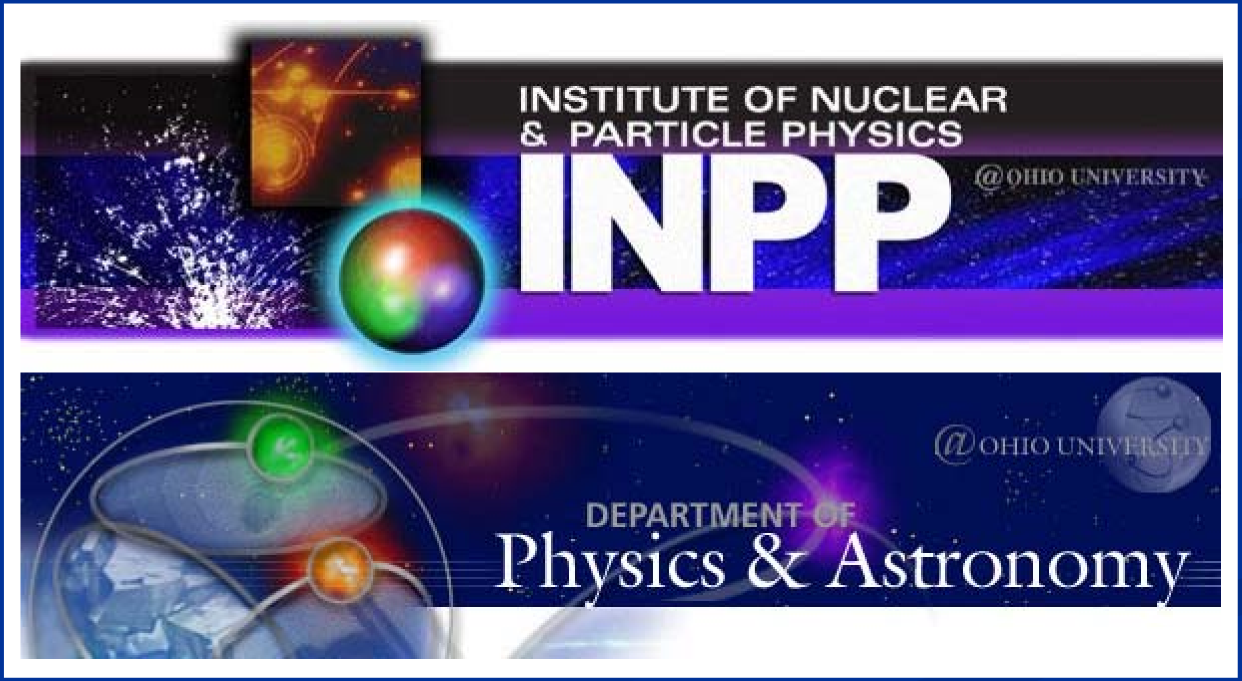
Nuclear Astrophysics - I

Carl Brune



Astrophysics and Cosmology

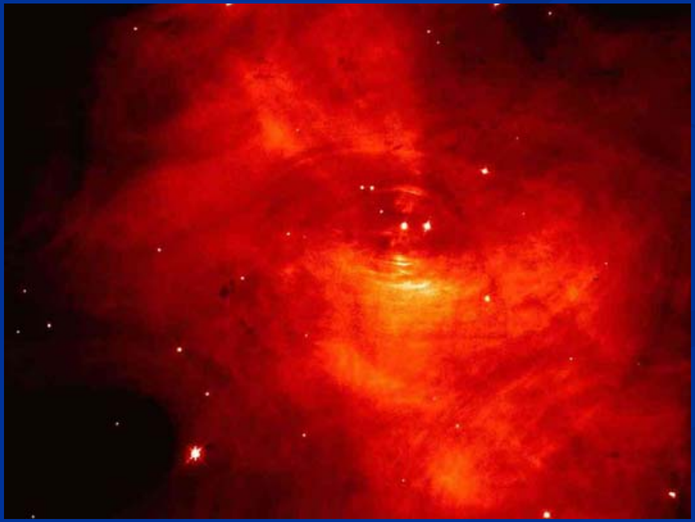
Observations

- Electromagnetic Spectrum: radio, microwave, IR, optical, UV, x-rays, γ-rays
- Neutrinos
- Cosmic Rays
- Meteorites
- Terrestrial Abundances
- Gravitational Waves

↔

Underlying Physics

- Atomic Physics
- Nuclear Physics
- Particle Physics
- Statistical Mechanics
- Hydrodynamics
- Gravity (General Relativity)
- …..



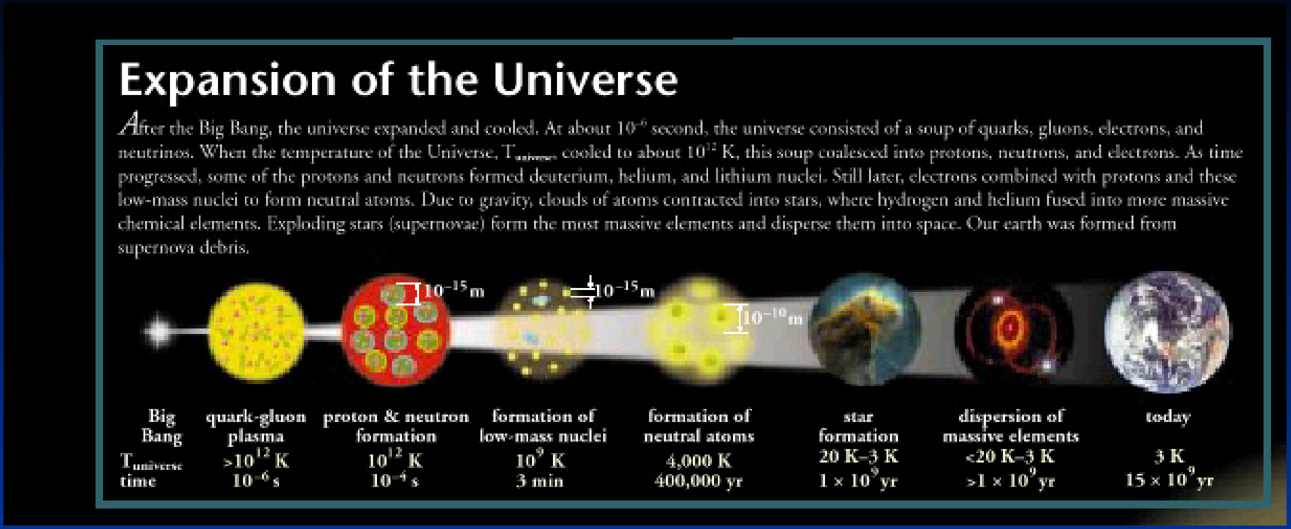
Nuclear Astrophysics

Nuclear Physics plays a very important role in astrophysics because:

- Nuclear reactions can provide a tremendous amount of energy e.g. $^{3}He + ^{3}He \rightarrow 2p + ^{4}He + 13\ MeV$
- Nuclei are created and destroyed via nuclear reactions (aka nucleosynthesis)

Scenarios include:

- Stellar processes
- Big Bang
- Cosmic-ray induced processes
- …

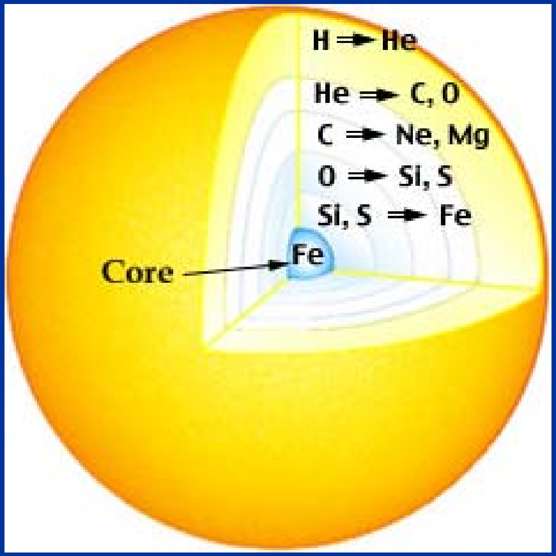


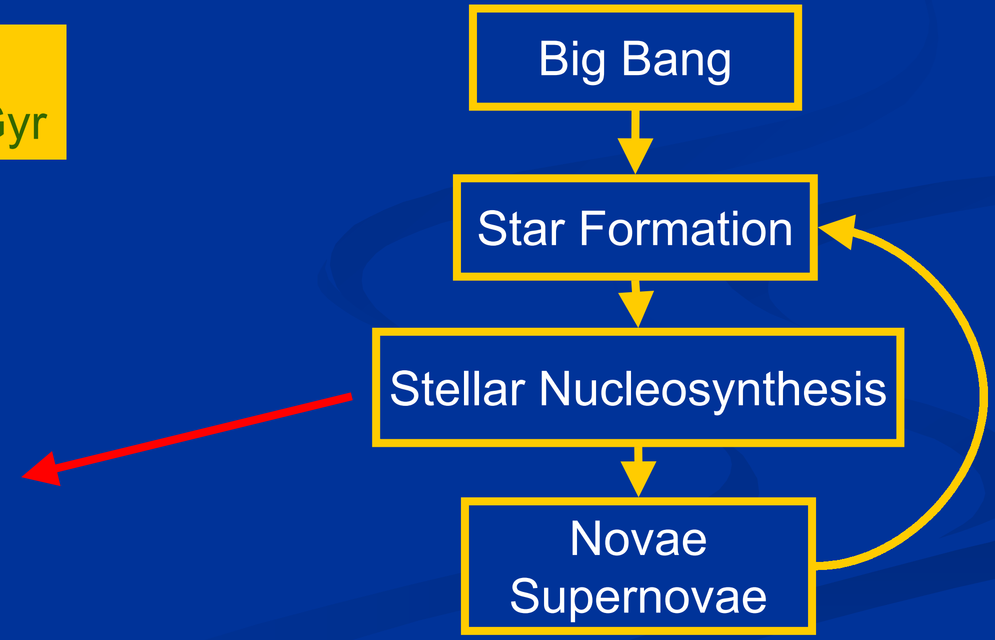
Expansion of the Universe

After the Big Bang, the universe expanded and cooled. At about 10^{-6} second, the universe consisted of a soup of quarks, gluons, electrons, and neutrinos. When the temperature of the Universe, $T_{universe}$, cooled to about 10^{12} K, this soup coalesced into protons, neutrons, and electrons. As time progressed, some of the protons and neutrons formed deuterium, helium, and lithium nuclei. Still later, electrons combined with protons and these low-mass nuclei to form neutral atoms. Due to gravity, clouds of atoms contracted into stars, where hydrogen and helium fused into more massive chemical elements. Exploding stars (supernovae) form the most massive elements and disperse them into space. Our earth was formed from supernova debris.

Big Bang	quark-gluon plasma	proton & neutron formation	formation of low-mass nuclei	formation of neutral atoms	star formation	dispersion of massive elements	today
$T_{universe}$	$>10^{12}$ K	10^{12} K	10^{9} K	4,000 K	20 K–3 K	<20 K–3 K	3 K
time	10^{-6} s	10^{-4} s	3 min	400,000 yr	1×10^{9} yr	$>1 \times 10^{9}$ yr	15×10^{9} yr

- Age of Universe: 13.7 Gyr
- Age of Solar System: 4.5 Gyr





Big Bang

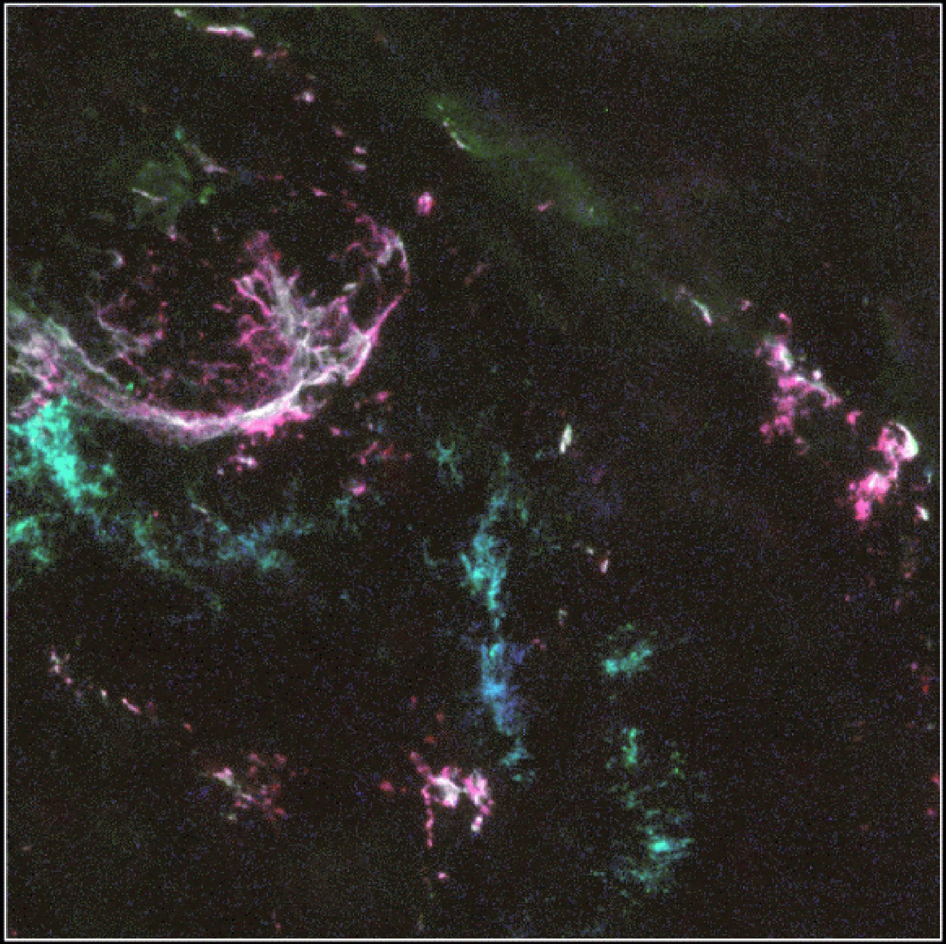
Star Formation

Stellar Nucleosynthesis

Novae Supernovae

Supernova Remnant N132D

- Exploded 3,000 years ago
- 169,000 light-years away
- Blue: O^{+}
- Green: O^{2+}
- Pink: S^{+}



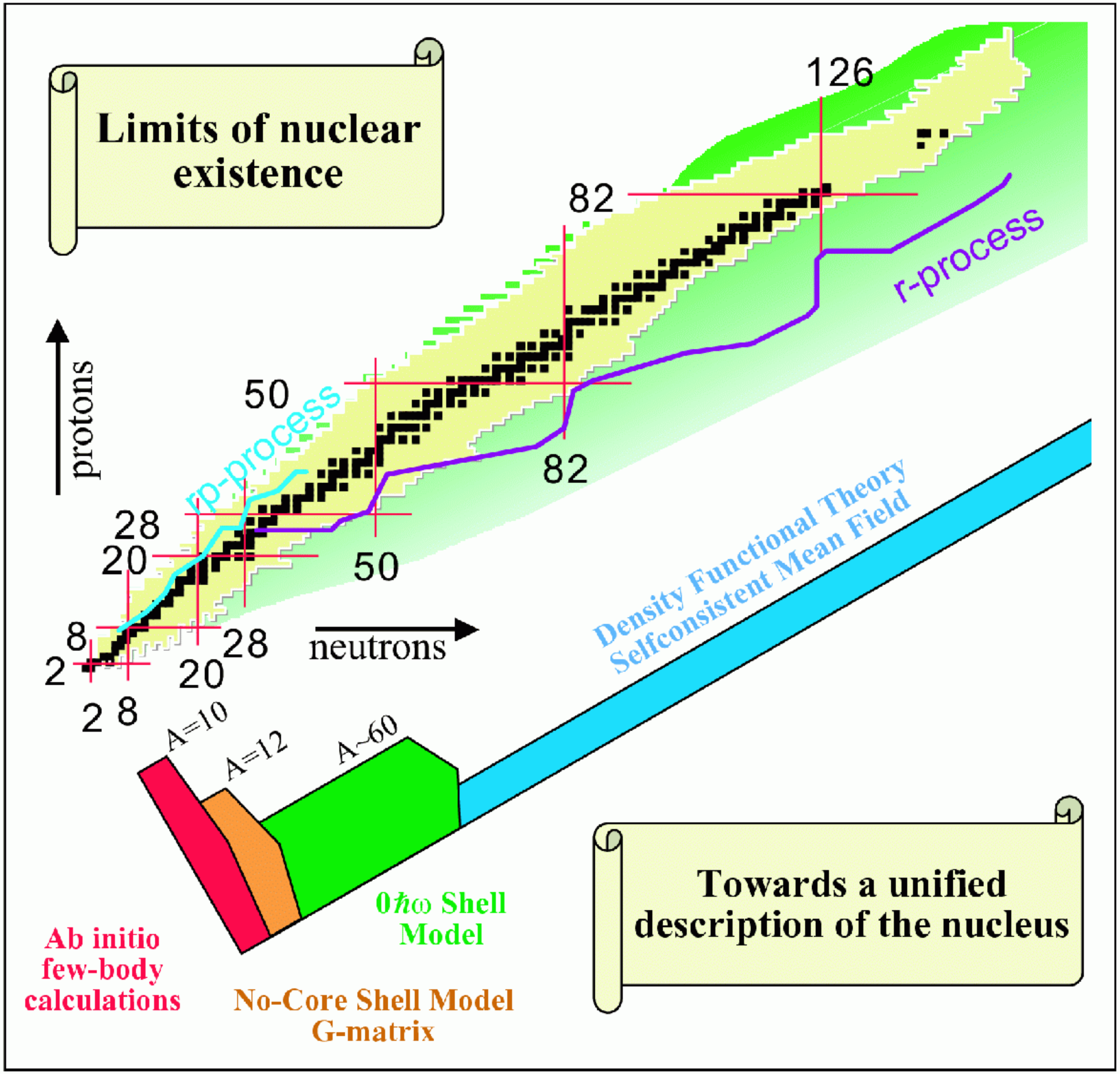
N132D HST • WFPC2

SN Remnant in LMC

PF95-13 • ST ScI OPO • April 10, 1995 • J. Morse (ST ScI), NASA

"Laundry List" of Processes

Big Bang Nucleosynthesis	Light Elements ($A<10$)
Hydrogen Burning	Main sequence of stellar evolution ($A<60$)
Helium Burning	Red giants ($A<60$, especially ^{12}C and ^{16}O)
"Heavy Ion" Burning	Late stages of massive star evolution (terminates at Fe)
S Process	"Slow" neutron capture ($A>60$)
R Process	"Rapid" neutron capture ($A>60$)
RP Process	Rapid proton capture: novae and x-ray bursters
γ Process	Photodisintegration
Cosmic-Ray Spallation	Li and Be
ν–induced reactions	?
Neutron Stars	R-Process site?

