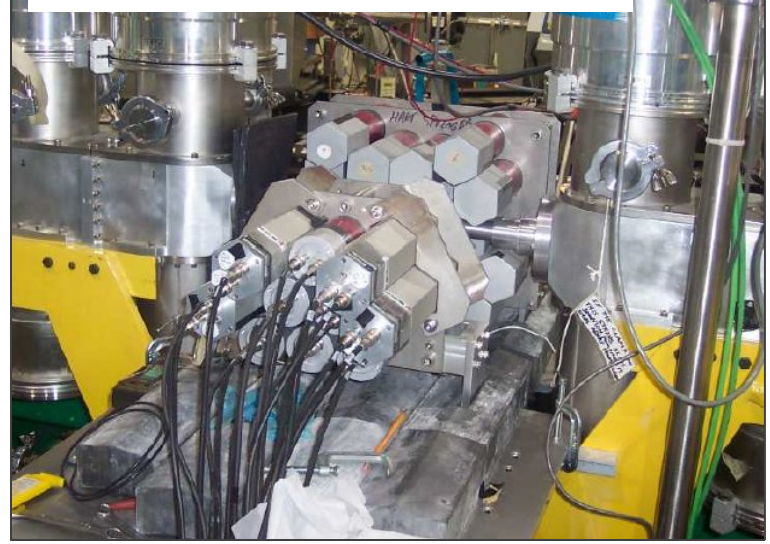




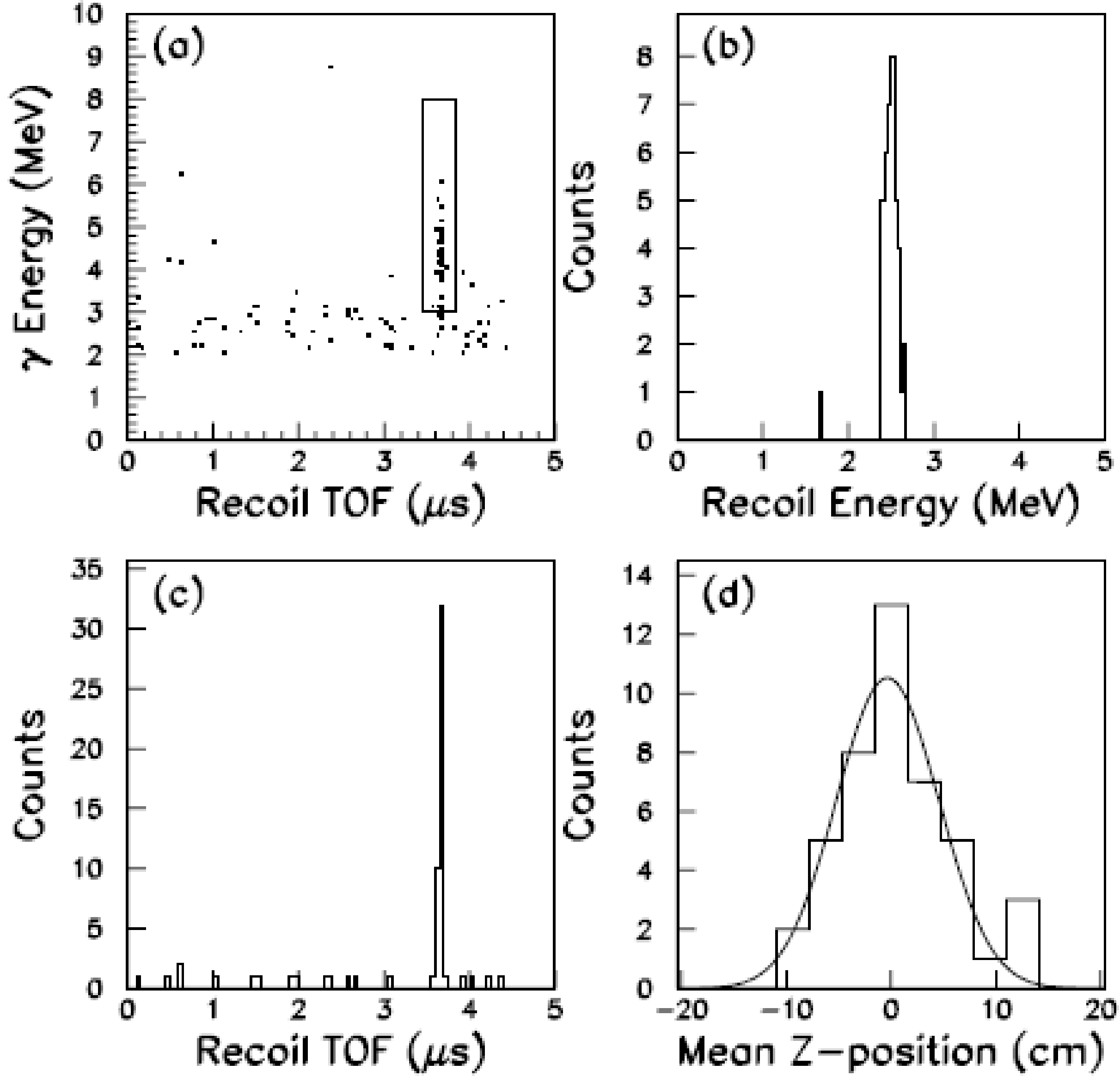

17.15 cm
11.05 cm
Beam

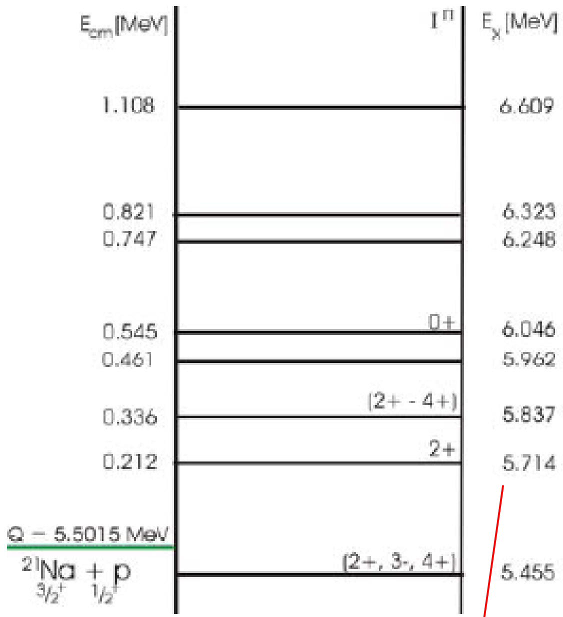

Beam
H2

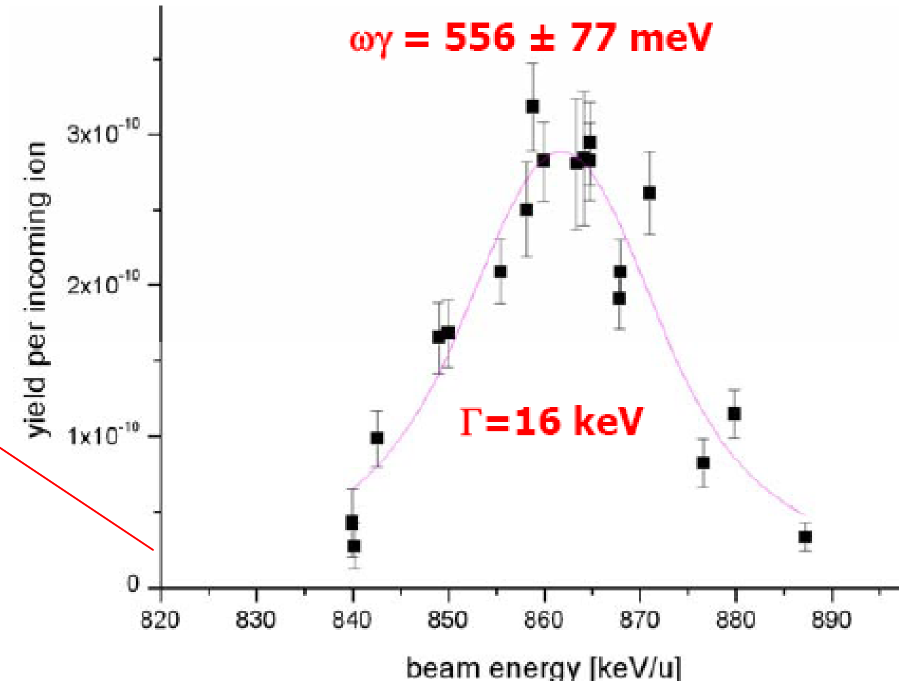

BGO Scintillator
Lead Shielding
Detector #3
Photomultiplier Tube
4
5
6
7
15
21
27
9
30
29
10
25
8
Beam
and Recoils
Gas Target Box
Aluminum Collimators
5 cm

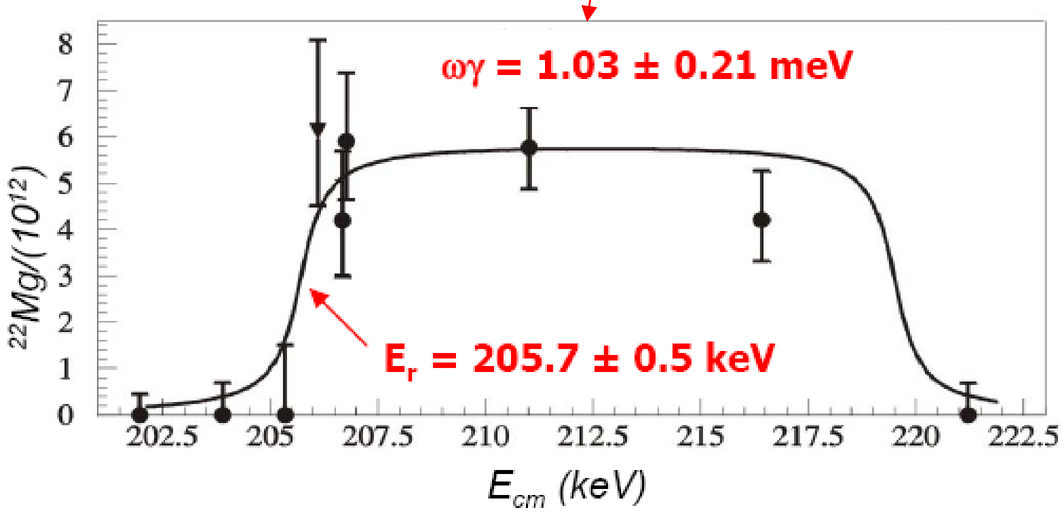


$^{21}Na(p,\gamma)^{22}Mg$

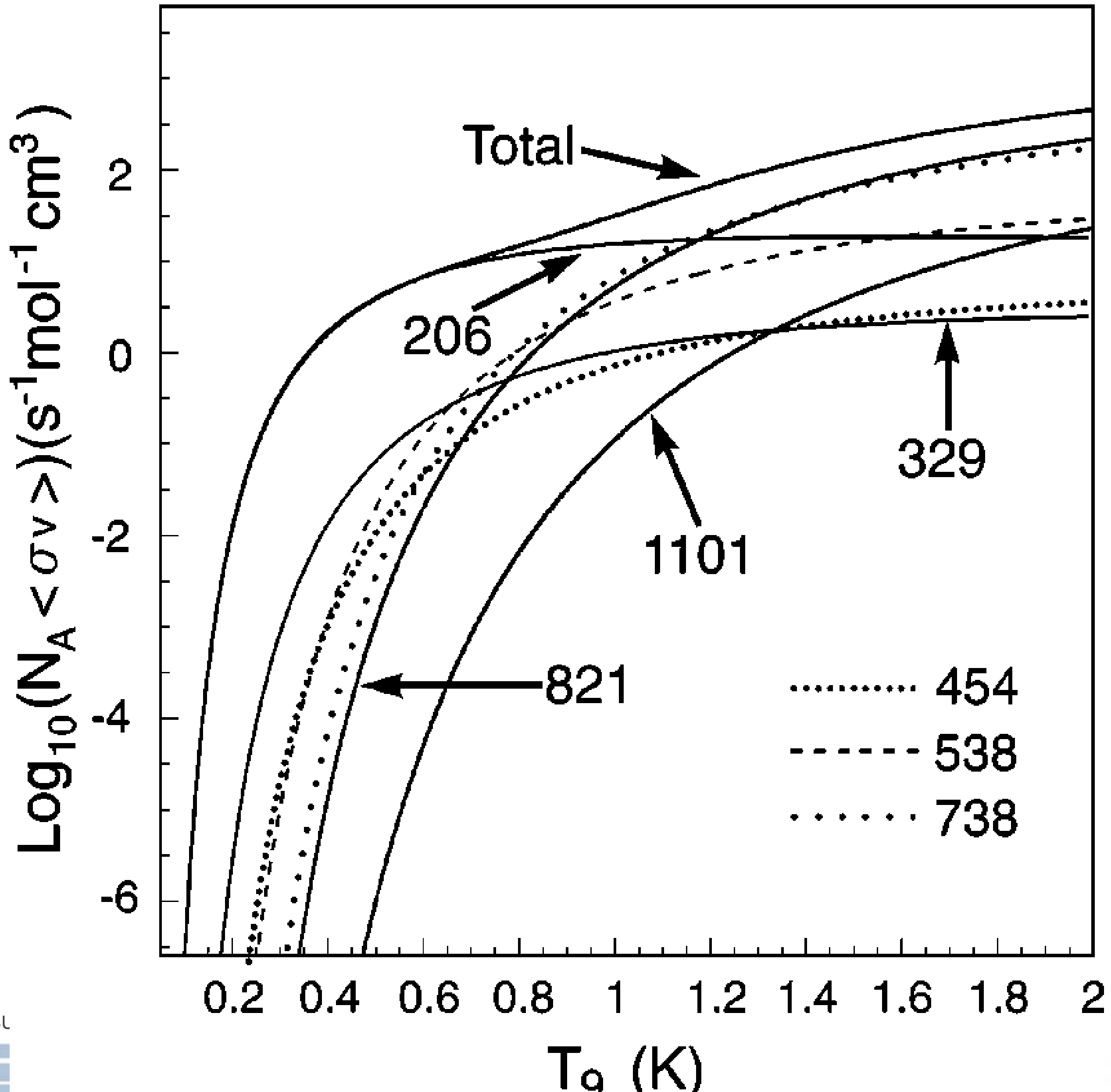



E_{cm} [MeV]
J^{π}
E_x [MeV]
1.108 6.609
0.821 6.323
0.747 6.248
0.545 0+ 6.046
0.461 5.962
0.336 (2+ - 4+) 5.837
0.212 2+ 5.714
Q = 5.5015 MeV
^{21}Na + p
3/2+ 1/2+
(2+, 3-, 4+) 5.455


