# Nuclear Physics in the Cosmos

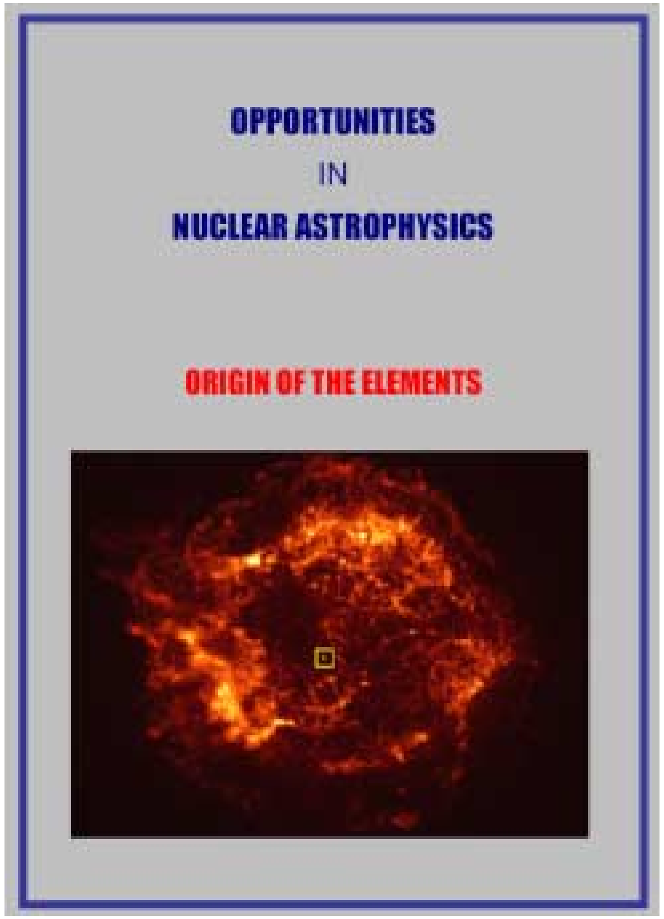
## Understand nuclear processes that

- Power the stars
- Synthesize the elements
- Mediate explosive phenomena

## Determine

- Nature of stellar evolution
- Sites of astrophysical processes
- Properties of universe
- Neutrino properties

## For background, see




**http://www.nscl.msu.edu/~austin/nuclear-astrophysics.pdf**

# An Intellectual Opportunity

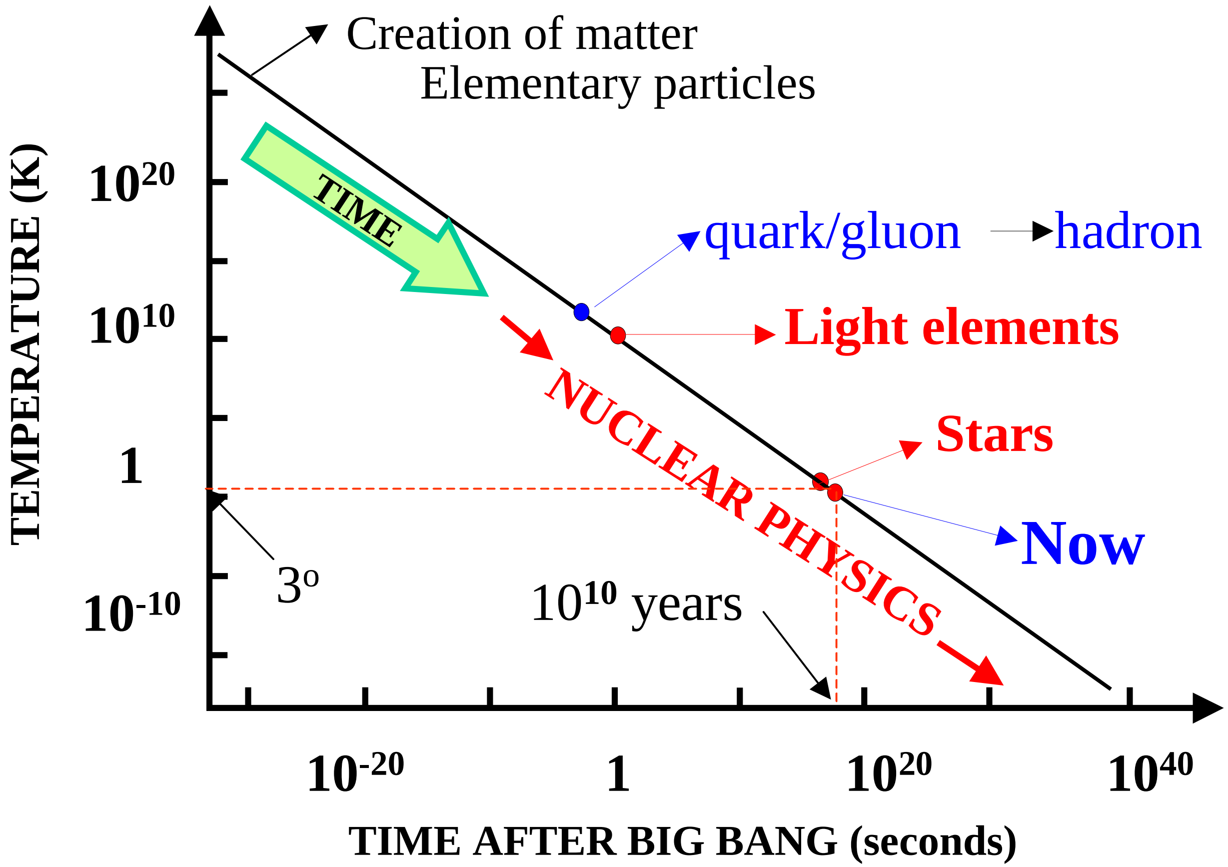
## This is a special time

- **Wealth of new astronomical observations--require new nuclear data for a credible interpretation**
- **New accelerators of radioactive nuclei to provide this data**
- **Growing computational power to simulate the phenomena**

# Cosmic History—a Long View

## Universe began as a hot, sense primeval fireball-Big Bang

- It then cooled: $T \propto 1/t^{1/2}$
- Light elements were made
- Galaxies and stars formed



## Outline of the Lectures:

**The observables:** Cosmic abundances, abundances in the solar system and elsewhere

**Nature of the nuclear processes involved:**

- Reaction rates
- Resonant and non-resonant processes
- Technical details: Gamow peak, S-factor, etc.

**The Big Bang and the Nature of the Universe**

Baryons, dark matter, dark energy

**Stellar evolution with some digressions**

- Quasistatic evolution, solar neutrinos, s-process , stellar onion
- Explosive phenomena: supernovae, r-process, neutrinos
- Binary systems: x-ray bursters and x-ray pulsars, the surface of neutron stars.

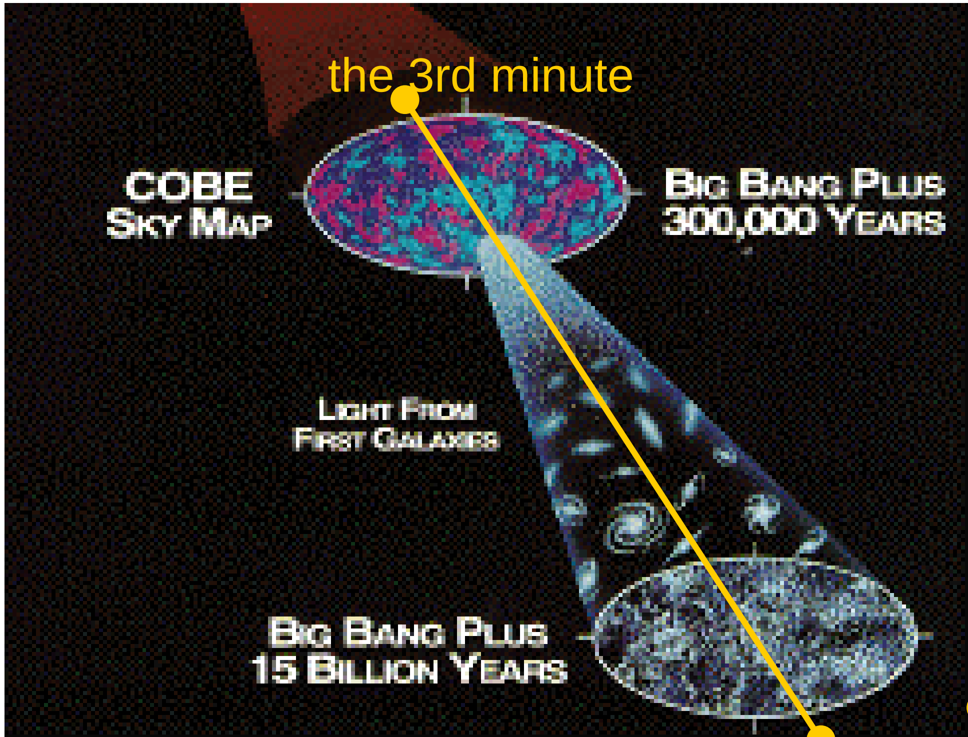
# Outline-Continued

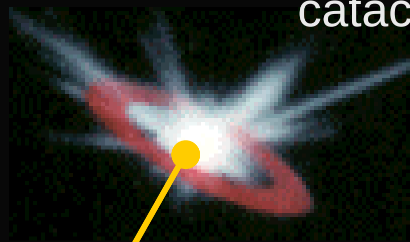
**What nuclear physics do we need to know?**

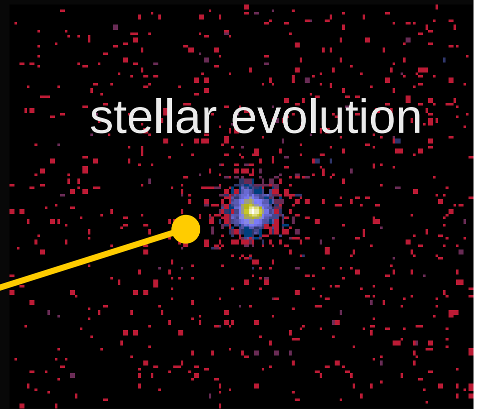
- Throughout the presentation
- Theoretical and experimental needs, and their coordination with astrophysicists

**Nature of experiments at low and high energy facilities**

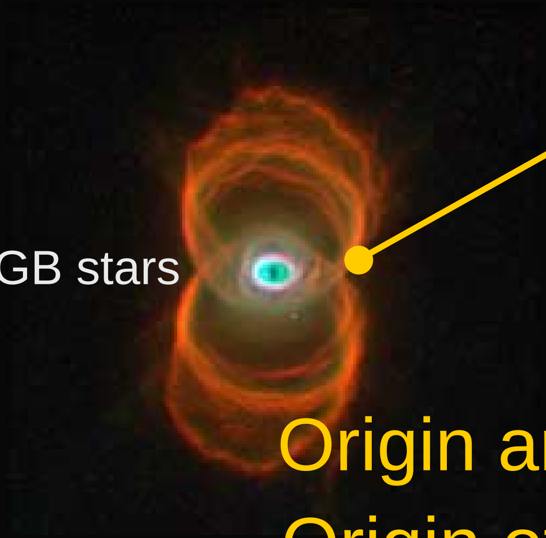
- High energy approaches to low energy astrophysics
- The NSCL--an extant fast-radioactive-beam-facility
- The proposed RIA facility