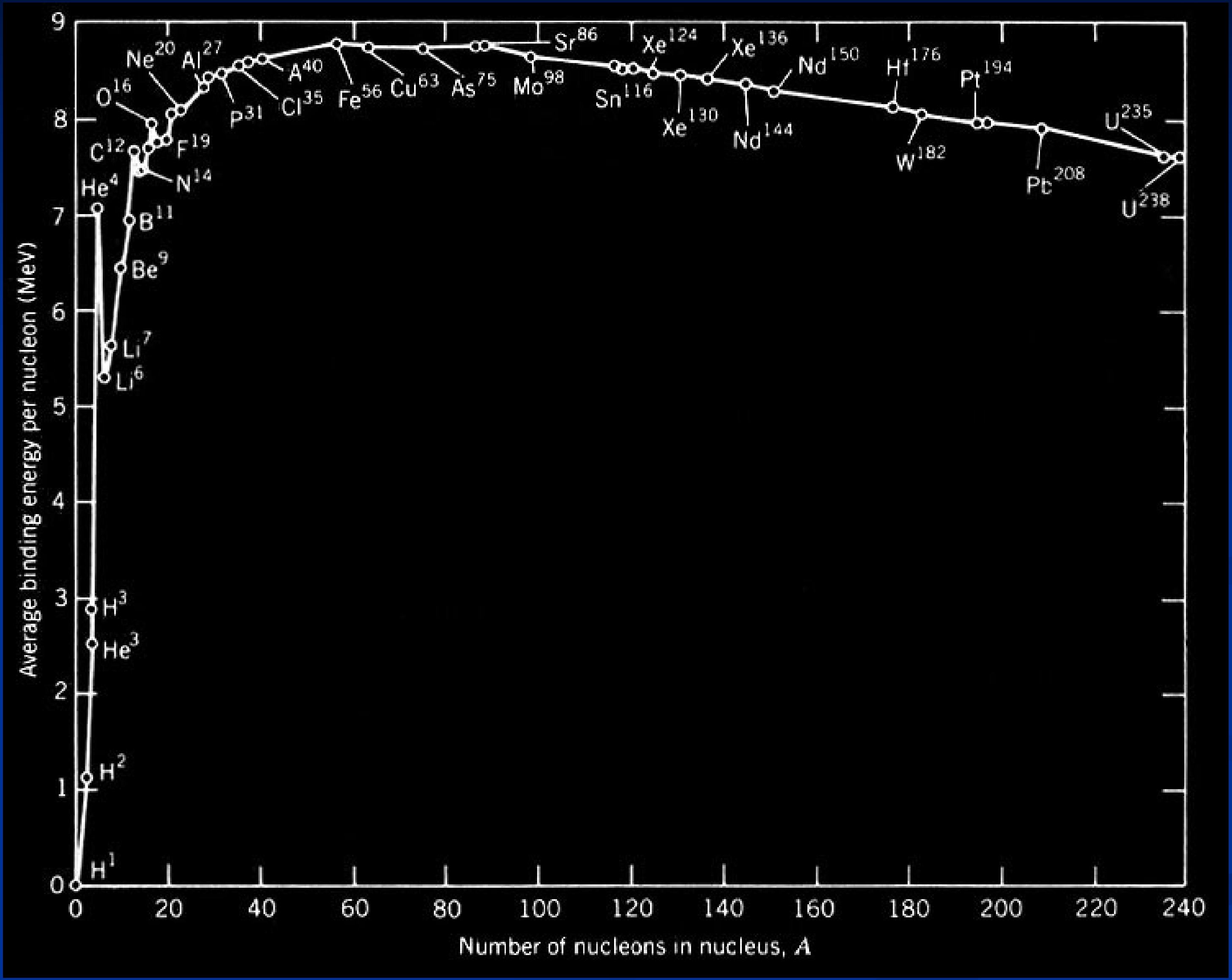


Limits of nuclear existence

Towards a unified description of the nucleus

Nuclear Binding Energies

Binding energy per nucleon



Number of nucleons in nucleus

What is the needed Nuclear Physics?

- Nuclear masses, Q values
- Half lives, decay modes
- Resonance energies, partial widths →
- Reaction cross sections

Breit-Wigner Formula

$$\sigma(E) = \frac{2J+1}{(2J_1+1)(2J_2+1)} \frac{\pi}{k^2} \frac{\Gamma_1 \Gamma_3}{(E-E_R)^2 + \Gamma^2/4}$$

Reaction Rate Formalism:
T = temperature
k = Boltzmann constant

consider the process: $1 + 2 \rightarrow 3 + 4$

where n_i = number density of species i

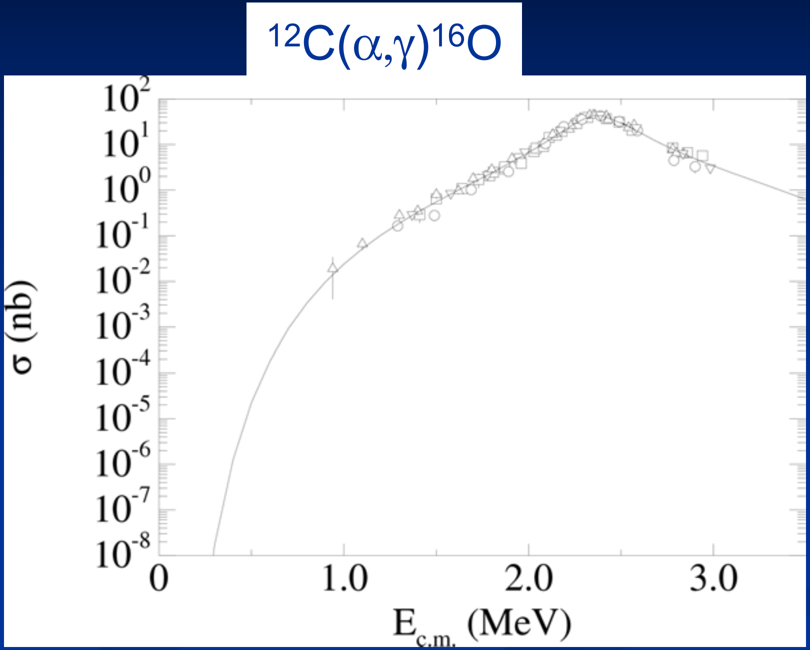
$$\begin{aligned} \frac{\mathrm{d}n_3}{\mathrm{d}t} &= n_1 n_2 \langle \sigma v \rangle \\ \langle \sigma v \rangle &= \sqrt{\frac{8}{\pi \mu}} (kT)^{-3/2} \int_0^\infty E\, \sigma(E)\, \exp(-E/kT)\, \mathrm{d}E \end{aligned}$$

More Nuclear Physics

Charged Particles

Coulomb barrier:
S = “astrophysical S factor”

$$\sigma = \frac{S}{E}\exp\left(-\sqrt{\frac{E_G}{E}}\right)$$



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

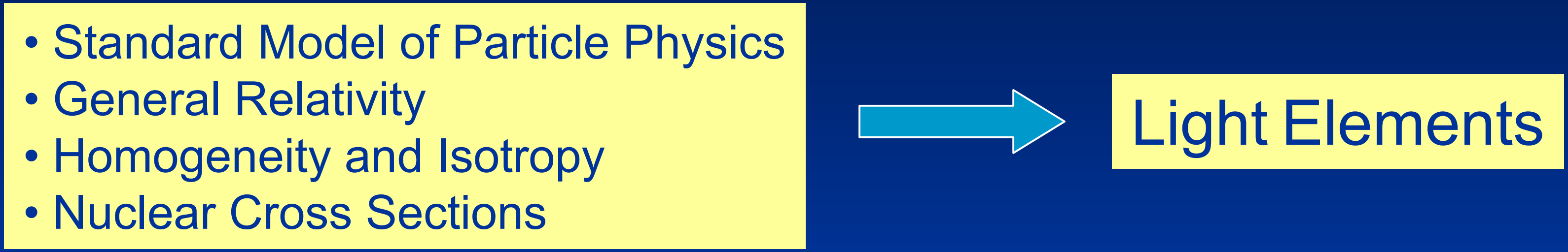
Neutron-induced Reactions

No Coulomb barrier
$\sigma \sim E^{-1/2}$

Statistical Reactions (A>60)

- Reaction rate determined by many resonances
- Rates can be computed using statistical methods
- Requires systematic information: level densities, optical potentials,…

Big Bang Nucleosynthesis



- Standard Model of Particle Physics
- General Relativity
- Homogeneity and Isotropy
- Nuclear Cross Sections

Light Elements

single free parameter: Baryon Density
(or 0 = baryon-to-photon ratio)

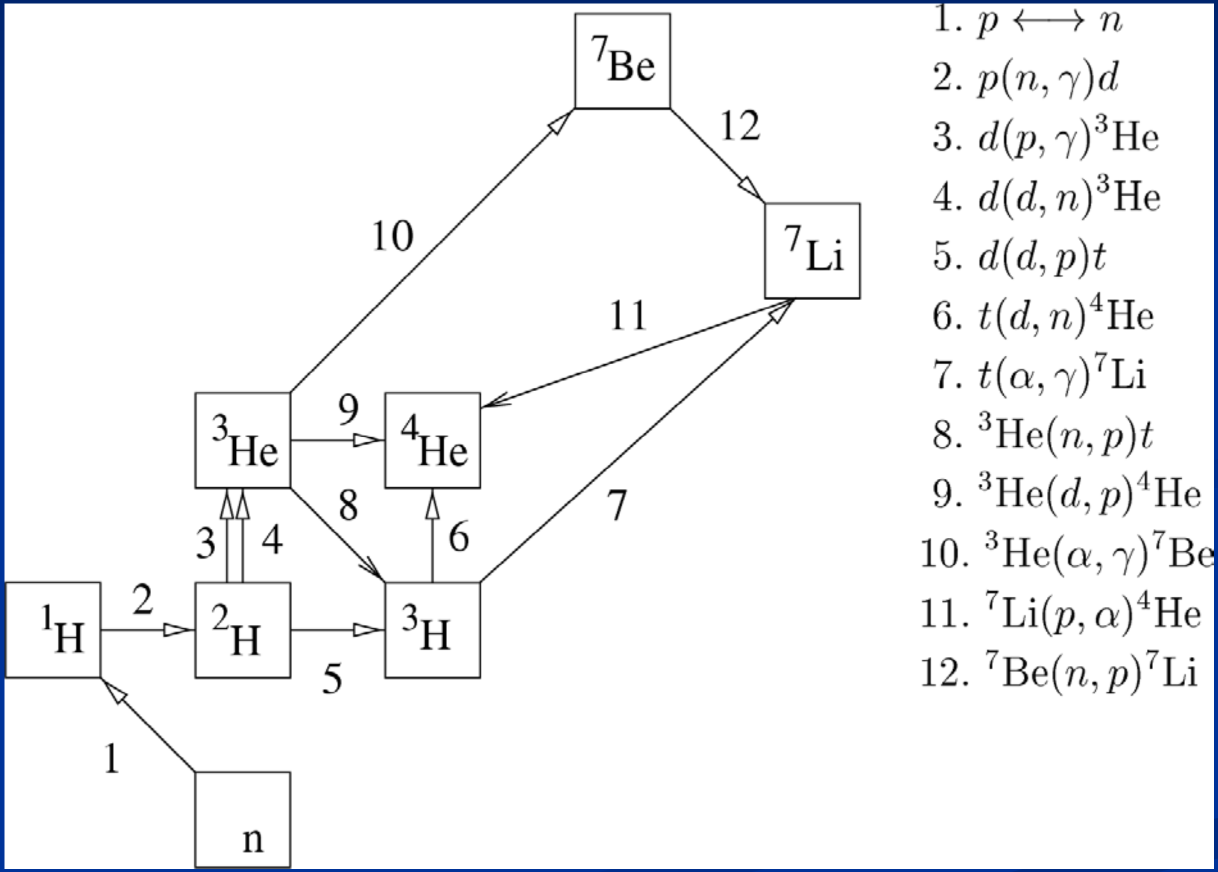
Goals:

- Determine 0
- Compare to astronomical observations
- Test physics input, e.g.
  - 3 neutrino generations
  - phase transitions?

Nuclear Physics

- 11 cross sections
- neutron lifetime
- E ~ 100 keV

Measure in the lab!

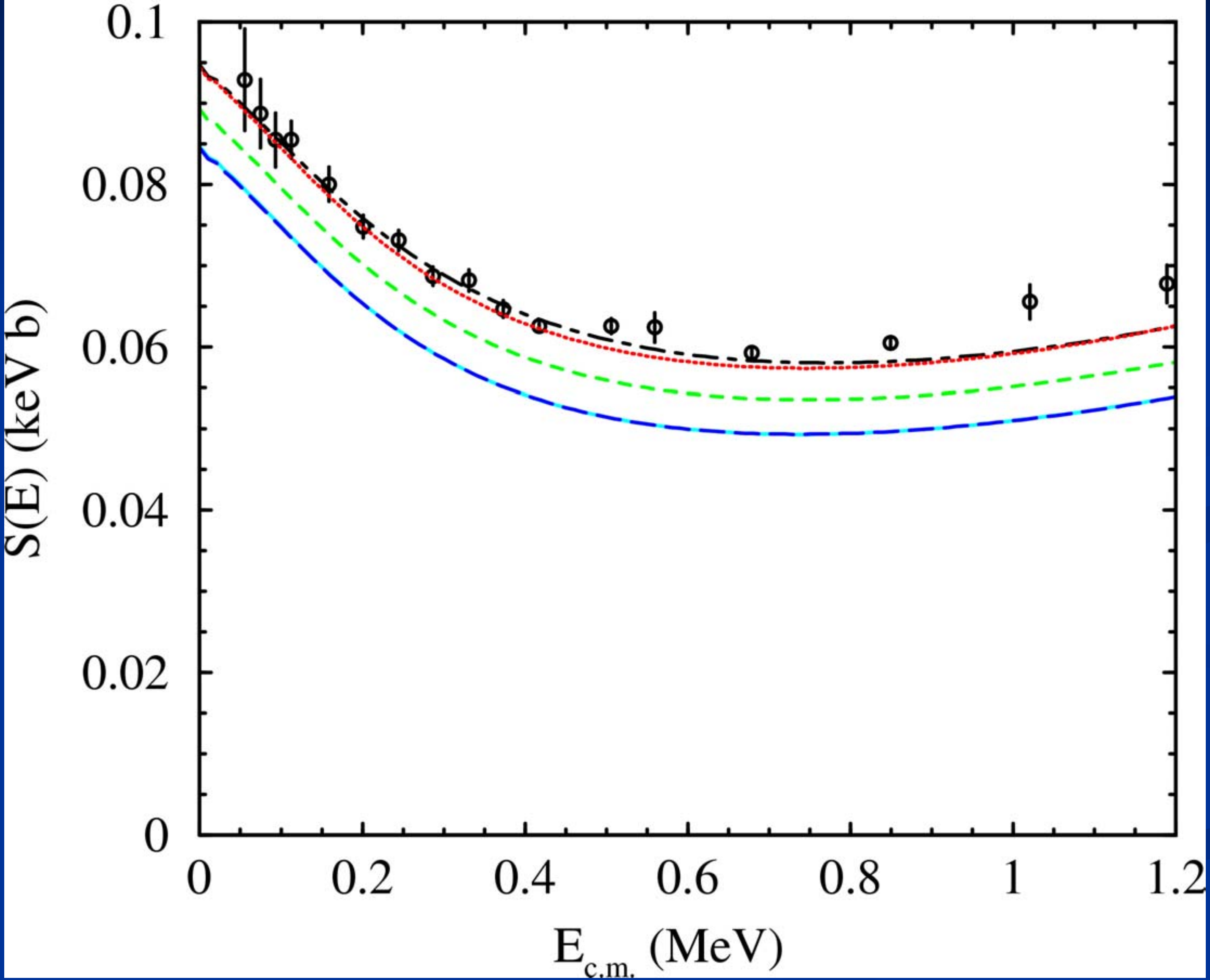


1. $p \longleftrightarrow n$
2. $p(n,\gamma)d$
3. $d(p,\gamma)^3\mathrm{He}$
4. $d(d,n)^3\mathrm{He}$
5. $d(d,p)t$
6. $t(d,n)^4\mathrm{He}$
7. $t(\alpha,\gamma)^7\mathrm{Li}$
8. $^3\mathrm{He}(n,p)t$
9. $^3\mathrm{He}(d,p)^4\mathrm{He}$
10. $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$
11. $^7\mathrm{Li}(p,\alpha)^4\mathrm{He}$
12. $^7\mathrm{Be}(n,p)^7\mathrm{Li}$