ωγ = 556 ± 77 meV
Γ=16 keV
yield per incoming ion
3x10^{-10}
2x10^{-10}
1x10^{-10}
0
820 830 840 850 860 870 880 890
beam energy [keV/u]

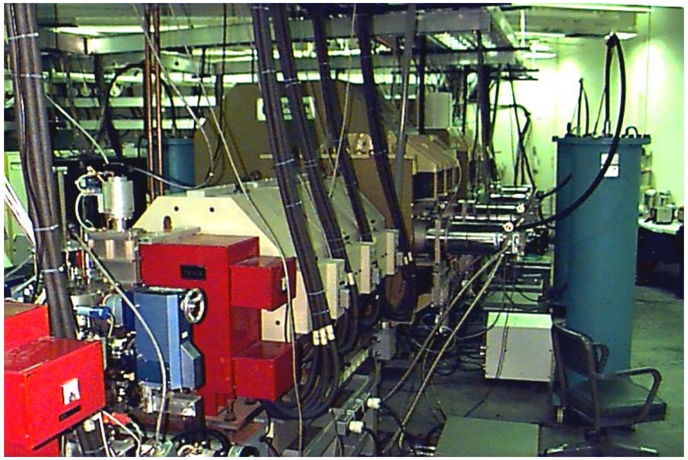

ωγ = 1.03 ± 0.21 meV
E_r = 205.7 ± 0.5 keV
^{22}Mg/(10^{12})
0 1 2 3 4 5 6 7 8
202.5 205 207.5 210 212.5 215 217.5 220 222.5
E_{cm} (keV)

Conversion from cross section to reaction rate



Other Recoil Separators for Astrophysics

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



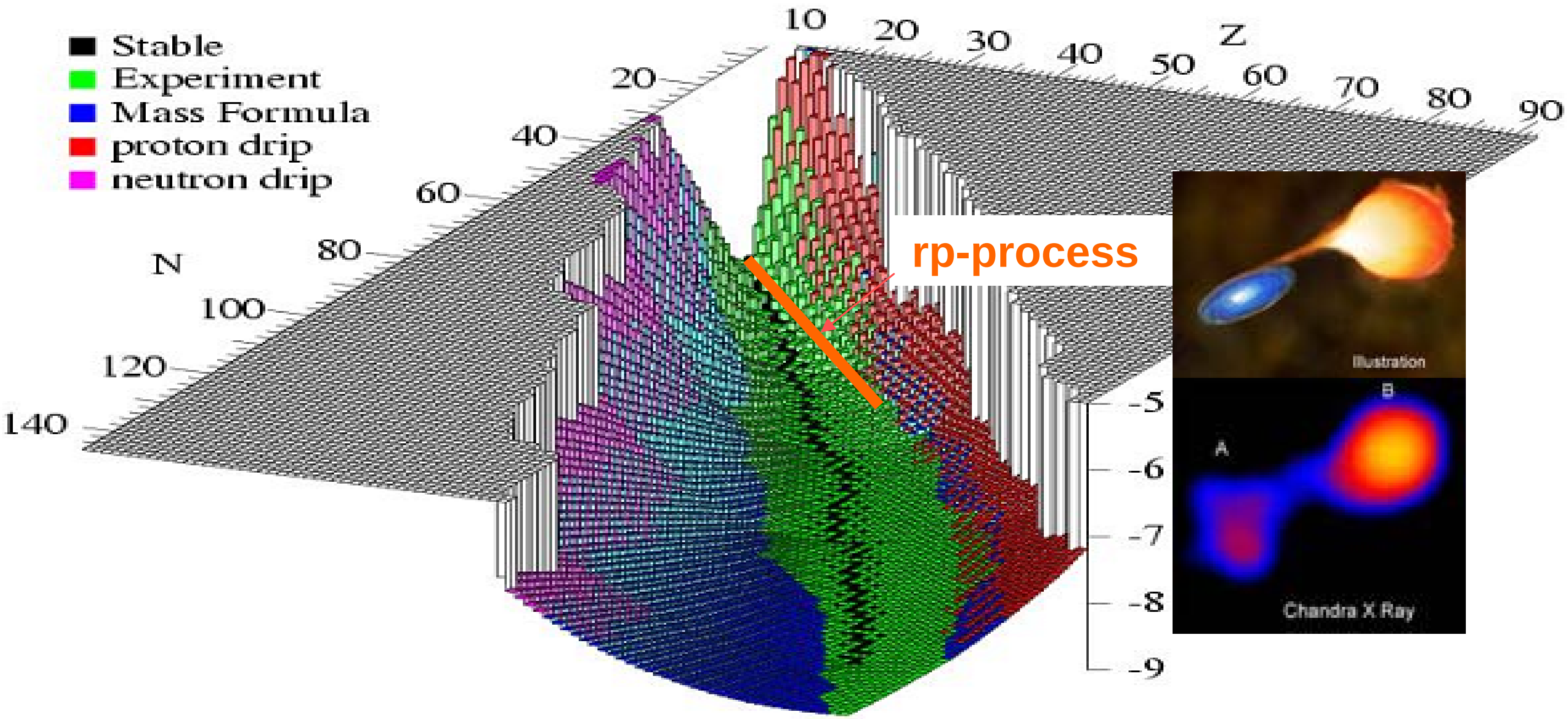
DRS at ORNL HRIBF
Used to measure $^{17}F(p,\gamma)^{18}Ne$

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

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

Future: SECAR at NSCL

Nuclei involved in Astrophysics



Example 2:

Nucleosynthesis beyond ^{56}Fe:

(r and s-processes)

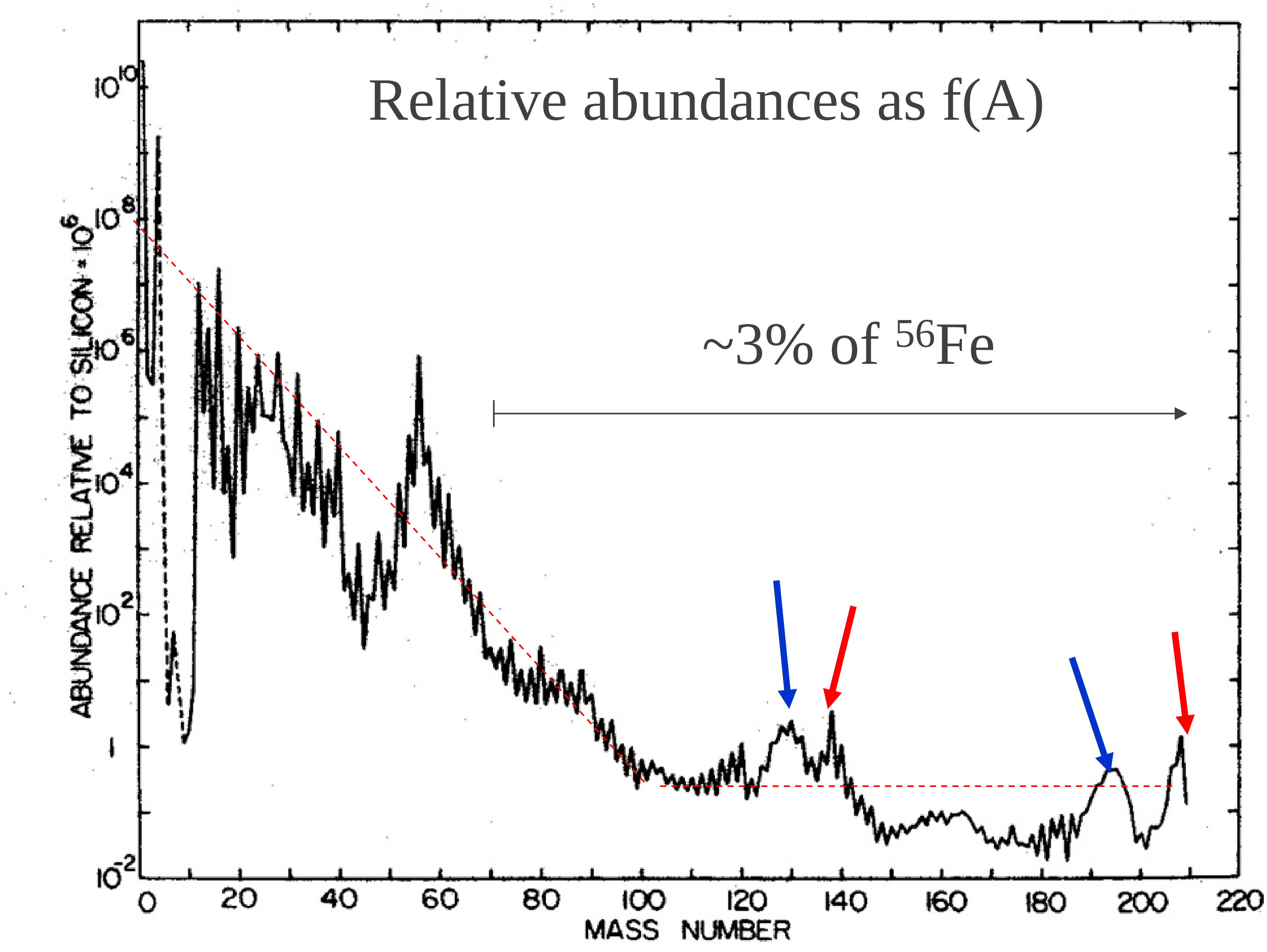
Coulomb barrier too high for charged-particle reactions

→reactions involving neutrons

from the mass distributions: at least two processes

slow neutron capture (s-process)

rapid neutron capture (r-process)


Relative abundances as f(A)
~3% of 56Fe
ABUNDANCE RELATIVE TO SILICON = 10^6
MASS NUMBER
0
20
40
60
80
100
120
140
160
180
200
220
10^10
10^8
10^6
10^4
10^2
1
10^-2

Where does nature produce neutrons in stars?