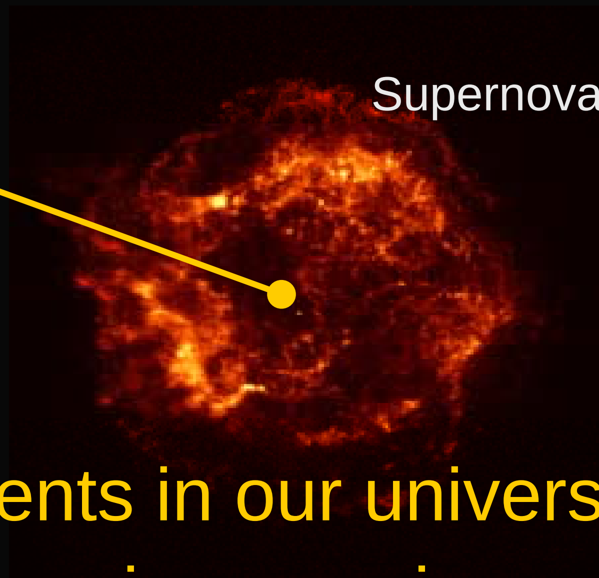



# Nuclear Astrophysics




Origin and fate of the elements in our universe

Origin of radiation and energy in our universe

# Some Quotes to Keep in Mind

**Simplicius (Greek 6th AD) on ideas of Leucippus (5th BC)**:
"The atoms move in the void and catching each other up jostle together, and some recoil in any direction that may chance, and others become entangled with on another in various degrees according to the symmetry of their shapes and sizes and positions and order, and they remain together and thus the coming into being of composite things is affected."

**King Lear, Act IV, scene 3:**
"It is the stars, the stars above us govern our condition"

**Arthur Eddington, 1928**
I ask you to look both ways. For the road to a knowledge of the stars leads through the atom; and important knowledge of the atom has been reached through the stars"

**Mark Twain, *Life on the Mississippi***

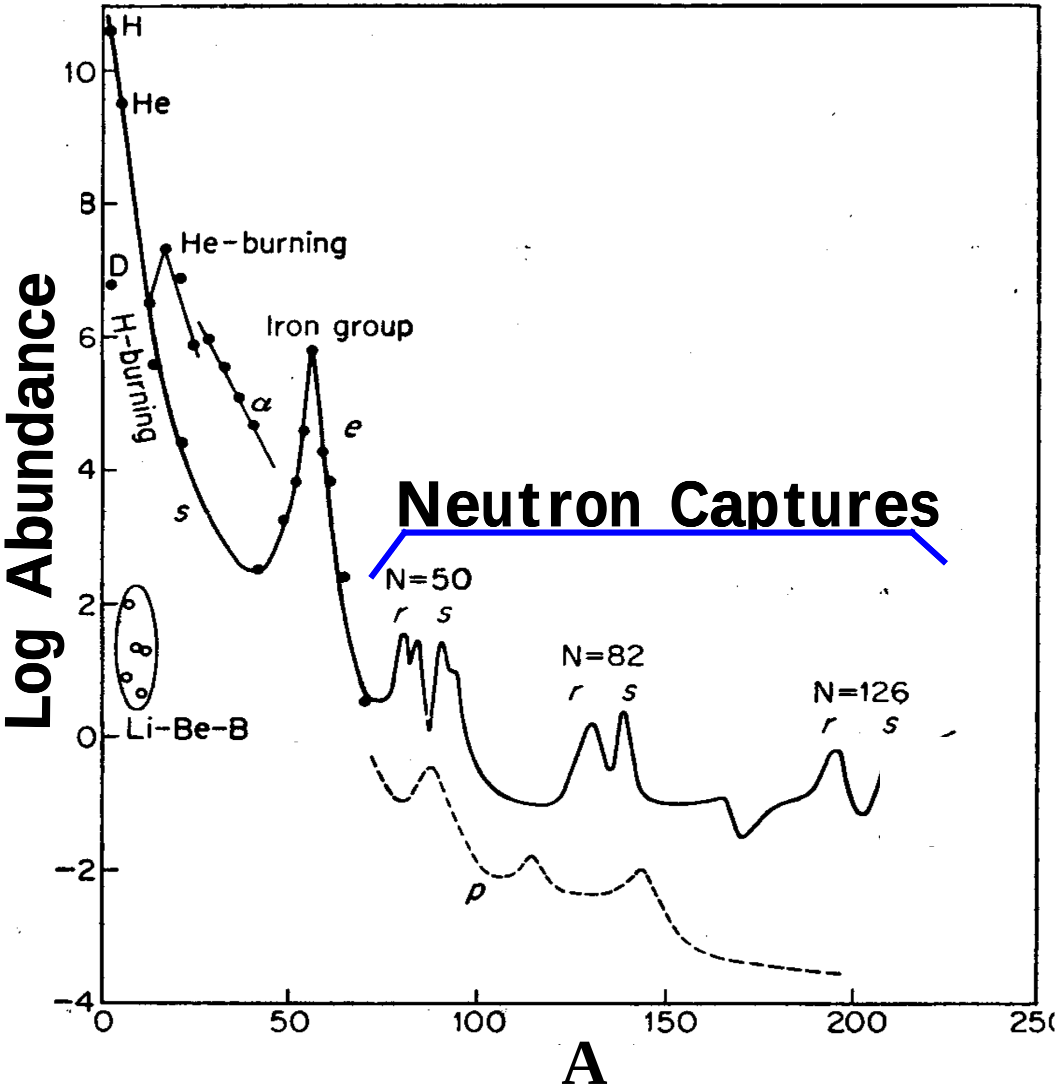
"There is something fascinating about science. One gets such wholesale returns of conjecture out of such a trifling investment of fact."

**Willy Fowler:**

"We got to get all this theory out of things".