Inverse reactions also included

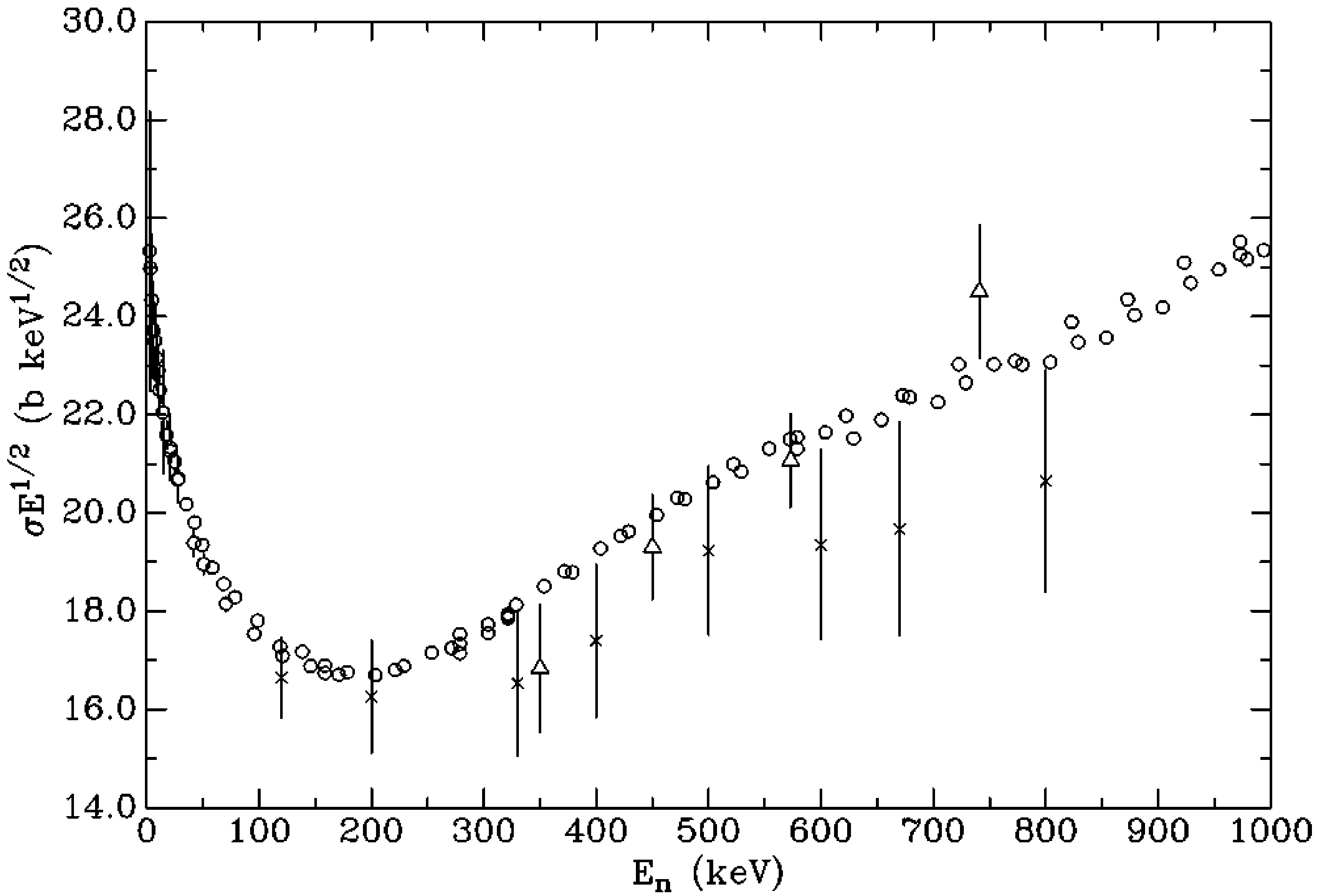
$^3H(\alpha,\gamma)^7Li$

calculation: K.M. Nollett



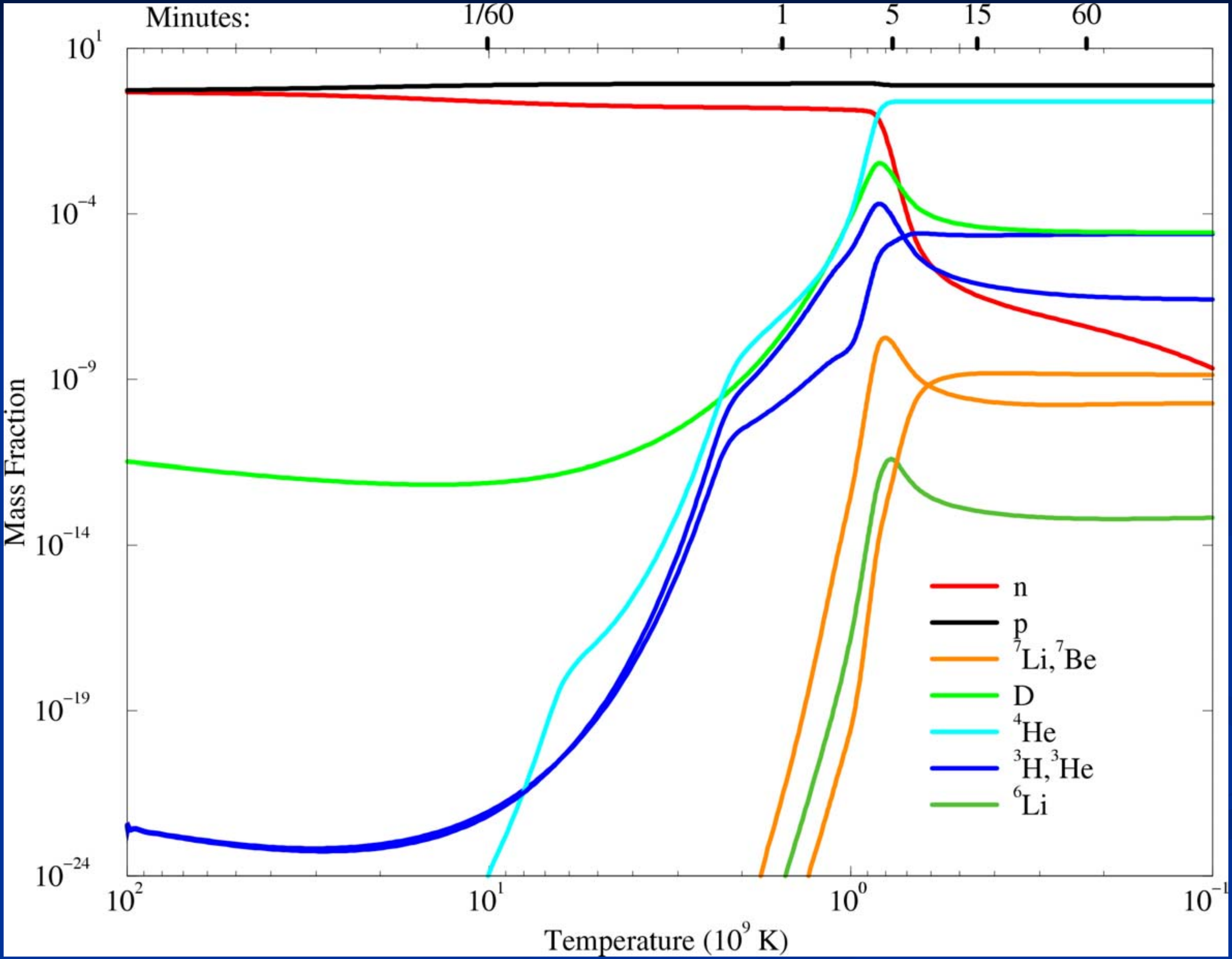
data: CRB PhD Thesis

$^3He(n,p)^3H$



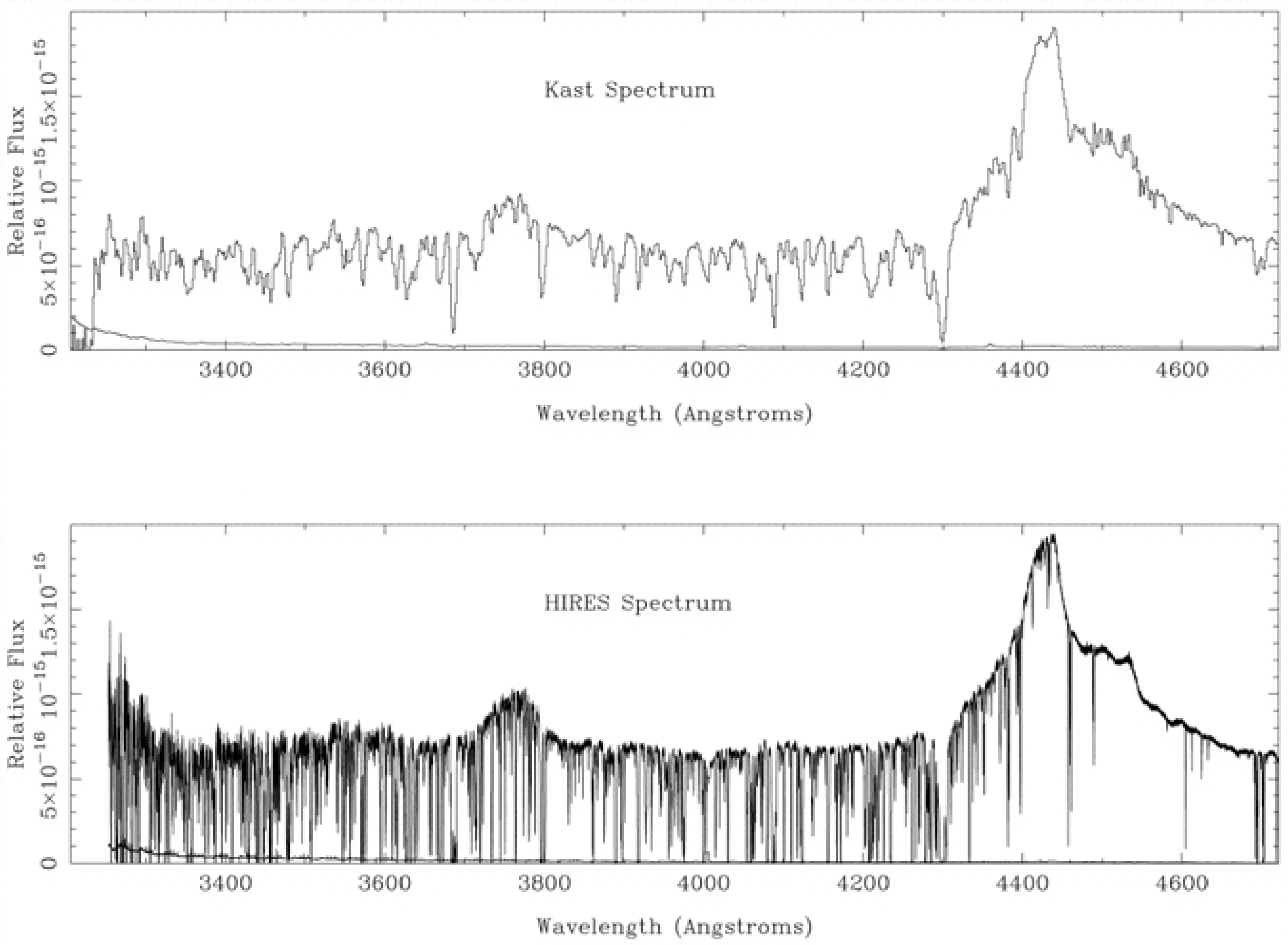
Data: CRB et al. (1999)

Evolution of the Elements



Observing ^{2}H with QSOs

HS 0105+1659



Older data

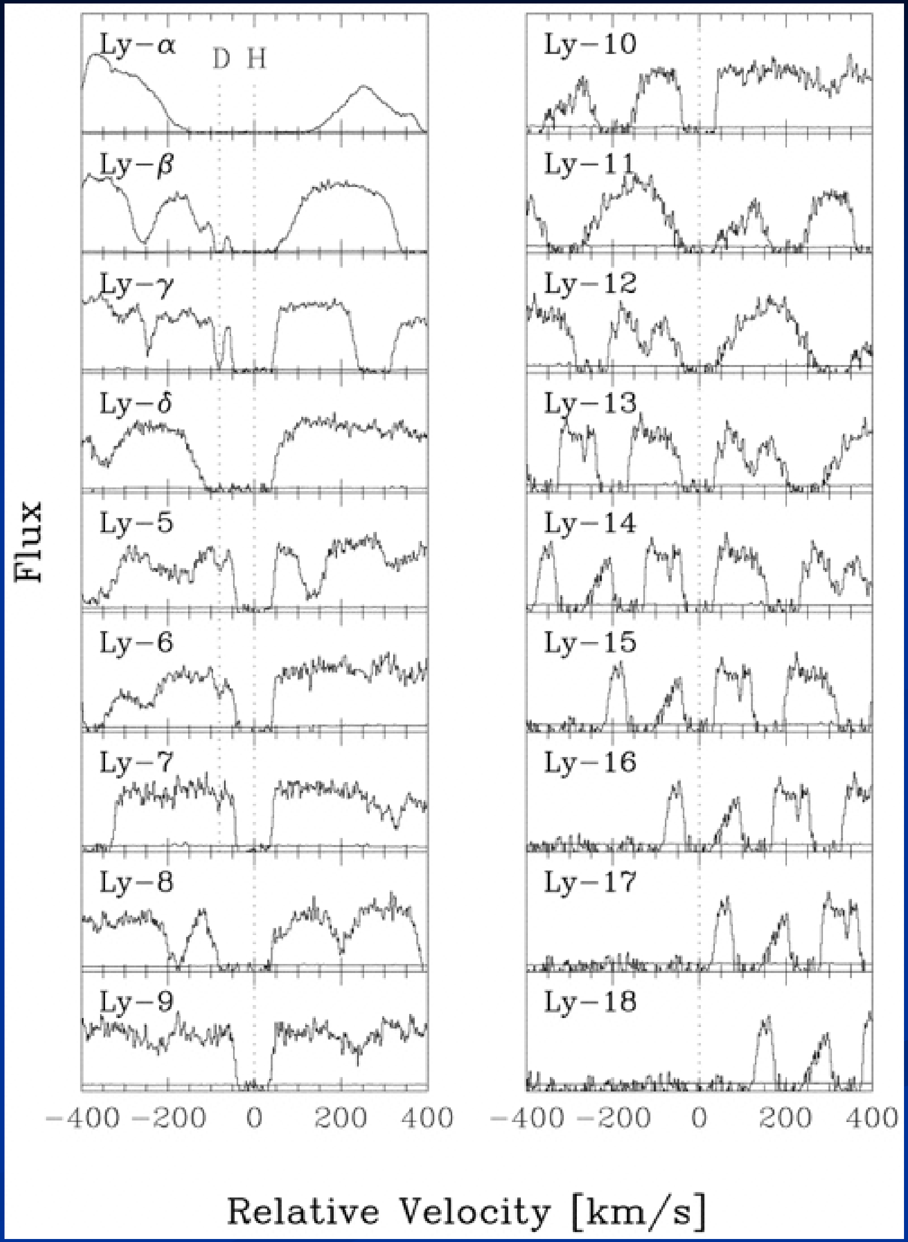
Keck Data

D/H can be extracted:

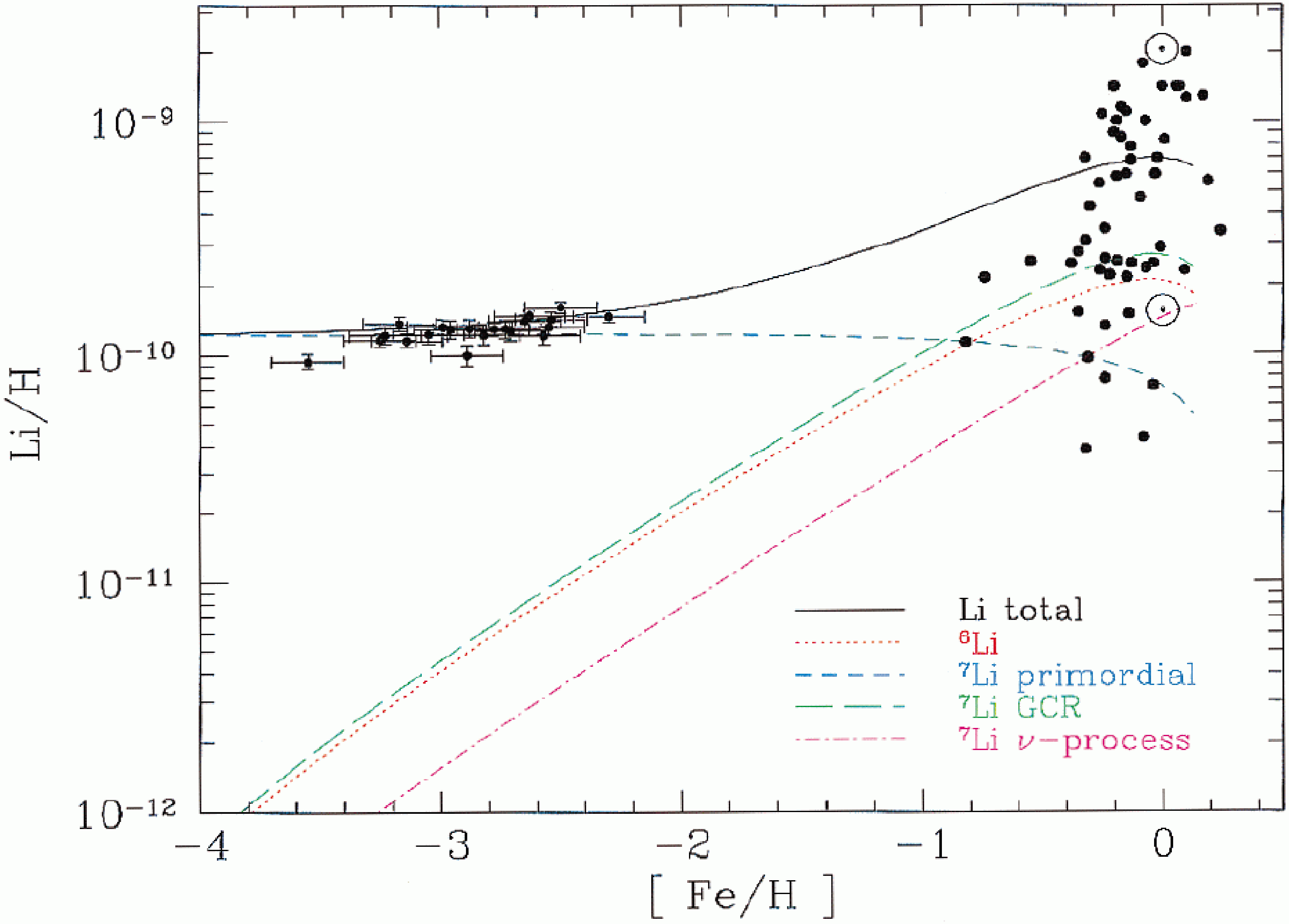
QSO	$\log_{10} D/H$
PKS 1937-1009	-4.49(4)
Q1009+2956	-4.40(7)
Q0130-4021	< -4.17
HS 0105+1619	-4.60(4)

It would appear that we know the primordial Deuterium abundance within ~5%!