Charged-particle reactions

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

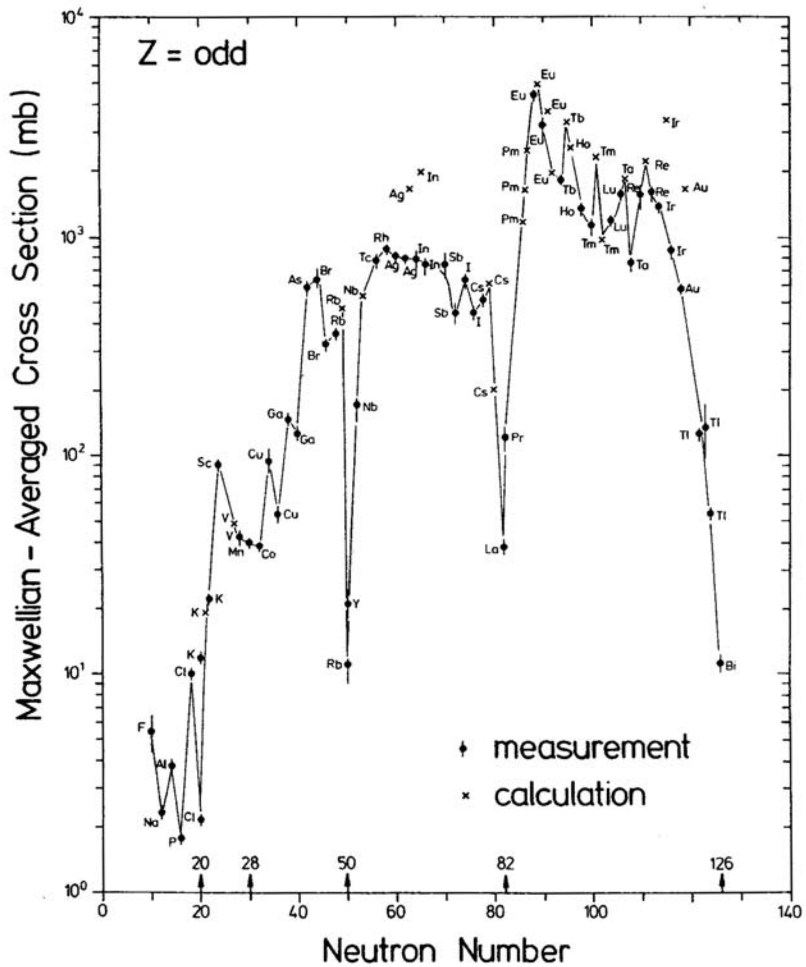
$^{22}Ne(\alpha,n)^{25}Mg$ Q=-0.480 MeV

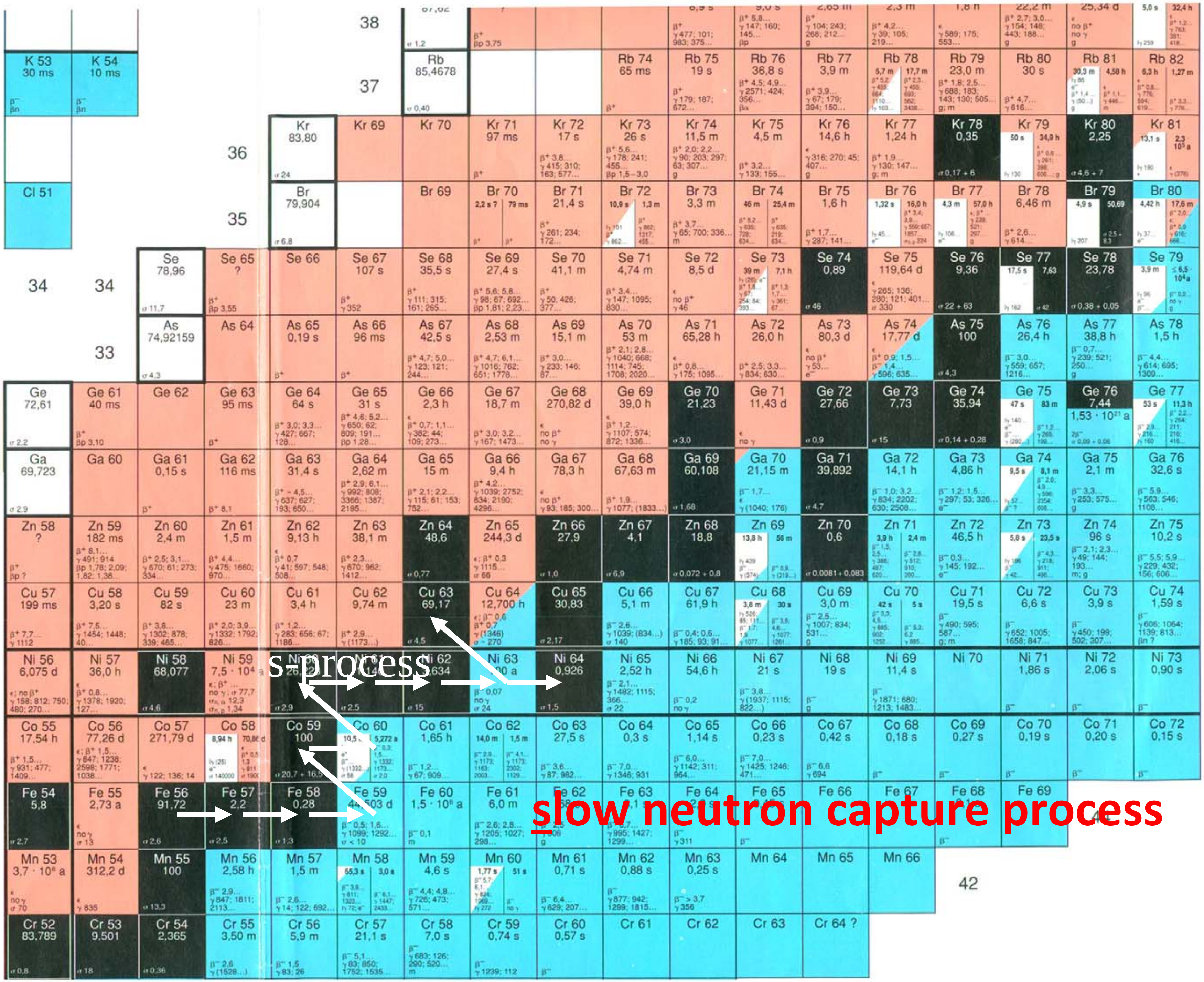
Cross sections for neutron capture

reactions are usually quite large.

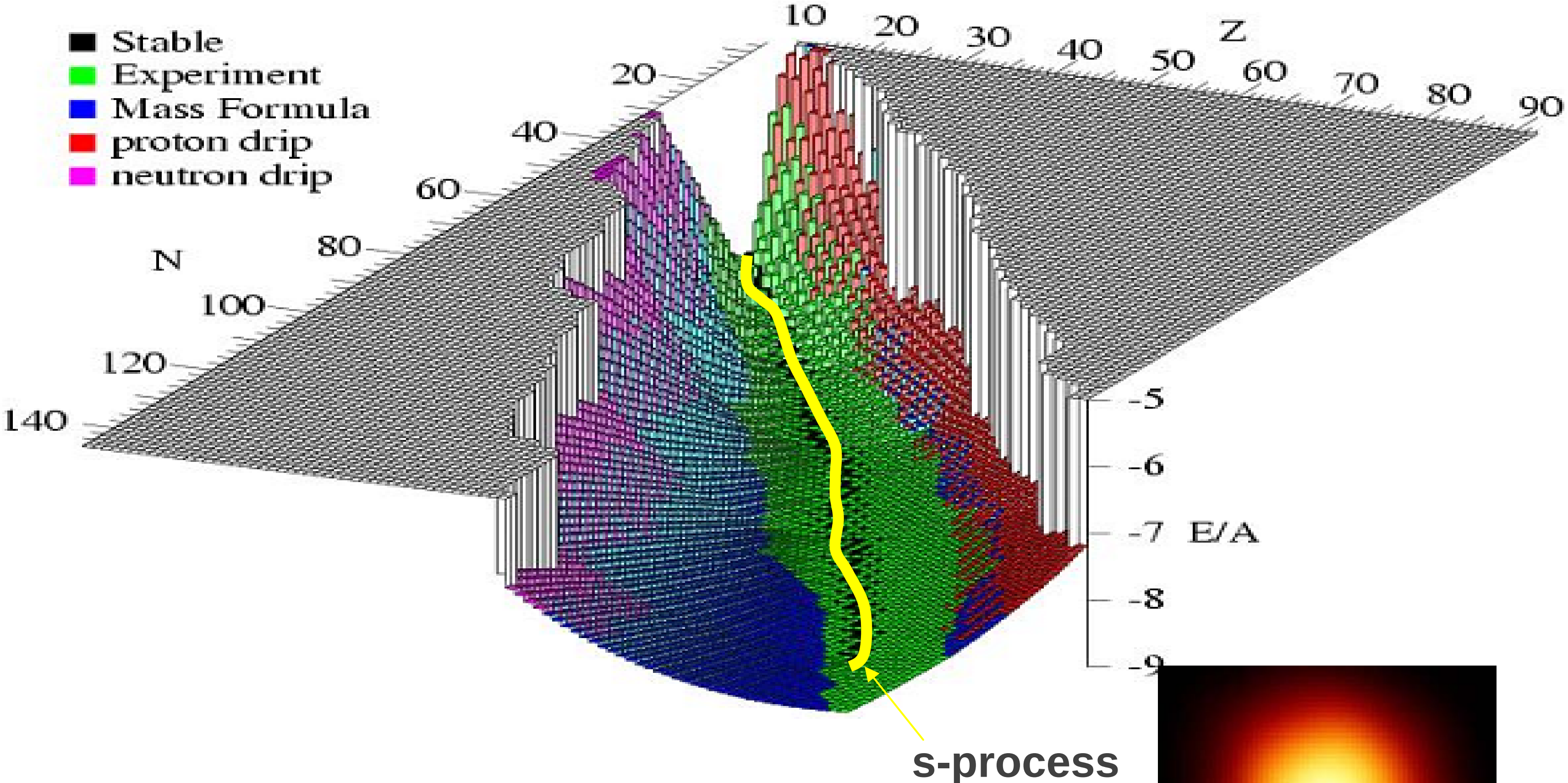
(100-5000 mb)

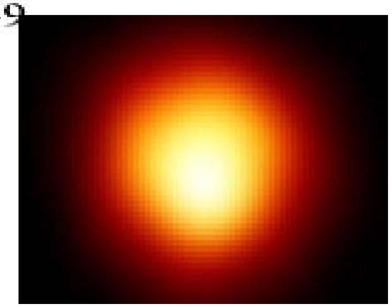
Shell effects!




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

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

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

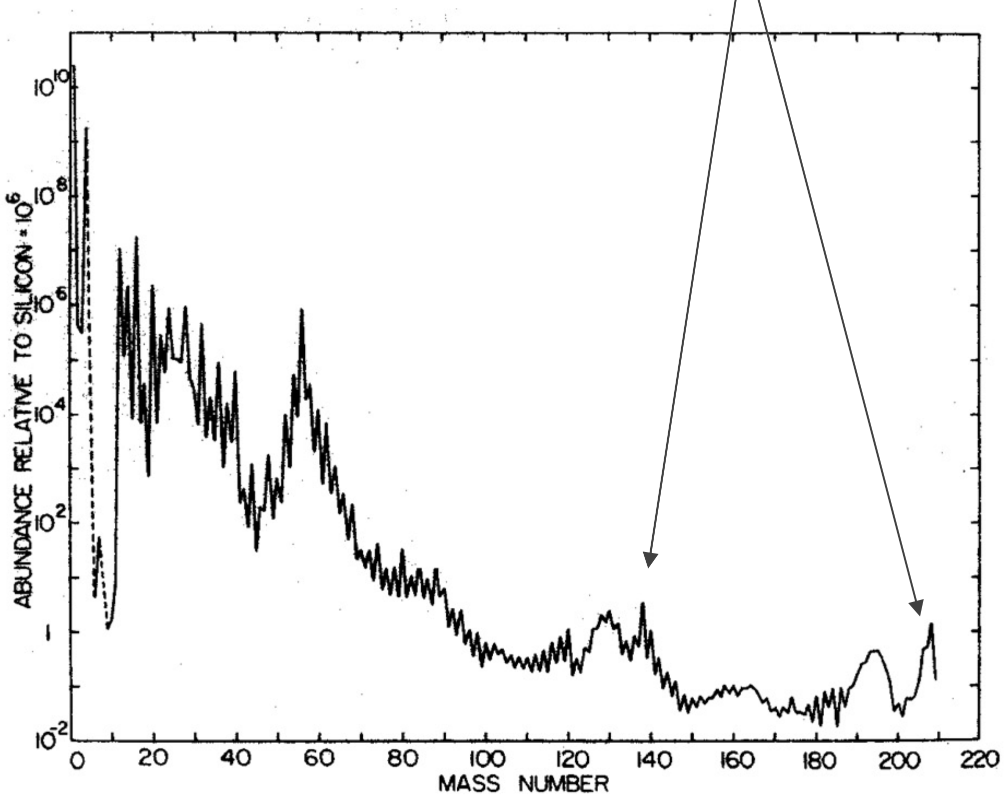
$\sigma \sim 100$ mb , $v \sim 10^8$ cm/sec