# Cosmic Abundances (Really solar system, mainly)

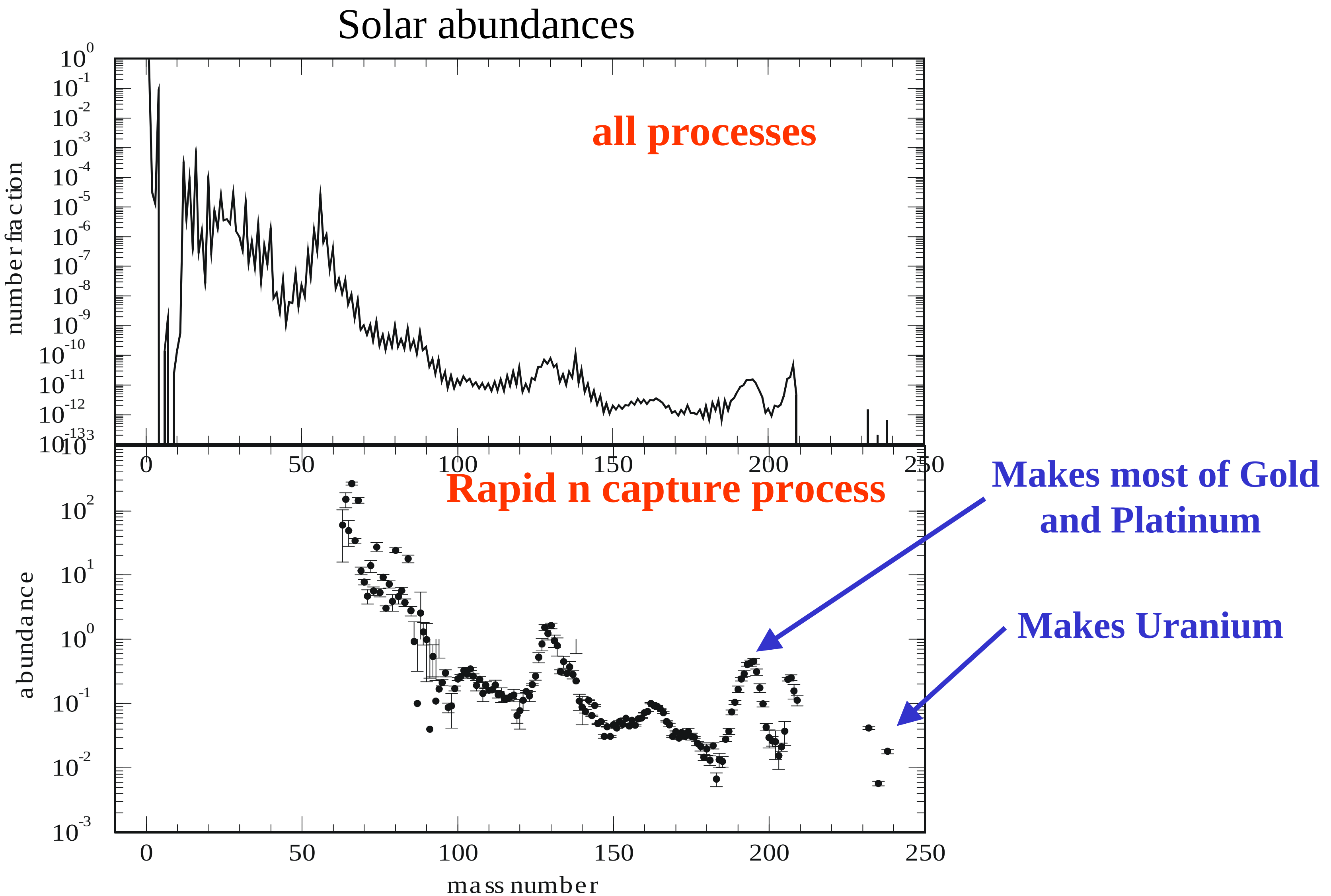
## A qualitative view-Suess-Urey Plot




- Very large range of abundances
- Names denote various creation processes

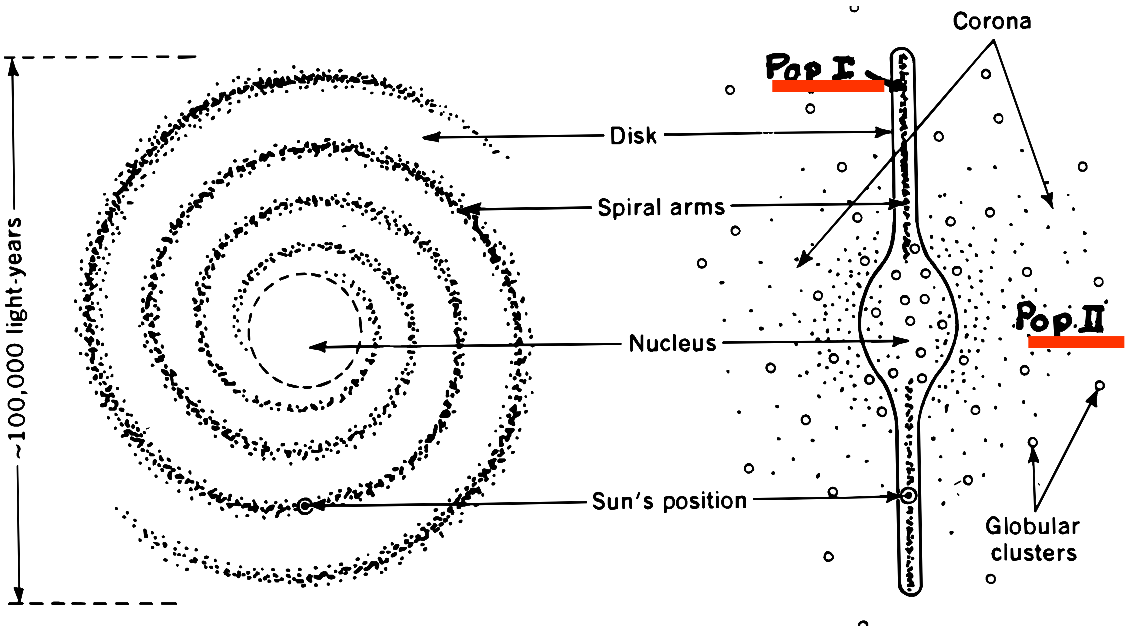
| Group | Mass Fraction |
|---|---|
| $^{1,2}H$ | 0.71 |
| $^{3,4}He$ | 0.27 |
| Li, Be, B | 10-8 |
| CNO Ne | $2 \times 10^{-2}$ |
| Na-Sc | $2 \times 10^{-3}$ |
| A=50-62 | $2 \times 10^{-4}$ |
| A=63-100 | $10^{-6}$ |
| A>100 | $10^{-7}$ |

# A More Detailed Picture



# Populations I, II and III

## What about elsewhere?




In the halo of the galaxy find (old) stars (**Pop II stars**) with small abundances of metals (A > 4) compared to the solar system values typical of **Pop I stars**.

## Pop II stars

- Reflect processes in the early galaxy
- Investigation of Pop II stars is a hot area of astrophysics

## What are Pop III stars?

- Stars that produce the material from which Pop II are made.
- Probably very large (> 100 $M_{sun}$) fast evolving stars made from products of the Big Bang.

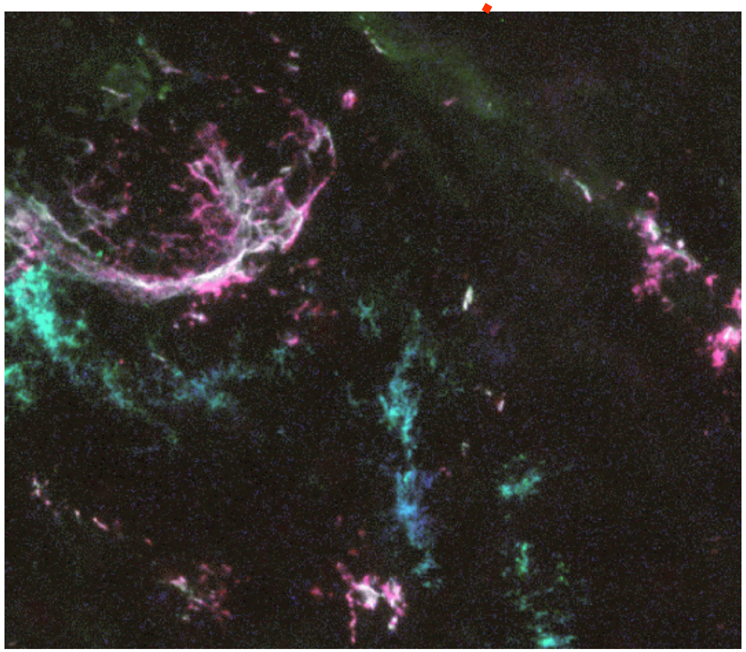
# The Stars as Element Factories

Condensation

**Stars**
Nuclear Reactions
Element Synthesis

**Interstellar**
Gas
Dust

Ejection-Supernovae
Planetary nebulae



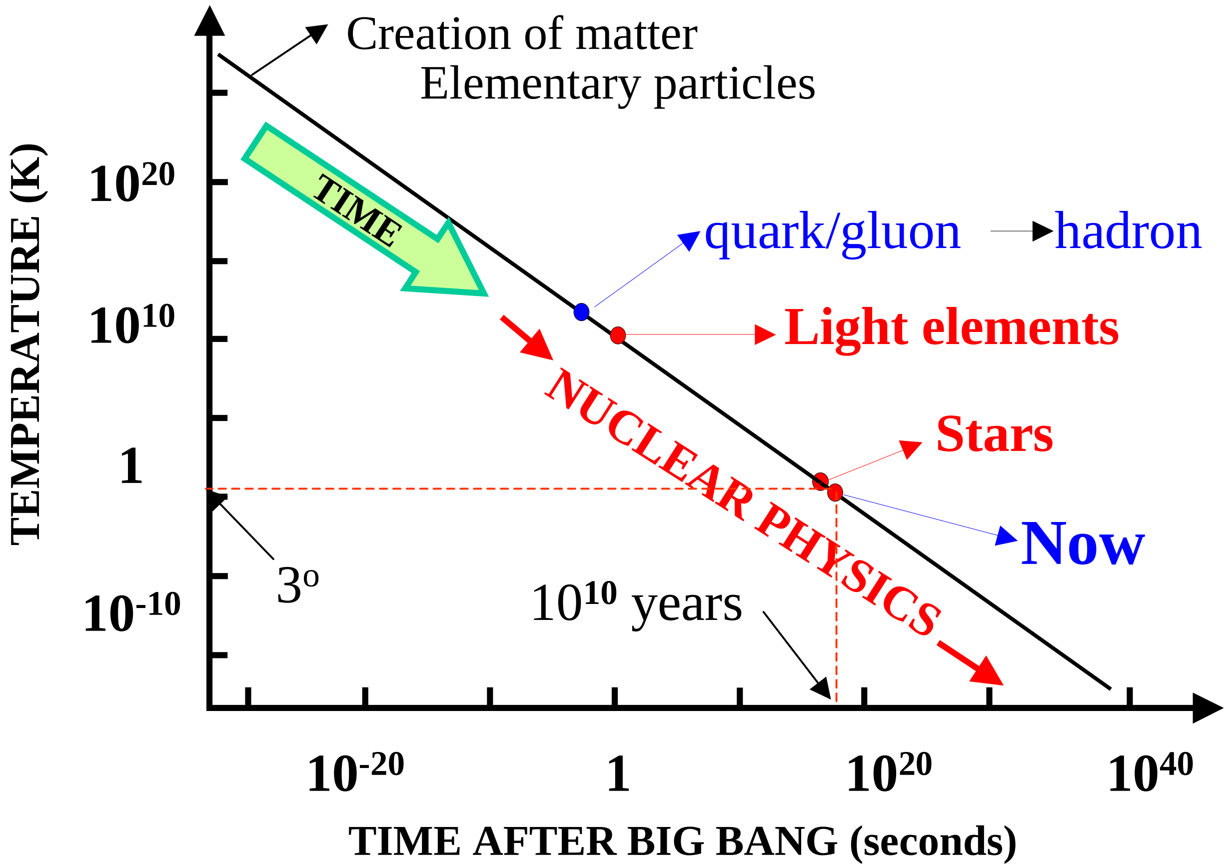
Supernova remnant
N132D-LMC

Star Forming Region
DEM192-LMC

# Back to the Big Bang

## Universe began as a hot, sense primeval fireball-Big Bang

- It then cooled: $T \propto 1/t^{1/2}$
- Light elements were made
- Galaxies and stars formed



# Element Production in the Big Bang

## Assumptions:

- General relativity
- Universe isotropic, homogeneous
- $T_{now}$= 2.735 K (CBR))

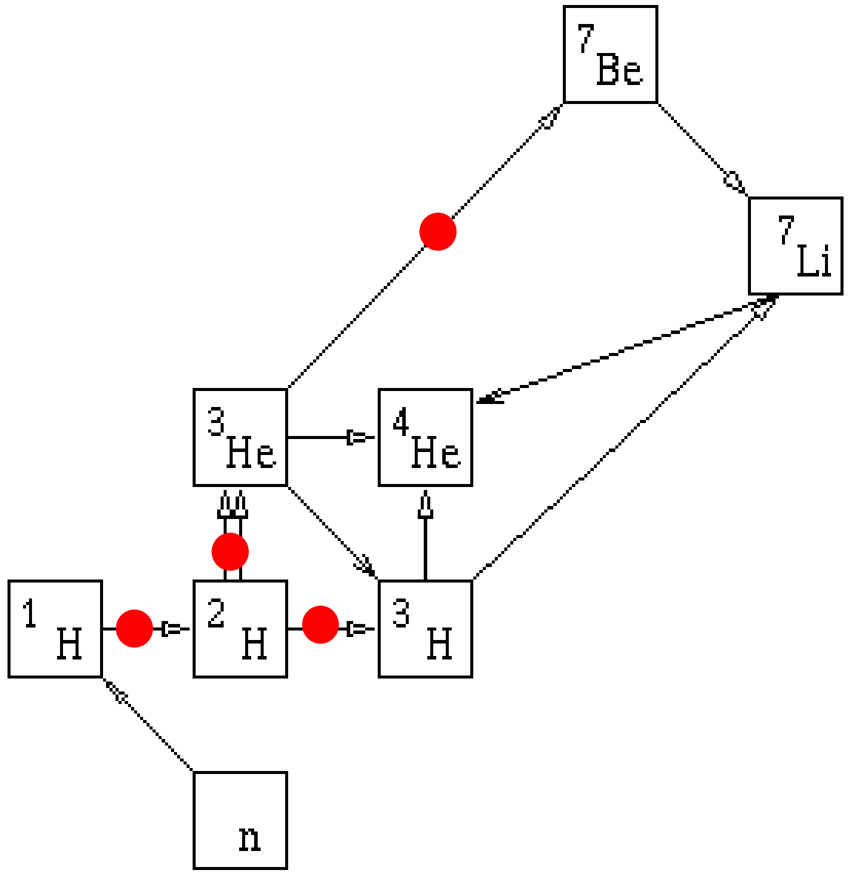
## Production of elements

- 10-300 sec after BB
- $T \approx 10^{10}$ K, $\rho \approx 1 g/cm^3$
- Big Bang produces only $^{1,2}H, ^{3,4}He, ^{7}Li$
- Yield depends on density $\rho_B$ of baryons

