Stellar Evolution:

what do we know?

New Tools - Astronomy

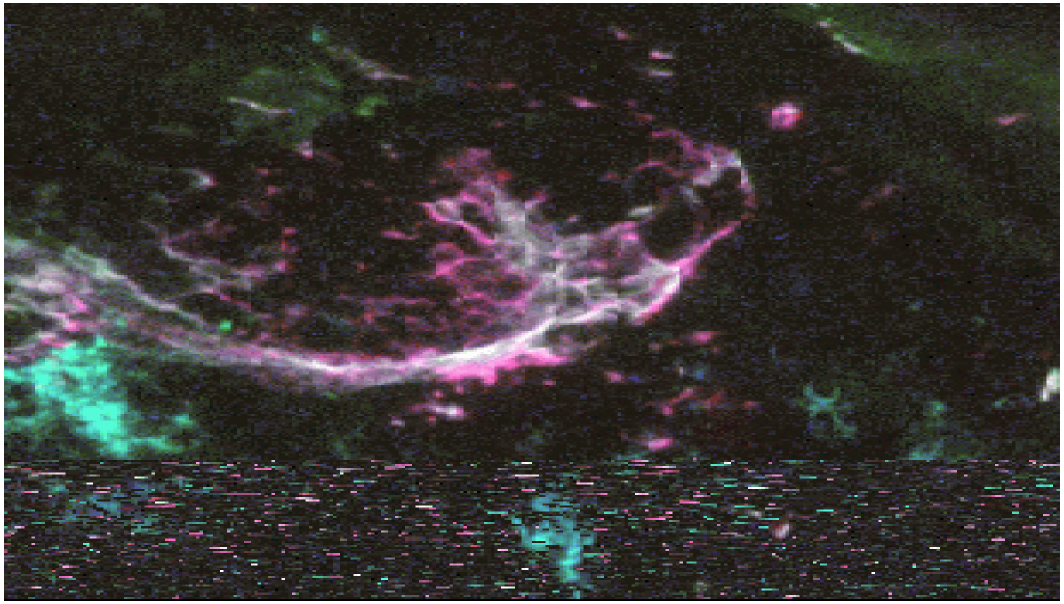
satellite based observatories

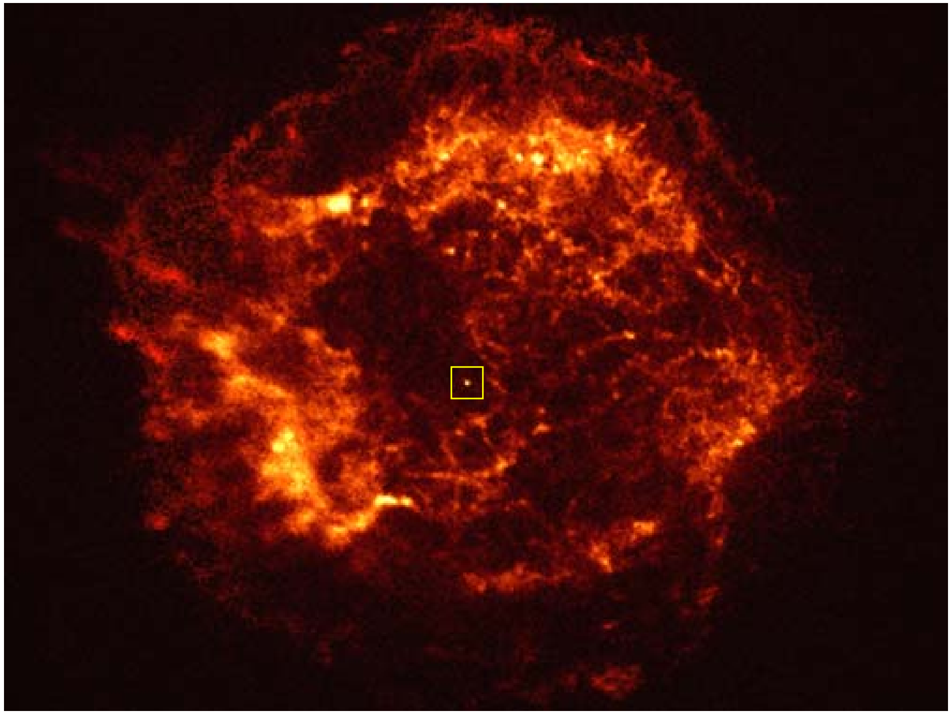
- **Hubble** Space Telescope
- **Compton** Gamma-Ray Observatory
- **Chandra** X-Ray Observatory
- **INTEGRAL**

ground based ‘observatories’

- **Conventional** telescopes
- **LIGO** (gravitational waves)
- **Neutrino** Detectors

Hubble Image
supernova remnant
N132D



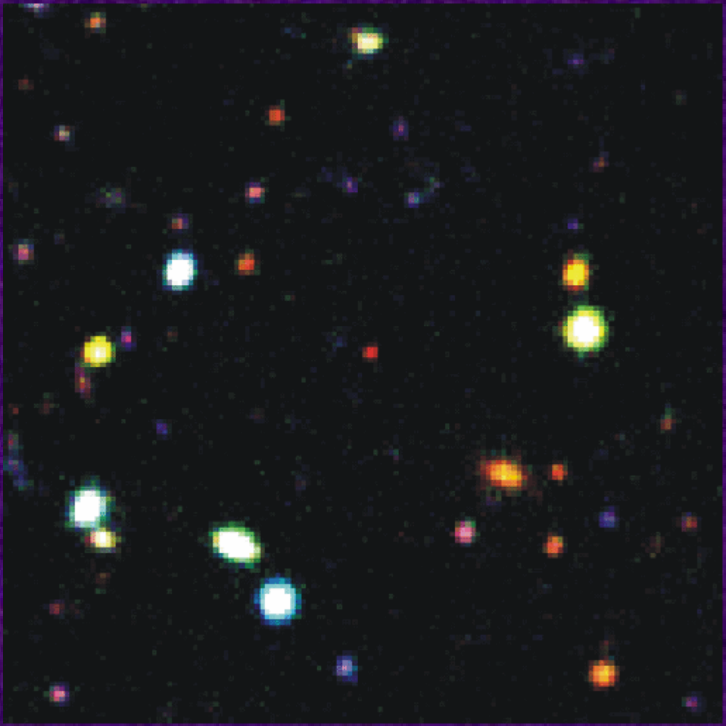


Cassiopeia A
supernova remnant
Chandra X-ray
Observatory

Telescope Image Star Forming Region DEM192 [In Large Magellenic Cloud]

QUAsi StellAr Radio source

- strong radio and optical source
- high red shift (Dl/l) (Doppler shift)



➢“RDJ030117+002025” in the constellation Centus;

➢ redshift of 5.5 {13-14 billion years ago}; near age of universe!

➢vital to understanding evolution of universe

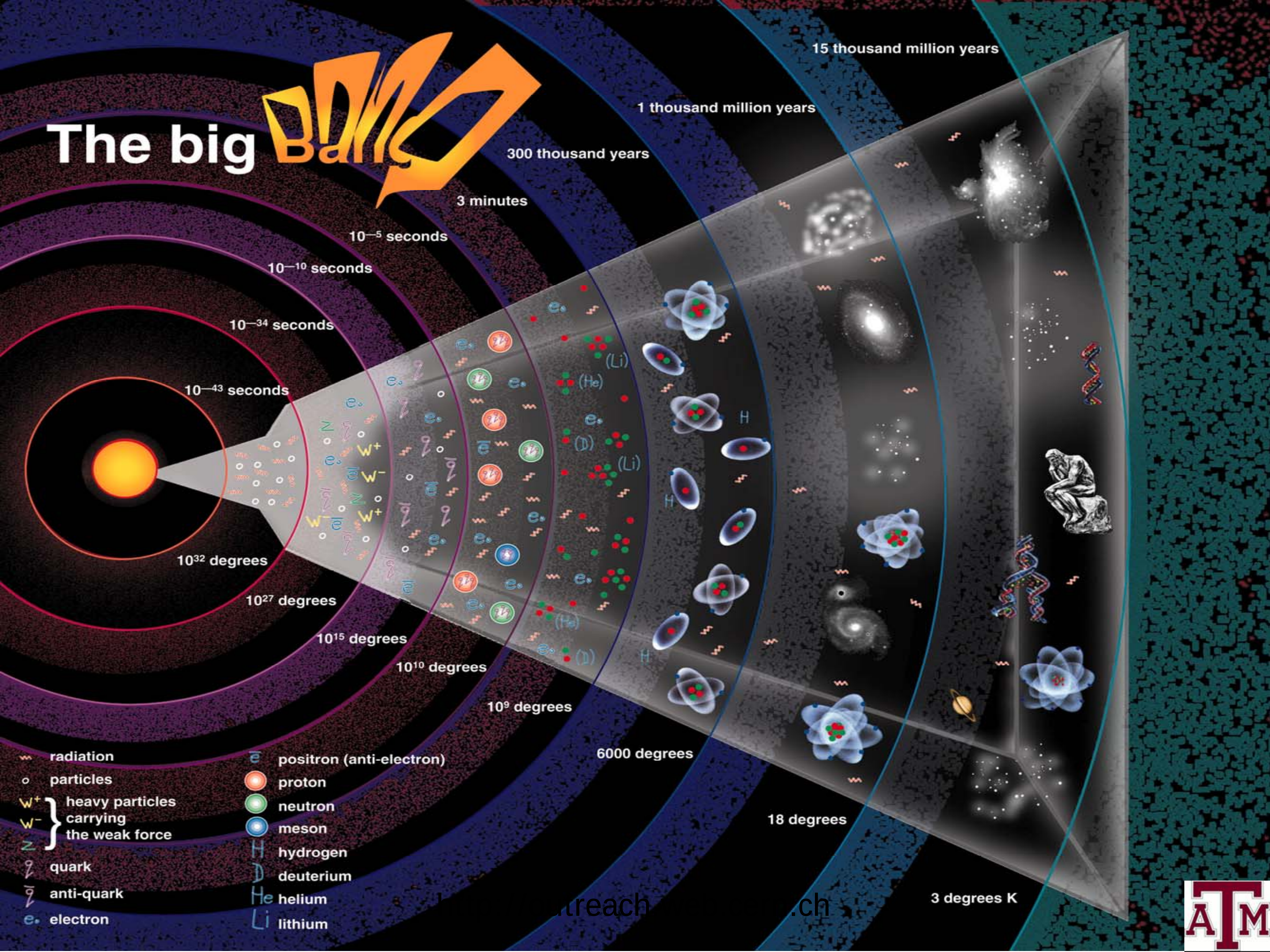
http://www.jpl.nasa.gov/pictures/quasar/

Quasars

- size ~ a few light years
- luminosity ~ 10^{44}-10^{46} erg/s
- mass ~ **10^{8} M_{sun}**
- lifetime ~ 10^{6} years
- fate? - hydrodynamics computation

  (Fuller & Woosley, 1989)

Wait! Let’s go back to the beginning!


The big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
10—5 seconds
10—10 seconds
10—34 seconds
10—43 seconds
10³² degrees
10²⁷ degrees
10¹⁵ degrees
10¹⁰ degrees
10⁹ degrees
6000 degrees
18 degrees
3 degrees K
(Li)
(He)
(D)
H
e
W+
W−
Z
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