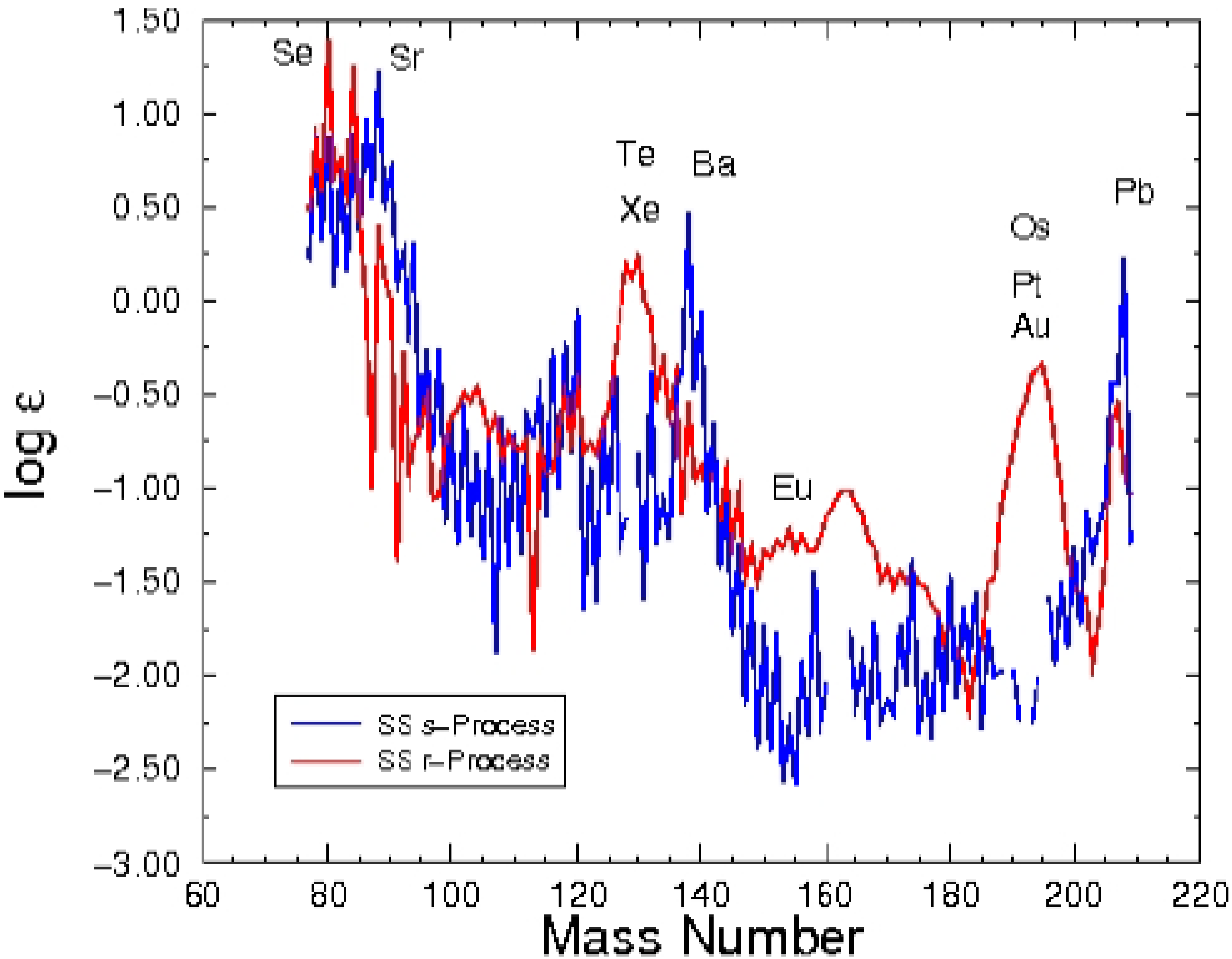
$\tau N_n \sim 10^{17}$ s neutrons/cm^3

To have capture times <10y ($=\pi \bullet 10^8$ s)

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

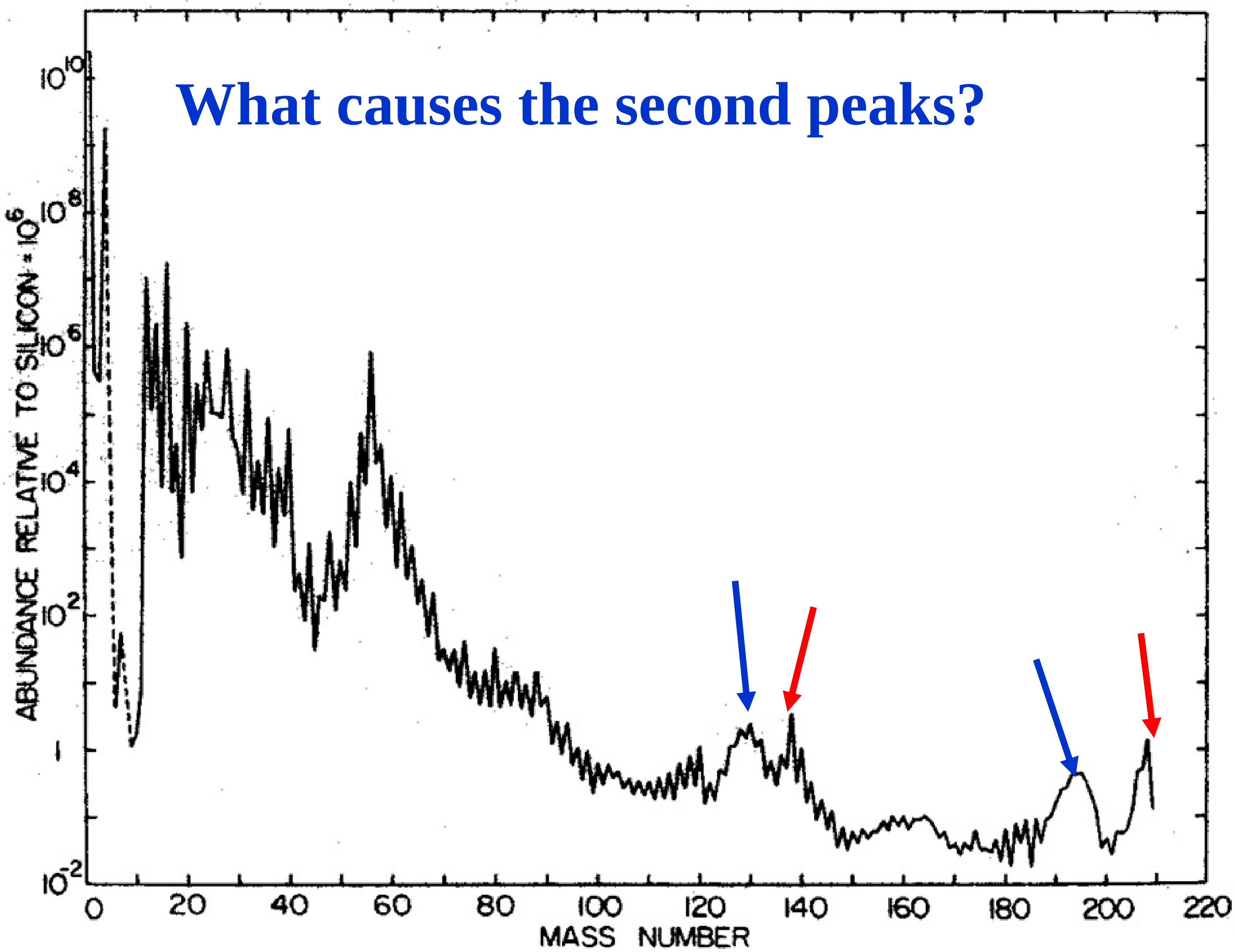
Nuclei with small $\sigma_{n\gamma}$ (e.g. closed shell nuclei) have a large τ and form a 'bottleneck' resulting in the s process abundance peaks.



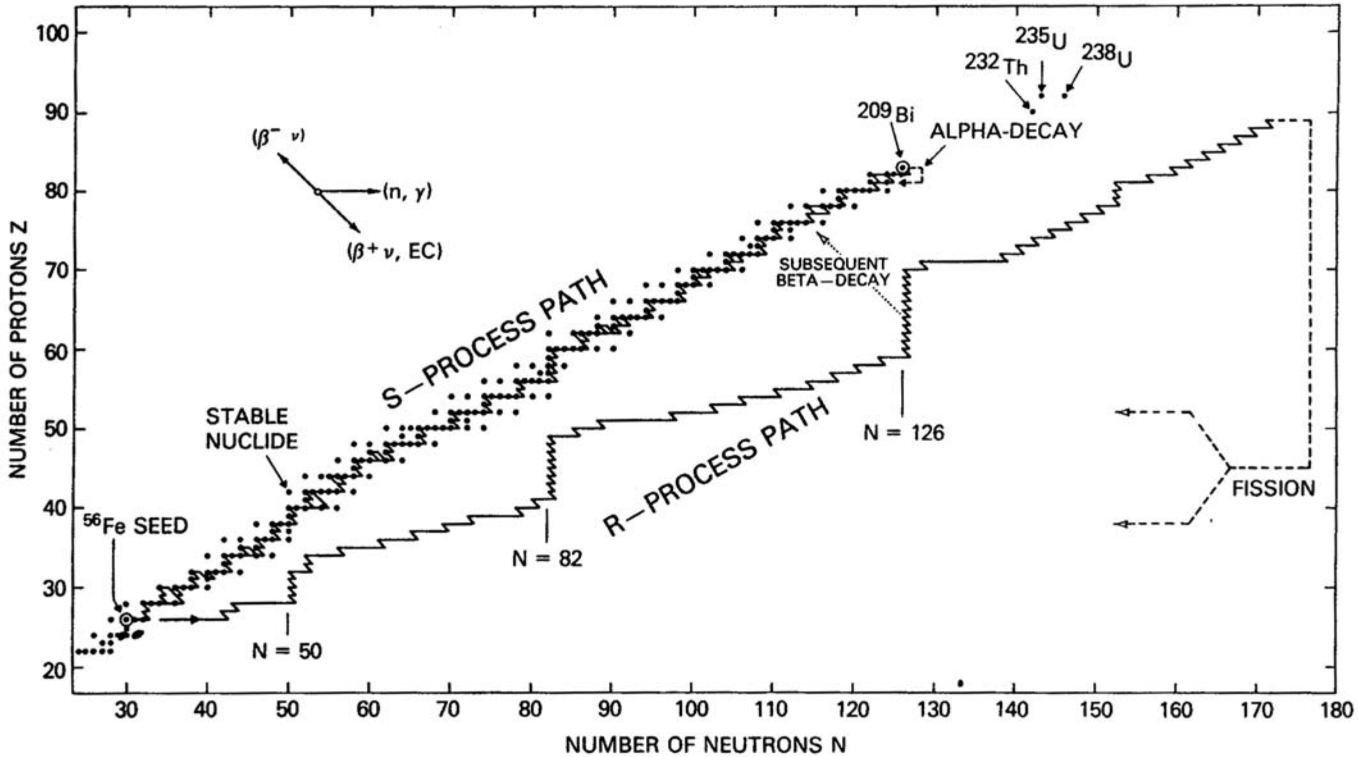


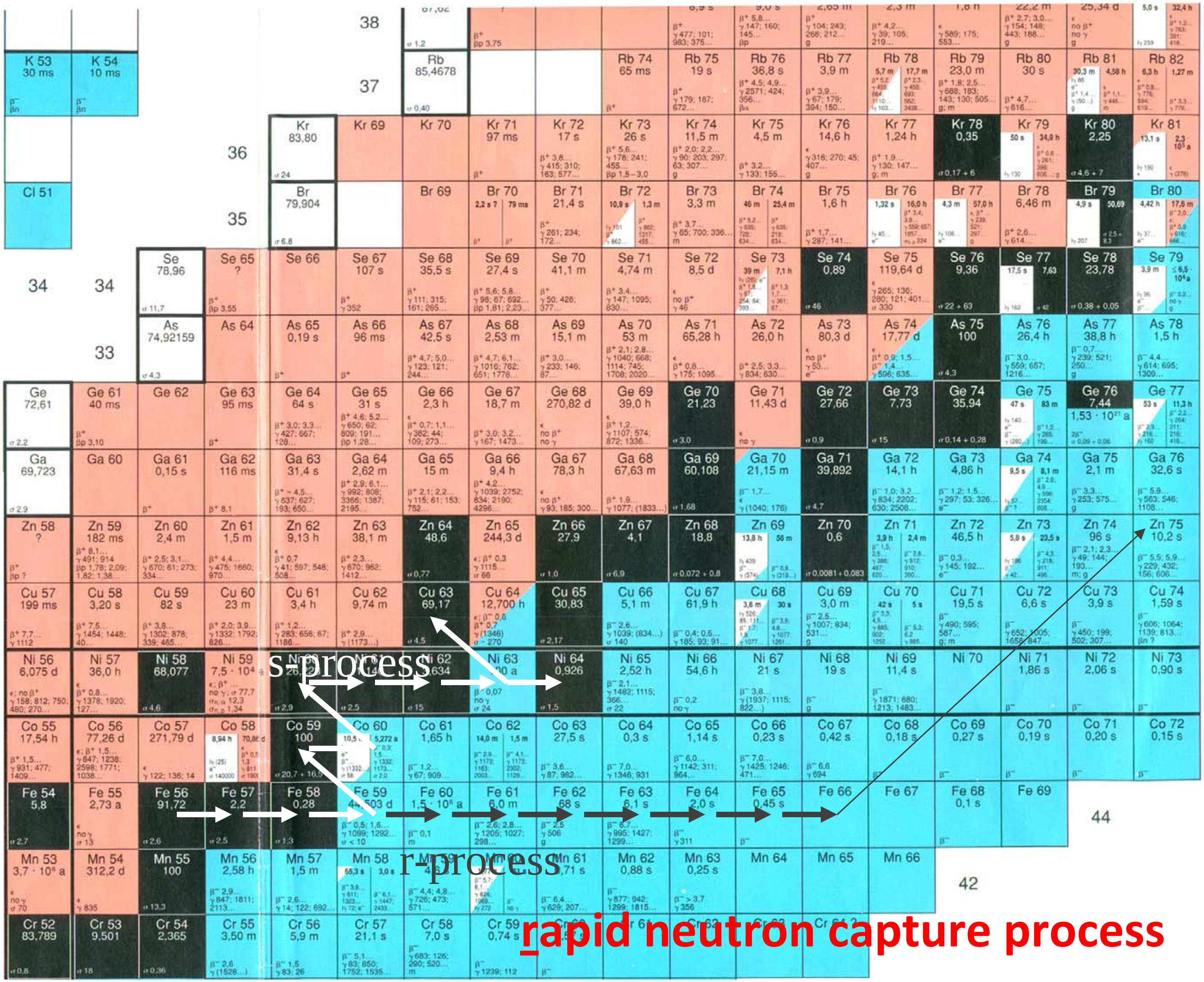
Se
Sr
Te
Xe
Ba
Eu
Os
Pt
Au
Pb
SS s–Process
SS r–Process
log ε
1.50
1.00
0.50
0.00
−0.50
−1.00
−1.50
−2.00
−2.50
−3.00
60
80
100
120
140
160
180
200
220
Mass Number