## Reaction network

Need to know noted reactions-

● = Poorly known reactions



# Can we Determine the Baryon Density from the Big Bang?

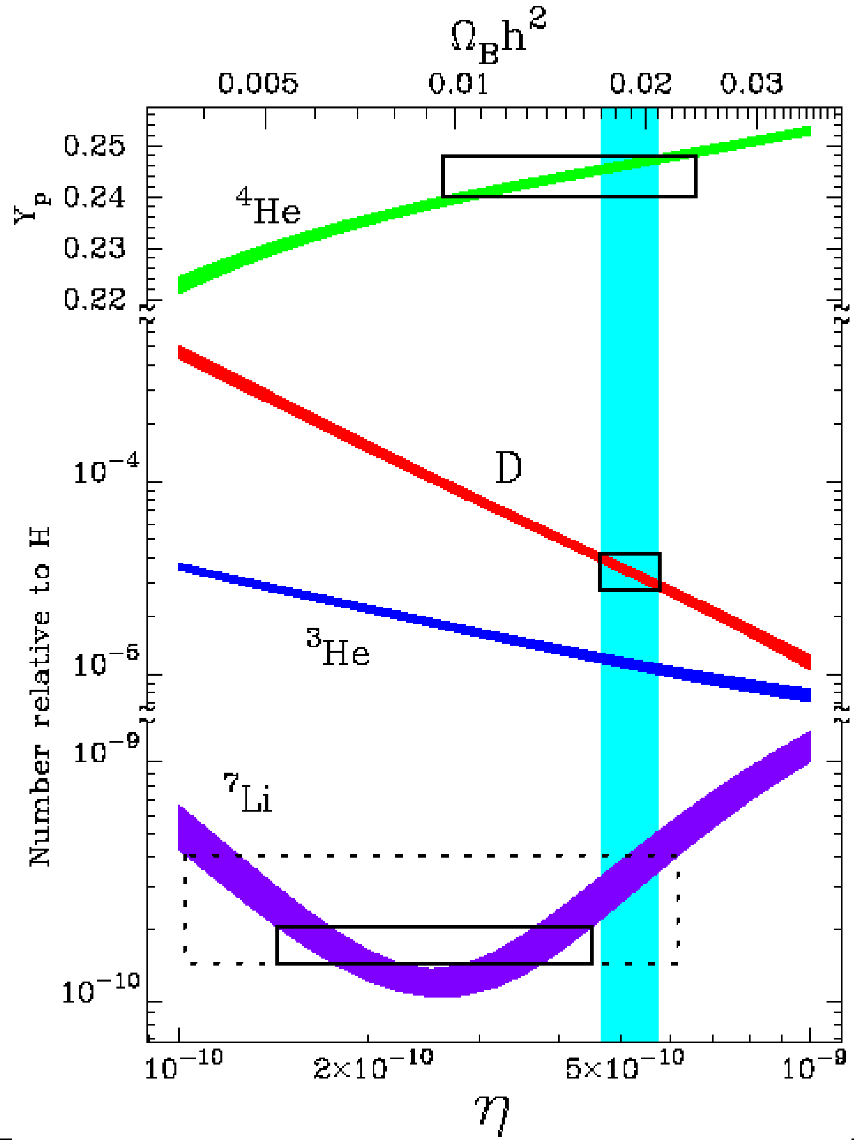
## Method

- Find $\rho_B$ where predicted and observed abundances equal.
- If $\rho_B$ same for all nuclides, it assume it is the universal density

## Result

OK, EXCEPT for $^7$Li. Perhaps predicted abundance wrong (poor cross sections) or primordial Li higher (star destroyed).

Nollett and Burles, PRD 61,123505 (2000)



# It’s Close, Why Does It Matter?

## Cosmic Background Radiation

- Surrounds us, Planck distribution (T~2.7 K), remnant of early BB
- Fluctuations (at $10^{-5}$ level) give information on total density of Universe and on $\rho_B$.

## It implies

Universe is just bound $\boldsymbol{\Omega_{tot} = 1}$

- Baryon density $\boldsymbol{\rho_B \sim 0.05}$
- Dark matter density, $\boldsymbol{\rho_D \sim 0.3}$ perhaps WIMPS, weakly interacting massive particles
- Dark energy $\boldsymbol{\rho_\Lambda \sim 0.65}$

## Era of precision cosmology

- Far reaching conclusions must be checked and the value of $\rho_B$ is the best possibility.
- Need more accurate cross sections for several reactions affecting $^7$Li.

# What energy source powers the stars?

## All energy comes from mass

Mass $_{initial}$ → Mass $_{final}$

Reaction

Mass $_{converted}$ = f Mass $_{initial}$

Energy released
f $\text{Mass}_{\text{initial}}\, c^2$

**Must provide solar luminosity for >4.6 x $10^9$ yrs**

$$L_{sun} = 3.826 \times 10^{33} \text{ erg/sec}$$

$$M_{sun} = 1.989 \times 10^{33} \text{ g}$$

## Of the possibilities

$f_{chemical} \approx 1.5 \times 10^{-10}$ $\Rightarrow$ *2200 yrs*

$f_{gravity}$ $\Rightarrow$ *$10^7$ yrs*

$f_{nuclear} \approx 0.007$ $\Rightarrow$ *$10^{11}$ yrs*

**Only nuclear remains**

## Other evidence

Technetium is seen in stellar spectra. BUT the longest lived isotope is unstable--lifetime of 4 x $10^6$ yrs. Must have been synthesized in the star.

# Reaction Rates and Energy Scales

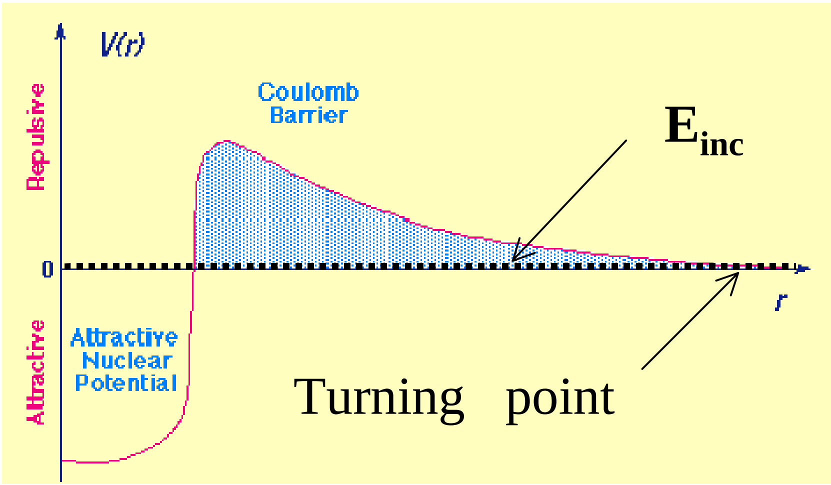
## Reaction Rate

- Ionized gas (plasma) with $N_i$ /cm$^3$ of species "i"
- Assume species x moving at velocity v through species y at rest. Rate of reactions $r_{xy}$ is $\mathbf{r_{xy} = N_x N_y v \sigma_{xy}}$
- Average over velocity distribution (Max. Boltz.)

$$\mathbf{r_{xy} = \underbrace{N_x N_y (1+\delta_{xy})^{-1}}_{\#\text{ of pairs/cm}^3} \langle v\sigma_{xy} \rangle}$$

## Environment

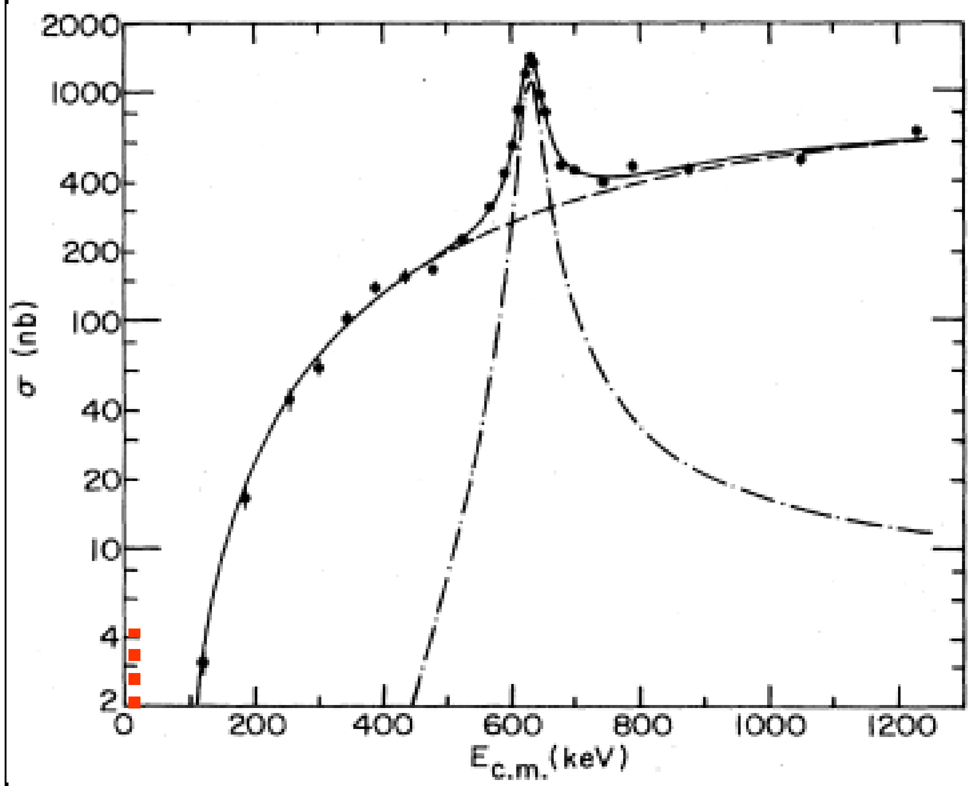
- k = 8.6171 x $10^{-5}$ eV/K
- T = $10^7$-$10^{10}$ K $\Rightarrow$kT=1-900 keV
- Coulomb barriers MeV range
- Reactions are far sub-coulomb