[illegible]outreach[illegible].ch

After the **Big Bang**

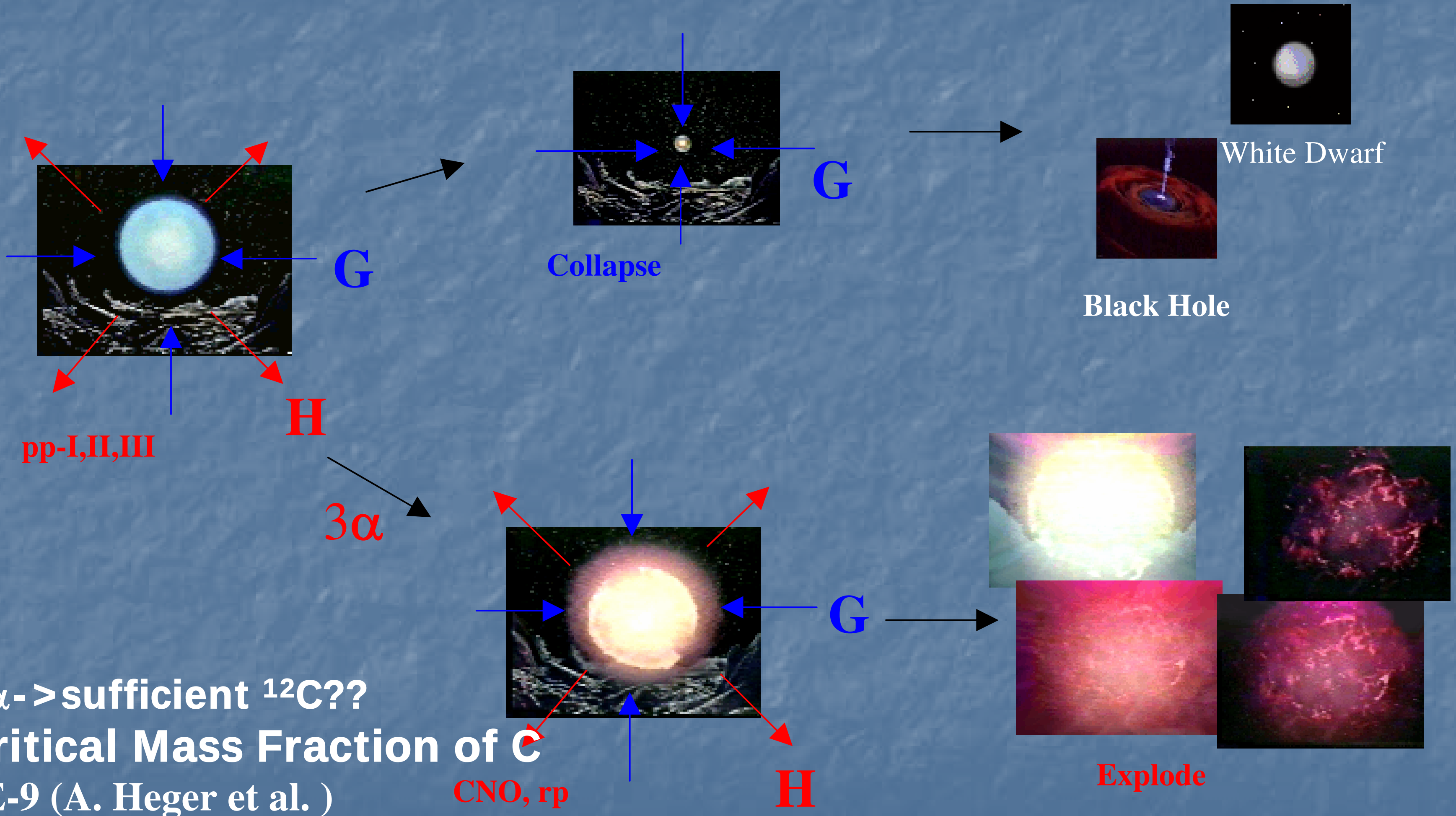
Nuclear Reactions:

energy source that *drives* the cosmos

Nucleo-synthesis and energy production via:

- pp chain
- CNO cycle, NeNa cycle, …
- **rp** process
- **r** process
- rapid α capture
- s process
- . . .

Fate of Massive Pop III Stars



3α->sufficient ^{12}C??

Critical Mass Fraction of C

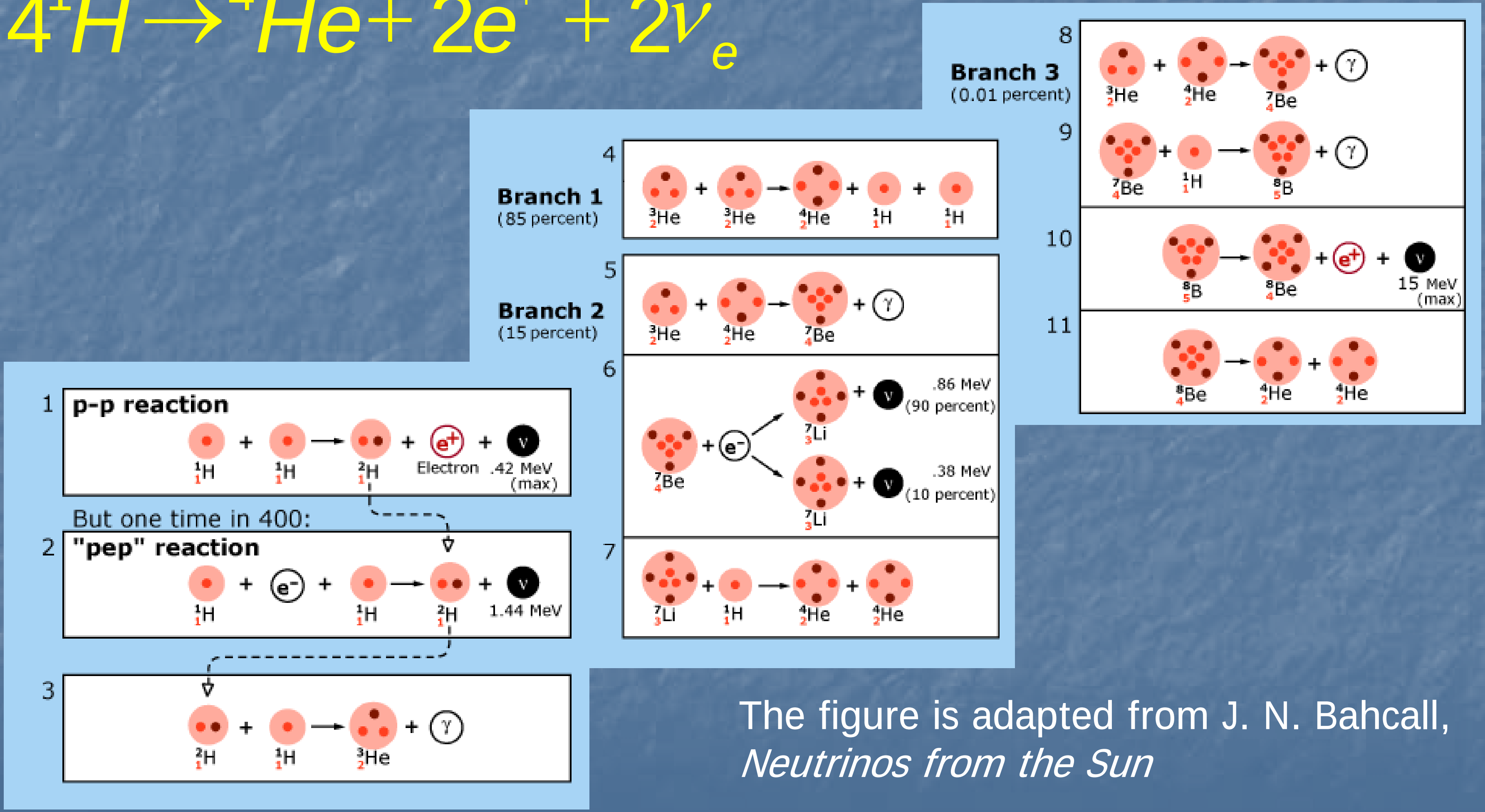
1E-9 (A. Heger et al.)

1E-10 (Weiss et al. 2000)

1E-12 (Siess et al. 2002)