HS 0105+1619



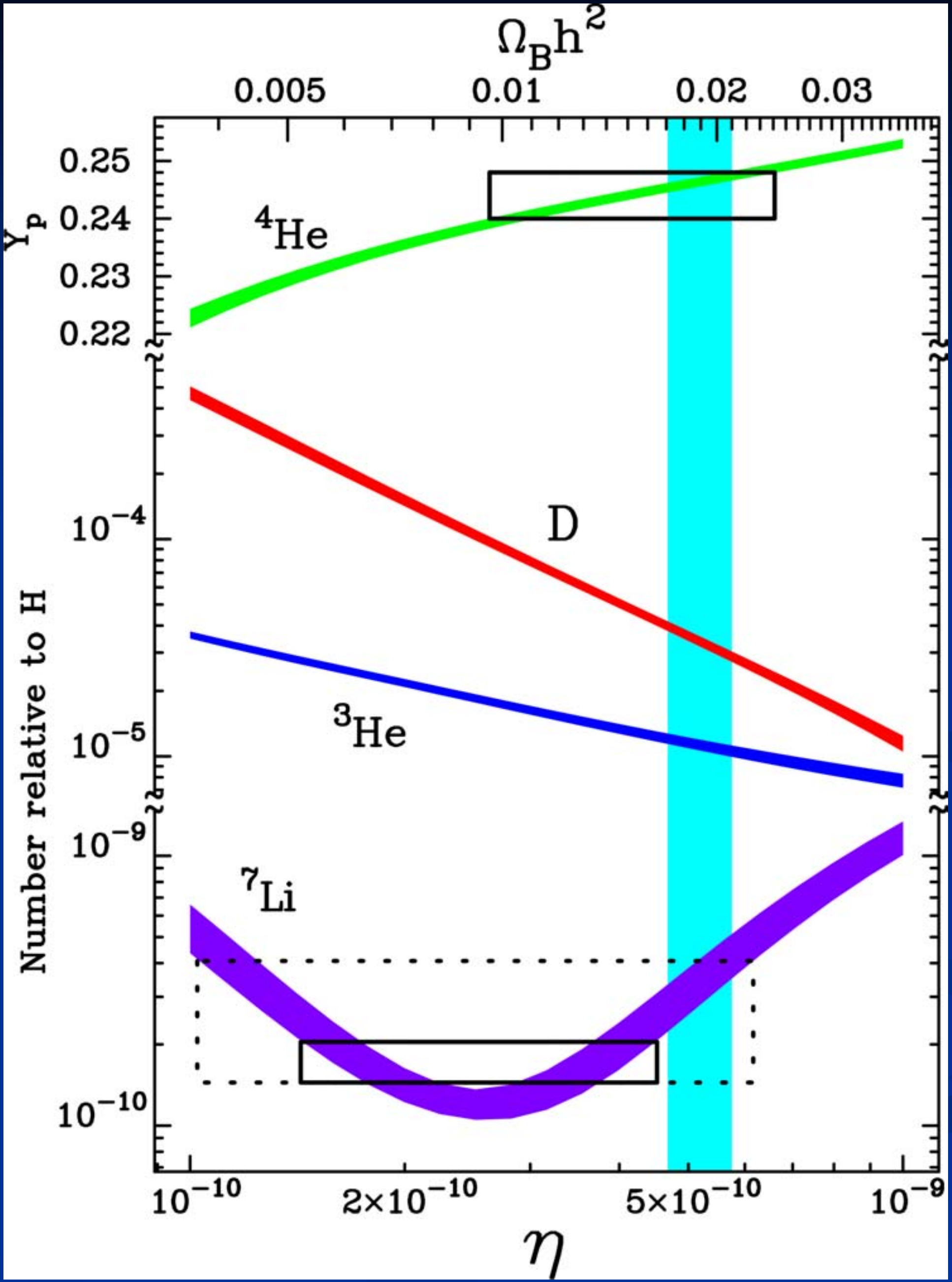
Lithium Observations



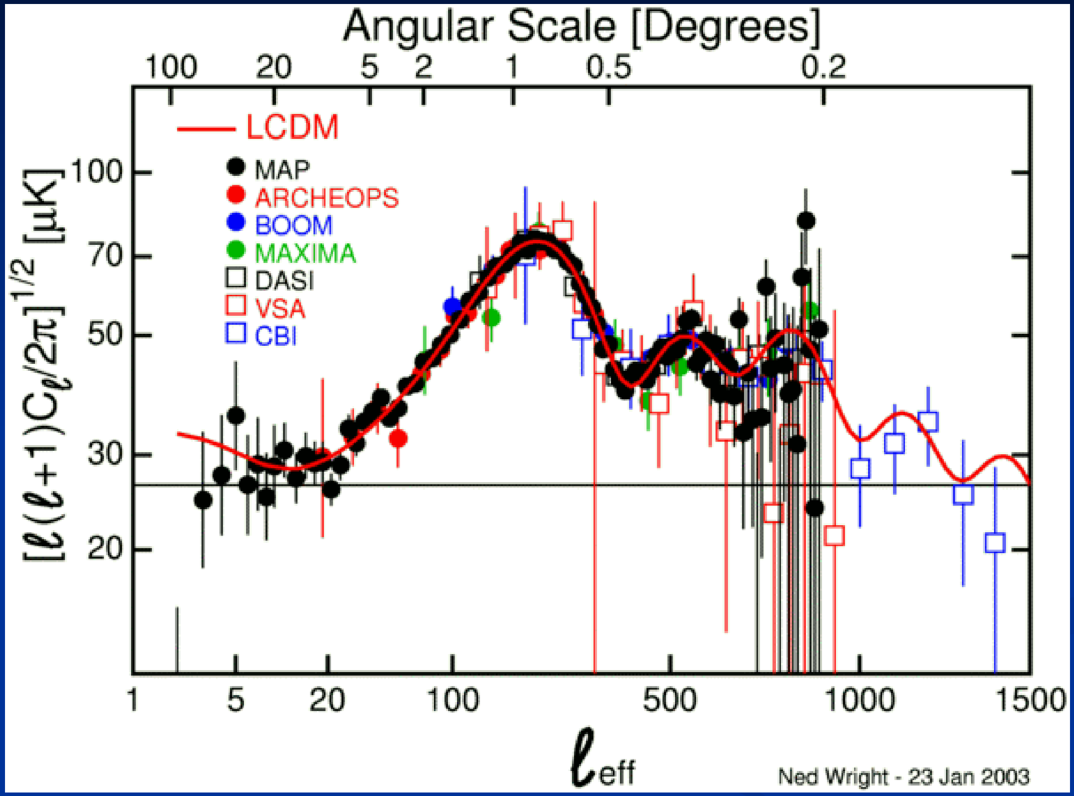
We have observations for D, ^{3}He, ^{4}He, and ^{7}Li which are thought to represent primordial abundances.

Big Bang Nucleosynthesis:
0 = 5.1(6) x 10^{-10}

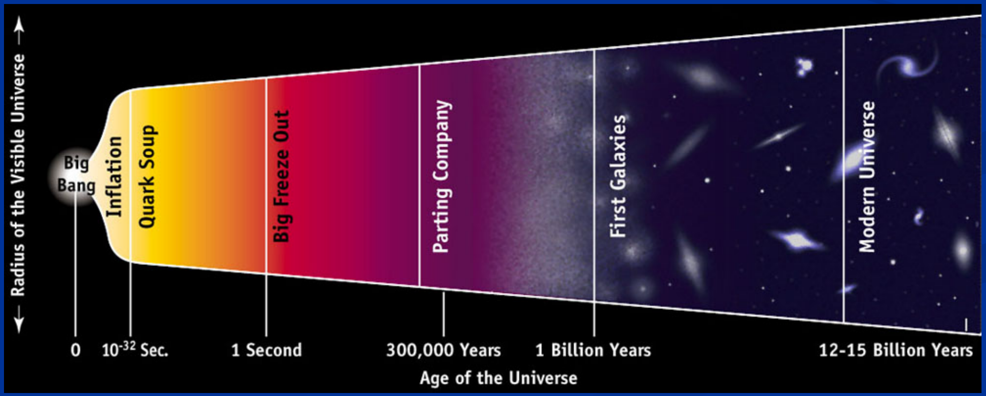
The lithium data are not in good agreement.



Cosmic Microwave Background



Ned Wright - 23 Jan 2003



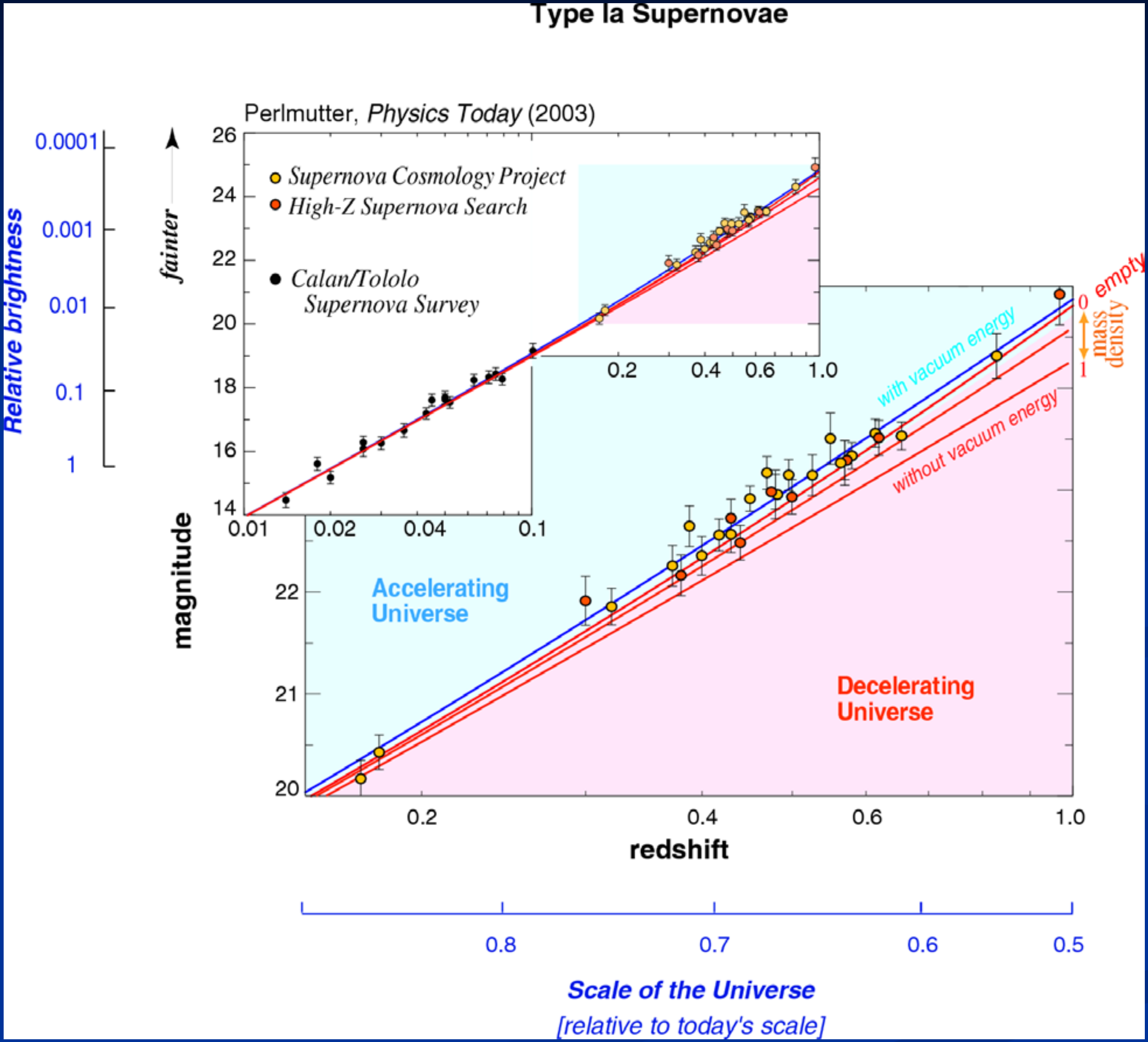
Cosmic Microwave Background: Inferences

WMAP Year 1 (Bennett et al.)

quantity	value
S_{tot} (total density)	1.02(2)
S_7 (dark energy density)	0.73(4)
S_m (matter density)	0.27(4)
S_b (baryon density)	0.044(4)
t_0 (age of universe)	13.7(2) Gyr
Θ (baryon-to-photon ratio)	$6.1(3) \times 10^{-10}$

↕ Consistent (sort of…)

Big Bang Nucleosynthesis: $\Theta = 5.1(6) \times 10^{-10}$



$S_m + S_7 = 1$

$S_7 \sim 0.75$

Present Status of BBN

- Exciting new developments in observations of the CMB, light elements, and distant supernovae. New CMB data, including polarization, are coming soon from WMAP.
- Agreement is reasonable but not perfect. Lithium?
- From a nuclear physics point of view the field is mature, but higher-accuracy data are needed.
- Recently completed or ongoing measurements:
  - $p(n,(\ )d$
  - $d(d,p)t$ and $d(d,n)^3\mathrm{He}$ - D.S. Leonard et al. (UNC/TUNL)
  - $^3\mathrm{He}(^4\mathrm{He},(\ )^7\mathrm{Be}$

Classical Novae

- 2-3 / month in our Galaxy

- Binary star systems

- Mass transferred from less massive star (red giant) to white dwarf companion

- Hydrogen gas burns explosively with CNO nuclei → thermonuclear explosion

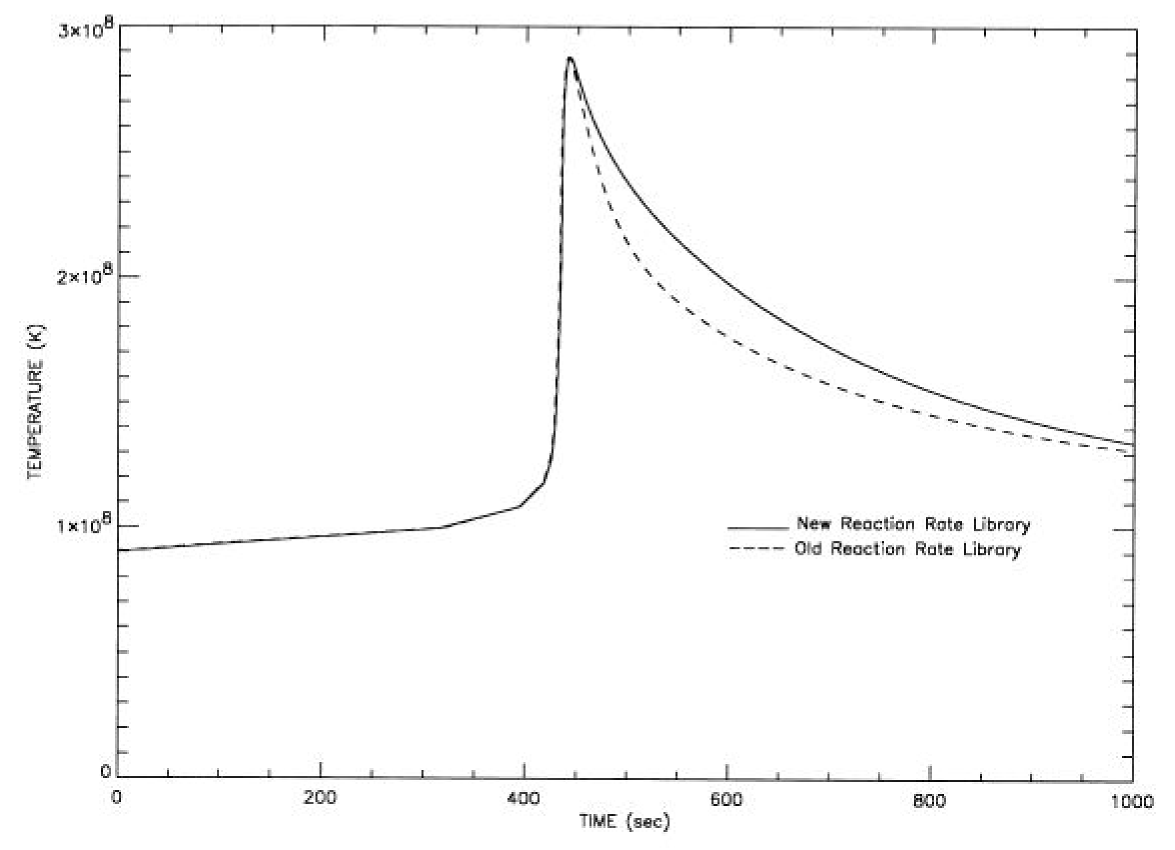
- Elements as heavy as calcium may be synthesized

- Primary target for gamma-ray telescopes (^{7}Be, ^{18}F, ^{22}Na, ^{26}Al)

Additional Features of Novae

- CO WDs: $X(^{12}C) : X(^{16}O) : X(^{20}Ne) = 5 : 5 : 0.1$
- ONe WDs: $X(^{16}O) : X(^{20}Ne) : X(^{24}Mg) = 10 : 6 : 1$
- Peak temperatures ~0.2-0.4 GK (~20 keV)
- 30 novae / yr, 10^{10} yr, 2×10^{-5} M_{sun} / outburst
- Barely contribute to overall Galactic abundances
- Important for individual nuclei (e.g. $^{17,18}O$)