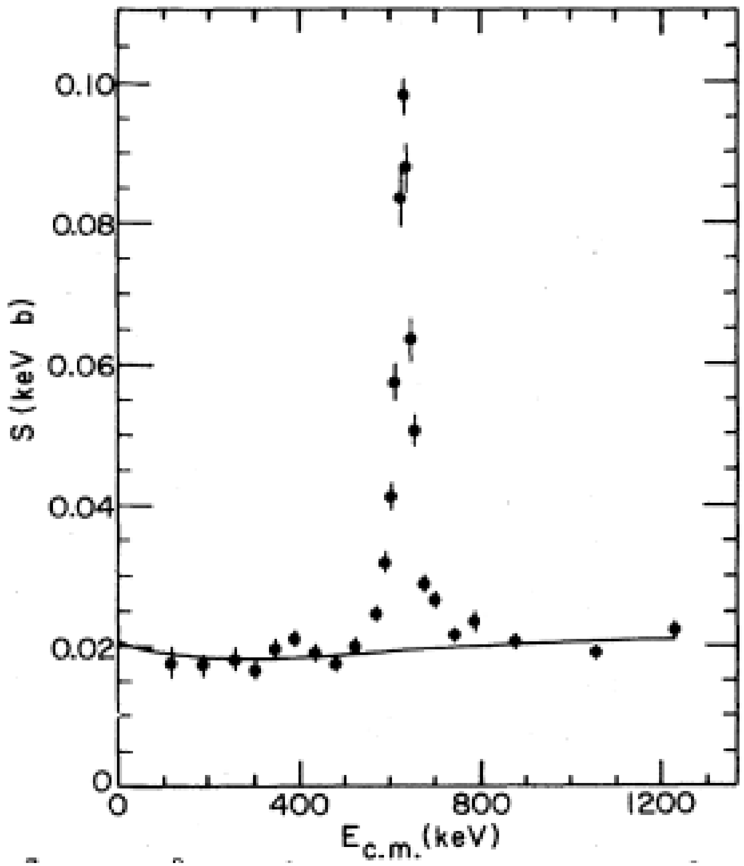

**$\sigma_{xy}$(E) $\propto$ tunneling probability for point coulomb charge**

# Example Reaction – $^7Be(p,\gamma)^8B$

**Nature of Cross Sections** | **S Factor = $\sigma E \exp(b/E^{1/2})$**



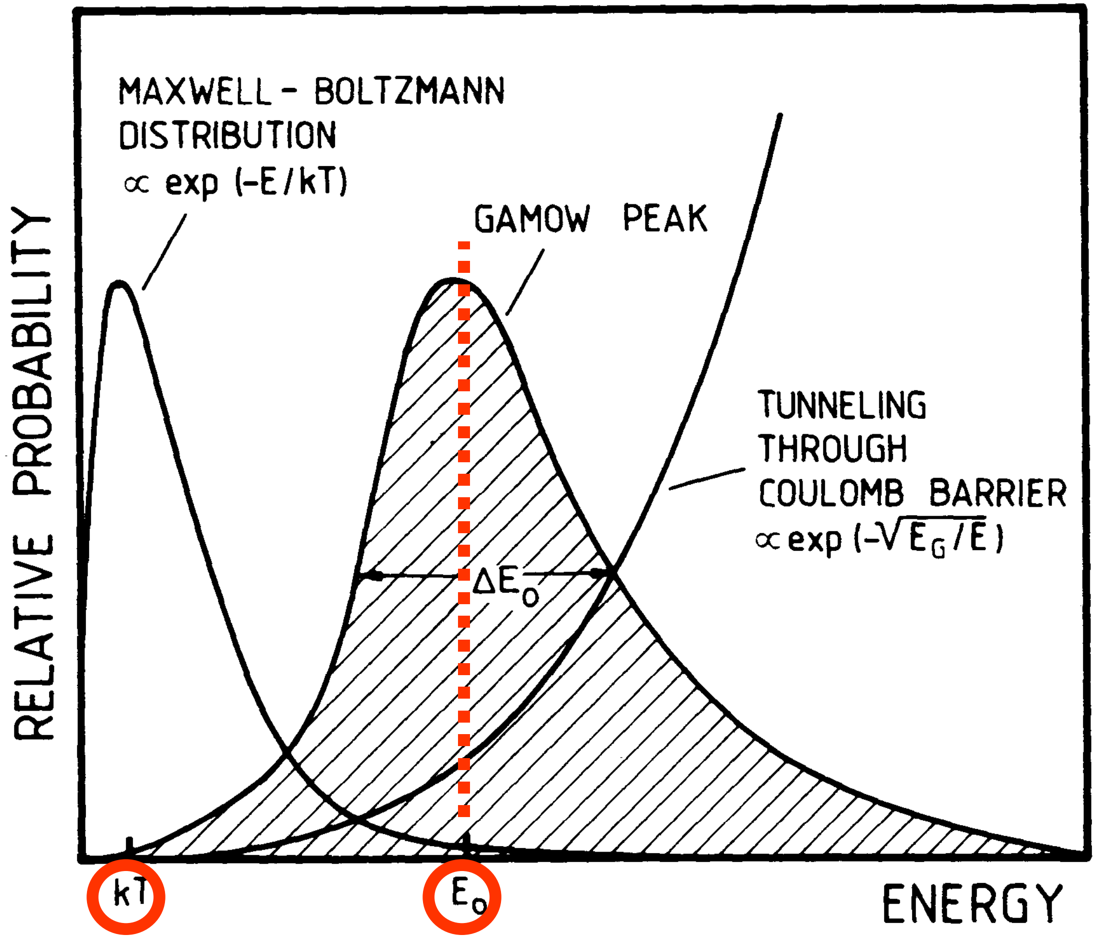

Increase Rapidly with Energy




Removes penetrability, nearly constant away from resonance

# What Energies are Important?

**S contains the nuclear structure information-**At what energy do we need to determine it?




**Gamow Peak**: Maximum in product of MB distribution and penetrability of Coulomb barrier

$E_0 =$ 5.9 keV p + p

27 keV $p+{}^{14}N$

56 keV $\alpha + \alpha$

237 keV ${}^{16}O+{}^{16}O$

**Cross sections at $E_o$ too small to be measured**

# S for Resonant and Non-Resonant Phenomena

**Resonance in Gamow Peak dominates the rate**

- Rate $\propto \Gamma_p \Gamma_\gamma / (\Gamma_p + \Gamma_\gamma) \cdot \exp(-E_r/kT)$
- Measure: $\Gamma$s, $E_r \Rightarrow$ Rate.
- $\Gamma$s may be strong functions of E

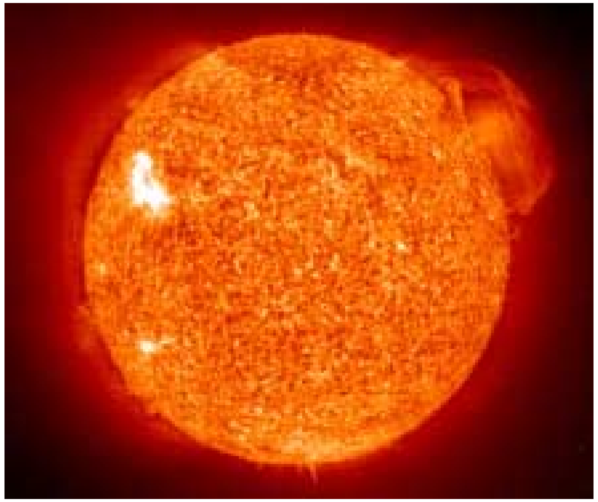
**No resonance--Rate characterized by slowly varying S factor at low energy.**

- Classic expts. with low-E accelerators: small $\sigma$'s at low-E
- Measure cross sections to low-E, extrapolate to $E_o$ to extract S-Factor.

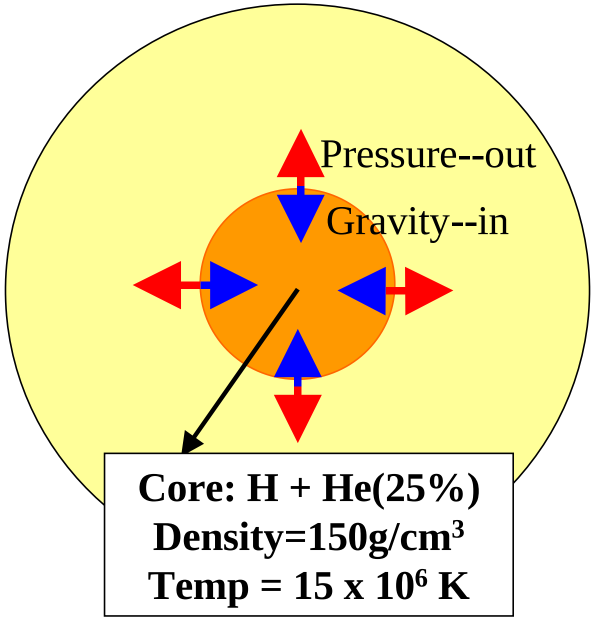
**Role of High-E facilities**

- Long used for resonant rates, esp. $E_r$
- Recent emphasis on new techniques to measure non-resonant rates. Subject of this talk and several talks at this meeting.

# Nature of Stellar Evolution



**How it looks!**
**Image of Sun: Goddard Space Flight Center**
(http://antwrp.gsfc.nasa.gov/apod/image/9709/solprom1_eit_big.jpg)




How it works!
Gravity pushes inward, but the center of the sun in heated by nuclear reactions, making a high pressure that pushes outwards. They balance, and the sun just sits there burning its nuclear fuel. This has gone on for 4.5 billion years and will continue for another 5 billion years.

# "Energy Production in Stars"

## A Scenario-H.A. Bethe (CNO Cycles)

Physical Review 55, 103(L) 1939.



**Energy Production in Stars**

In several recent papers,[1-3] the present author has been quoted for investigations on the nuclear reactions responsible for the energy production in stars. As the publication of this work which was carried out last spring has been unduly delayed, it seems worth while to publish a short account of the principal results.

The most important source of stellar energy appears to be the reaction cycle:

$$\begin{aligned} &C^{12}+H^1=N^{13}\ (a),\quad N^{13}=C^{13}+\epsilon^+\ (b)\\ &C^{13}+H^1=N^{14}\ (c)\\ &N^{14}+H^1=O^{15}\ (d),\quad O^{15}=N^{15}+\epsilon^+\ (e)\\ &N^{15}+H^1=C^{12}+He^4\ (f). \end{aligned} \qquad (1)$$

In this cycle, four protons are combined into one $\alpha$-particle (plus two positrons which will be annihilated by two electrons). The carbon and nitrogen isotopes serve as catalysts for this combination. There are no alternative reactions between protons and the nuclei $C^{12}C^{13}N^{14}$; with $N^{15}$, there is the alternative process

$$N^{15}+H^1=O^{16},$$

but this radiative capture may be expected to be about 10,000 times less probable than the particle reaction ($f$). Thus practically no carbon and nitrogen will be consumed and the energy production will continue until all protons in the star are used up. At the present rate of energy production, the hydrogen content of the sun (35 percent by weight[4]) would suffice for $3.5\times10^{10}$ years.

The reaction cycle (1) is preferred before all other nuclear reactions. Any element *lighter* than carbon, when reacting with protons, is destroyed permanently and will not be replaced. E.g., $Be^9$ would react in the following way:

$$\begin{aligned} &Be^9+H^1=Li^6+He^4\\ &Li^6+H^1=Be^7\\ &Be^7+\epsilon^-=Li^7\\ &Li^7+H^1=2He^4. \end{aligned}$$

Therefore, even if the star contained an appreciable amount of Li, Be or B when it was first formed, these elements would have been consumed in the early history of the star. This agrees with the extremely low abundance of these elements (if any) in the present stars. These considerations apply also to the heavy hydrogen isotopes $H^2$ and $H^3$.

The only abundant and very light elements are $H^1$ and $He^4$. Of these, $He^4$ will not react with protons at all because $Li^5$ is unstable, and the reaction between two protons, while possible, is rather slow[5] and will therefore be much less important[6] in ordinary stars than the cycle (1).