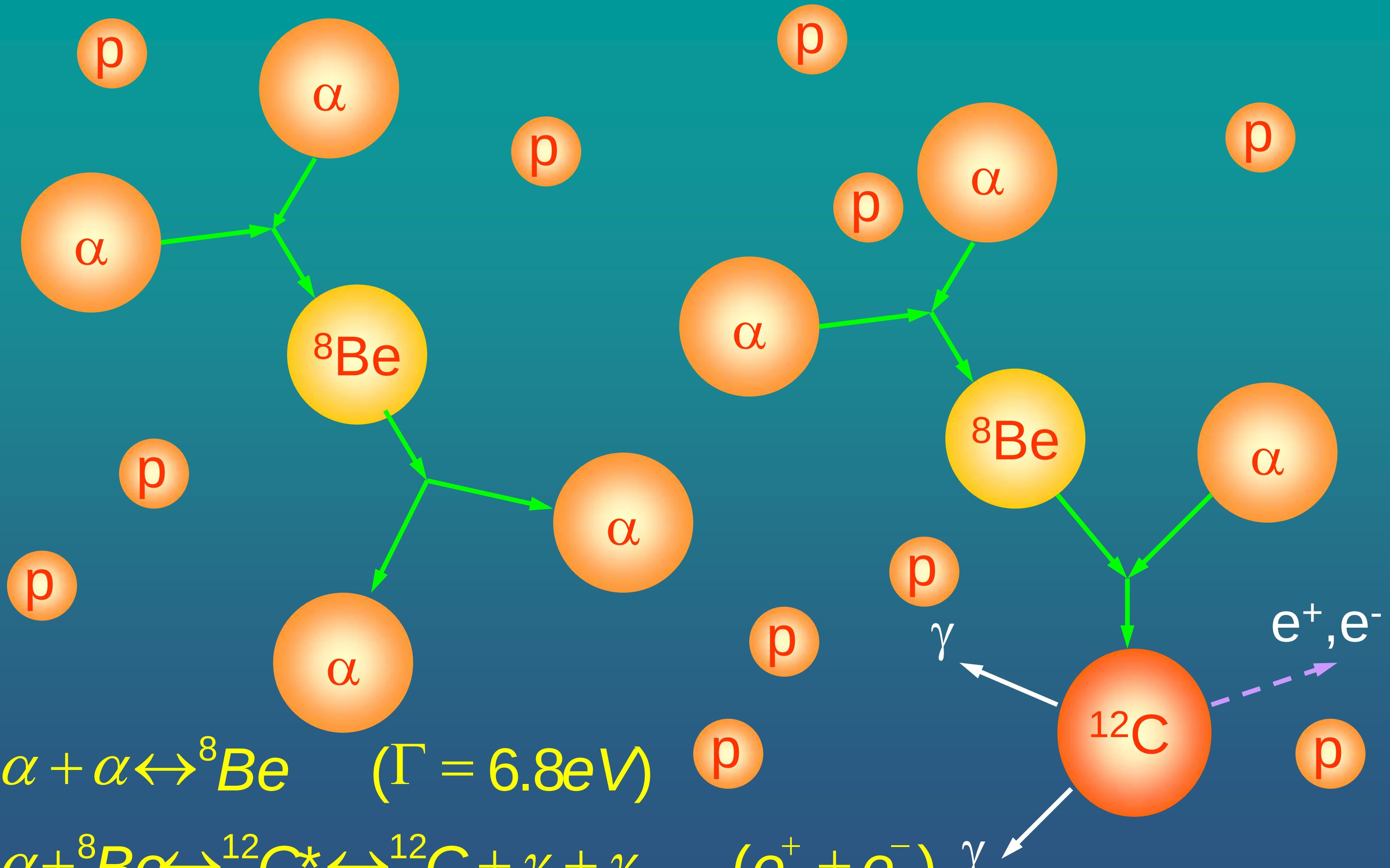
The p—p chain reaction

$$4\,{}^{1}H \rightarrow {}^{4}He + 2e^{+} + 2\nu_{e}$$



The figure is adapted from J. N. Bahcall, *Neutrinos from the Sun*

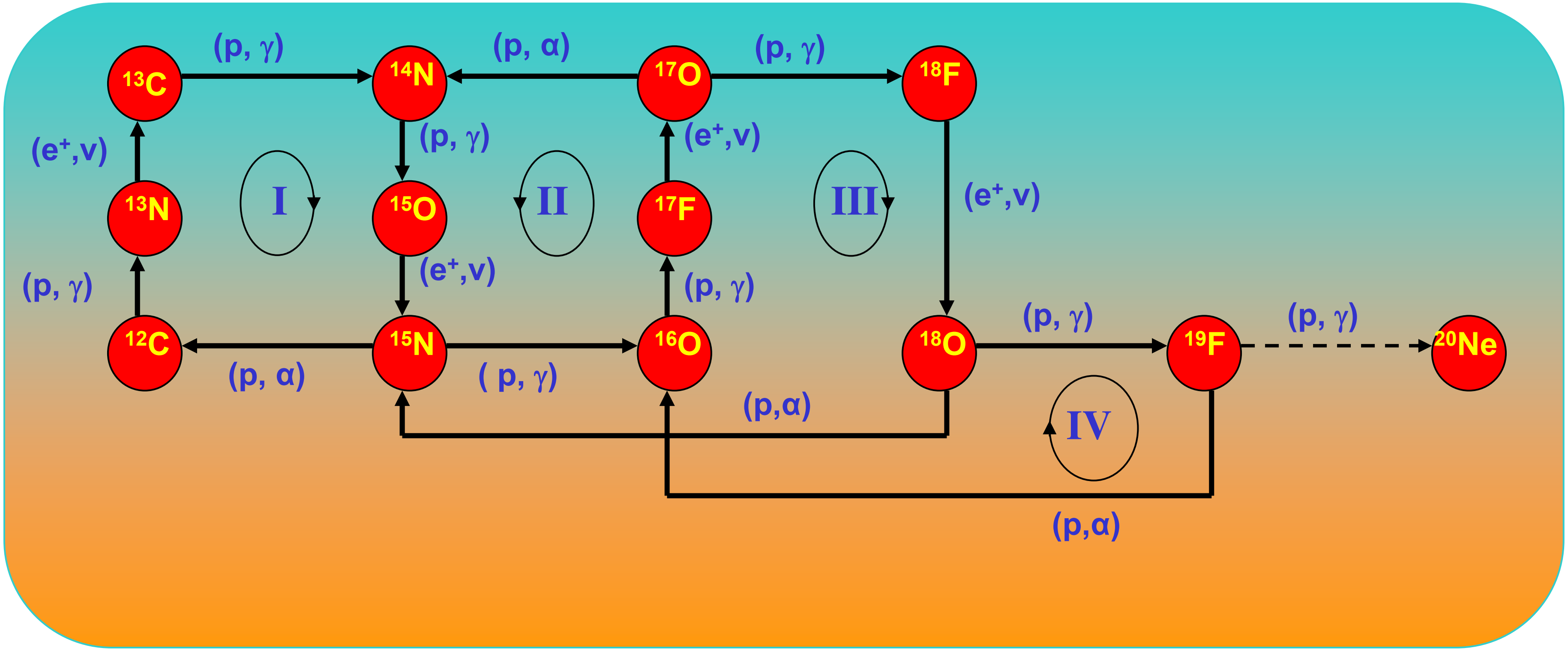
Triple Alpha Process



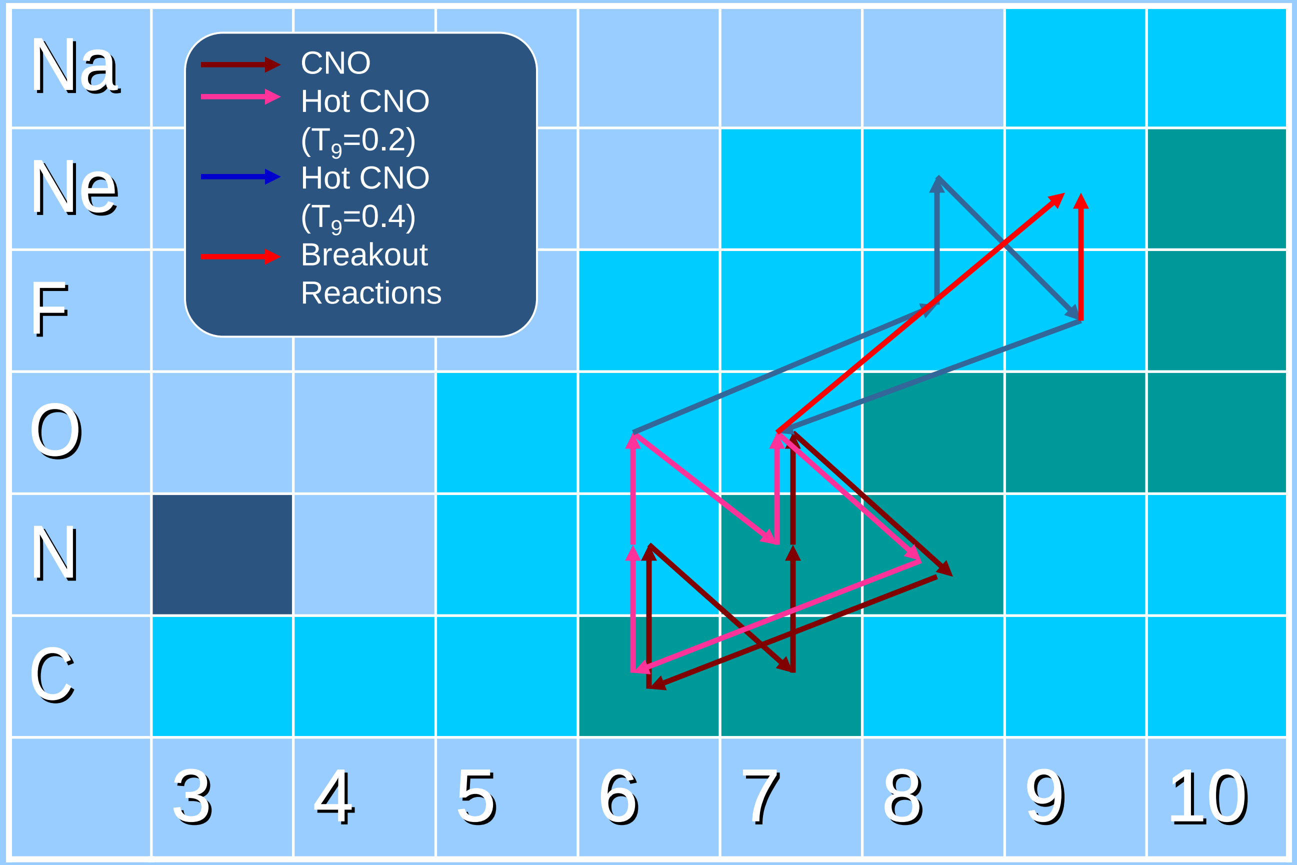
$$\alpha + \alpha \leftrightarrow {}^{8}Be \qquad (\Gamma = 6.8eV)$$

$$\alpha + {}^{8}Be \leftrightarrow {}^{12}C^{*} \leftrightarrow {}^{12}C + \gamma + \gamma \qquad (e^{+} + e^{-})$$

CNO Cycles

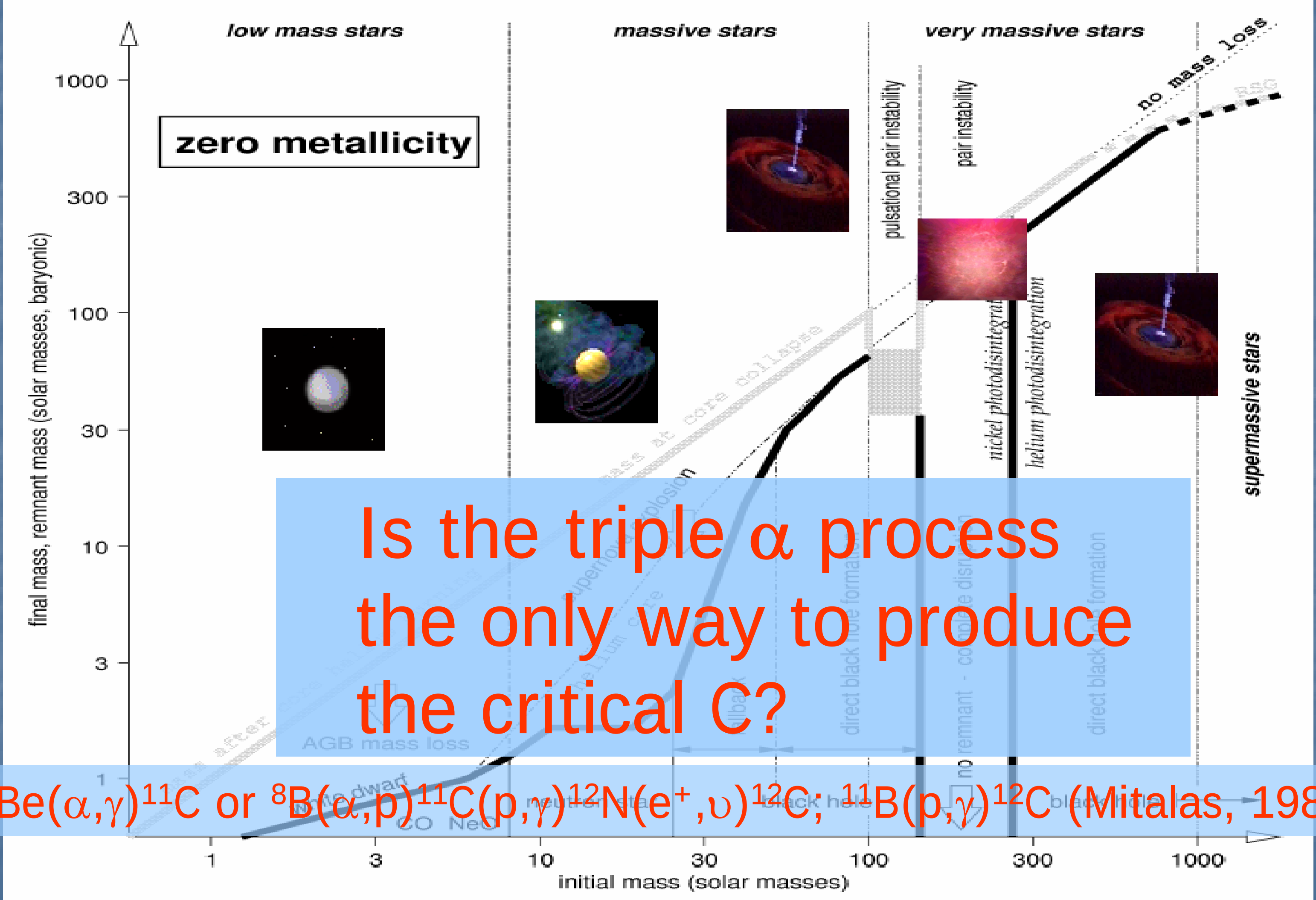

(p, γ)
(p, α)
(p, γ)
13C
14N
17O
18F
(e+,v)
(p, γ)
(e+,v)
I
II
III
(e+,v)
13N
15O
17F
(e+,v)
(p, γ)
(p, γ)
(p, γ)
(p, γ)
12C
15N
16O
18O
19F
20Ne
(p, α)
(p, γ)
(p,α)
IV
(p,α)

Hot CNO Cycle and $^{13}\mathrm{N}(p,\gamma)^{14}\mathrm{O}$



http://csep10.phys.utk.edu/guidry/NC-State-html/cno.html

Fate of Zero Metallicity Pop III Stars

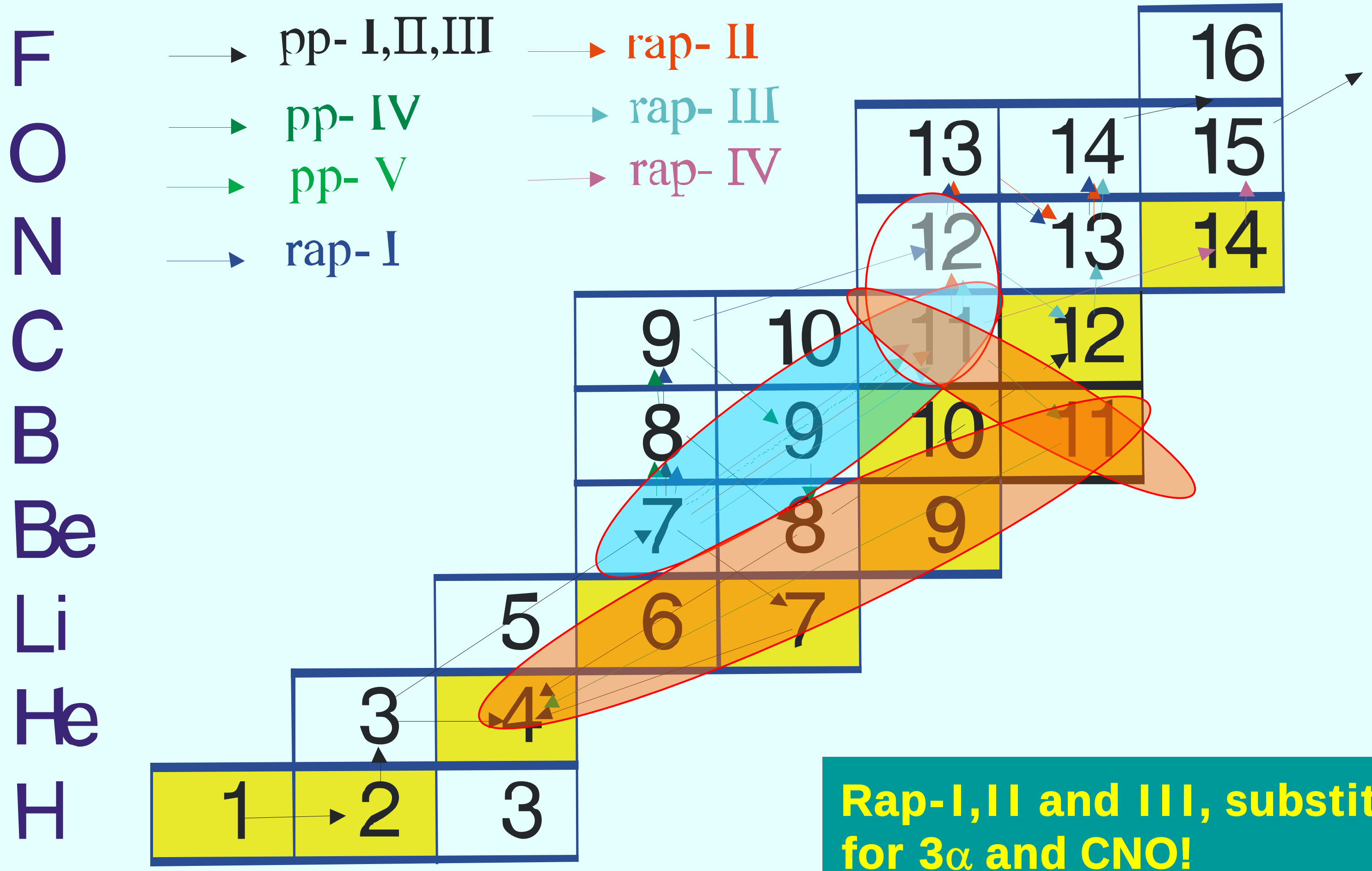


Is the triple α process the only way to produce the critical C?