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.**




s-process
r-process
rapid neutron capture process

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

With $\tau N_n \sim 10^{17}$ →

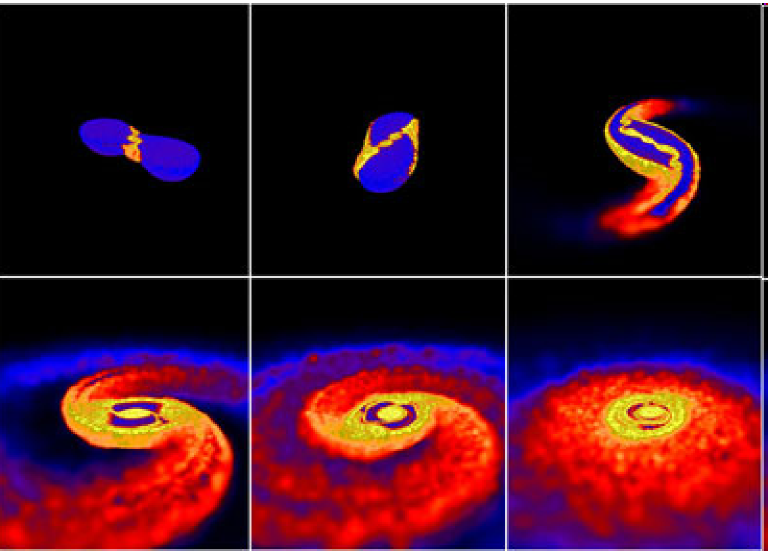
$N_n \sim 10^{20}$ n/cm^3

At which astrophysical sites do we have these neutron densities?

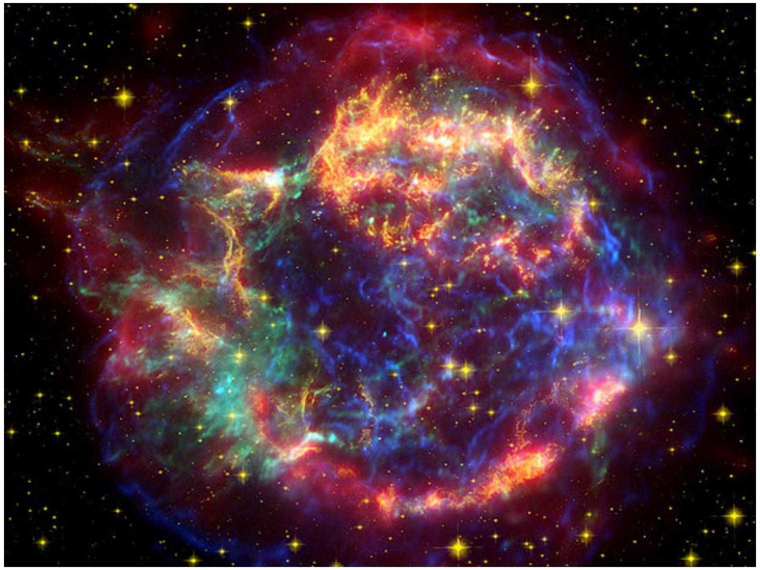
Where can we get these high neutron densities?

Neutron star mergers

core-collaps supernovae

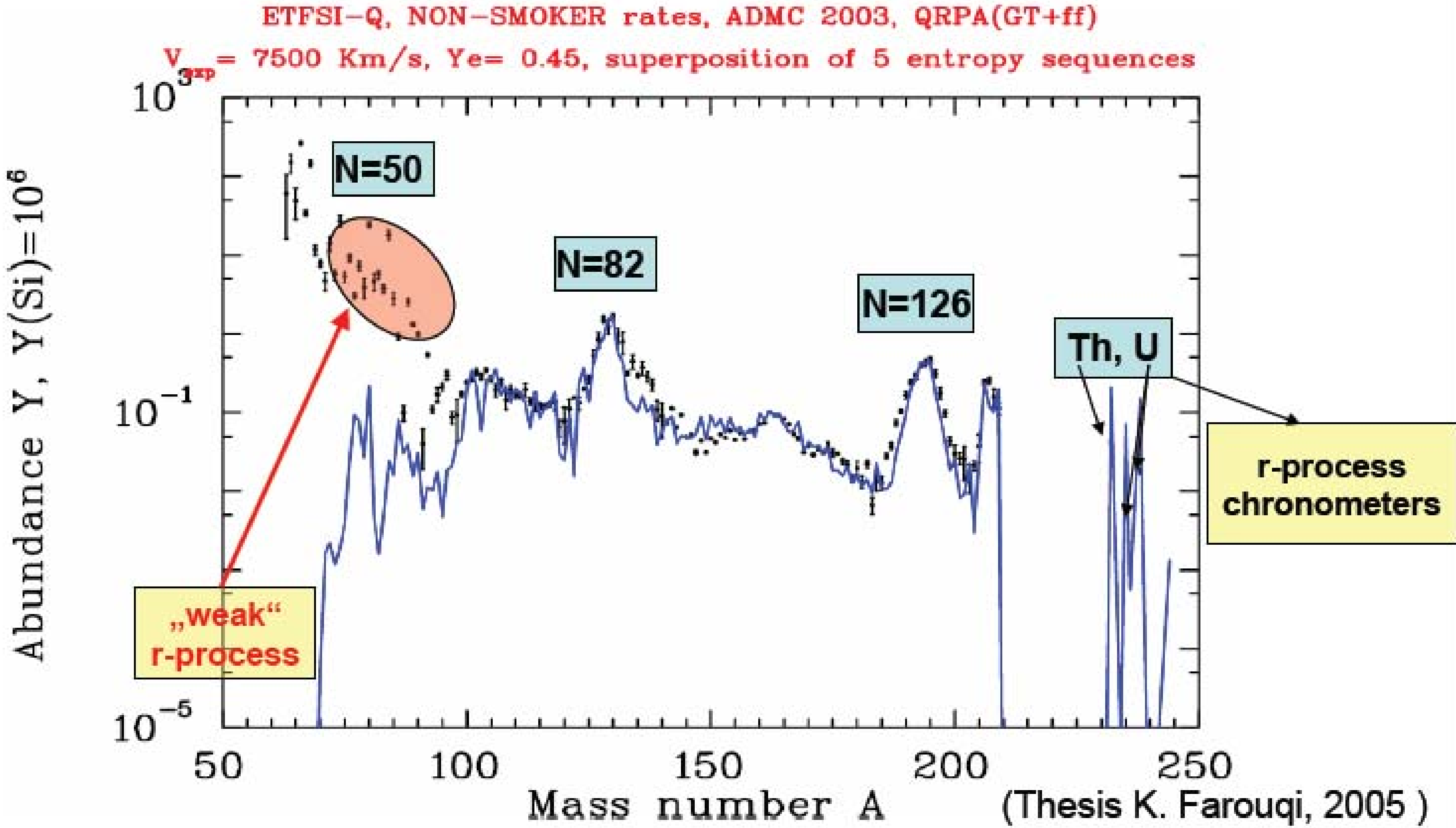


Price and Rosswog



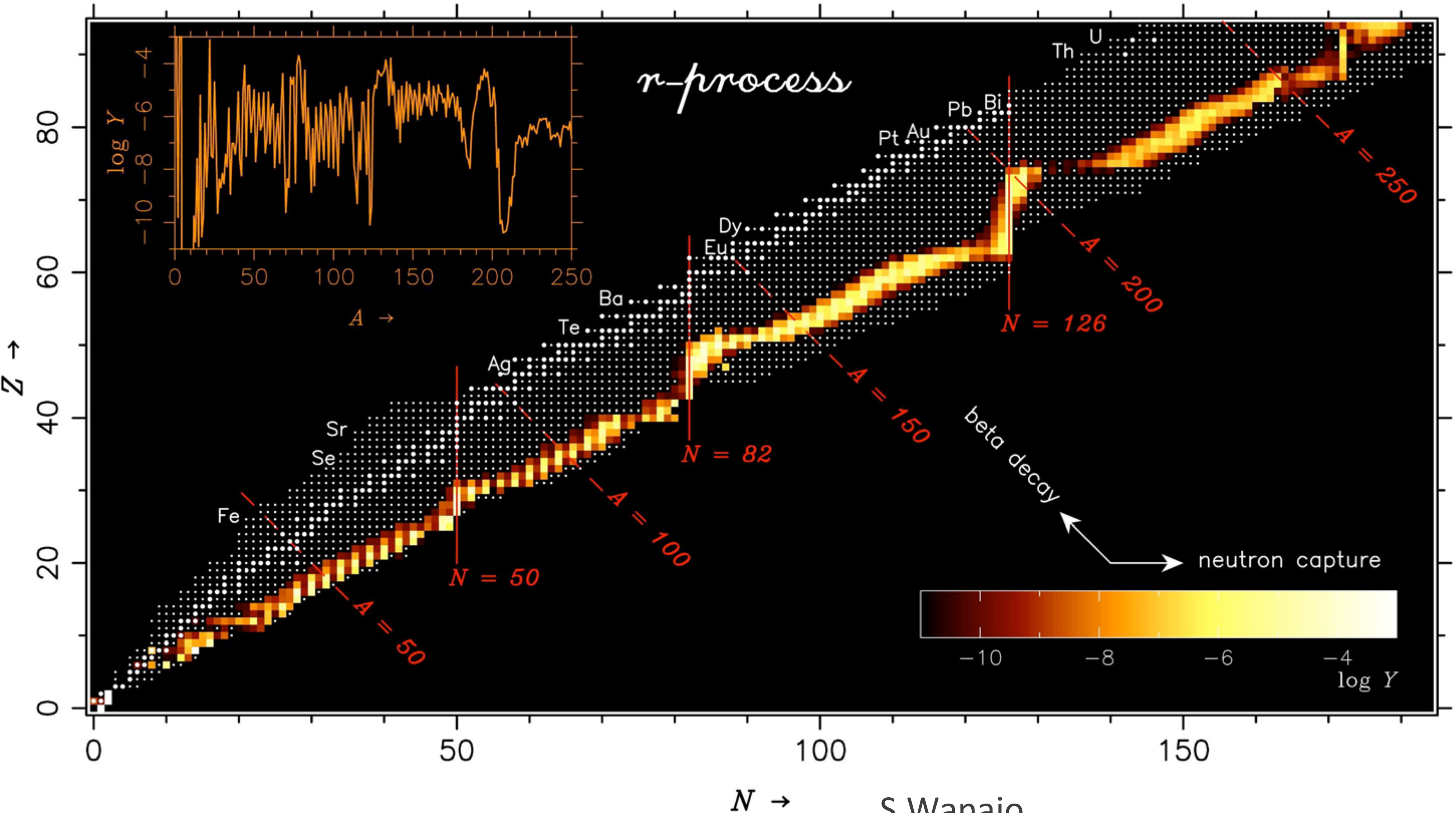
- **Site of the r-process is unknown**
- **Properties of nuclei in the r-process path are unknown (half-lives, masses, n-capture cross sections..)**