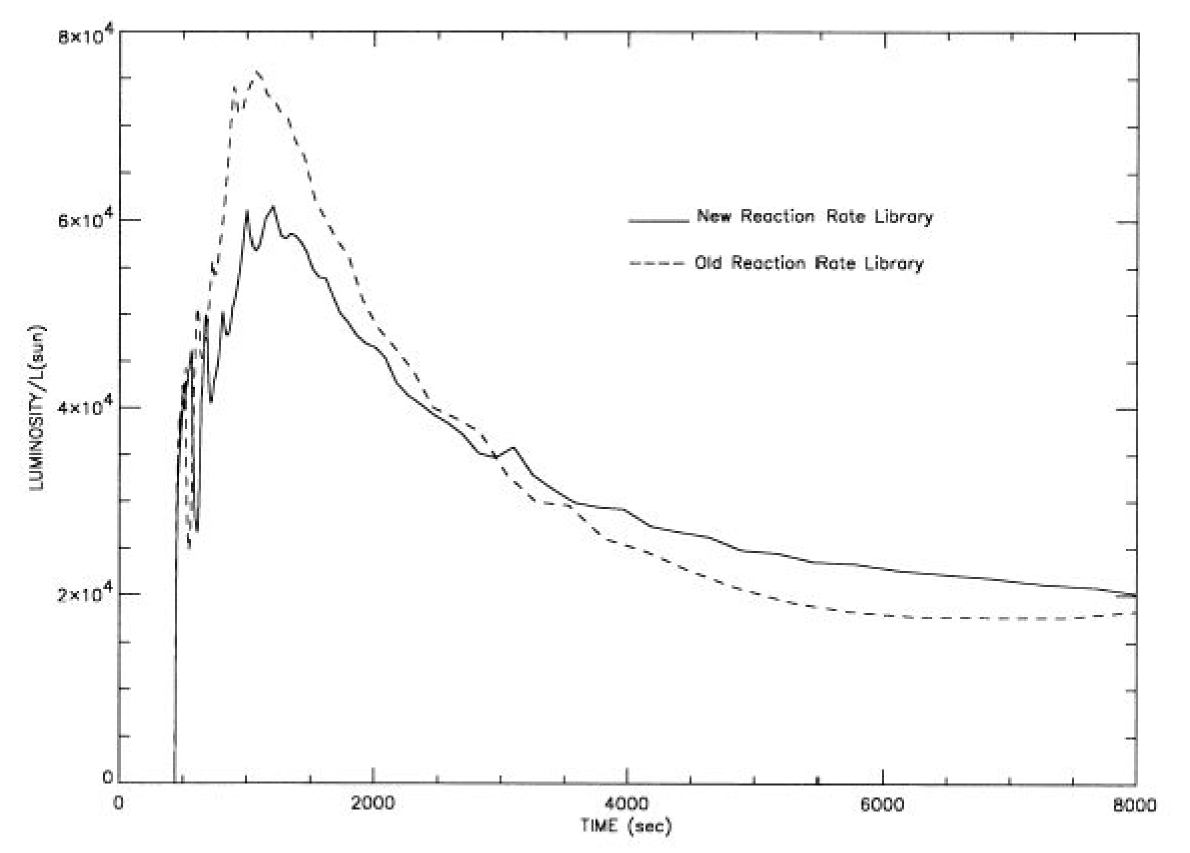
Time Evolution of Peak Temperature



V1974 Cygni

S. Starrfield et al.

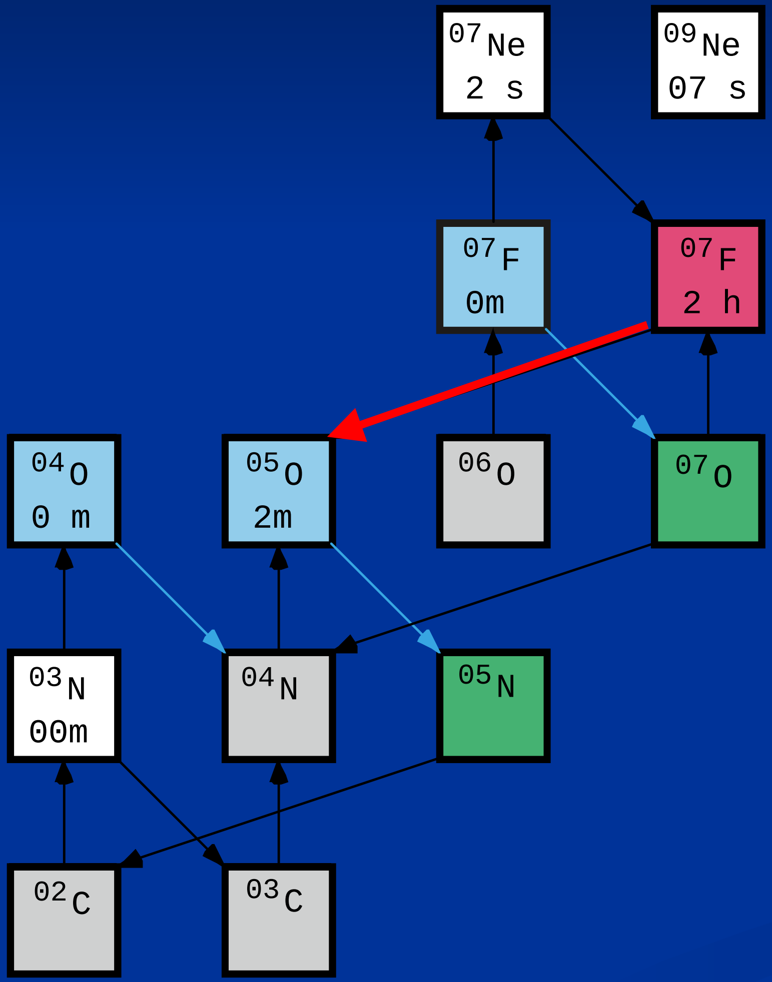
Time Evolution of Peak Luminosity



V1974 Cygni

S. Starrfield et al.

The Hot CNO Cycle



- Powers nova explosions
- Hydrogen → Helium
- Large uncertainties in some reactions

- **$^{17}\text{F}(p,\gamma)^{18}\text{Ne}$**

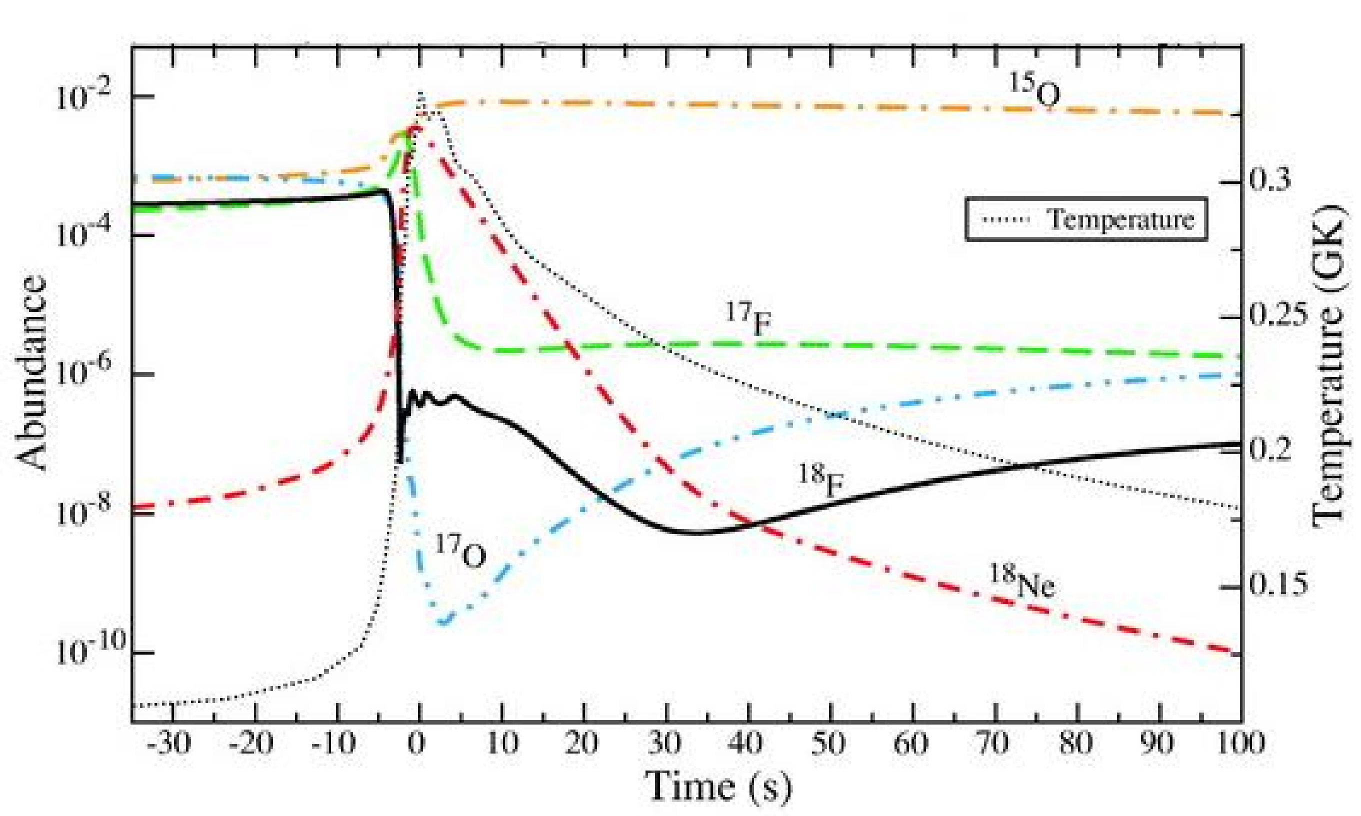
  ^{17}O, ^{18}F production

- **$^{18}\text{F}(p,\alpha)^{15}\text{O}$** and $^{18}\text{F}(p,\gamma)^{19}\text{Ne}$

  ^{15}N, ^{18}F production

  $^{17}\text{O}/^{18}\text{O}$ ratios

Time Evolution of Abundances



Iliadis et al.

Charged Particle Reactions A = 15 - 40

Key Features:

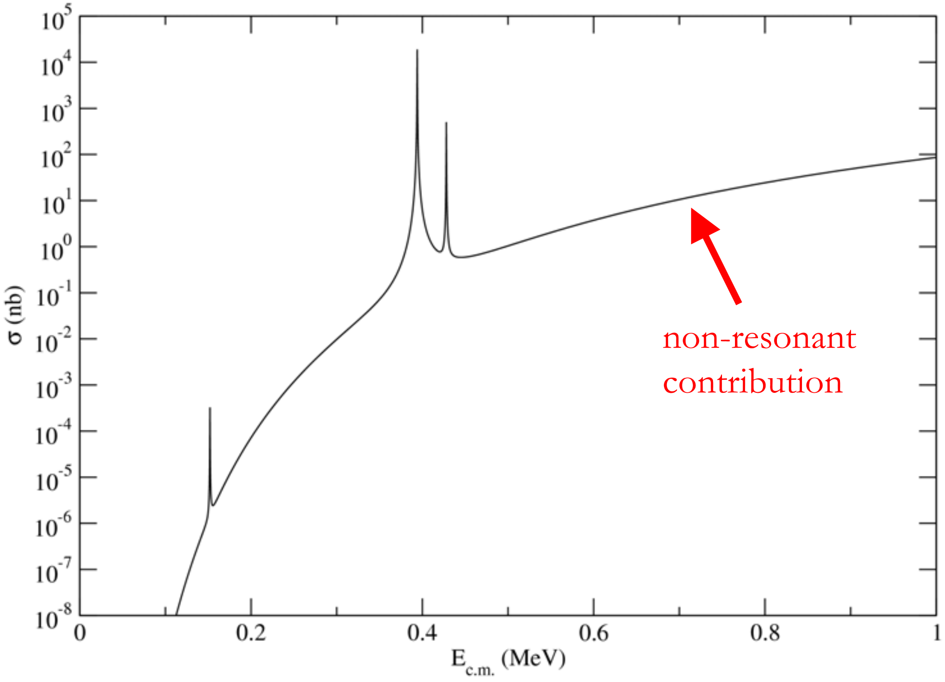
- Resonant contributions (usually dominant)
- Non-resonant contributions
- Coulomb barrier

Resonance Properties:

- Energy
- Partial Widths
- Spin and Parity

All properties are important!

Typical Cross Section



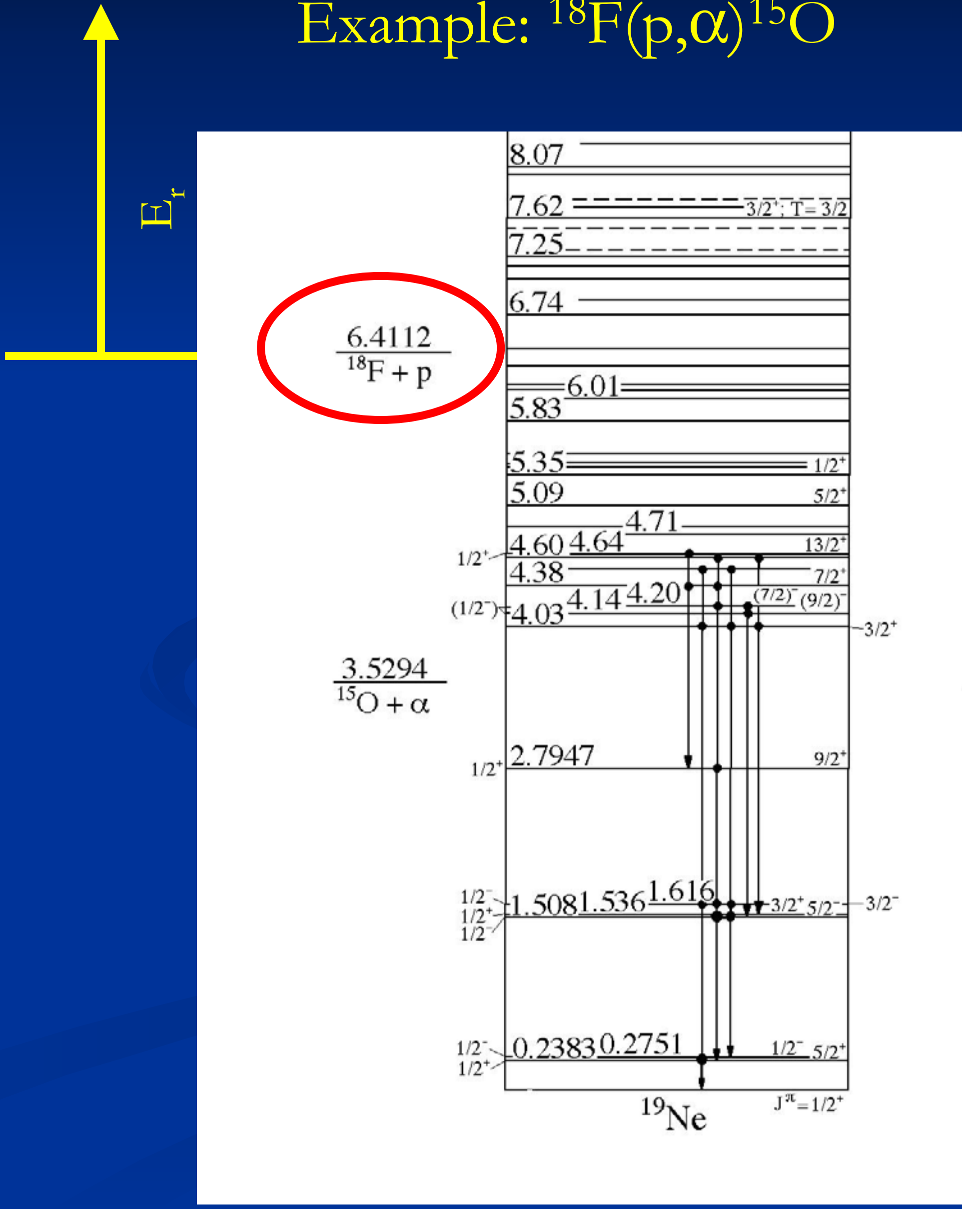
More on Resonances

Example: $^{18}F(p,\alpha)^{15}O$

For a narrow resonance:

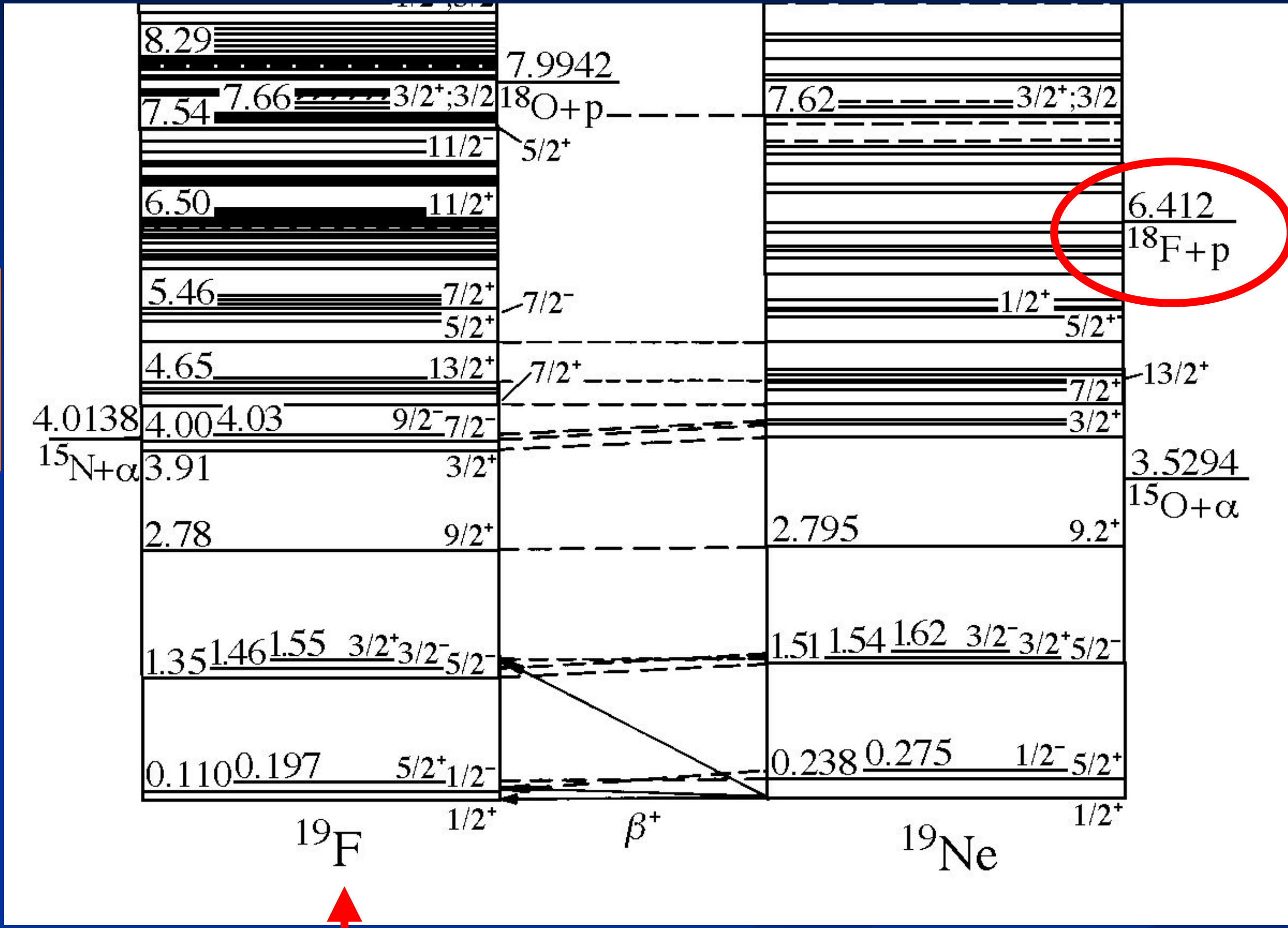
$<\sigma v>$ % (strength) $(kT)^{-3/2}\, e^{-Er/kT}$

- Need high precision for E_r (~few keV)
- Must rely on experiment
- Theoretical approaches are more helpful for the strength



Mirror Symmetry

- Predict resonance energies
- Estimate partial widths
- Isobaric Mass Multiplet Eq.