$^{7}Be(\alpha,\gamma)^{11}C$ or $^{8}B(\alpha,p)^{11}C(p,\gamma)^{12}N(e^{+},\upsilon)^{12}C$; $^{11}B(p,\gamma)^{12}C$ (Mitalas, 1985)

A. Heger & S. Woosly, ApJ.. 567(2002)532

Updated Reaction Sequences in Pop III Stars



Rap-I,II and III, substitution for 3α and CNO! (Wiescher et al., 1989)

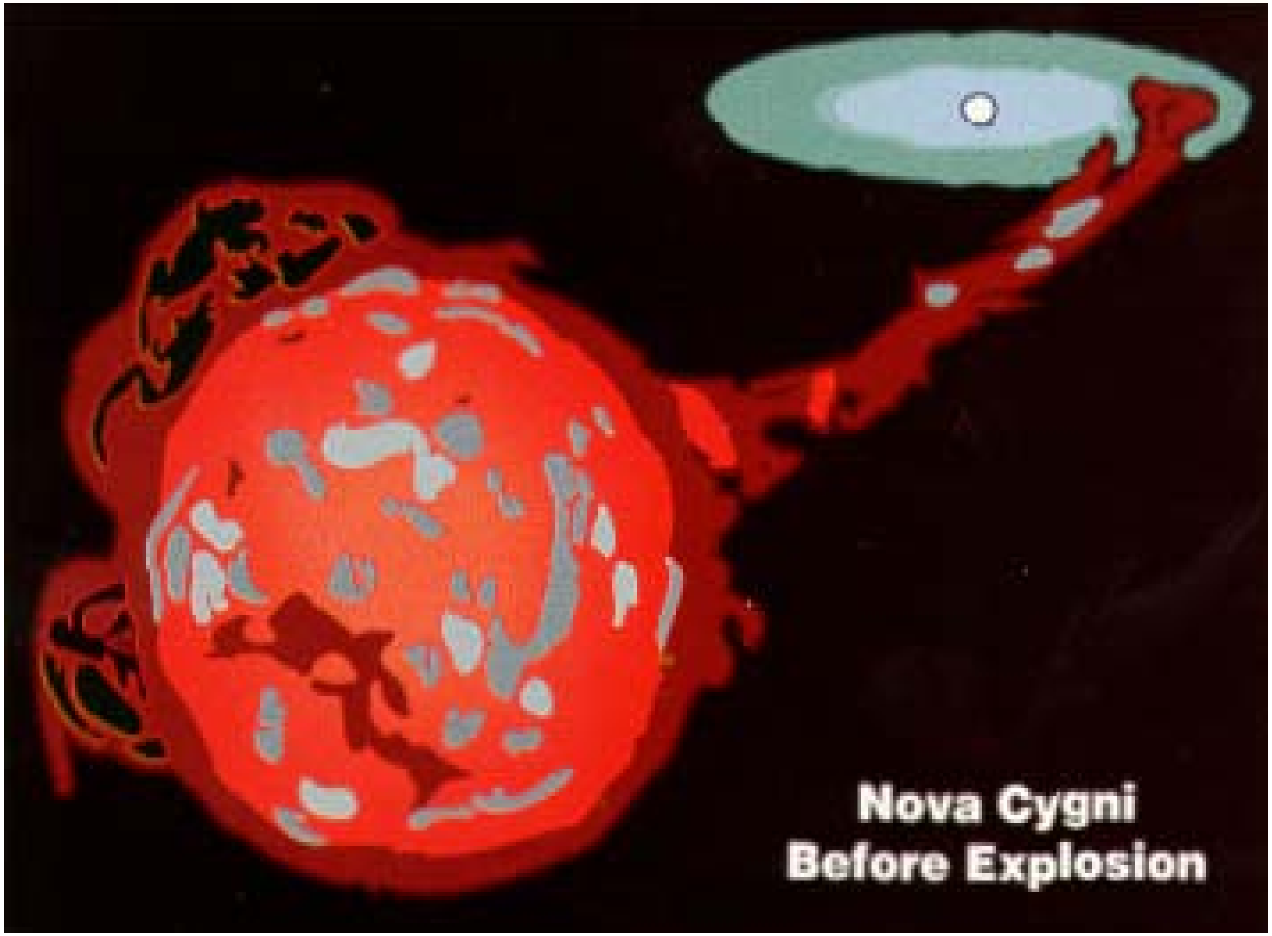
At **TAMU**: studying rapid αp capture reactions to better understand fate of Pop III Stars

Many other phenomena:

- **explosive processes**

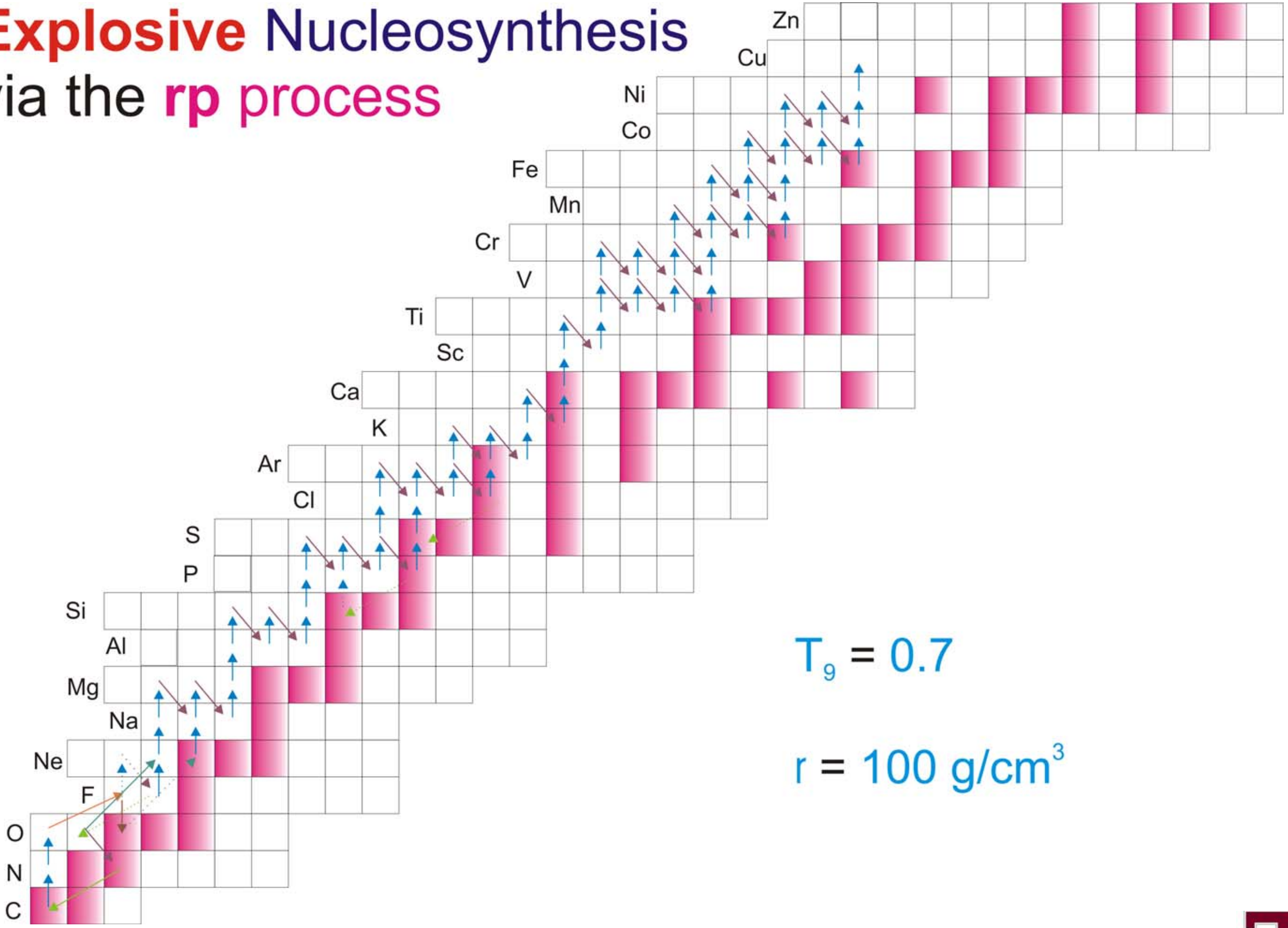
  novae, supernovae, x-ray bursts
- **heavy element production**
- . . .

Mass accretion in a binary system



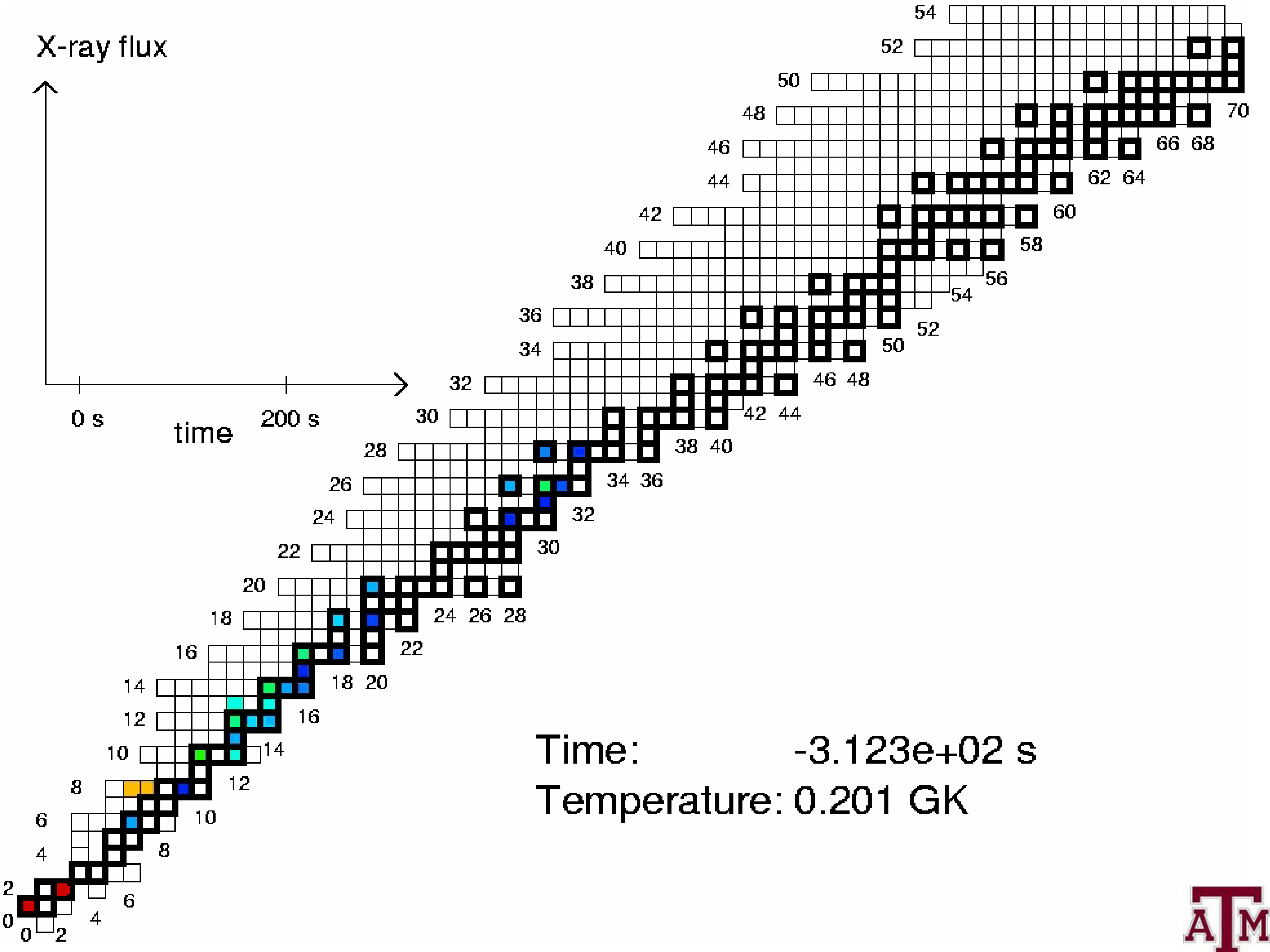
Novae explosions
Supenovae of Type Ia
X-ray bursters, X-ray pulsars