Elements heavier than nitrogen may be left out of consideration entirely because they will react more slowly with protons than carbon and nitrogen, even at temperatures much higher than those prevailing in stars. For the same reason, reactions between $\alpha$-particles and other nuclei are of no importance.

To test the theory, we have calculated (Table I) the energy production in the sun for several nuclear reactions, making the following assumptions:

(1) The temperature at the center of the sun is $2\times10^7$ degrees. This value follows from the integration of the Eddington equations with any reasonable "star model."[4] The "point source model" with a convective core which is a very good approximation to reality gives $2.03\times10^7$ degrees.[7] The same calculation gives 50.2 for the density at the center of the sun. The central temperature is probably correct to within 10 percent.

(2) The concentration of hydrogen is assumed to be 35 percent by weight, that of the other reacting element 10 percent. In the reaction chain (1), the concentration of $N^{14}$ was assumed to be 10 percent.

(3) The ratio of the average energy production to the production at the center was calculated[7] from the temperature-density dependence of the nuclear reaction and the temperature-density distribution in the star.

TABLE I. *Energy production in the sun for several nuclear reactions.*

| Reaction | Average Energy Production $\epsilon$(erg/g sec.) |
|---|---|
| $H^1+H^1=H^2+\epsilon^++f.$* | 0.2 |
| $H^2+H^1=He^3$ | $3\times10^{18}$ |
| $Li^7+H^1=2He^4$ | $4\times10^{16}$ |
| $B^{10}+H^1=C^{11}+f.$ | $3\times10^{8}$ |
| $B^{11}+H^1=3He^4$ | $10^{10}$ |
| $N^{14}+H^1=O^{15}+f.$ | 3 |
| $O^{16}+H^1=F^{17}+f.$ | $10^{-4}$ |

* "+f." means that the energy production in the reactions following the one listed, is included. E.g. the figure for the $N^{14}+H^1$ includes the complete chain (1).

It is evident from Table I that only the nitrogen reaction gives agreement with the observed energy production of 2 ergs/g sec. All the reactions with lighter elements would give energy productions which are too large by many orders of magnitude if they were abundant enough, whereas the next heavier element, $O^{16}$, already gives more than 10,000 times too small a value. In view of the extremely strong dependence on the atomic number, the agreement of the nitrogen-carbon cycle with observation is excellent.

The nitrogen-carbon reactions also explain correctly the dependence of mass on luminosity for main sequence stars. In this connection, the strong dependence of the reaction rate on temperature ($\sim T^{18}$) … massive stars have much greater … slightly higher central temperature … $T=3.2\times10^7$ and $\epsilon=1200$ ergs/g sec …

With the assumed reaction chain … preciable change in the abundance … than helium during the evolution … transmutation of hydrogen into heli… is more general than the reaction c… to the commonly accepted "Aufbau…

A detailed account of these inve… lished soon.

Cornell University,
Ithaca, New York,
December 15, 1938.

[1] C. F. v. Weizsaecker, Physik. Zeits. 39, …
[2] J. Oppenheimer and R. Serber, Phys. R…
[3] G. Gamow, Phys. Rev. (in print).
[4] B. Strömgren, Ergebn. d. Exak. Naturw…
[5] H. Bethe and C. Critchfield, Phys. Rev. …
[6] Only for very cool stars (red dwarfs) … become important.
[7] The author is indebted to Mr. Marshak …

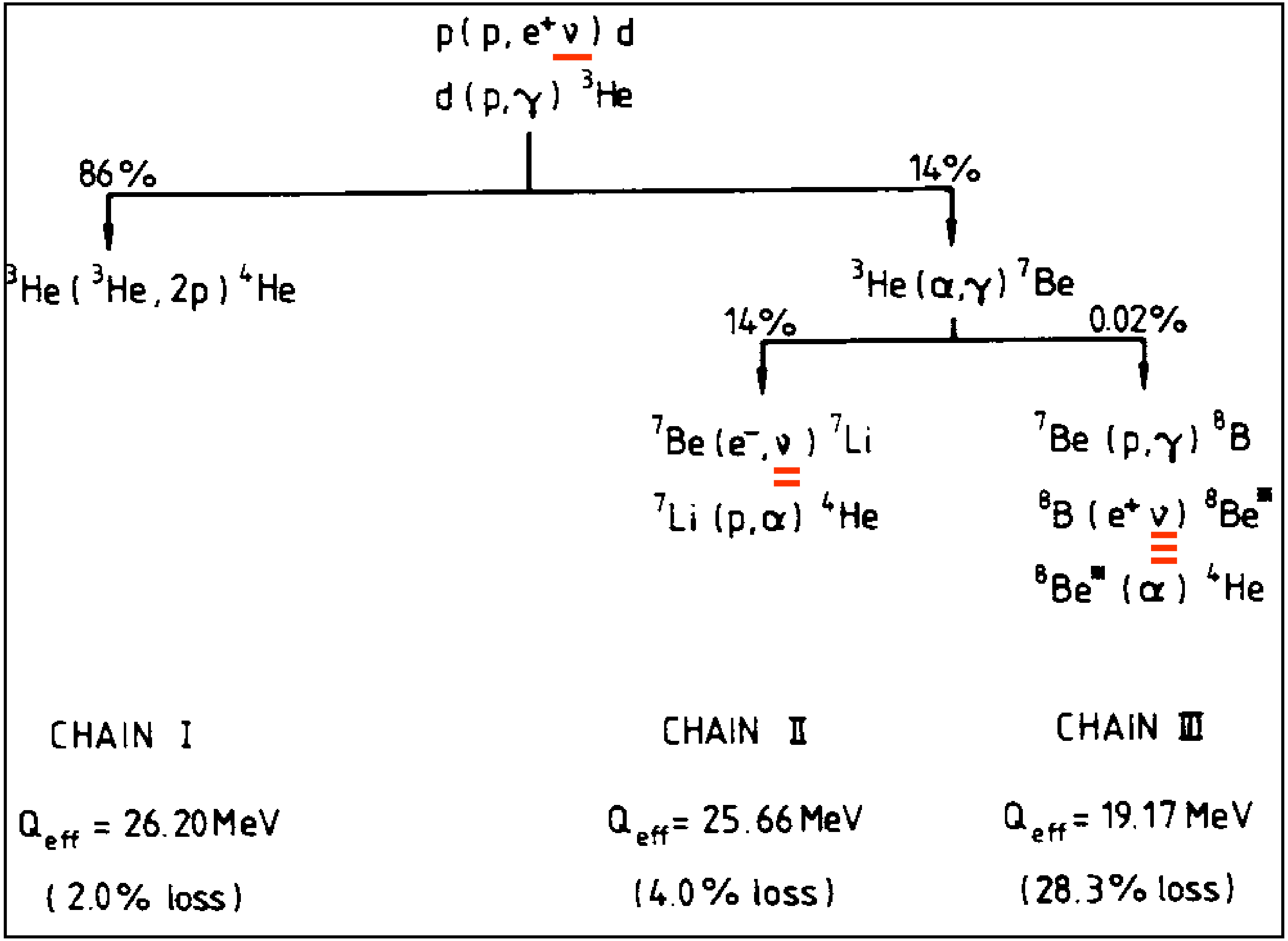
**One Page -**
**One Nobel - 1967**

**...for his contributions to the theory of nuclear reactions, especially his discoveries concerning energy production in stars.**

The most important source of stellar energy appears to be the reaction cycle:

$$\begin{aligned} &C^{12}+H^1=N^{13}\ (a),\quad N^{13}=C^{13}+\epsilon^+\ (b)\\ &C^{13}+H^1=N^{14}\ (c)\\ &N^{14}+H^1=O^{15}\ (d),\quad O^{15}=N^{15}+\epsilon^+\ (e)\\ &N^{15}+H^1=C^{12}+He^4\ (f). \end{aligned} \qquad (1)$$

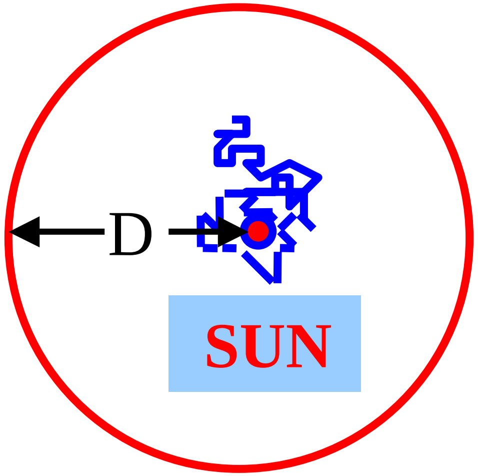
# The pp Chains and Neutrino Sources



# Observing the Center of the Sun with Solar Neutrinos

## Problem

- Can't look with telescopes
- Light is absorbed in L, re-emitted in random direction.
- Drunkard's walk: Distance covered = $(N)^{1/2}$ L
  - N number of steps;
  - L length of a step.