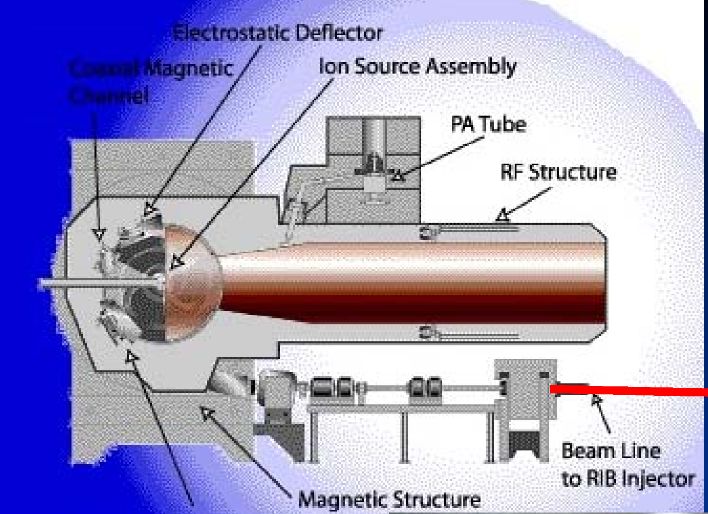
stable nucleus

Summary of Today's Lecture

- The Big Picture regarding Nuclear Astrophysics
- Big-Bang Nucleosynthesis
- Overview of Novae

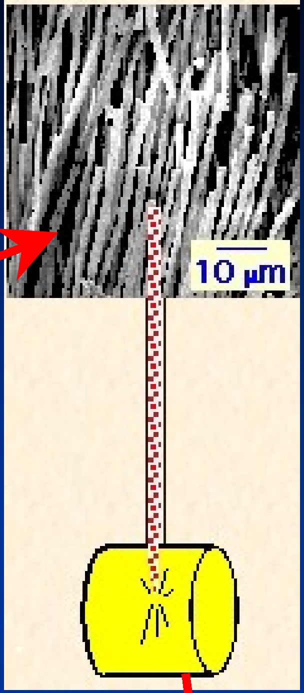
Next: experiments relevant to Novae

The Holifield RIB Facility at Oak Ridge National Lab



ORIC

p, d, or α



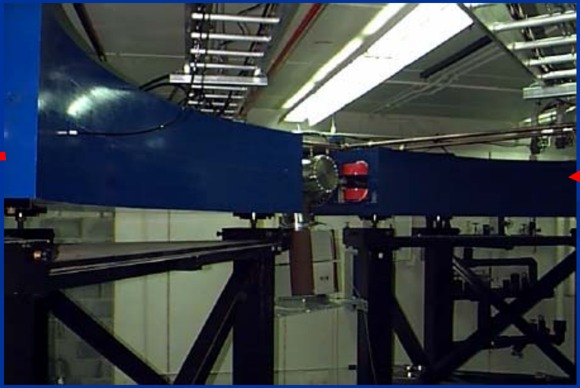
Hot, fibrous production target

Ion source

25 MV tandem

RIB (300 keV)

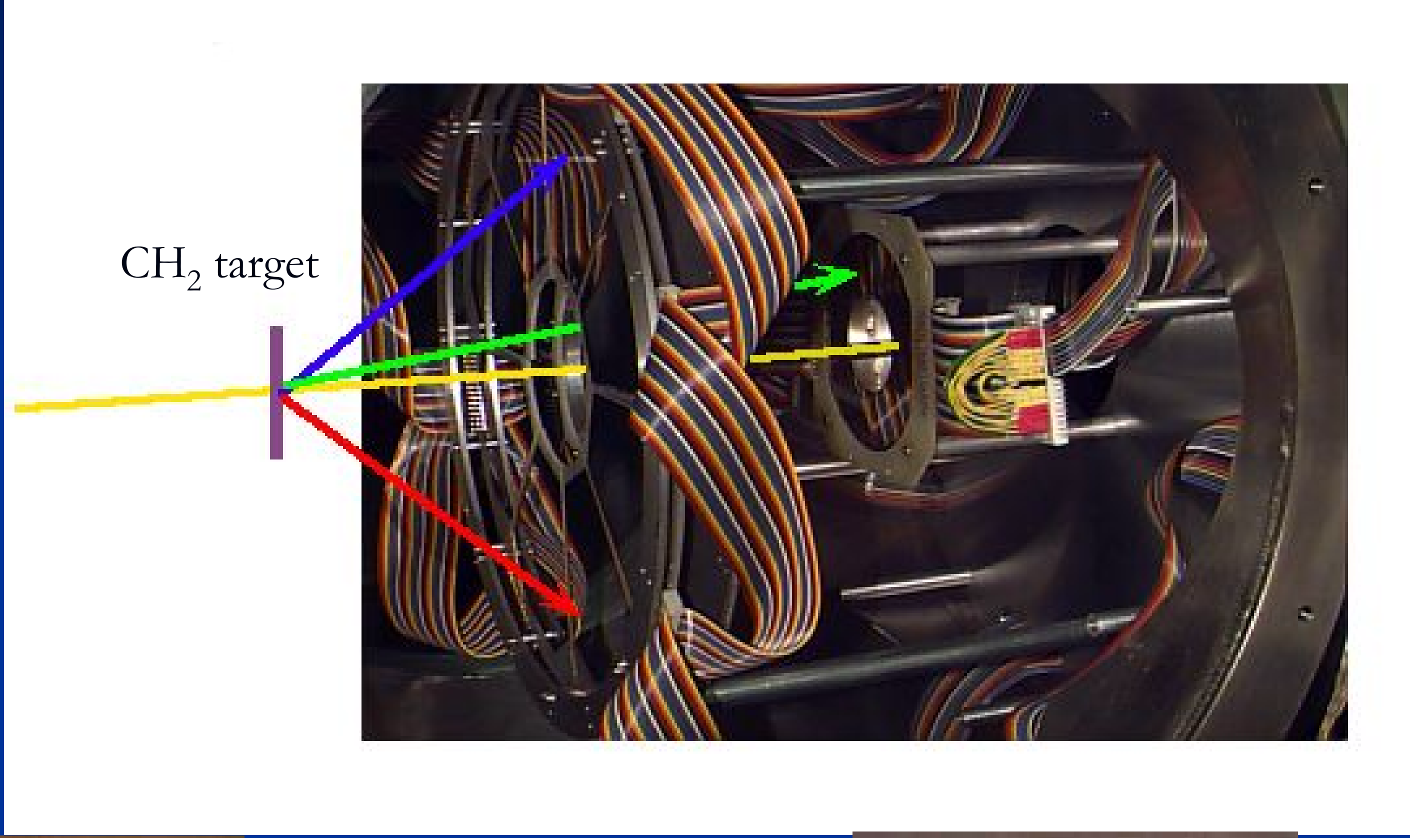
Mass analysis



To experiments

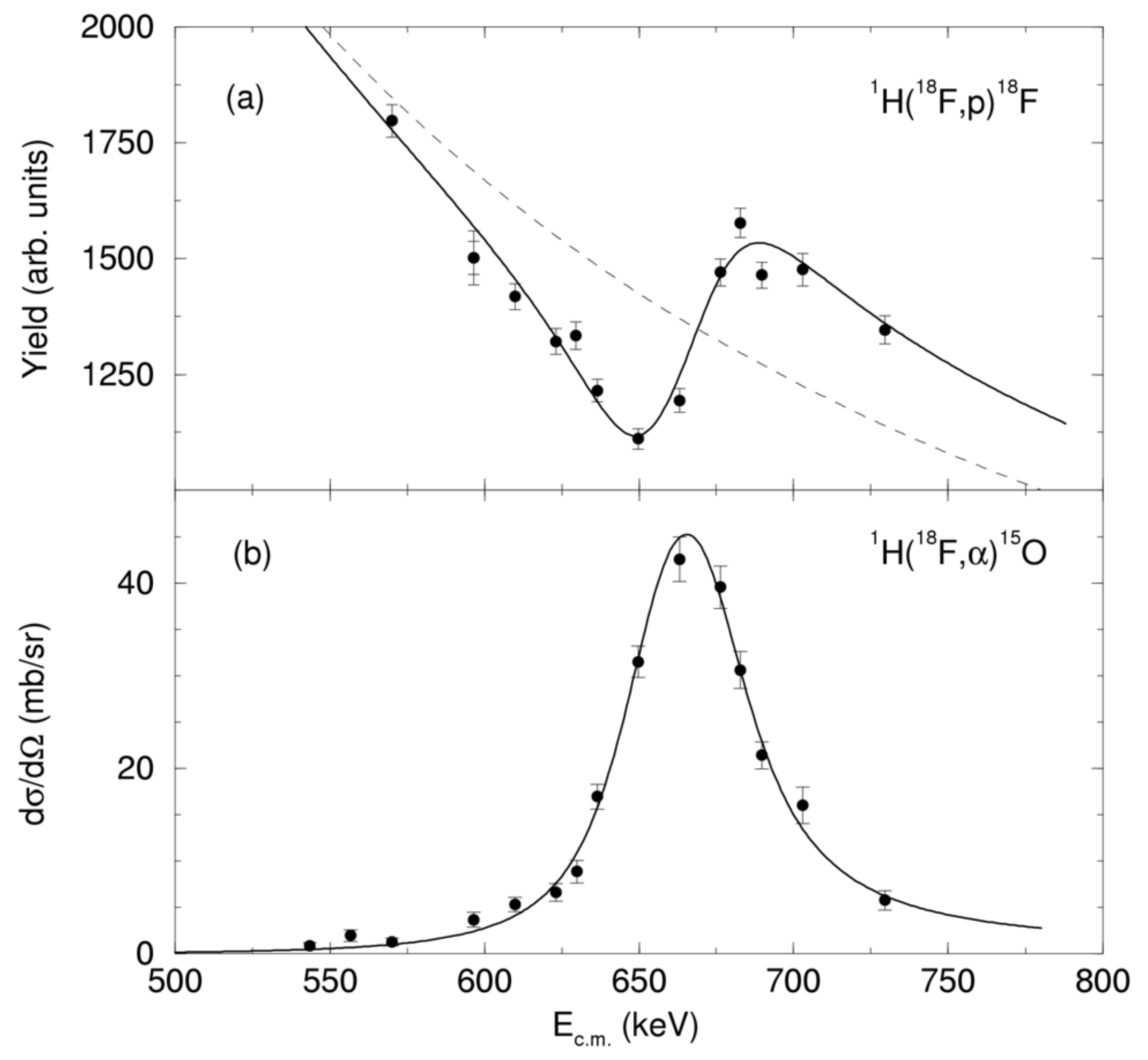
Experimental Approach

~5x10^5 ^{18}F/sec



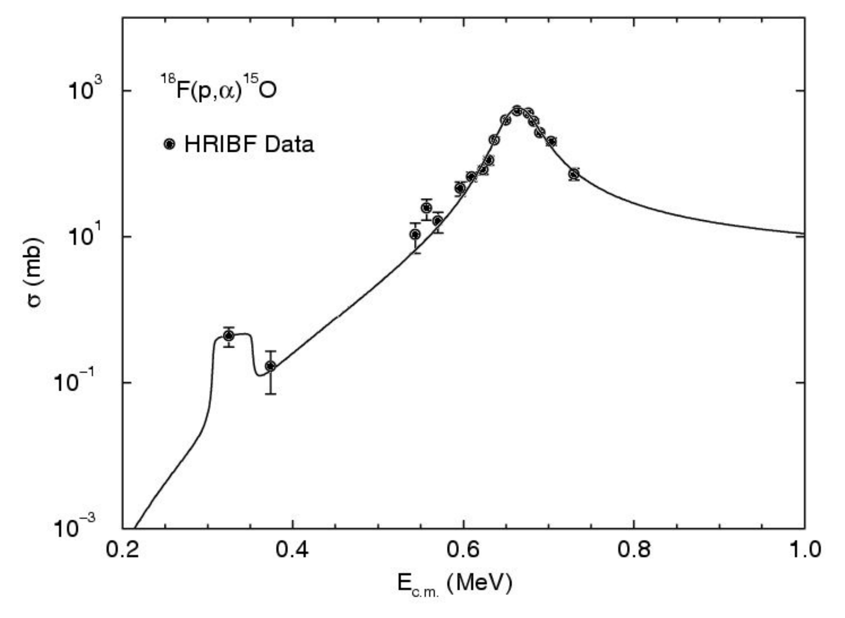
Si Strip Detectors

Results

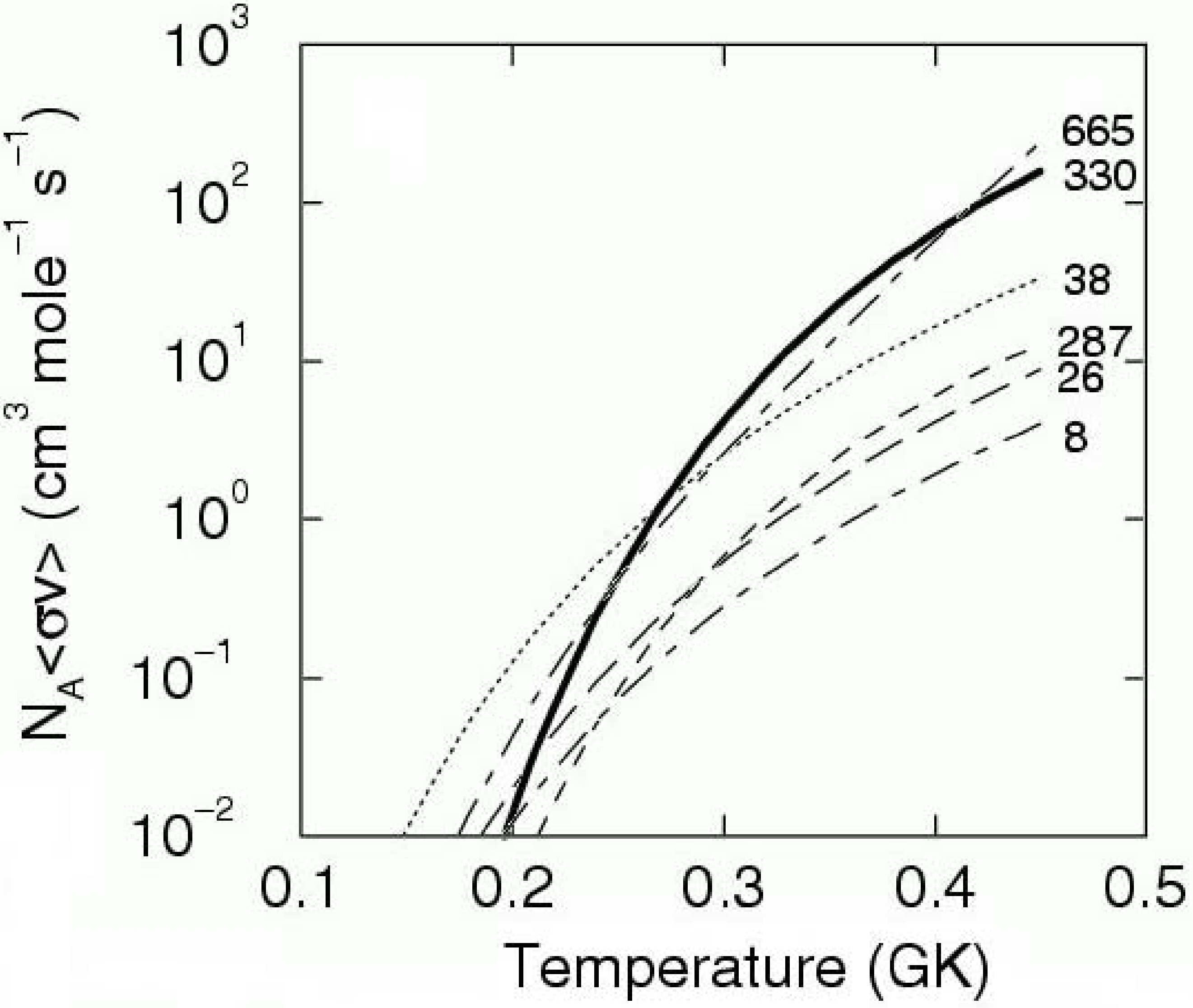

2000
1750
1500
1250
Yield (arb. units)
(a)
$^{1}H(^{18}F,p)^{18}F$
40
20
0
dσ/dΩ (mb/sr)
(b)
$^{1}H(^{18}F,\alpha)^{15}O$
500
550
600
650
700
750
800
$E_{c.m.}$ (keV)

Results

E_r (keV)	J^π	Γ_p (keV)
8	$3/2^+$	4H10^{-37}
26	$1/2^-$	3H10^{-20}
38	$3/2^+$	2H10^{-14}
287	$5/2^+$	4H10^{-5}
330	$3/2^-$	2.2(0.7)H10^{-3}
665	$3/2^+$	15.2(1.0)



Reaction Rate

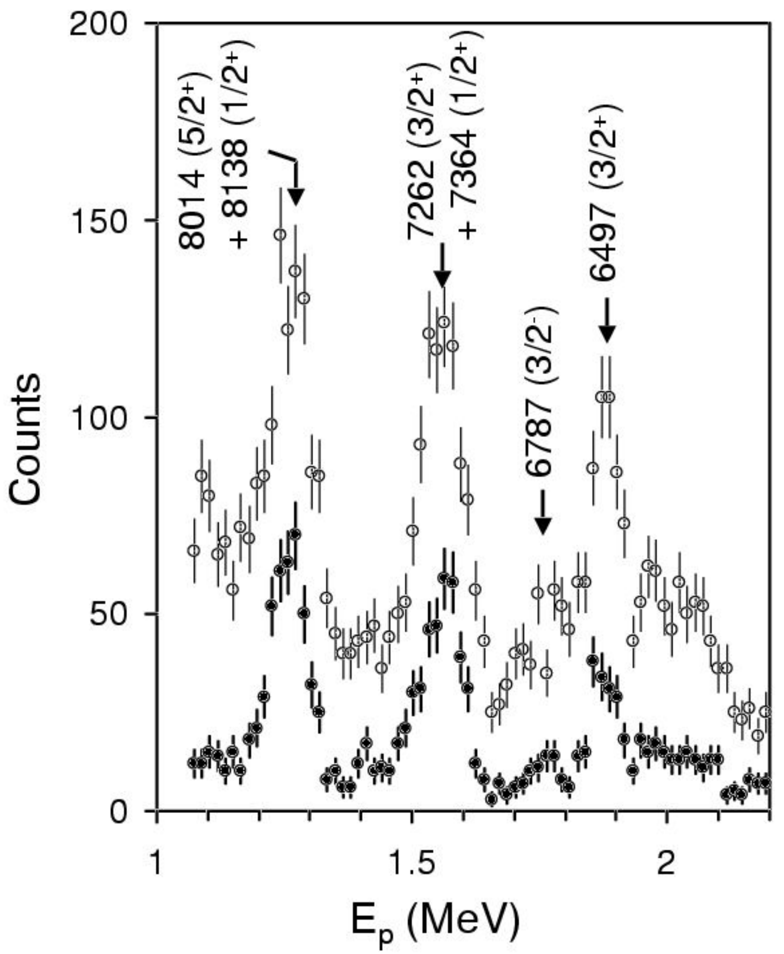


For the Future

Mirror Nucleus:
^{18}F(d,p)^{19}F
proton spectrum

- Lower-energy resonances very uncertain
- Too weak to measure directly
- Study mirror nucleus more carefully
- Proton transfer reactions?