Explosive Nucleosynthesis via the rp process



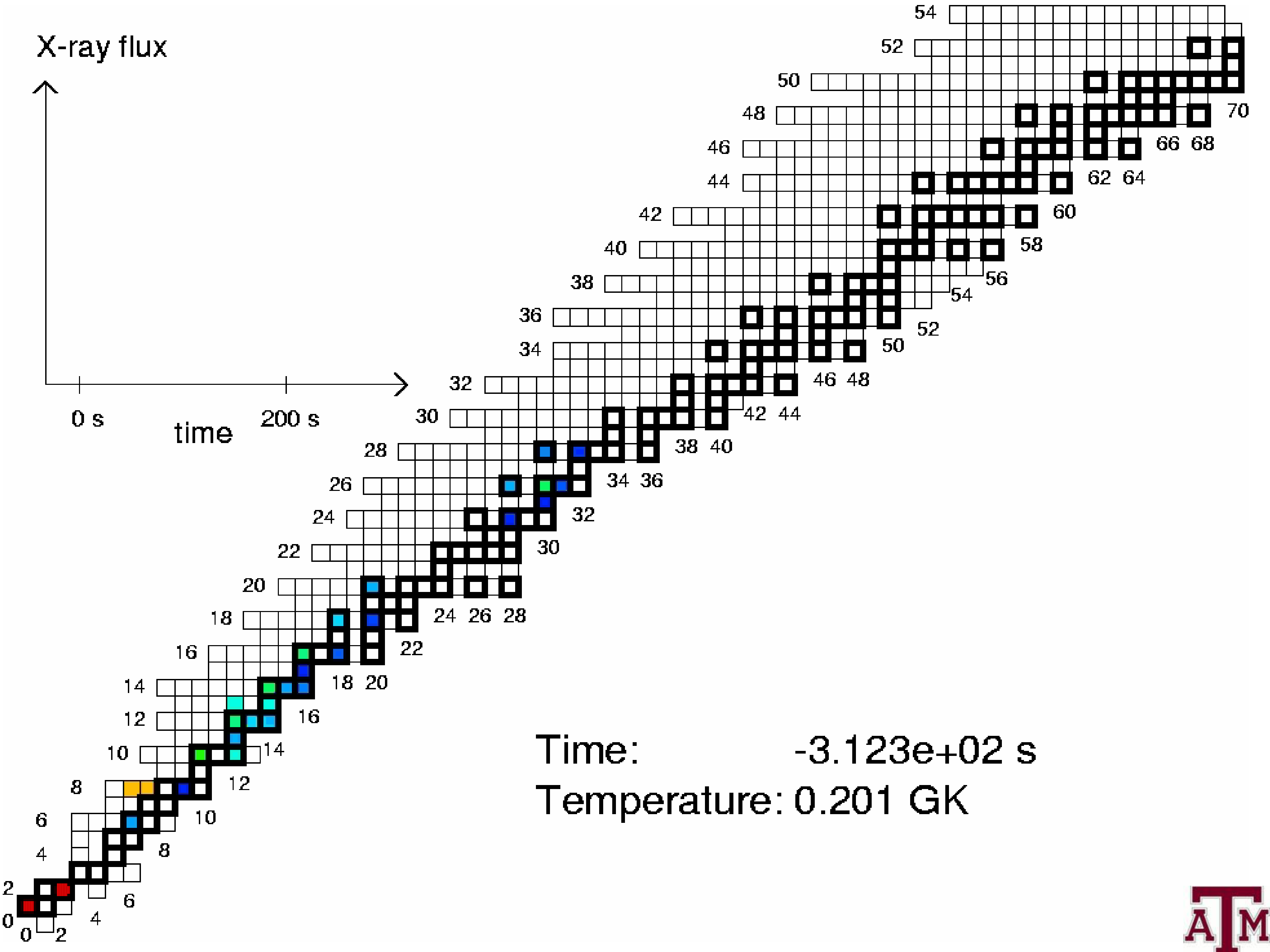
$T_9 = 0.7$

$r = 100\ \mathrm{g/cm^3}$



Time: -3.123e+02 s

Temperature: 0.201 GK

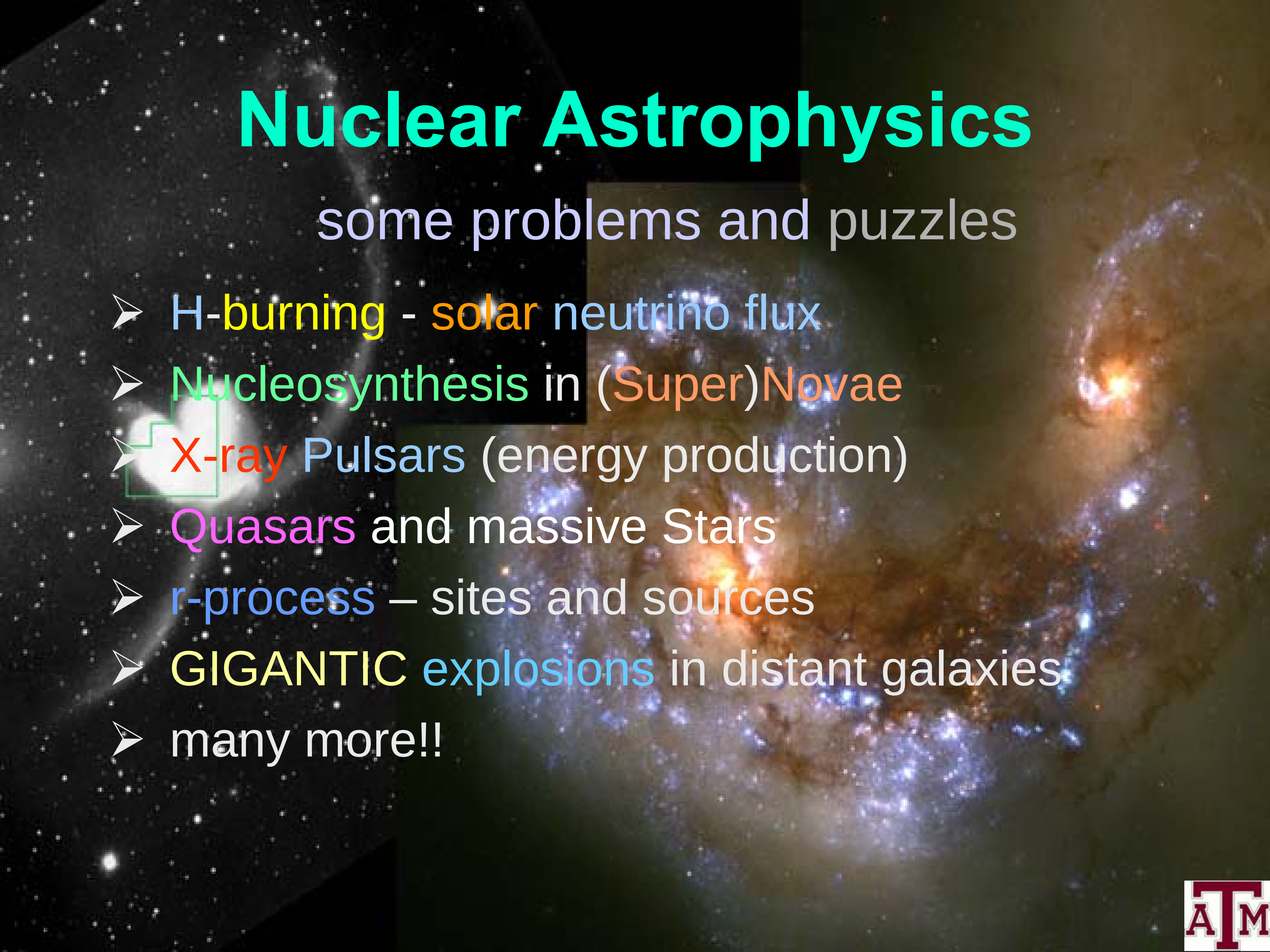


Time: -3.123e+02 s

Temperature: 0.201 GK

Nuclear Astrophysics

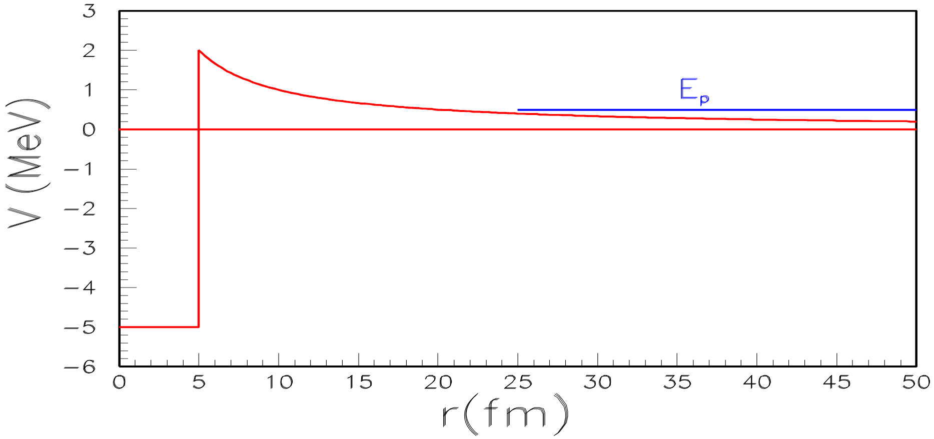
some problems and puzzles



- H-burning - solar neutrino flux
- Nucleosynthesis in (Super)Novae
- X-ray Pulsars (energy production)
- Quasars and massive Stars
- r-process – sites and sources
- GIGANTIC explosions in distant galaxies
- many more!!

Radiative p or α Capture

- Classical barrier penetration problem!



- Low energies ⇒ capture at large radii
- VERY small cross sections ⇒ define **S** factor

$$\sigma(E) = \frac{S(E)}{E}\exp\{-2\pi\eta(E)\} \qquad \eta(E) = \frac{Z_1 Z_2 e^2}{\hbar v}$$

Decades of **Work**

- **Capture reactions** at **low energy**

  p, α, n capture on stable targets

- **Indirect techniques**

  measure widths and locations of resonances

- **New techniques** in past decade

  Coulomb dissociation, ANCs, . . .

New Tools – Nuclear Physics

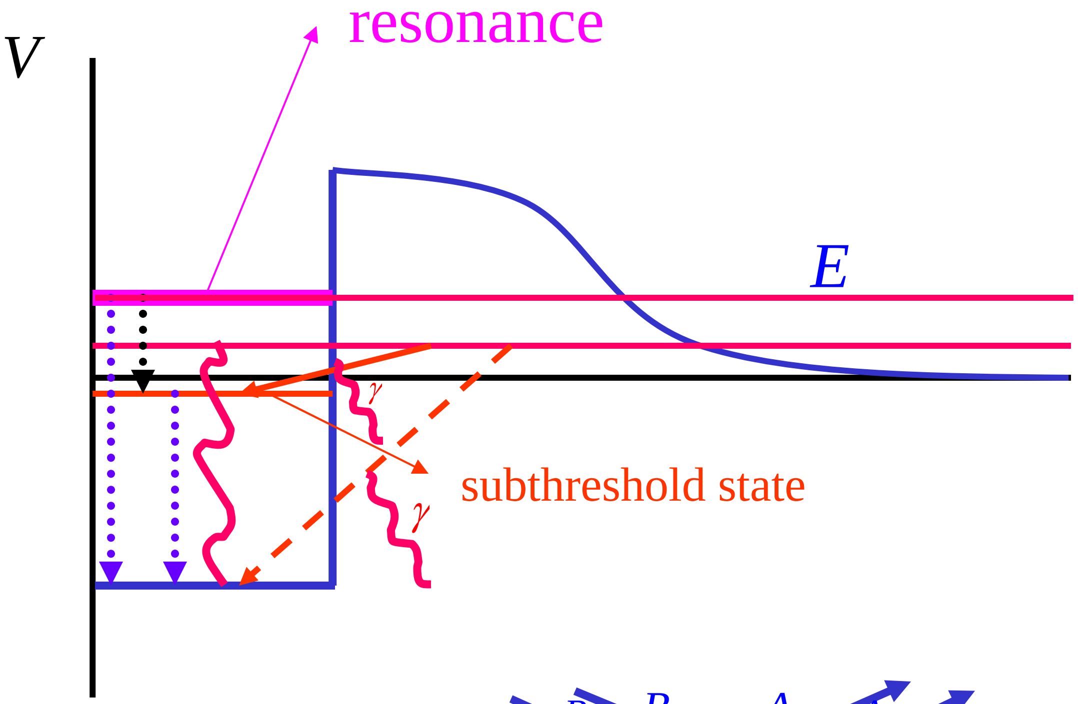
Radioactive (rare isotope) beams

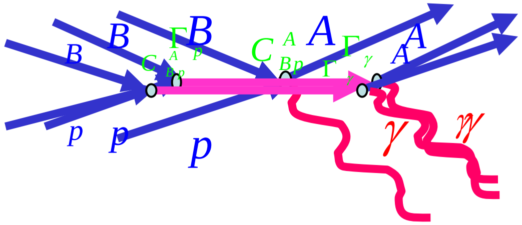
- **MSU**
- **ORNL**
- **ANL, Notre Dame, TAMU, . . .**
- **GANIL, RIKEN, . . .**

Detectors

- **GAMMA arrays**
- **Particle** detector arrays

Radiative [p(α)] **Capture** with **resonant** and **subthreshold** states: **ANCs**





Capture **through resonance**

$$M \propto \frac{\Gamma_p^{1/2}\,\Gamma_\gamma^{1/2}}{E - E_0 + \frac{i\Gamma}{2}}$$