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

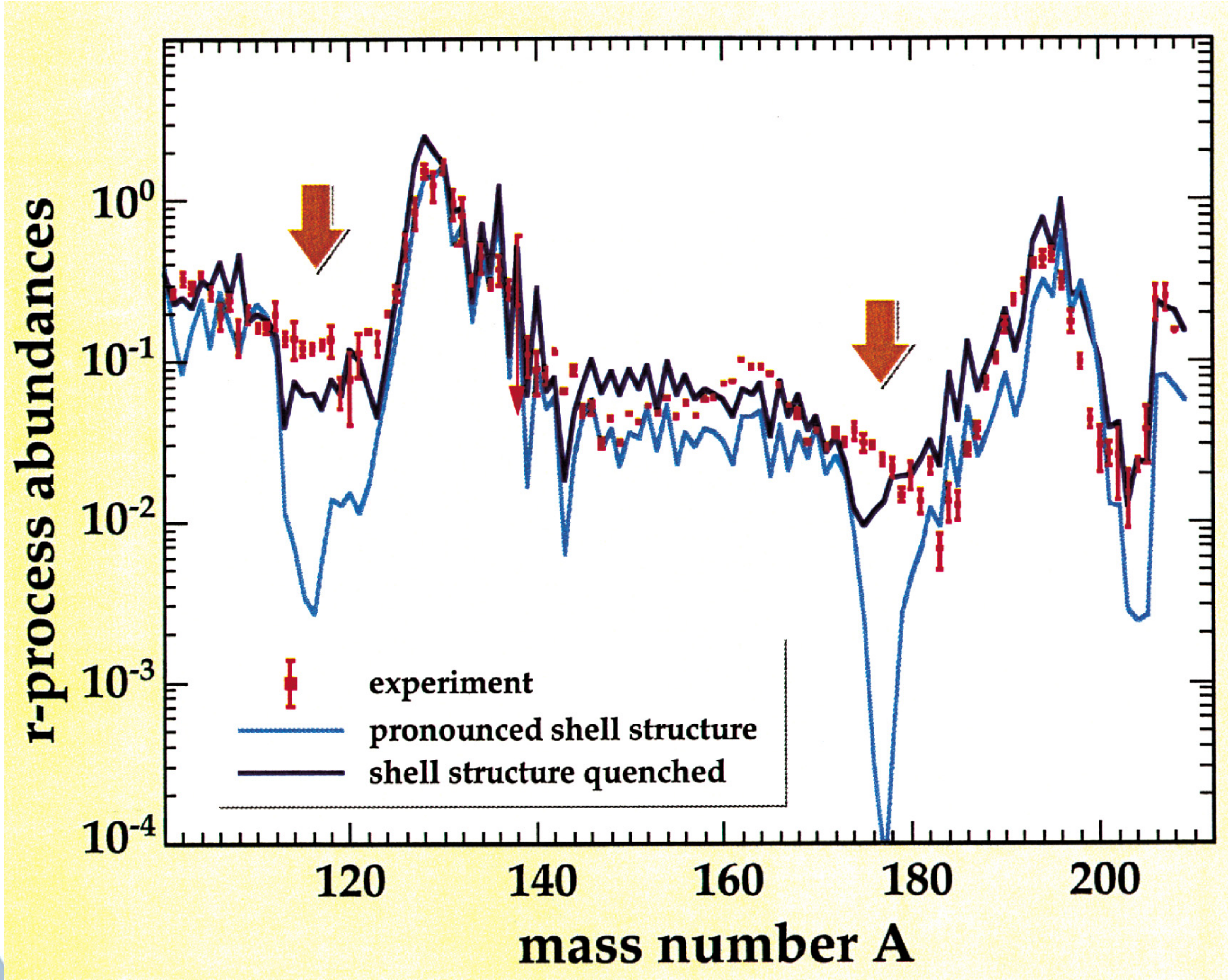


(Thesis K. Farouqi, 2005)

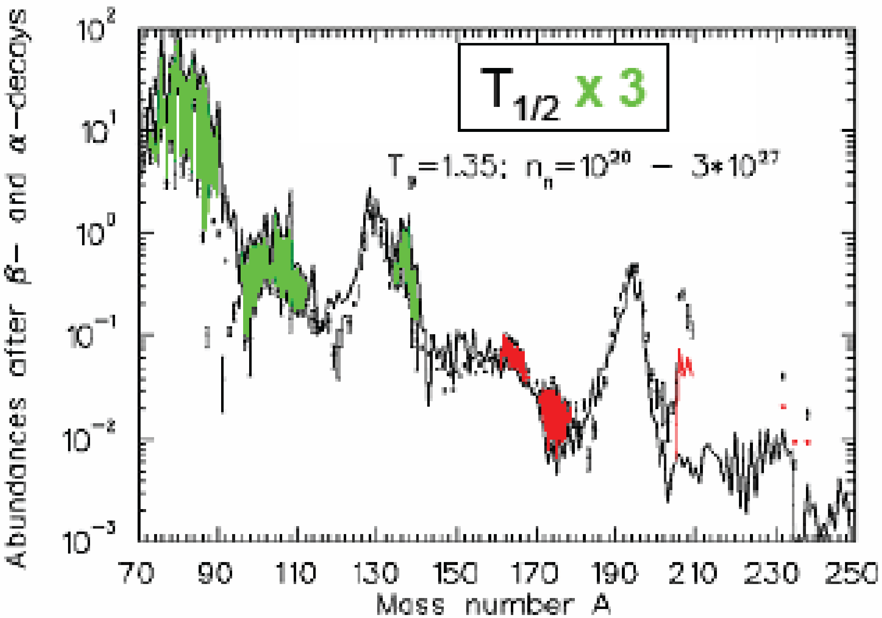
Basis for detailed astrophysical parameter studies


r-process
log Y
A →
N = 50
N = 82
N = 126
A = 50
A = 100
A = 150
A = 200
A = 250
Fe
Se
Sr
Ag
Te
Ba
Eu
Dy
Pt
Au
Pb
Bi
Th
U
beta decay
neutron capture
Z →
N →

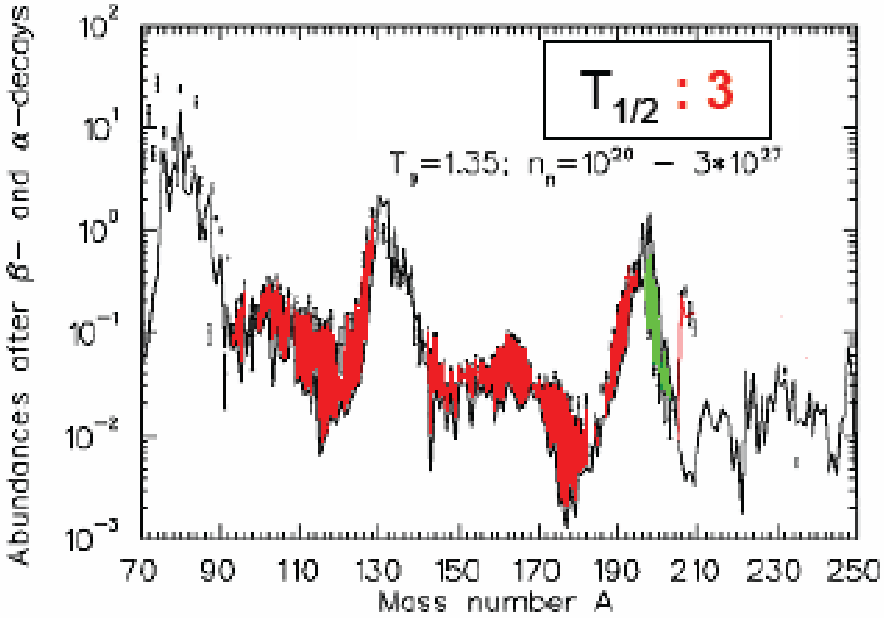
S.Wanajo



r-process abundances
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
experiment
pronounced shell structure
shell structure quenched
120
140
160
180
200
mass number A