Note: SPI/INTEGRAL should be able to see 511-keV photons following a nova outburst provided it is with ~5kpc of earth!



The Origin of ^{26}Al in our Galaxy

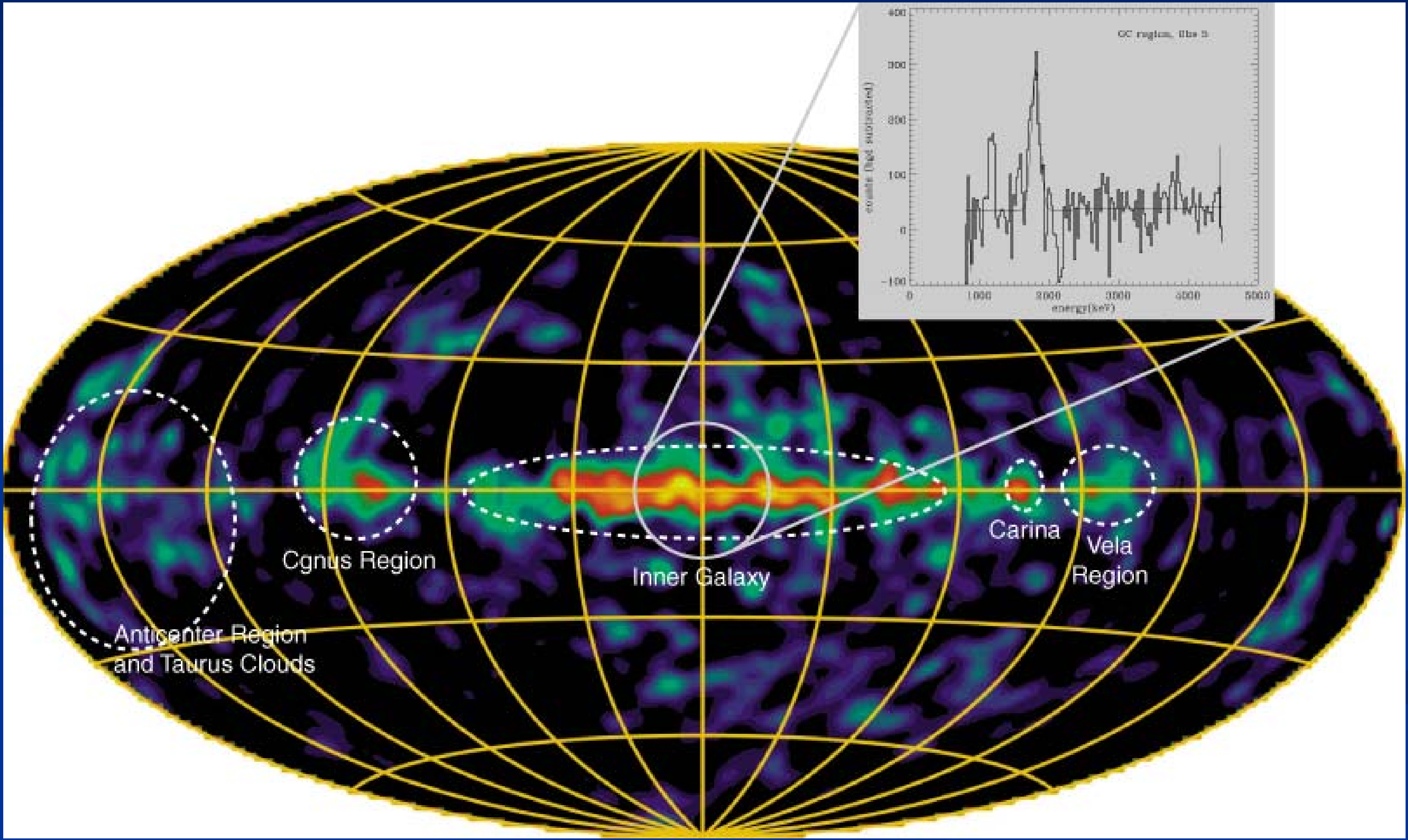
- source of 1809-keV gamma rays
- half-life = 0.73 million years

Novae are likely a significant source, via the sequence $^{24}\mathrm{Mg}(p,\gamma)^{25}\mathrm{Al}(\beta^{+})^{25}\mathrm{Mg}(p,\gamma)^{26}\mathrm{Al}$:

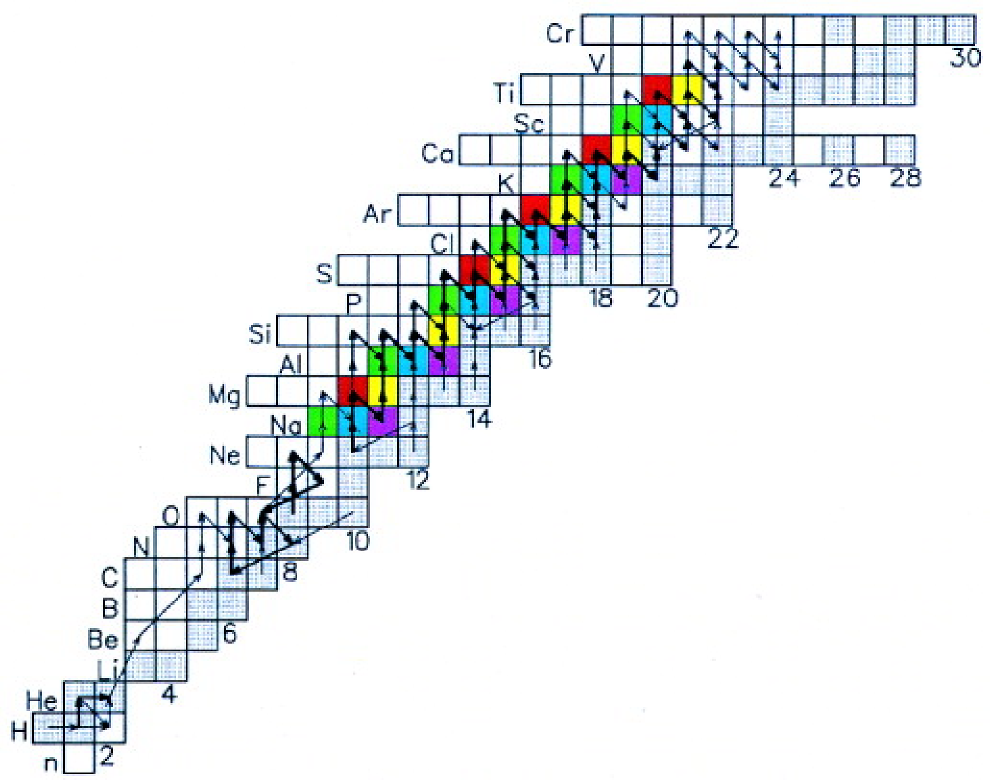
- Evidence from pre-solar grains
- Predicted by models (ONe novae)

^{26}Al is not produced if this sequence occurs:
$^{24}\mathrm{Mg}(p,\gamma)^{25}\underline{\mathrm{Al}(p,\gamma)^{26}}\mathrm{Si}(\beta^{+})^{26m}\mathrm{Al}(\beta^{+})^{26}\mathrm{Mg}$

1809-keV flux distribution (COMPTEL on CGRO)

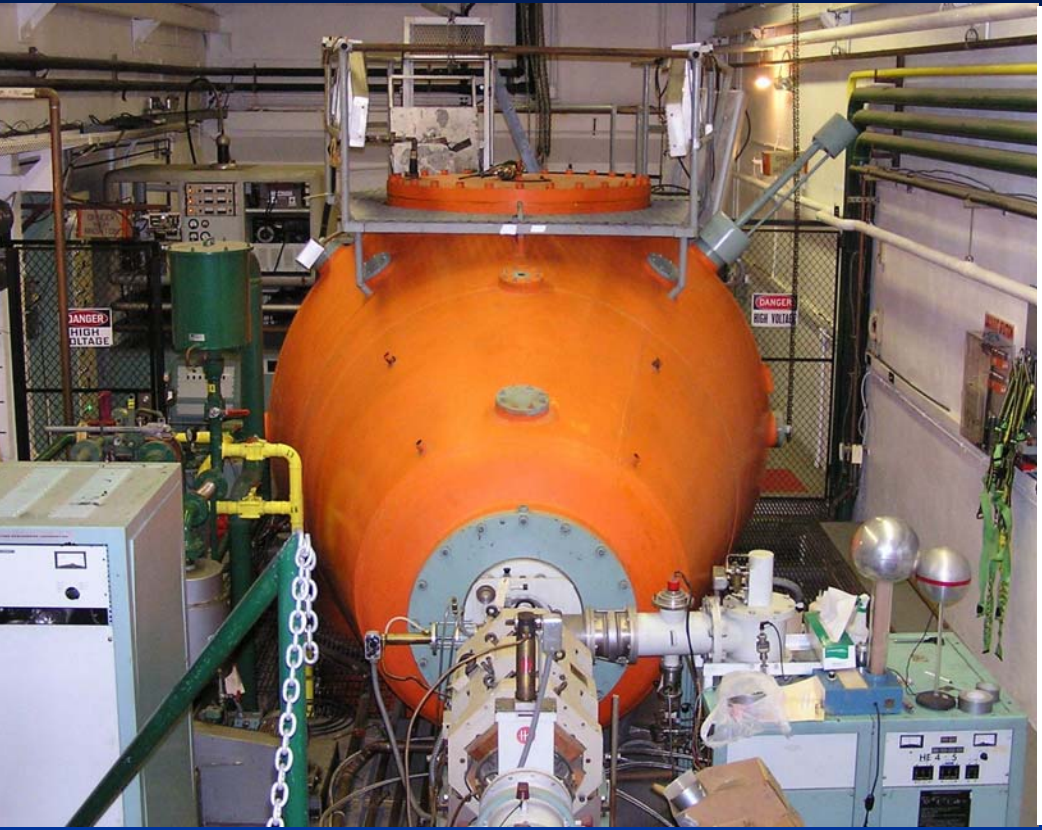


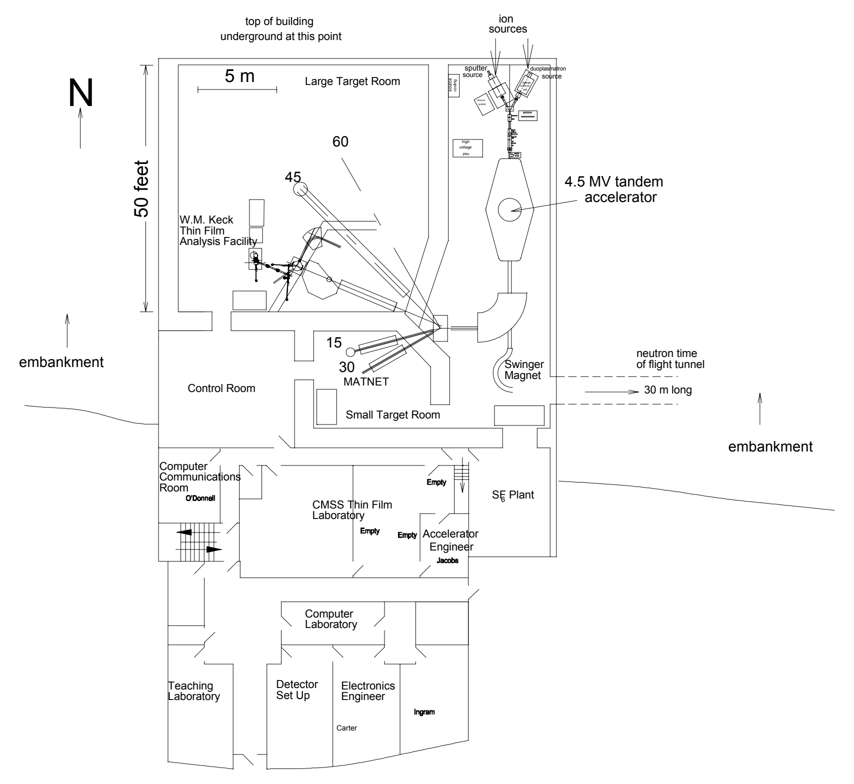
Expanded Reaction Network



Many more nuclei must be taken into consideration !
Changes in temperature can change the path !

Edwards Accelerator Laboratory





- 4.5-MV tandem accelerator
- p, d, ^{3,4}He, heavy ion beams
- 30 m time-of-flight tunnel

Neutron Time-of-Flight Technique

^{24}Mg + ^{3}He Y ^{26}Si(*) + n

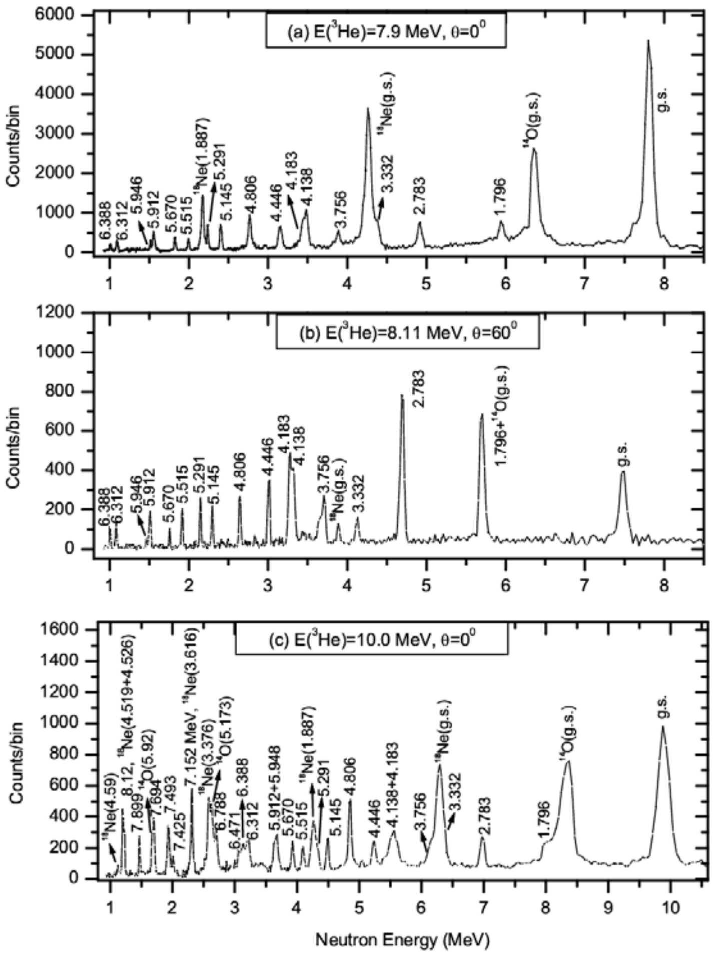
- time of flight Y neutron energy
- kinematics Y E_x in ^{26}Si
- Δt . 1ns
- long flight path, low E_n desirable

Excellent energy resolution achievable !