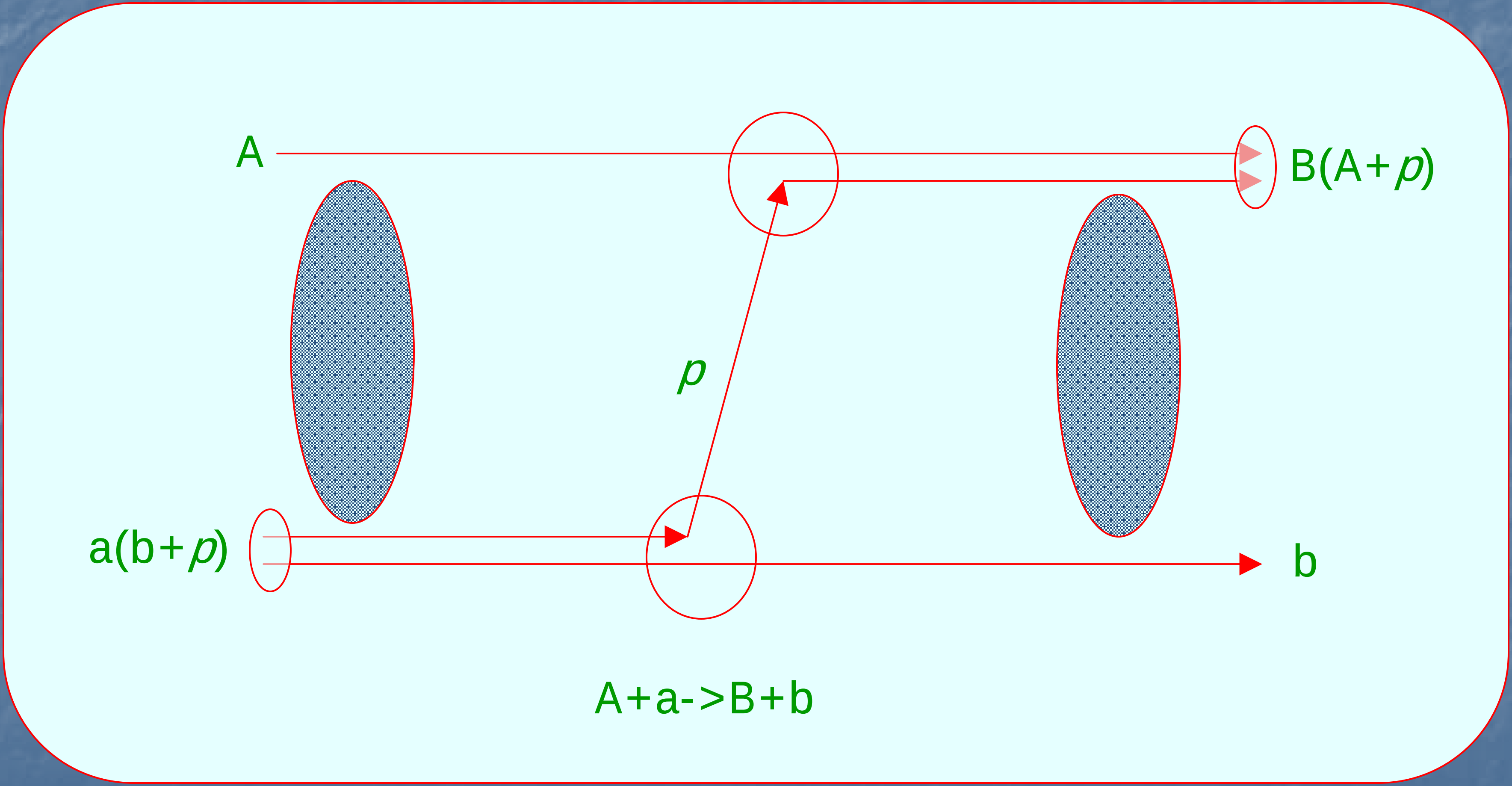
Direct capture

$$M \propto C^A_{Bp}$$

Capture **to ground state through subthreshold state**

$$M \propto \frac{C^A_{Bp}\,\Gamma_\gamma^{1/2}}{E + \varepsilon^* + \frac{i\Gamma}{2}}$$

Transfer Reaction



A+a->B+b

ANCs (p) measured using stable beams

- ^{9}Be + p $\leftrightarrow$ ^{10}B* [^{9}Be(^{3}He,*d*)^{10}B;^{9}Be(^{10}B,^{9}Be)^{10}B]
- ^{12}C + p $\leftrightarrow$ ^{13}N [^{12}C(^{3}He,*d*)^{13}N]
- ^{13}C + p $\leftrightarrow$ ^{14}N [^{13}C(^{3}He,*d*)^{14}N;^{13}C(^{14}N,^{13}C)^{14}N]
- ^{14}N + p $\leftrightarrow$ ^{15}O [^{14}N(^{3}He,*d*)^{15}O]
- ^{16}O + p $\leftrightarrow$ ^{17}F* [^{16}O(^{3}He,*d*)^{17}F]
- ^{20}Ne + p $\leftrightarrow$ ^{21}Na [^{20}Ne(^{3}He,*d*)^{21}Na]

beams $\approx$ 10 MeV/u

*** Test cases**

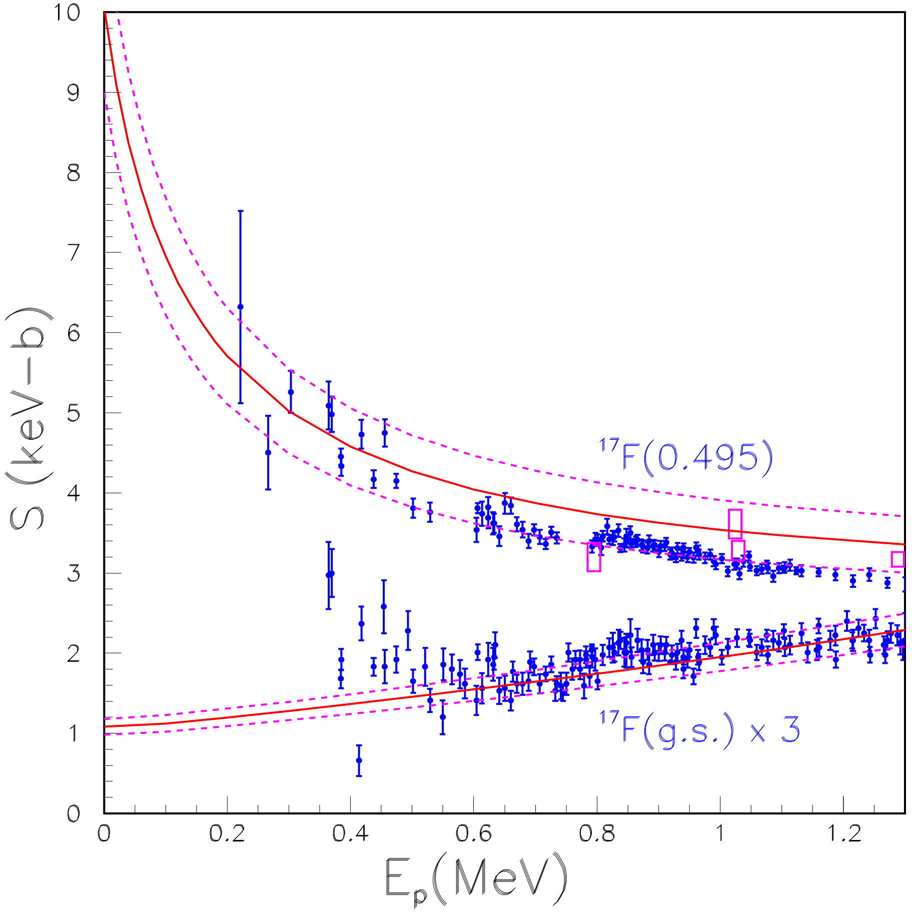
S factor for $^{16}O(p,\gamma)^{17}F$

- ANC's ⇐ $^{16}O(^3He,d)^{17}F$

  $(C^2)_{gnd} = 1.08 \pm .10\ fm^{-1}$

  $(C^2)_{ex} = 6490 \pm 680\ fm^{-1}$

- Direct Capture data from Morlock, et. al

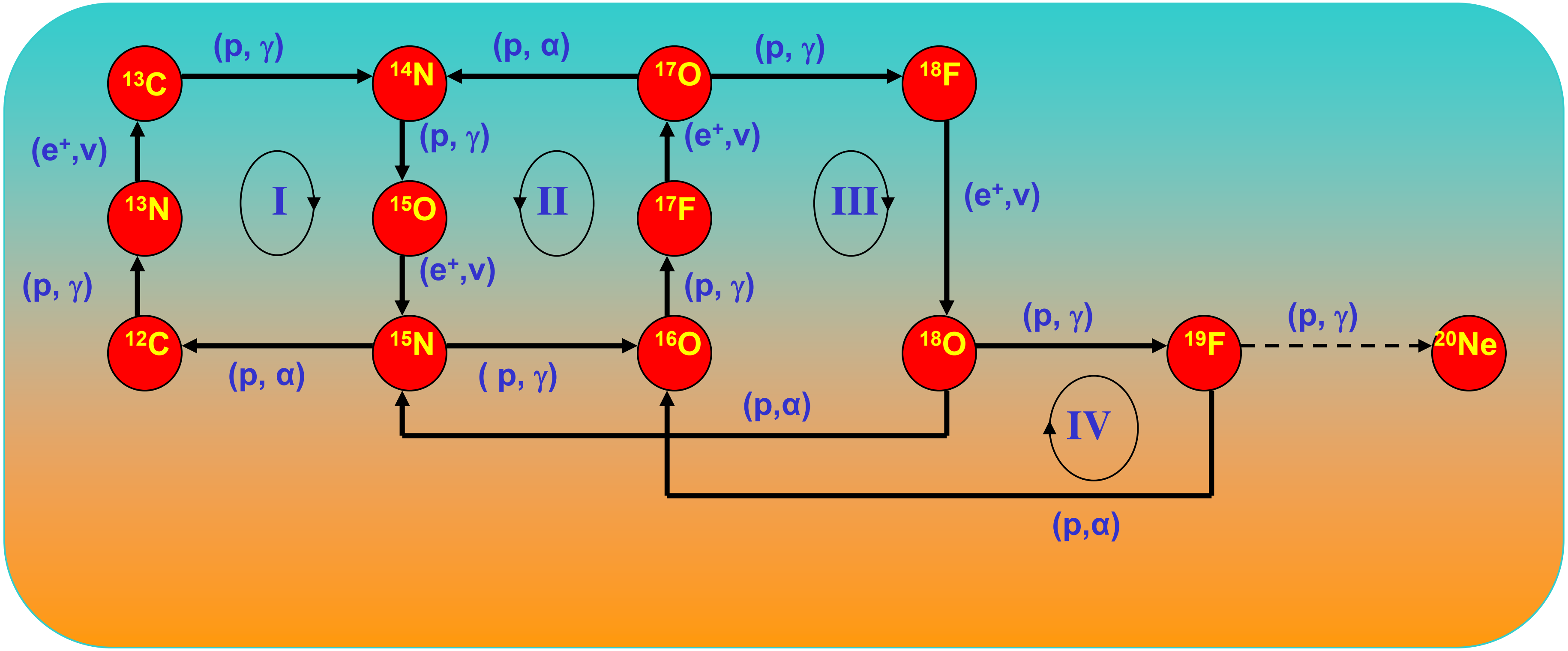


Nuclear Astrophysics Issues

Three Examples

- **CNO** cycle reaction
  - **$^{14}N(p,\gamma)^{15}O$** (ANCs from (**$^{3}He,d$**) reaction)
- **HCNO** cycle reaction
  - **$^{13}N(p,\gamma)^{14}O$** (ANCs from (**$^{13}N,^{14}O$**) reaction)
- **Ne**-**Na** cycle reaction
  - next cycle, ^{21}Ne likely source of neutrons

CNO Cycles



^{13}C (p, γ) ^{14}N (p, α) ^{17}O (p, γ) ^{18}F

(e⁺,ν) (p, γ) (e⁺,ν) (e⁺,ν)

^{13}N I ^{15}O II ^{17}F III

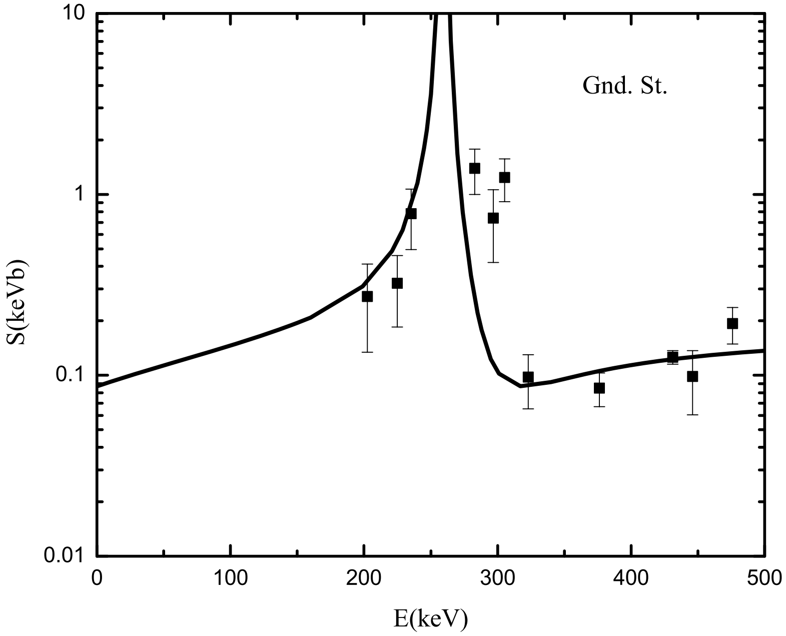
(p, γ) (e⁺,ν) (p, γ)