## Result:

For sun, L = 0.1 cm, D = 6.96 x $10^{10}$ cm. Takes: 5 x $10^4$ yr

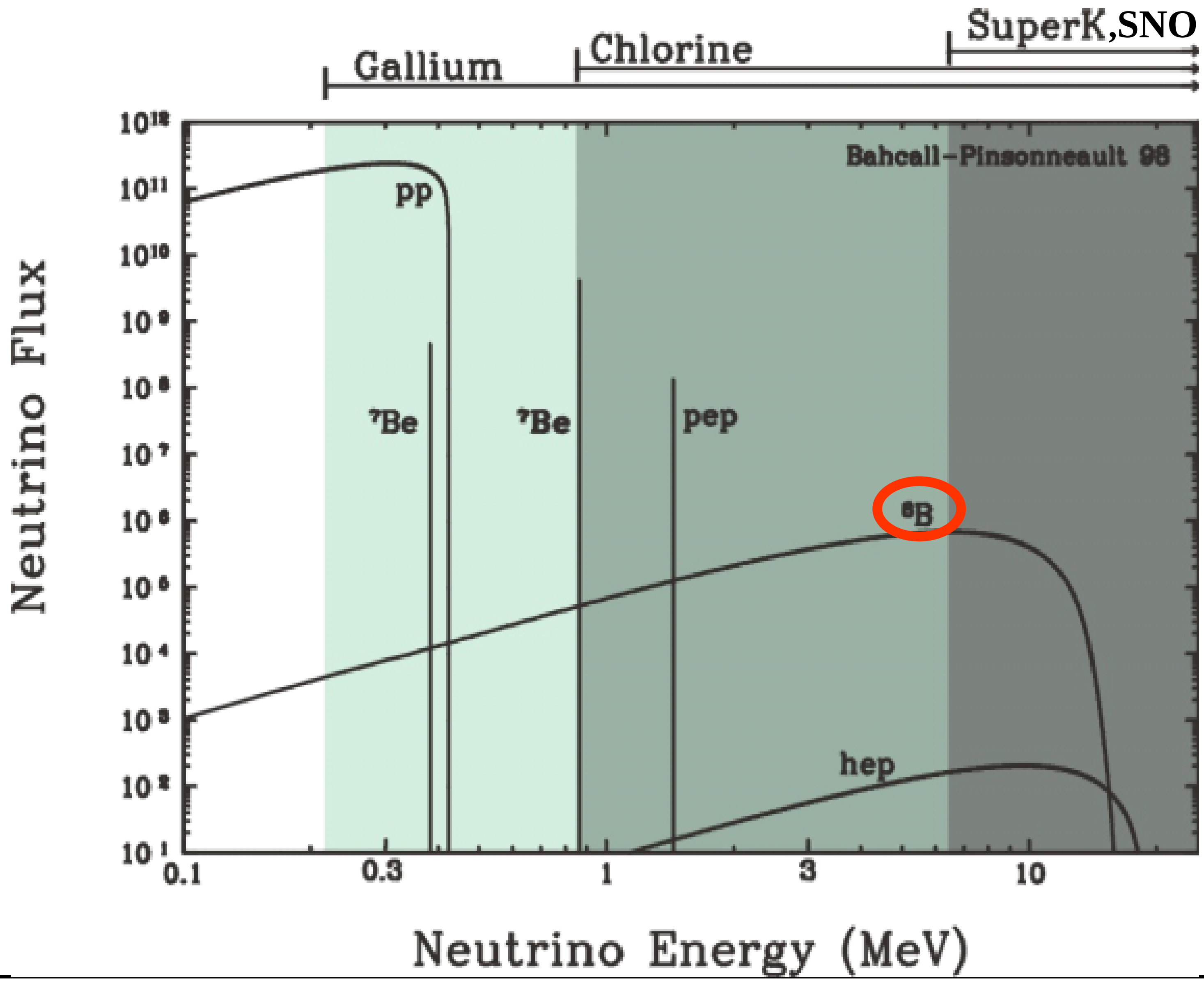
## Look at emitted neutrinos

- Made in solar cycle, escape without hindrance
- $N_\nu \sim T^{18}$, measuring flux measures T at center of sun

## But it's hard

- νs hardly interact
- Need a huge detector

# Solar Neutrino Spectra-Detector Thresholds



# First experiment-R. Davis (1968)

## The Detector

- 100,000 gallons cleaning fluid (perchlorethylene $C_2Cl_4$), Homestake gold mine, S.D.
- $\nu + {}^{37}Cl \rightarrow e + {}^{37}Ar$ - Inverse β-decay
- Collect by bubbling He through tank (every 30 days)-count radioactive $^{37}Ar$

## Motivation

"To see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation."

# Implications of the Davis Experiment

## Results

- Expected 2 $^{37}Ar$ per day.
  **Got 0.5/day-a shocker!**
- "Solar neutrino problem", a *one-number* problem
- Solution in solar physics? nuclear physics? particle physics?
- Motivated a search for the cause: 1968 to present
- Better solar models, improved input nuclear physics.

## New Experiments-different neutrino energy sensitivities

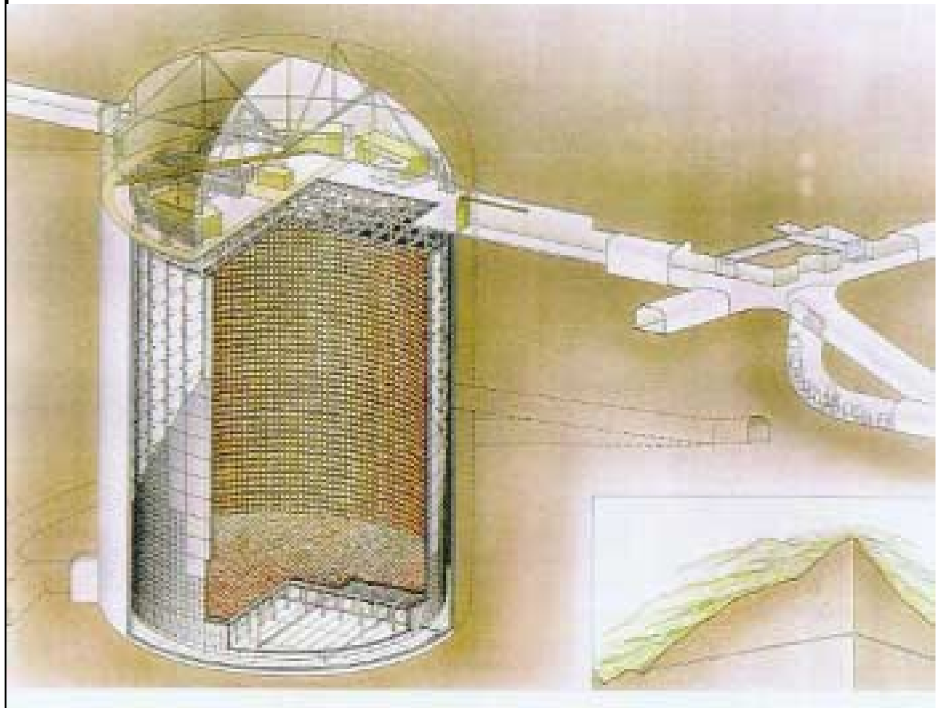
- Davis( Cl)----------$^{8}B$, $^{7}Be$ $\nu_e$
- Gallex/Sage (Ga)--p-p, $^{7}Be$ $\nu_e$
- SNO ($D_2O$)----------$^{8}B$ $\nu_e$, $\nu_x$
- Super-K($H_2O$)-------$^{8}B$ $\nu_e$, ($\nu_x$)

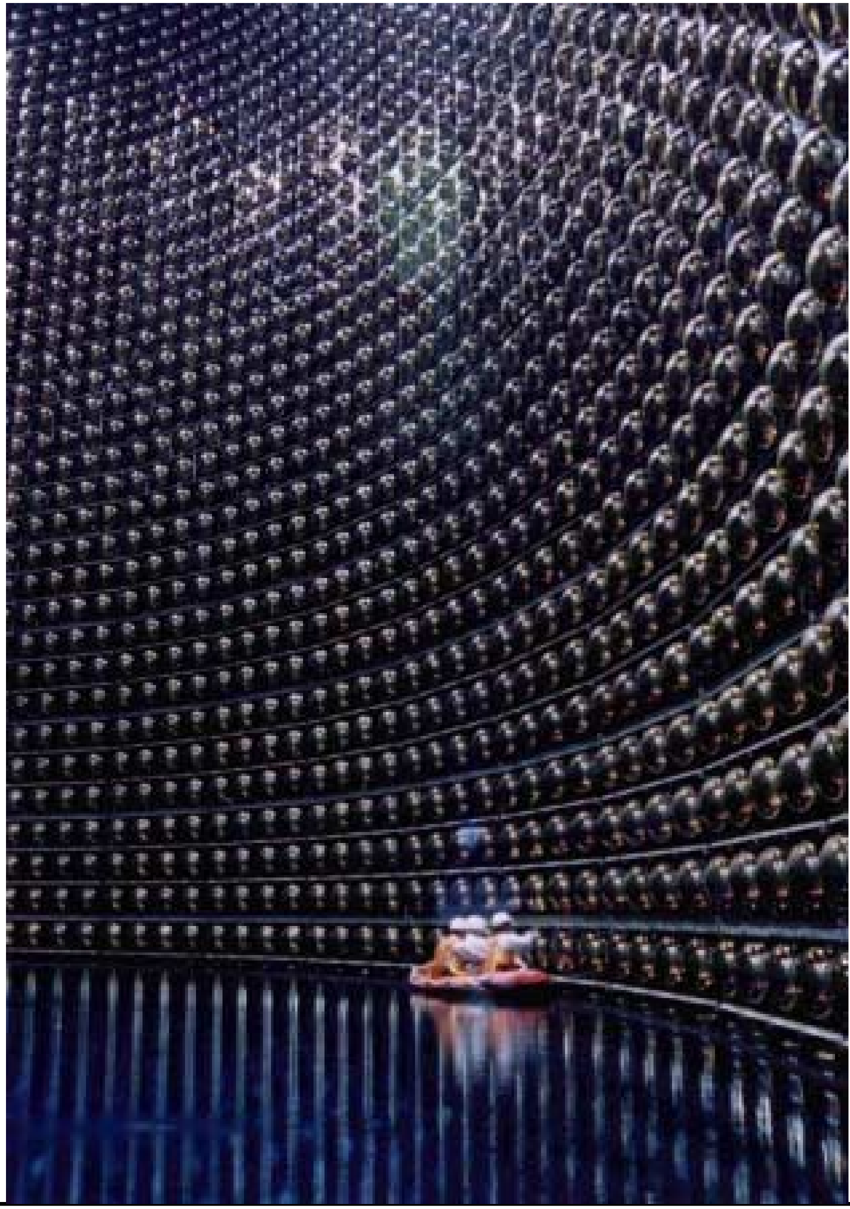
**Others yet to come, see**
http://www.sns.ias.edu/~jnb

## **The Super-Kamiokande Detector** Japan, US, Korea, Poland

### Properties

- 50,000 tons $H_2O$, 11200 P.M.s
- 1000m underground, Mozumi mine, Kamioka Mining Co.
- Observe $\nu_e$-e scattering (mainly)-via Ĉerenkov light