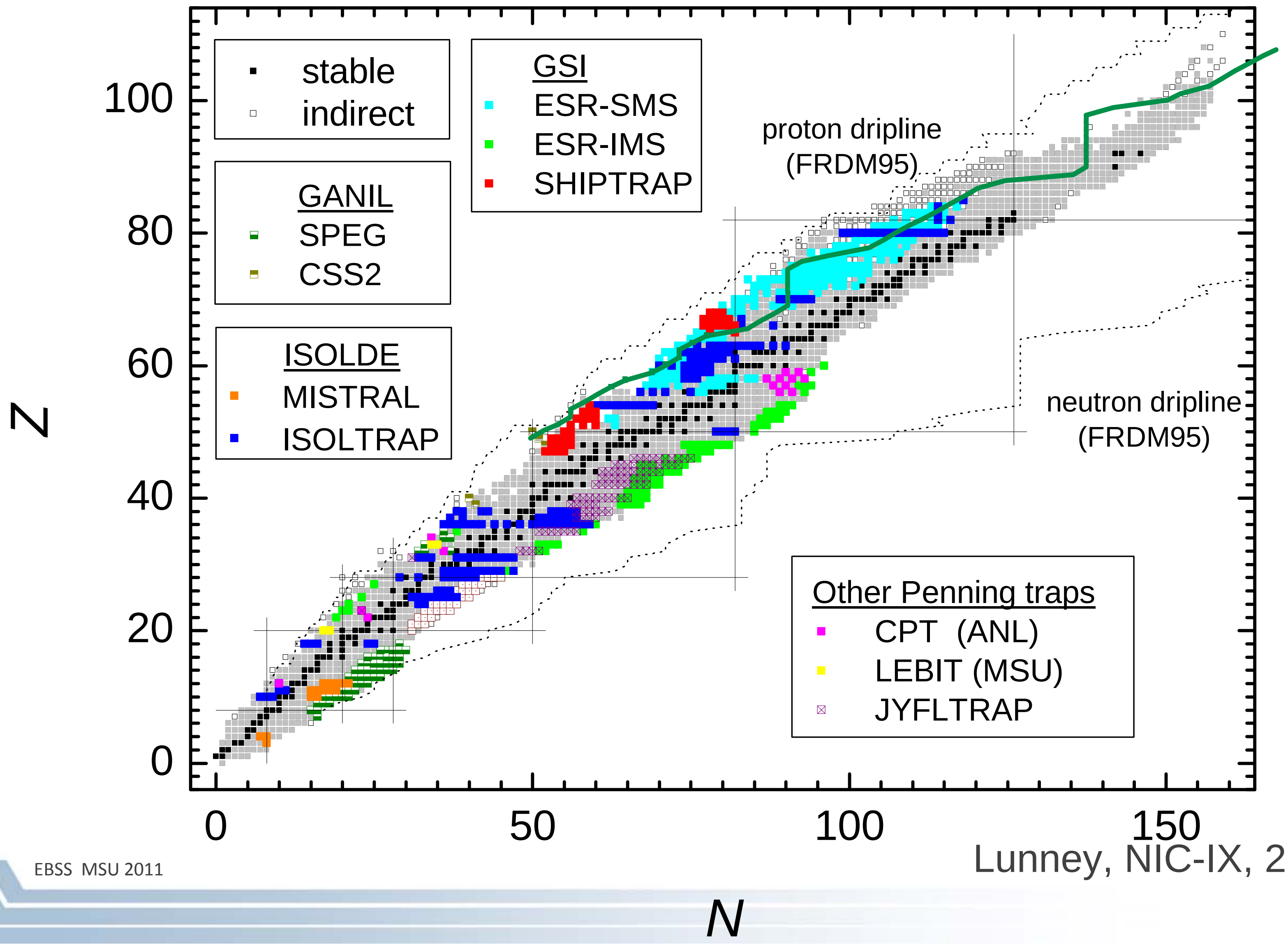


r-matter flow too slow



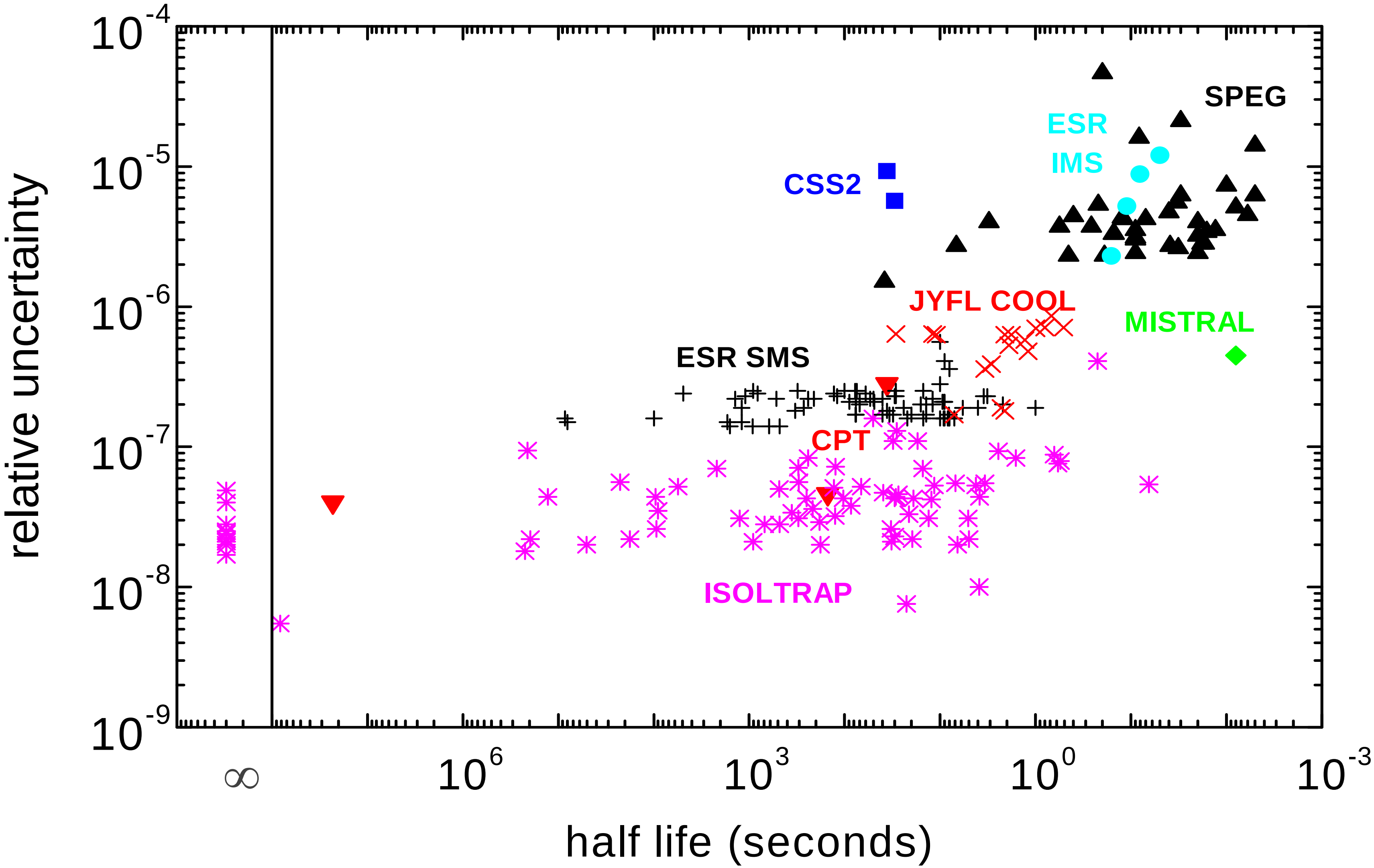
r-matter flow too fast

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



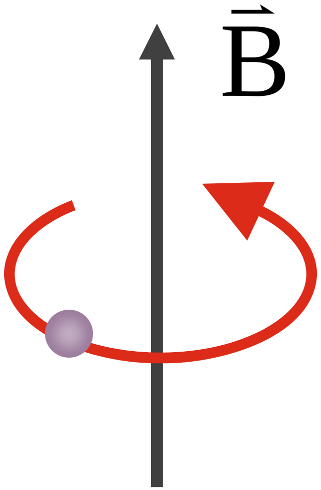
Lunney, NIC-IX, 2006

See: Lunney, Pearson & Thibault, Rev. Mod. Phys. 75 (2003) 1021



Most accurate mass measurements with Penning traps

How a Penning trap works -1

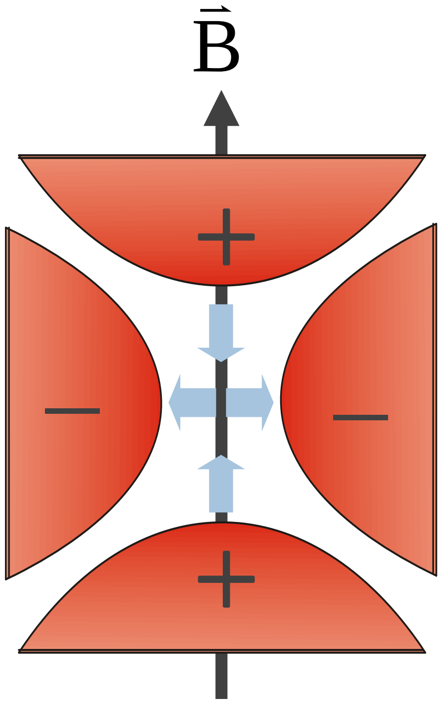


- constant axial magnetic field
- particle orbits in horizontal plane

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

- 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:

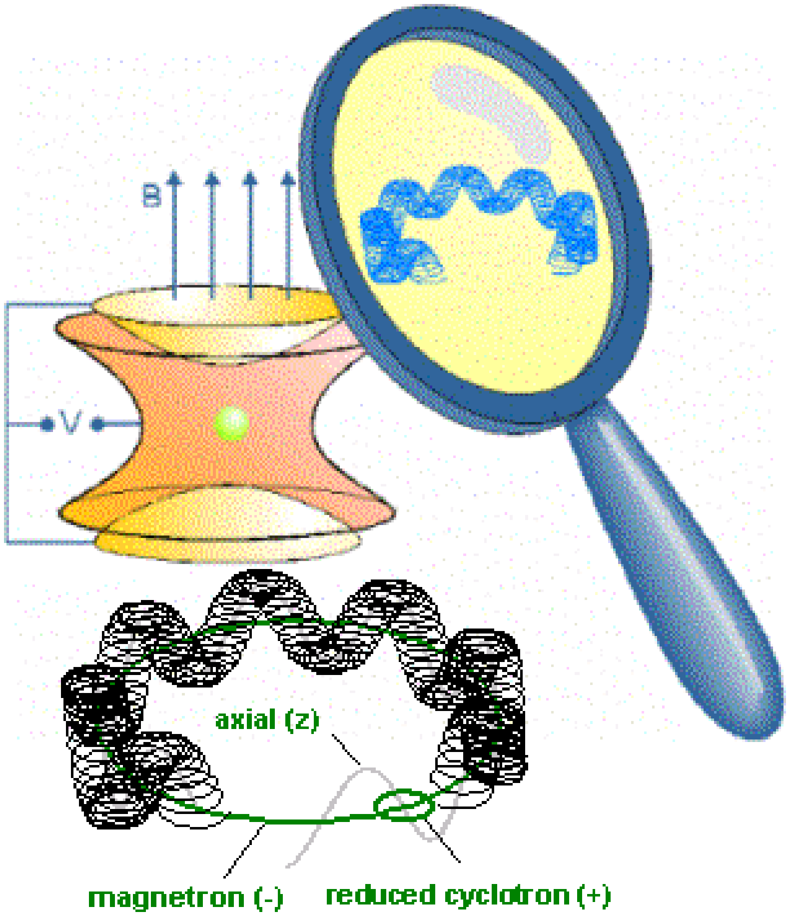
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

Axial oscillations:

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

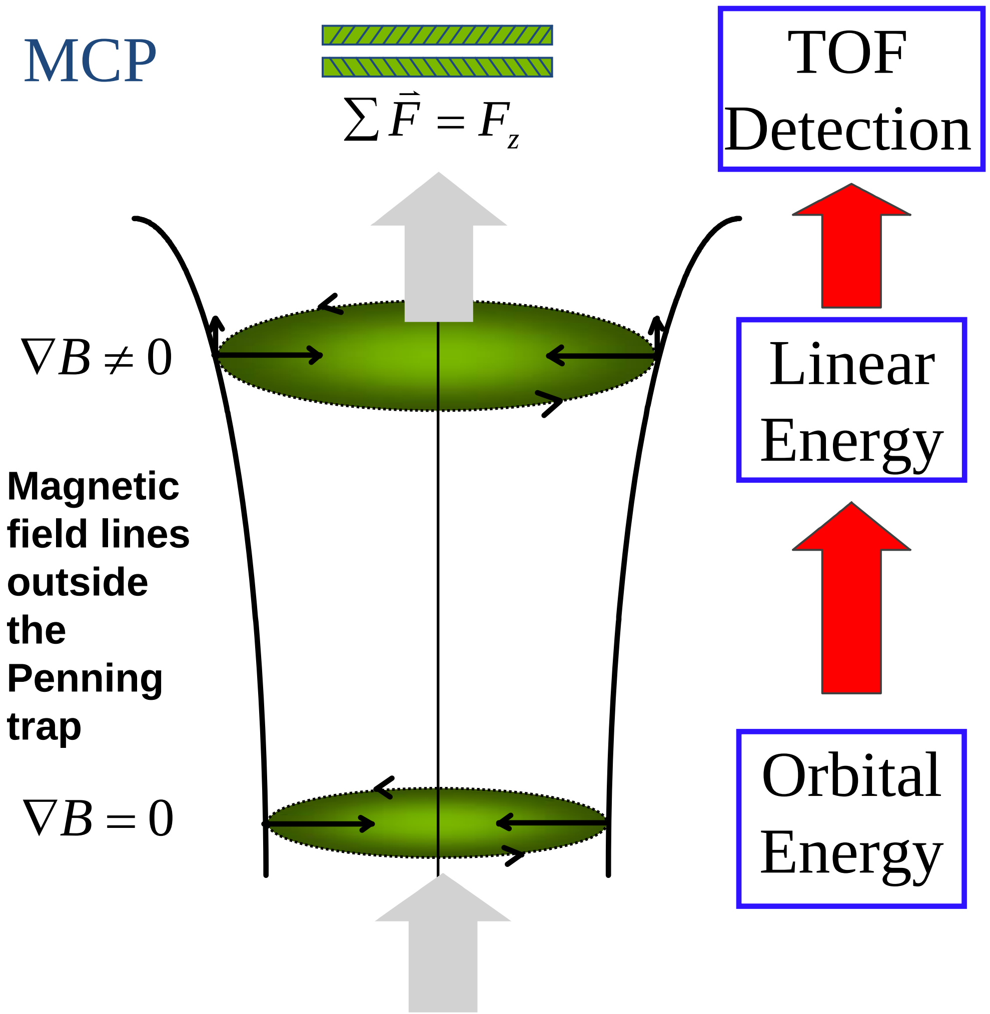
Radial motion:

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



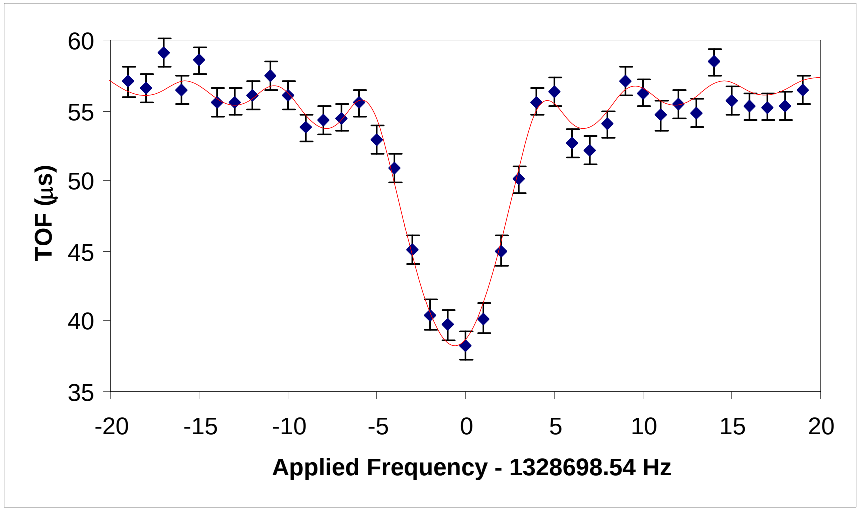
picture from http://isoltrap.web.cern.ch/isoltrap/