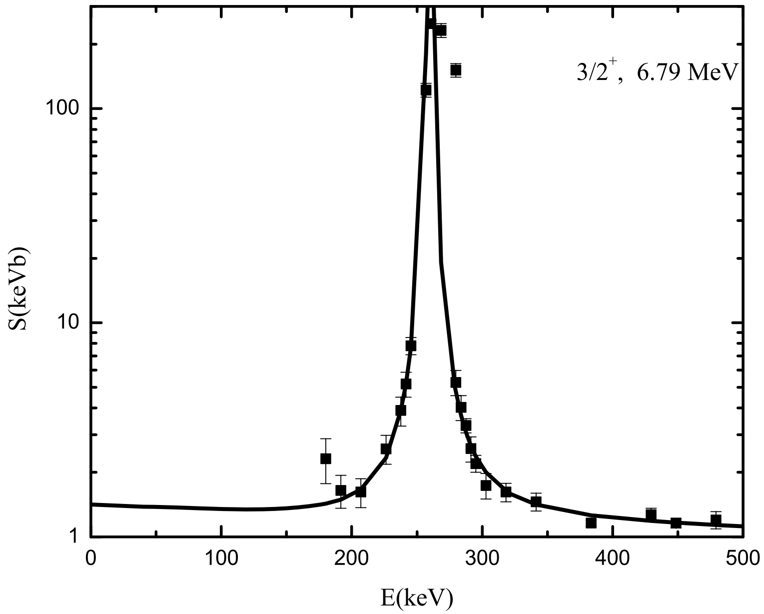
^{12}C ^{15}N ^{16}O ^{18}O (p, γ) ^{19}F (p, γ) ^{20}Ne

(p, α) (p, γ) (p,α) IV

(p,α)

S factor for $^{14}N(p,\gamma)^{15}O$





- $C^2(E_x = 6.79$ MeV$) \approx 27$ fm^{-1} [non-resonant capture to this state dominates S factor]
- S(0) = 1.40 ± 0.20 keV·b for $E_x = 6.79$ MeV
- $S_{tot}(0) = 1.70 \pm 0.22$ keV·b

S factor for $^{14}N(p,\gamma)^{15}O$

- **S** factor dominated by direct capture to the subthreshold state—our published value

  $S(0) = 1.62 \pm 0.25$ keV·b

  reduces previous results by ≈ 2

- New direct measurements from LUNA (1.7±0.2) and LENA (1.68±0.09±0.16) in ***excellent agreement*** with this

- Impacts stellar luminosity at transition period to red giants and ages of globular clusters by about 1 Gyr

Ne – **Na** Cycle

Important in **second generation stars**

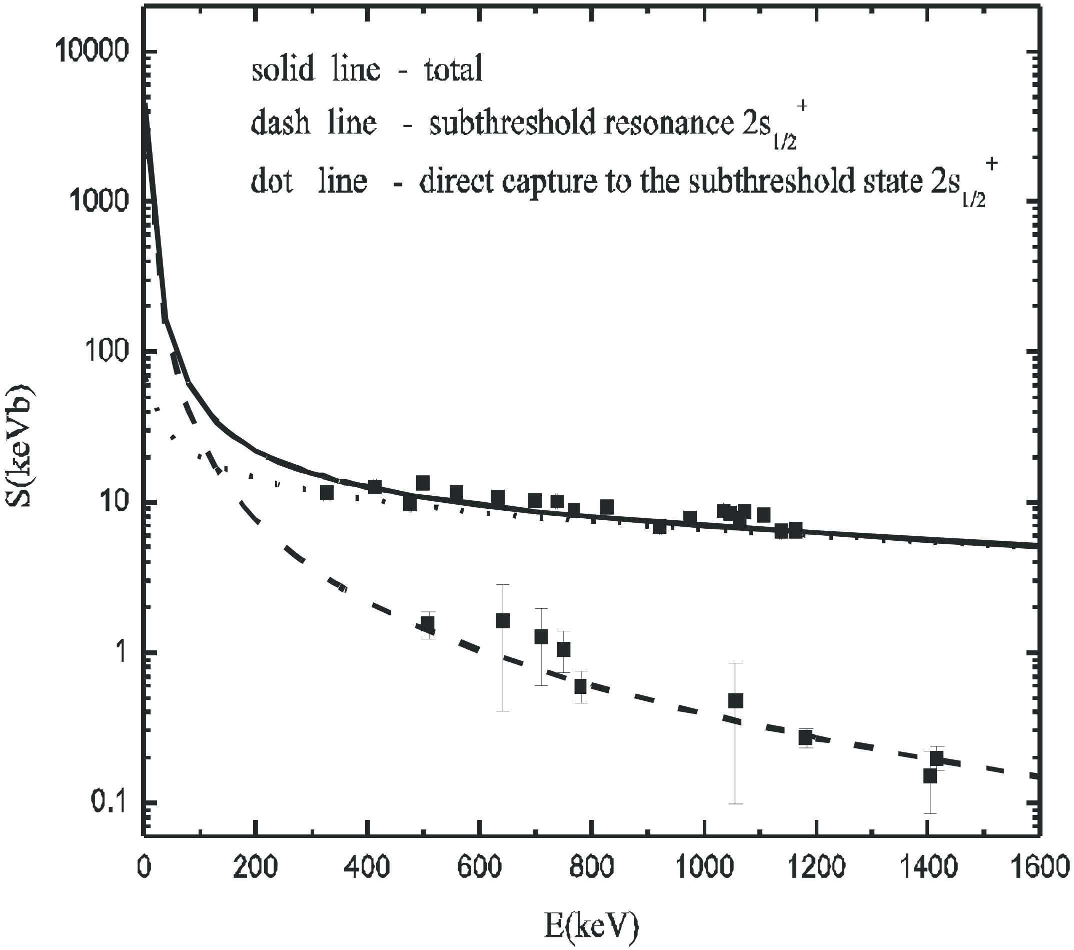
$$\begin{tikzcd}
{}^{21}Ne \arrow[r, "(p,\gamma)"] & {}^{22}Na \arrow[d] & \\
{}^{21}Na \arrow[u] & {}^{22}Ne \arrow[d] & \\
{}^{20}Ne \arrow[u] & {}^{23}Na \arrow[l] \arrow[r] & {}^{24}Al
\end{tikzcd}$$

S factor for $^{20}\mathrm{Ne}(p,\gamma)^{21}\mathrm{Na}$

- **Ne** - **Na** cycle reaction

- Subthreshold state dominates rate

  $2s_{1/2}$ at E_x = 2.425 MeV, ε =7.1± 0.6 keV



For subthreshold resonance (dashed line)

$$S \propto \Gamma_\gamma \left|C\right|^2$$

$\Gamma_\gamma \Rightarrow$ **fitting** parameter; new measurement would help!

$S(0) = 4550 \pm 800\,\mathrm{keVb}$ present work

$S(0) = 3500\,\mathrm{keVb}$ C. Rolfs and W. S. Rodney, NPA 241, 460 (1975)

Higher reaction rate for ^{21}Na increases the abundance of ^{21}Ne and, correspondingly, the number of neutrons from ^{21}Ne(α,n)^{24}Mg

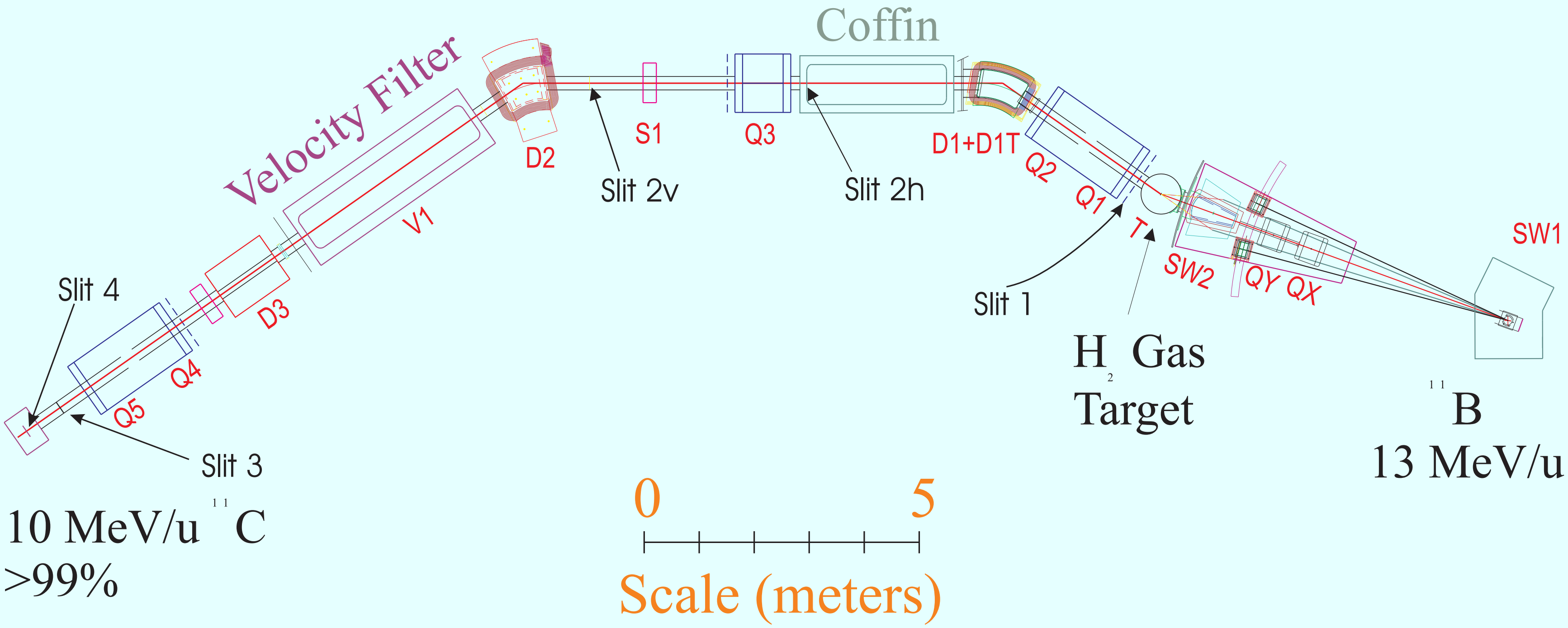
ANCs measured by our group radioactive (rare isotope) beams

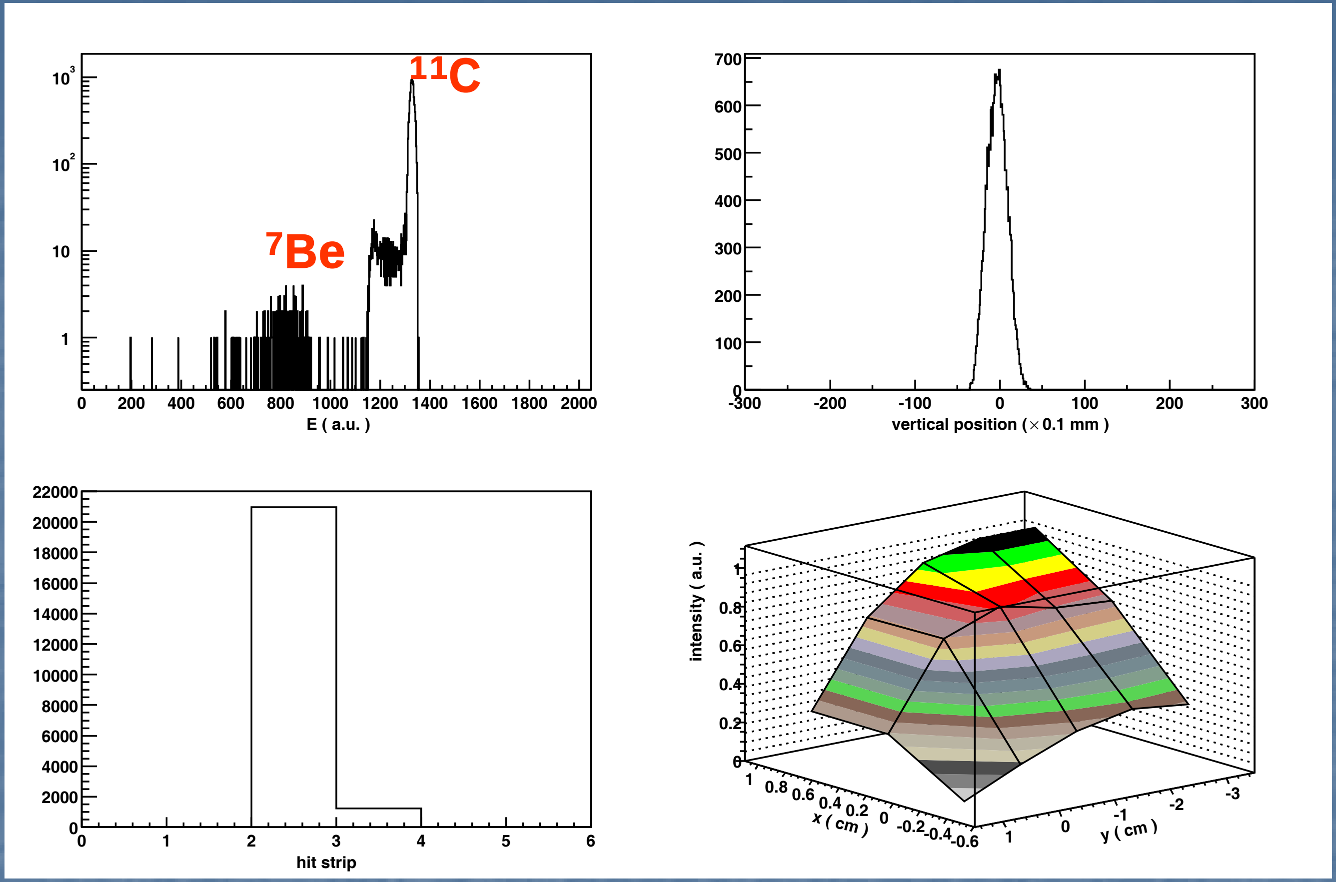
- **^{7}Be + p $\leftrightarrow$ ^{8}B** [^{10}B(^{7}Be,^{8}B)^{9}Be]
  [^{14}N(^{7}Be,^{8}B)^{13}C]
- **^{11}C + p $\leftrightarrow$ ^{12}N** [^{14}N(^{11}C,^{12}N)^{13}C]
- **^{12}N + p $\leftrightarrow$ ^{13}O** [^{14}N(^{12}N,^{13}O)^{13}C]
- **^{13}N + p $\leftrightarrow$ ^{14}O** [^{14}N(^{13}N,^{14}O)^{13}C]
- **^{17}F + p $\leftrightarrow$ ^{18}Ne** [^{14}N(^{17}F,^{18}Ne)^{13}C]