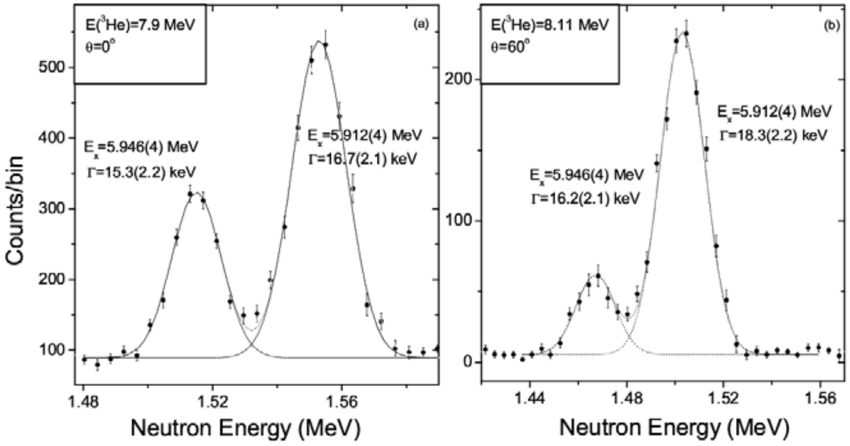
Neutron Energy Spectra

(Y. Parpottas)

full spectra



^{24}Mg(^{3}He,n)^{26}Si(*)

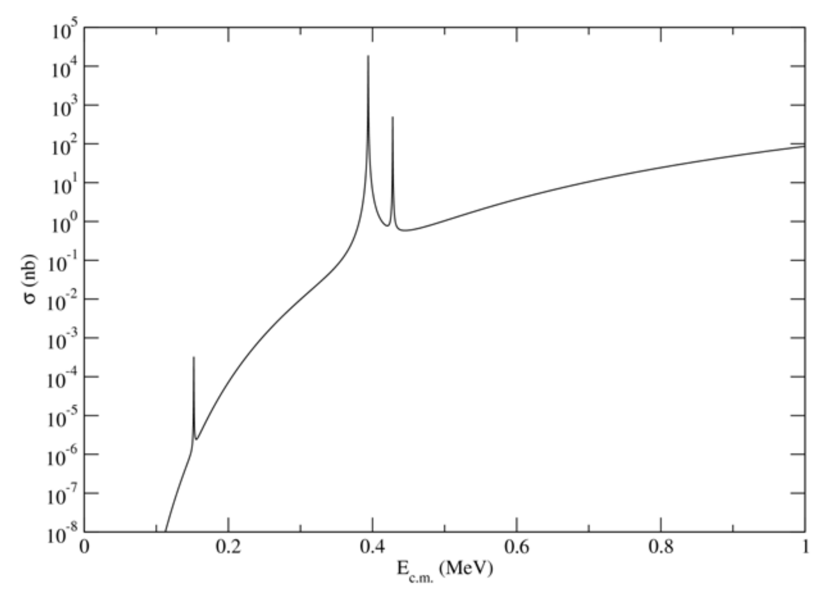


Key Result

Mirror nucleus leads us to expect 3^{+} and 0^{+} in this region.

Implications for $^{25}Al(p,\gamma)^{26}Si$

E_r (keV)	J^{π}	Γ_p (keV)
152	1^+	$1H10^{-12}$
394	3^+	$3H10^{-3}$
428	0^+	$2H10^{-5}$



- Our reaction rate is a factor ~20 smaller at nova temperatures than previously thought.
- The J^{π} assignments should be verified.

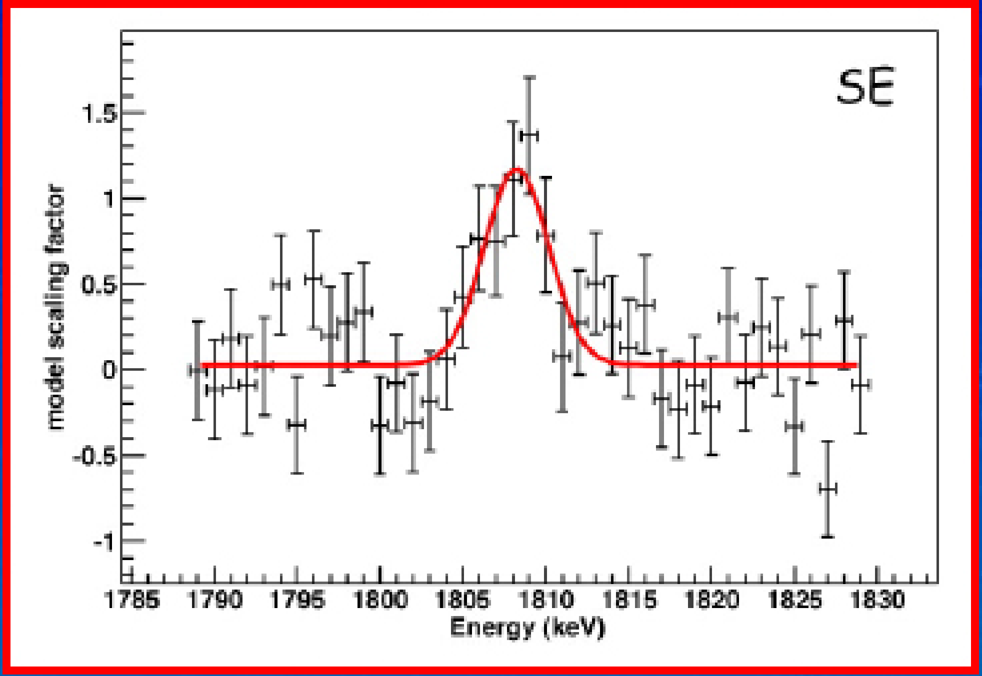
Implications for ^{26}Al production in Novae

- Calculations using the previous reaction rate found that novae could produce up to 20% of the observed galactic ^{26}Al (Jose' et al.).
- Recent numerical studies (Iliadis et al. 2002) find less sensitivity to this reaction rate than expected.
- Other nuclear physics inputs have significant uncertainties.
- Recent data from SPI/INTEGRAL indicates other source may be more important.

Unveiling massive star nucleosynthesis in Cygnus X

1809 keV gamma-ray line emission from radioactive ^{26}Al decay

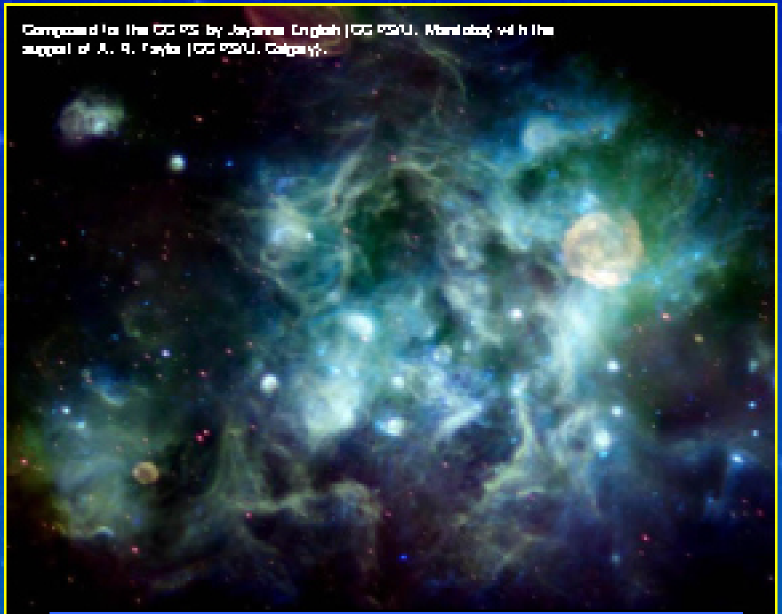
SPI/INTEGRAL 1809 keV line spectrum of Cygnus X



Flux : (7.2 ± 1.8) × 10^{-5} ph cm^{-2} s^{-1}

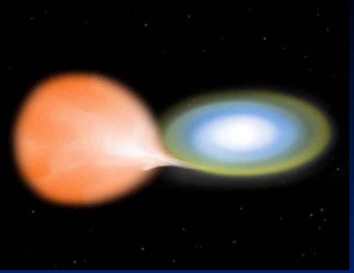
Position : 1808.4 ± 0.3 keV ⇒ v_{rad} = -41 ± 50 km s^{-1}

Width : 3.3 ± 1.3 keV ⇒ Δv = 550 ± 210 km s^{-1}

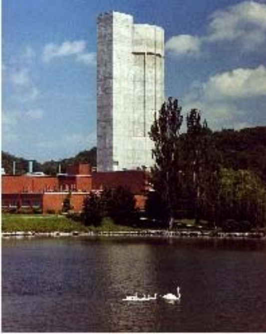

Composed for the CGPS by Jayanne English (CGPS/U. Manitoba) with the support of A. R. Taylor (CGPS/U. Calgary).

DRAO radio image of ionising massive star clusters in Cygnus X that are at the origin of the ^{26}Al production detected by SPI

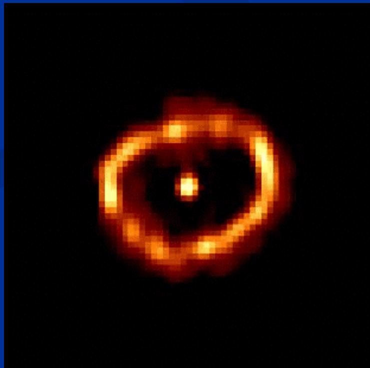
Jürgen Knödlseder (on behalf of the INTEGRAL team), Centre d'Etude Spatiale des Rayonnements, Toulouse, France



In Summary:



- Two reactions important for energy generation and nucleosynthesis in novae have been investigated.
- At Ohio University we are presently working on $^{17}O(^{3}He,n)^{19}Ne$ (M. Hornish, H. Hadizadeh, T. Massey, CRB,…).
- Many labs are working on these questions with both stable beams (OU, UNC/Duke, Yale, Texas A&M,…) and radioactive beams (ORNL, NSCL, ANL, TRIUMF,…).
- We look forward to new data from ground- and space-based observatories and other probes of our universe.



Rare Isotope Accelerator

Nuclear Astrophysics at RIA

<10 MeV beams

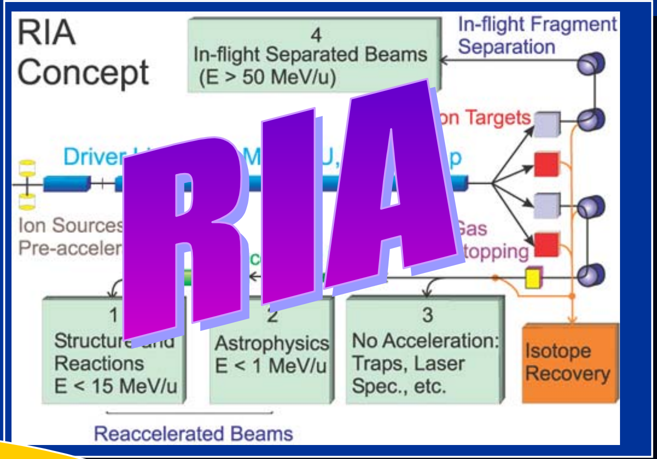
- p-,α-,n-induced reaction rates (ANC,nucleon transfer, …)
- nuclear structure experiments

Stopped beams

- Masses
- β,βn,βp,p decays

Neutron Facility

- n-capture on radioactive targets



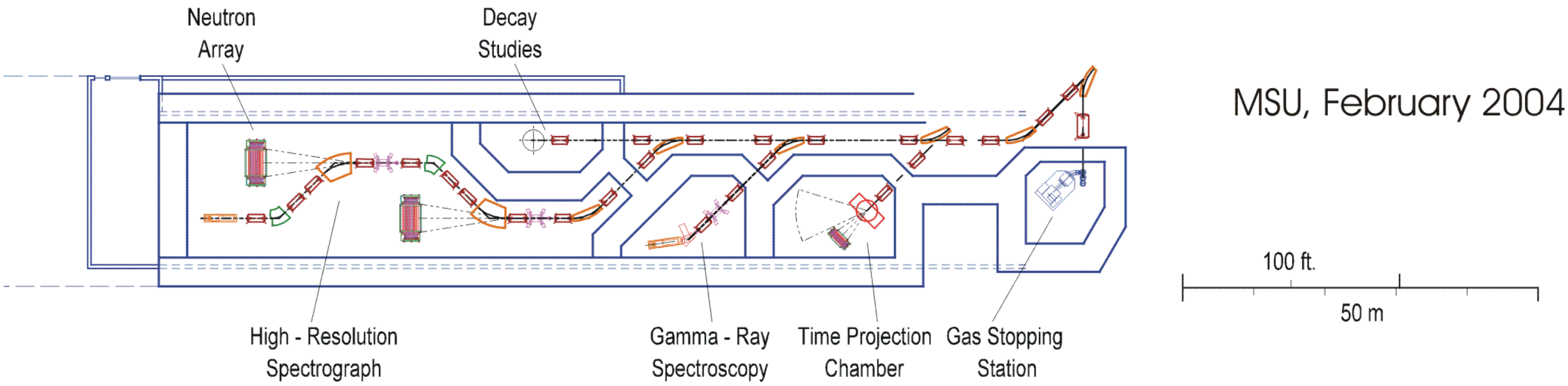
>100 MeV beams

- p-,α-,n-induced reaction rates (transfer/knockout, Coulomb breakup)
- β,βn,βp,p decays
- charge exchange reactions
- TOF mass measurements
- Nuclear structure experiments

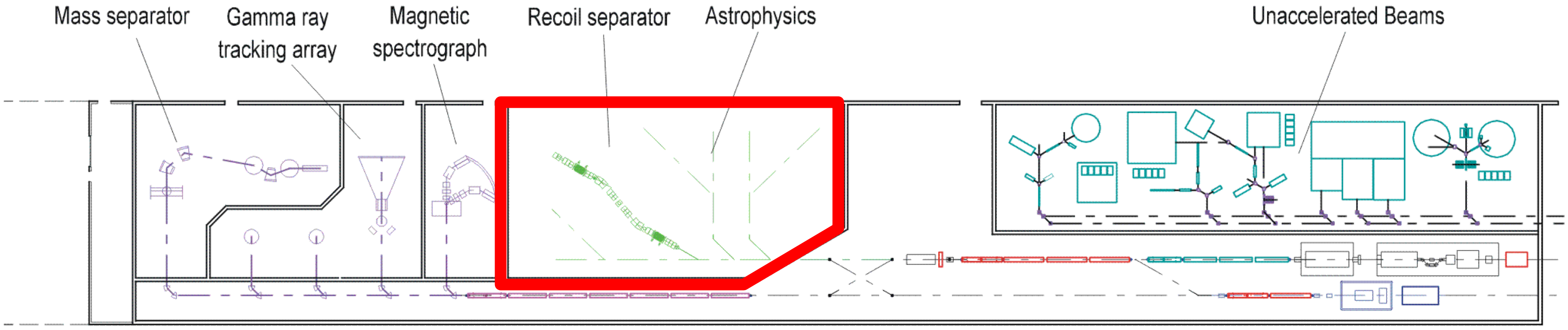
<1 MeV beams

- p-, α-induced reaction rates (direct measurements)
- resonant scattering

RIA Floor Plan



MSU, February 2004

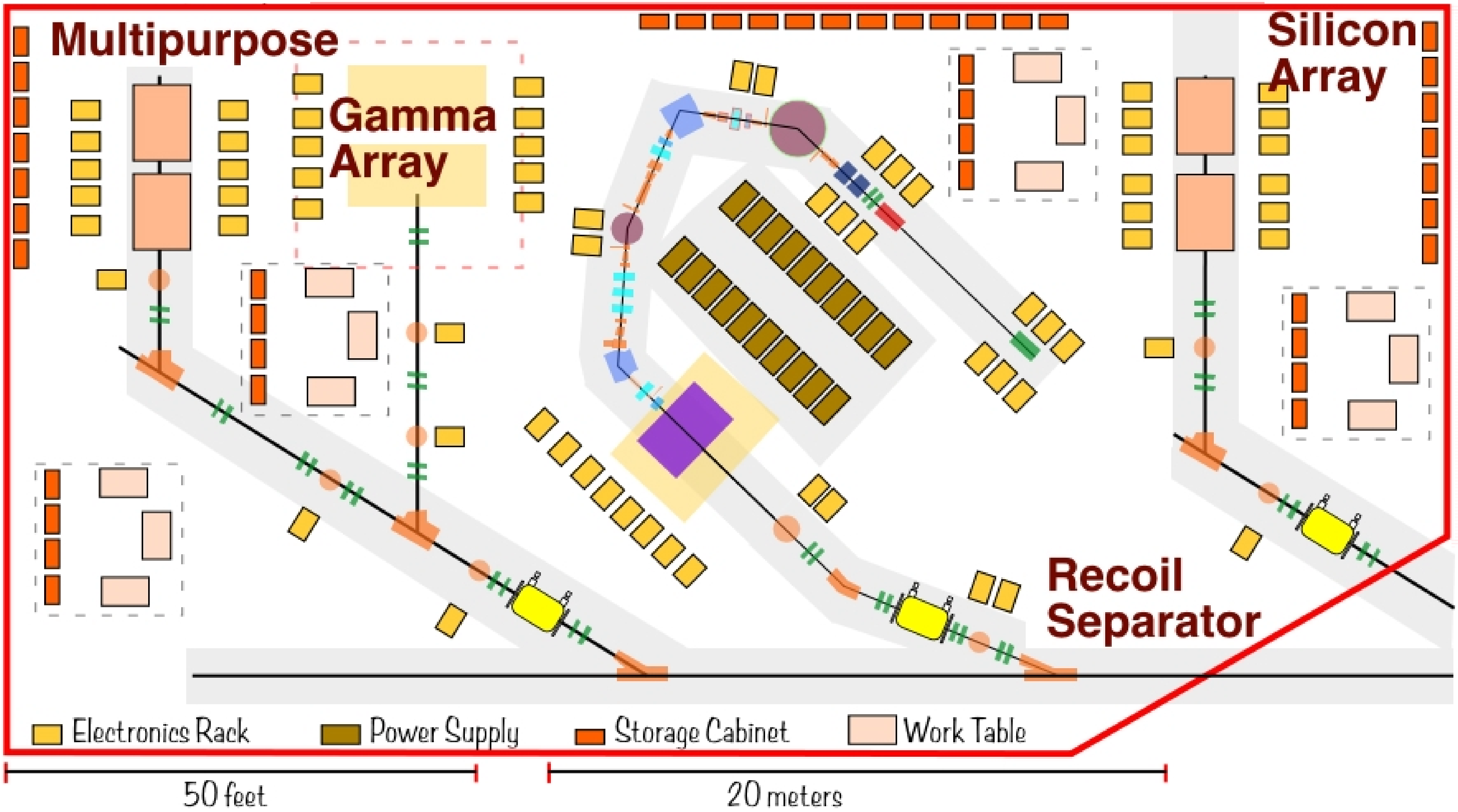


47 m • 24 m

Low Energy Experimental Hall

MSU

47 m •



RIA Intensities