Penning trap mass spectrometry

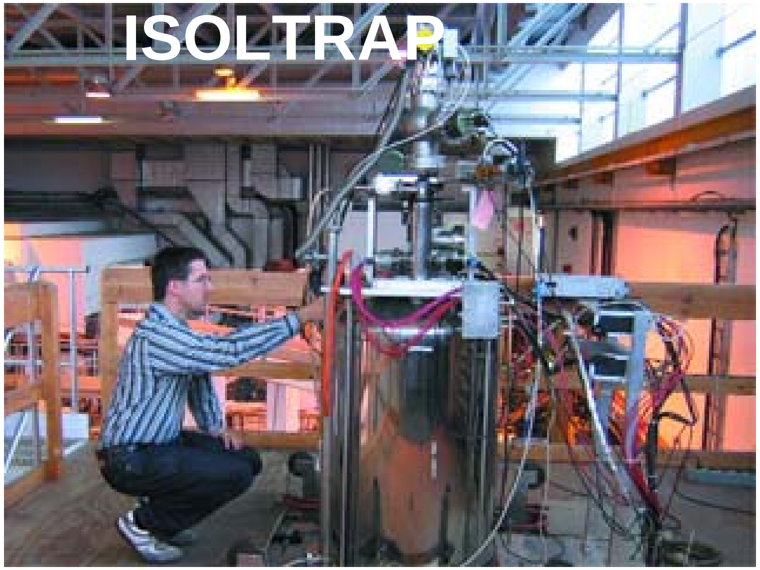


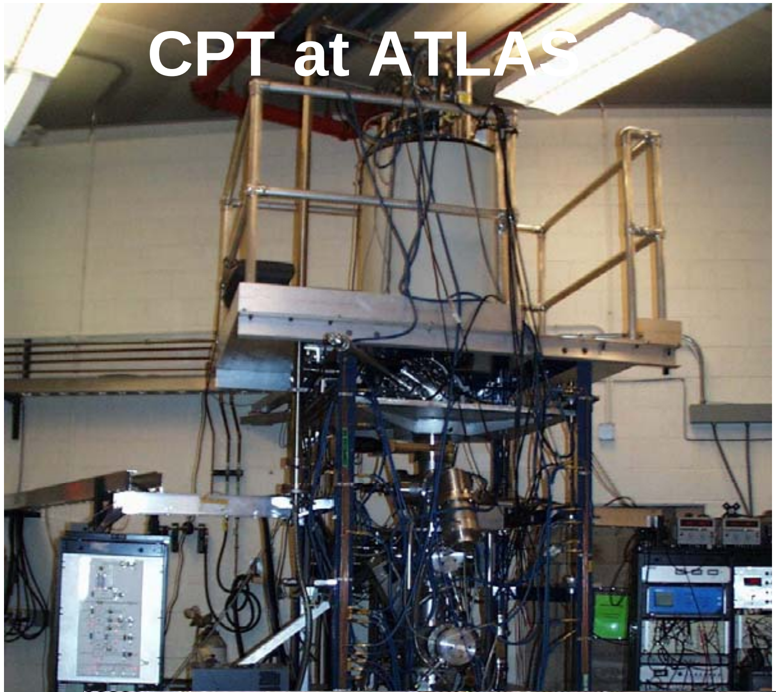
Ions from the Penning trap

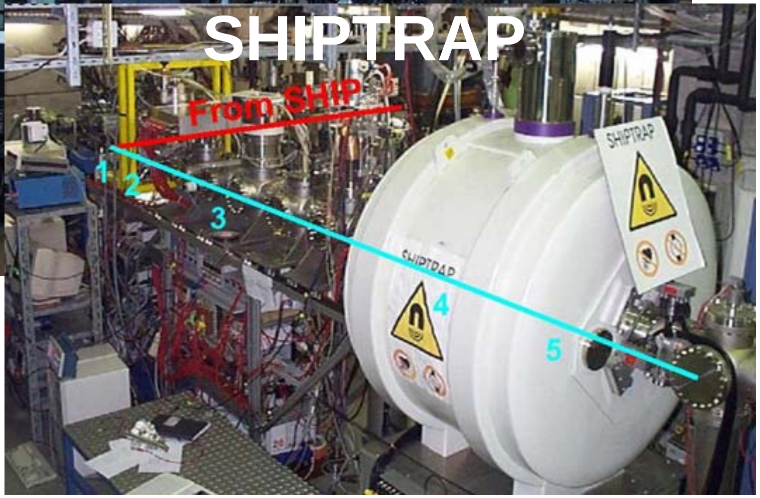
Sample TOF spectrum



Penning traps

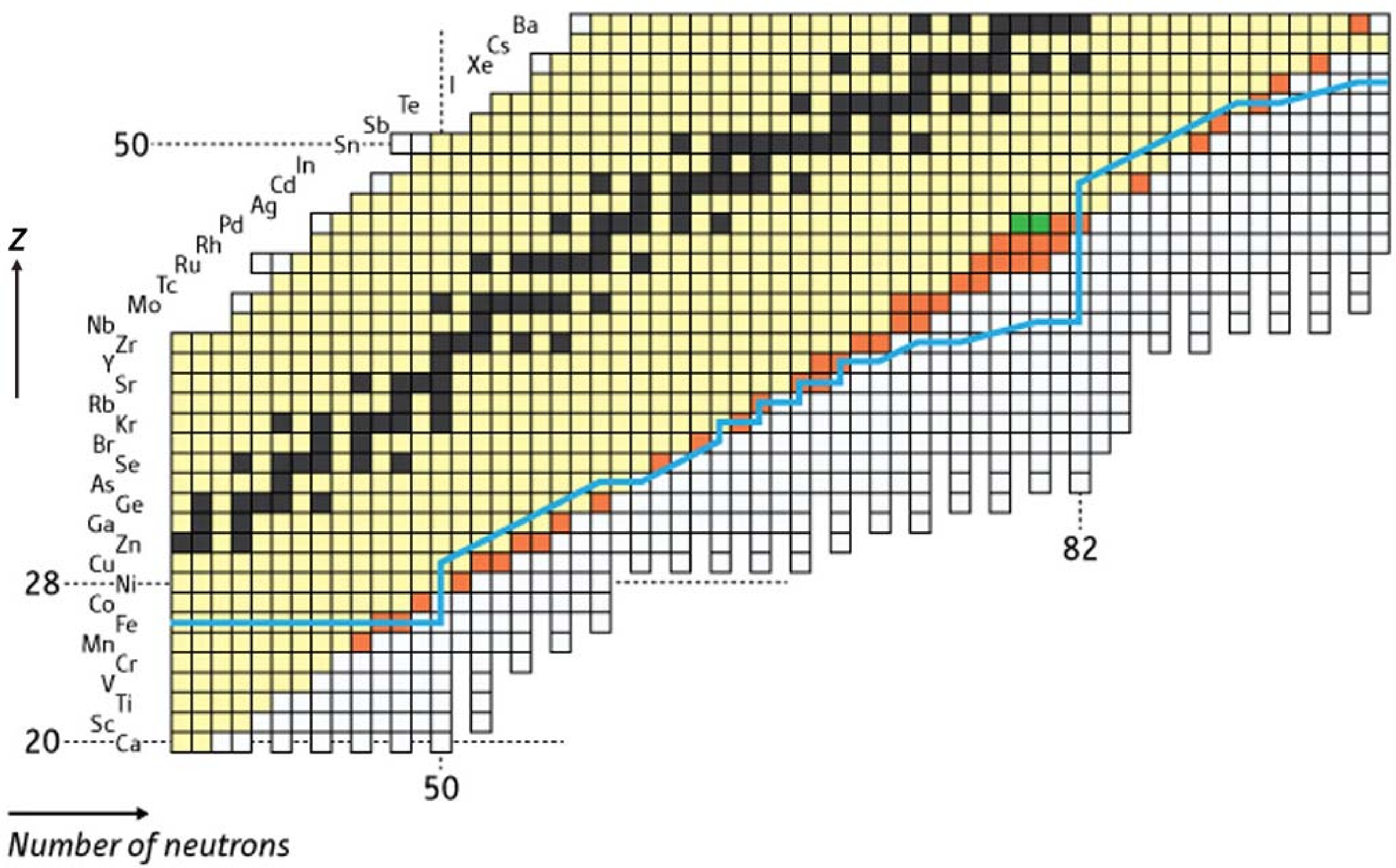


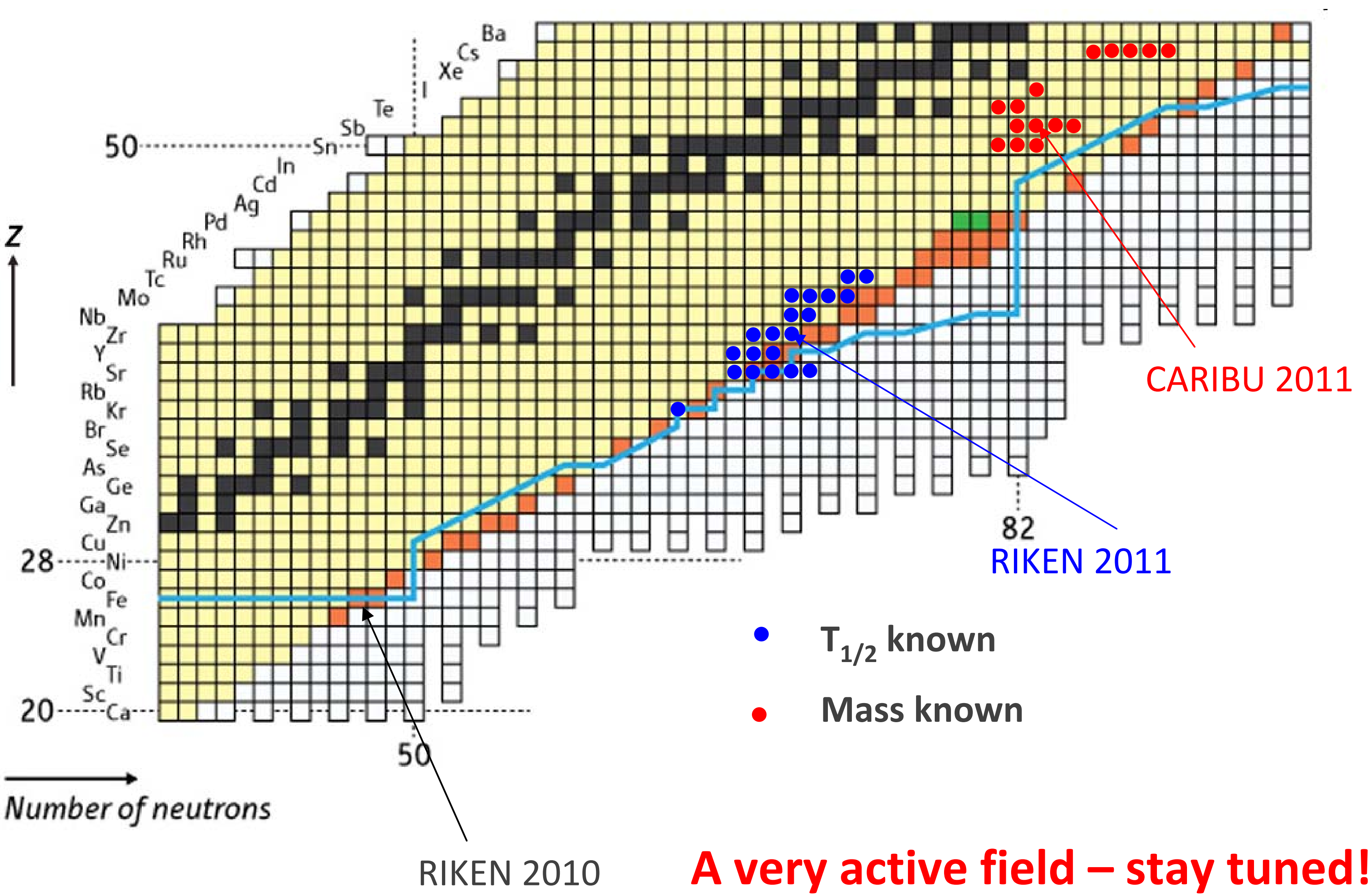




Need information of n-rich nuclei in the r-process path

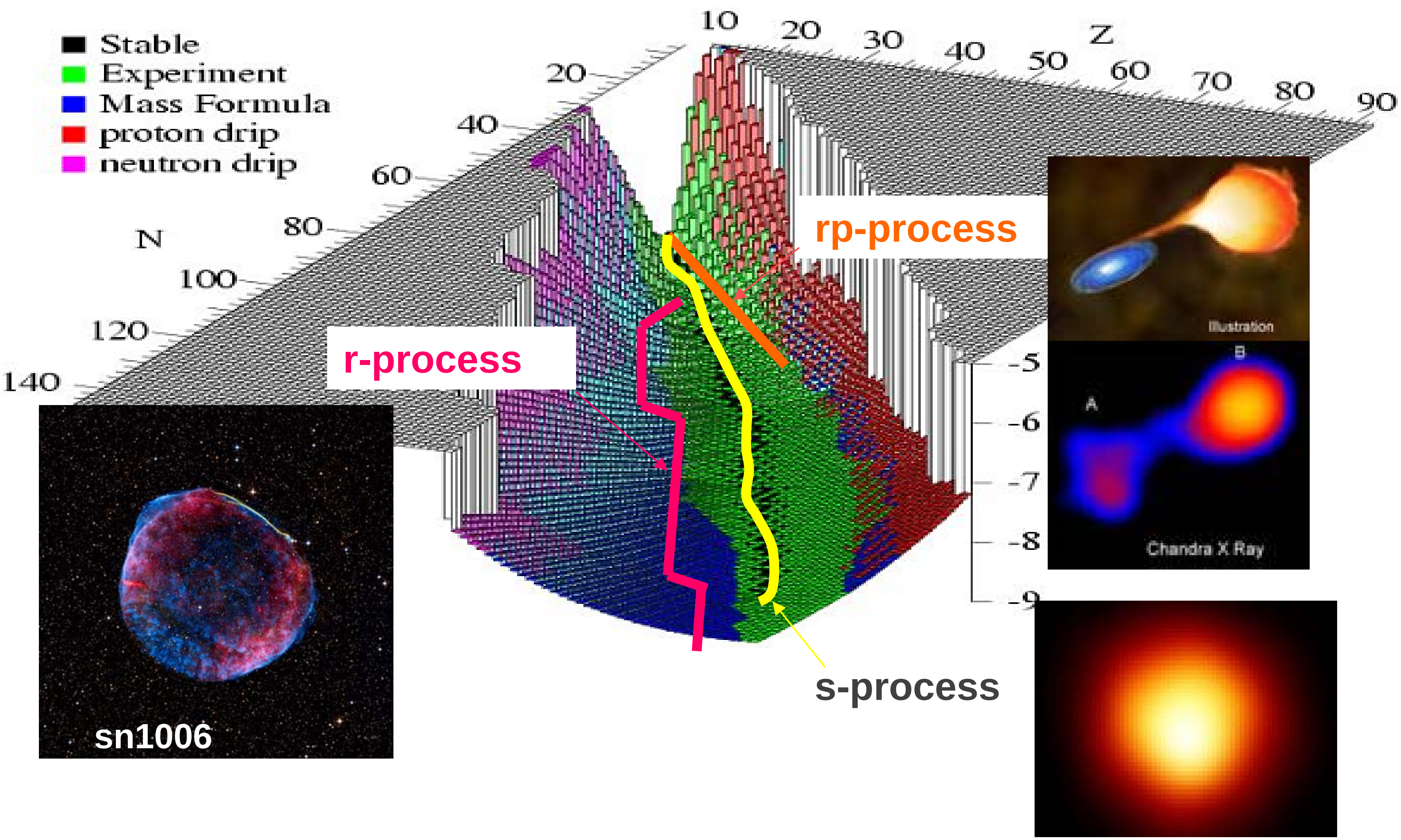
$T_{1/2}$, masses, n-capture rates





A very active field – stay tuned!

Nuclear Physics in Astrophysics




Thanks for listening ‘til the bitter end.