{ORNL (TAMU collaborator)}

beams ≈ 10 - 12 MeV/u

Momentum Achromat Recoil Separator





Primary Beam : $^{11}B^{2+}$@13 MeV/u, 800 enA
Primary Reaction : $^{11}B(^{1}H,n)^{11}C$
Secondary beam : ^{11}C
Intensity>400 kHz, PURITY>99%
E=110 MeV, ΔE=1.6 MeV (FWHM)
ΔX=3 mm (FWHM), ΔY=3.2 mm (FWHM)
Δθ=1.8 deg(FW), Δφ=1.9 deg (FW)

ANCs for
^{13}N + p $\leftrightarrow$ ^{14}O

- reaction:

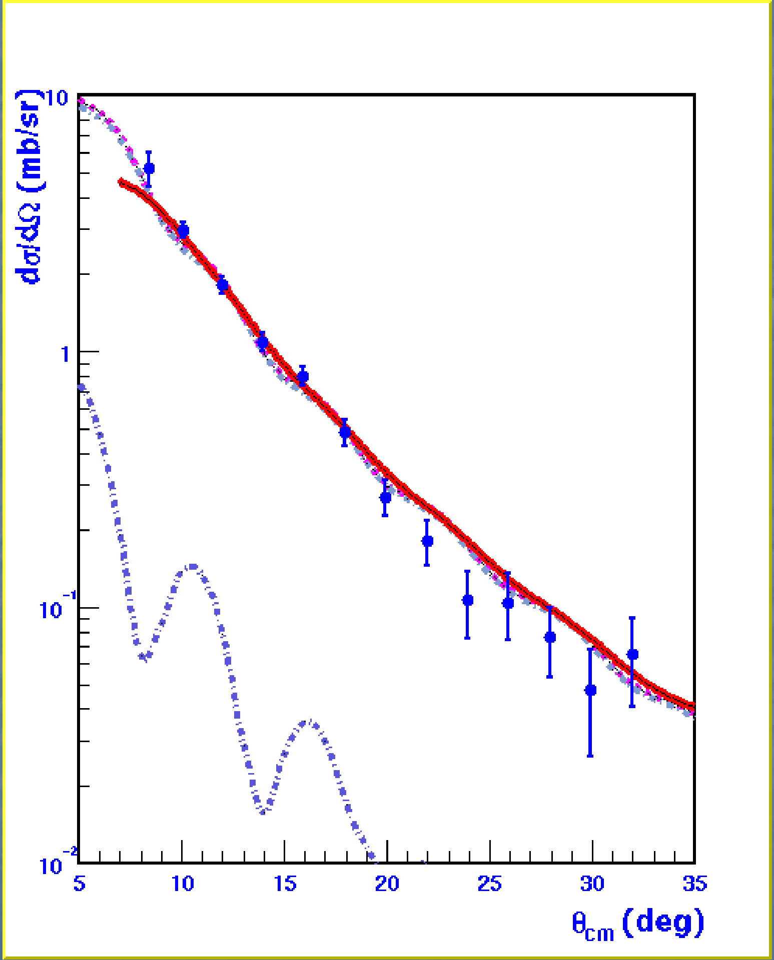
^{14}N(^{13}N,^{14}O)^{13}C

K500: ^{13}C beam ≈ 195 MeV

MARS: ^{13}N beam ≈ 153 MeV

$^{14}N(^{13}N,^{14}O)^{13}C$

(ANC for $^{14}N \to {}^{13}C + p$)

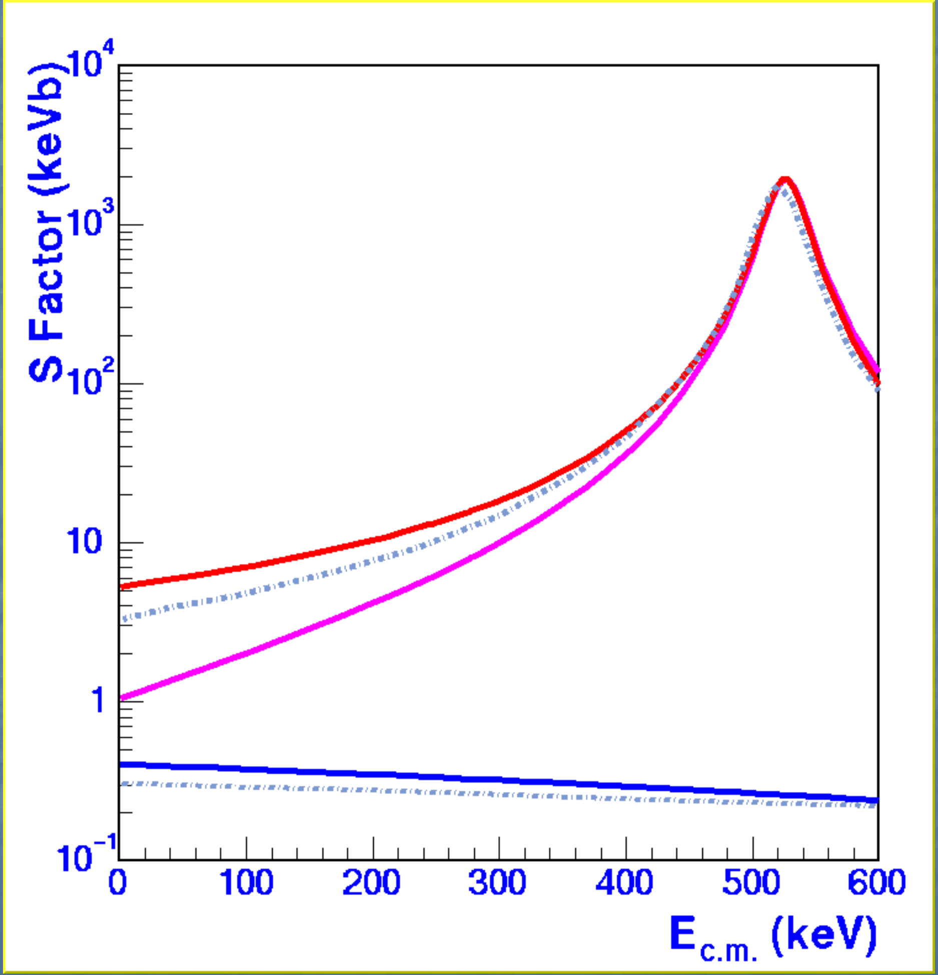


DWBA by FRESCO

$$\sigma_{\exp} = \left(C^{^{14}O}_{^{13}N\,1\frac{1}{2}}\right)^2 \left[\left(\frac{C^{^{14}N}_{^{13}C\,1\frac{3}{2}}}{b^{^{14}N}_{^{13}C\,1\frac{3}{2}}\, b^{^{14}O}_{^{13}N\,1\frac{1}{2}}}\right)^2 \sigma^{DW}_{1\frac{1}{2}1\frac{3}{2}} + \left(\frac{C^{^{14}N}_{^{13}C\,1\frac{1}{2}}}{b^{^{14}N}_{^{13}C\,1\frac{1}{2}}\, b^{^{14}O}_{^{13}N\,1\frac{1}{2}}}\right)^2 \sigma^{DW}_{1\frac{1}{2}1\frac{1}{2}}\right]$$

$C^2 = 29.0 \pm 4.3$ fm^{-1}

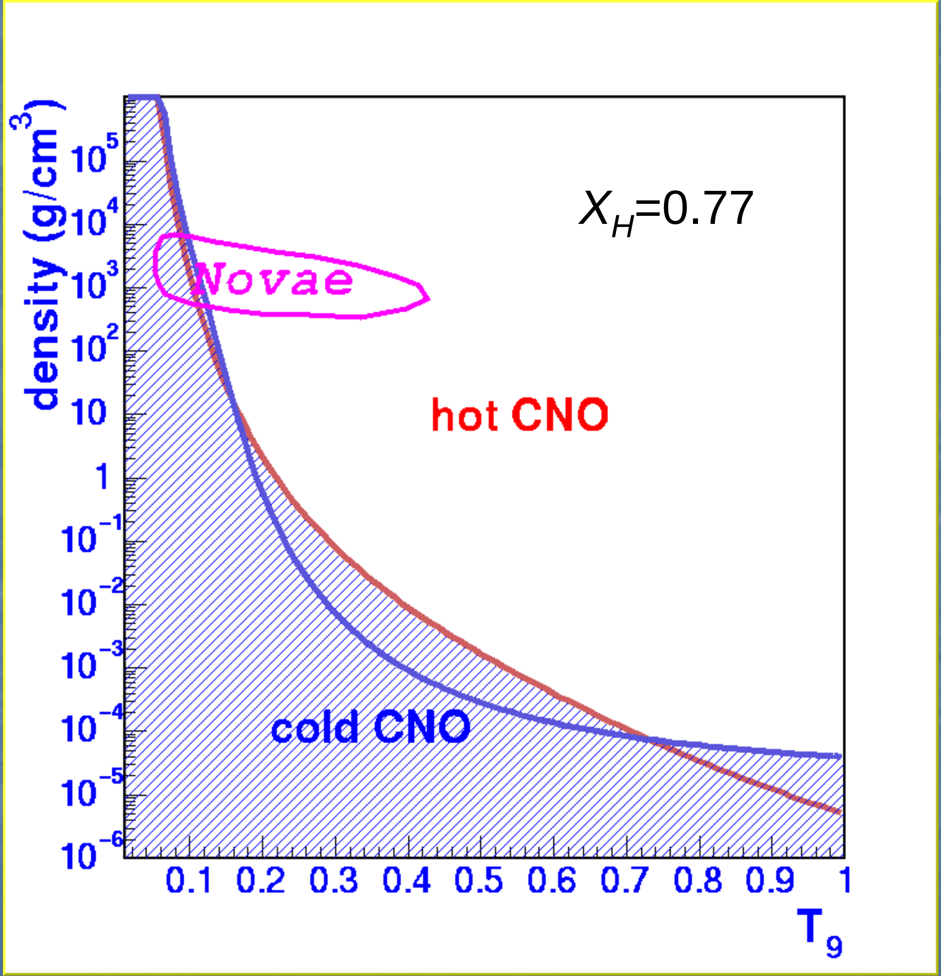
S Factor for $^{13}N(p,\gamma)^{14}O$



For Gamow peak at T_9=0.1,

- DC/Decrock_dc = 1.4
- Constructive/Decrock_tot =1.4
- Constructive/Destructive =4.0 (expected constructive interference for lower energy tail, useful to check)

Transition from CNO to HCNO



Crossover at $T_9 \approx 0.2$

- $^{13}N(p,\gamma)^{14}O$ vs β decay
- $^{14}N(p,\gamma)^{15}O$ vs β decay

For novae find that $^{14}N(p,\gamma)^{15}O$ slower than $^{13}N(p,\gamma)^{14}O$; $^{14}N(p,\gamma)^{15}O$ dictates energy production

Stellar Evolution:

what do we know?

A lot,
but still much to learn!!