# SNO—The Sudbury Neutrino Detector

## Unique characteristics

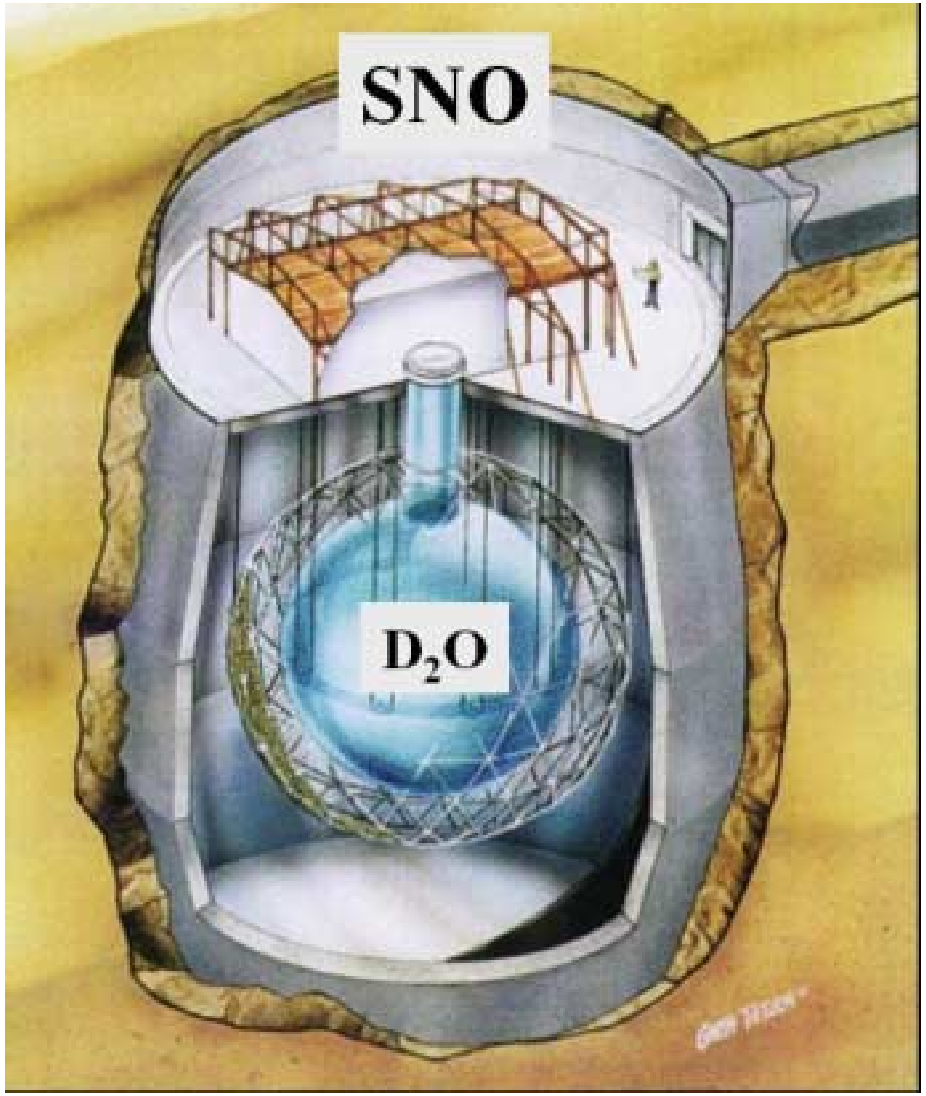
- 1000 tons heavy water ($D_2O$)
- See electron neutrinos **and** muon and tau neutrinos
- Charged current (CC)

  $\nu_e + D \rightarrow p + p + e^-$
- Neutral current (NC)

  $\nu_x + D \rightarrow \nu_x + p + n$
- $\nu_x + e \rightarrow \nu_x + e$ (ES)

## Location

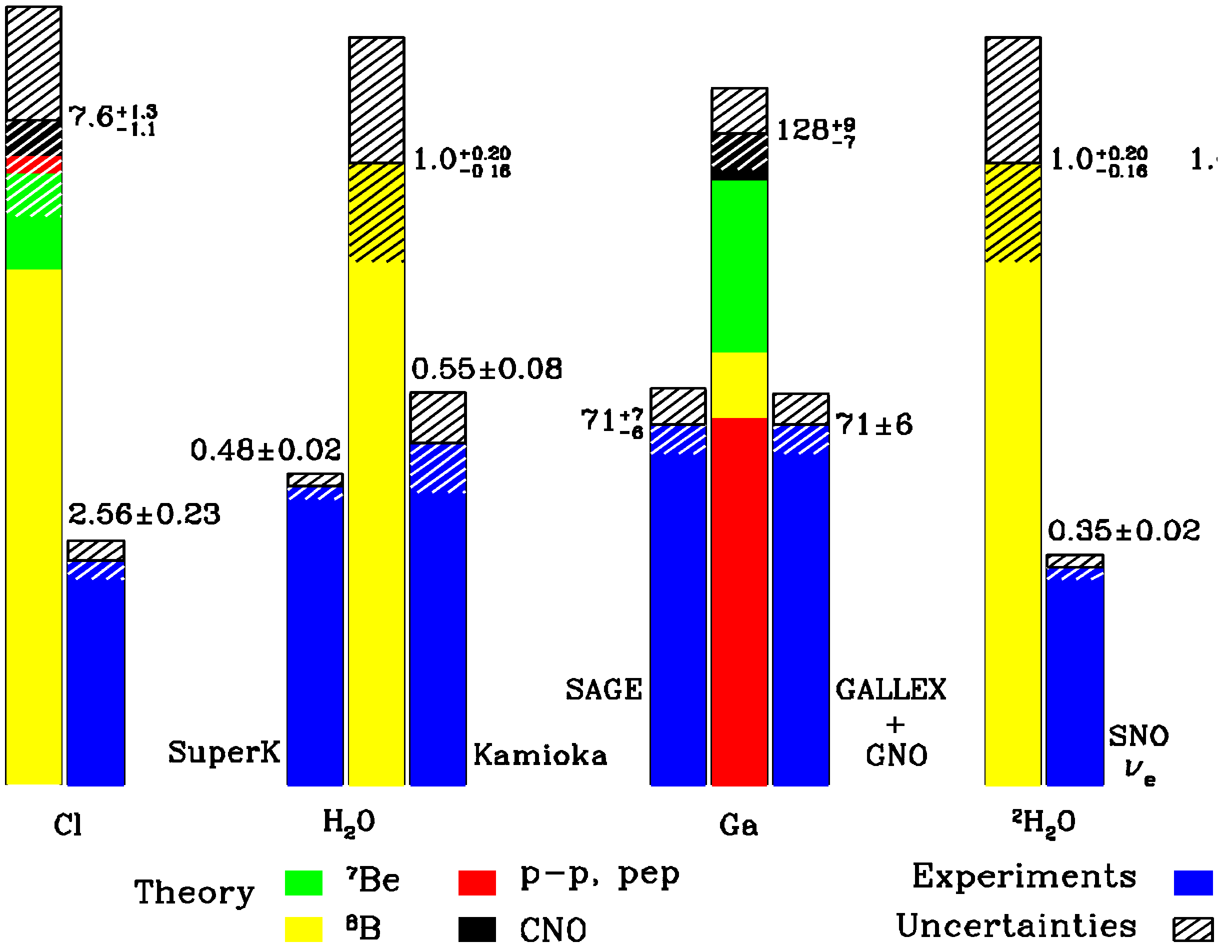
- 6800 feet under ground, Creighton mine Sudbury, Ontario.
- Canada, US, UK



# Solar Neutrino Experiments--Summary

## Standard solar model vs. Expt.

Bahcall and Pinsonneault, 2000




**It appears:** different fractions of neutrinos arrive at the detectors

- All of p-p ν's
- ~0.5 of $^8$B ν's
- Few of $^7$Be ν's

As compared to the standard solar model

**Note:** SNO differs from S-K because S-K sensitive to $\nu_x$

# How might this happen

## Flaws in the physics input?

- Stellar physics--no, details to be settled. A check from Helioseismology
- Nuclear Physics--no, but better prediction of fluxes needed .
- Properties of neutrinos--the consensus culprit

## Neutrino oscillations

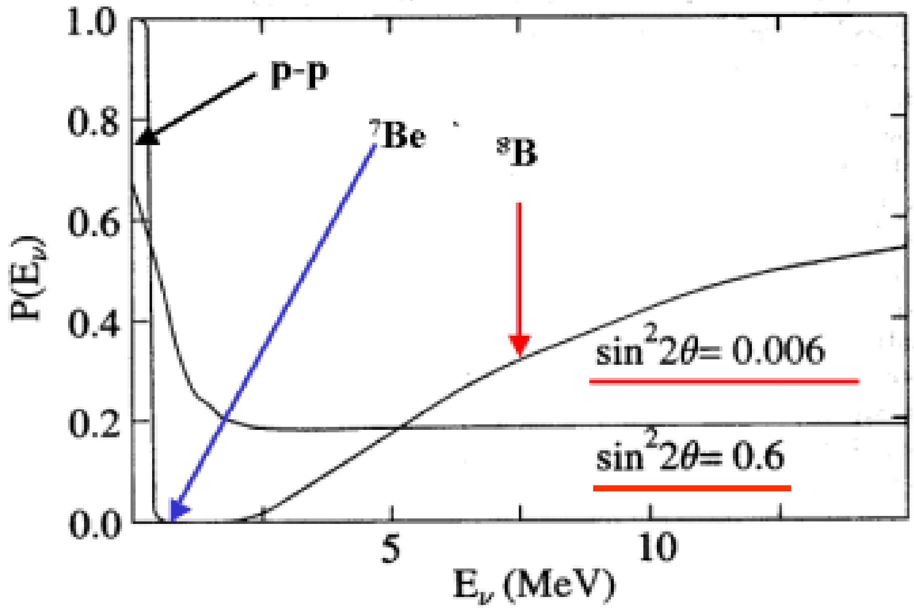
- Neutrinos have mass. Oscillate into another type of neutrino. ($\nu_e \rightarrow \nu_\mu$)
- Detector not sensitive to these neutrinos
- Probability of survival: $\mathbf{P(\nu_e \rightarrow \nu_e)}$
- $\mathbf{P(\nu_e \rightarrow \nu_e) = 1-(\sin^2\Theta_V) \sin^2(a\Delta m^2 d/E)}$

  $\Delta m^2 = (m_1{}^2 - m_2{}^2)$
- Passage through matter changes the constraints-resonant conversion.

# Determining $\Delta m^2$ and $\Theta_V$

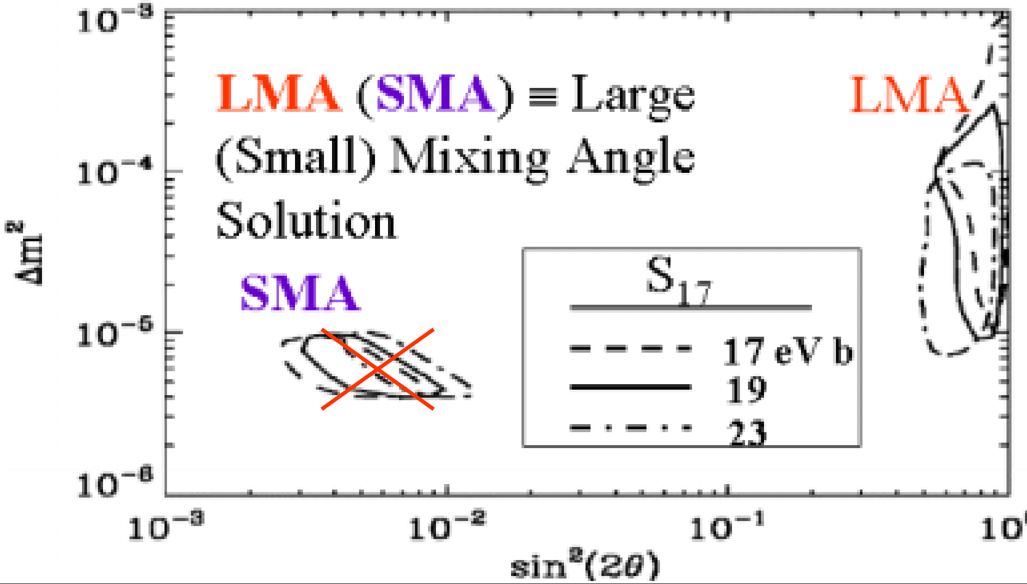
## Survival Probability

- Show two cases: large mixing angle (now favored) and small mixing angle.
- Analysis is complex and subtle




## Example

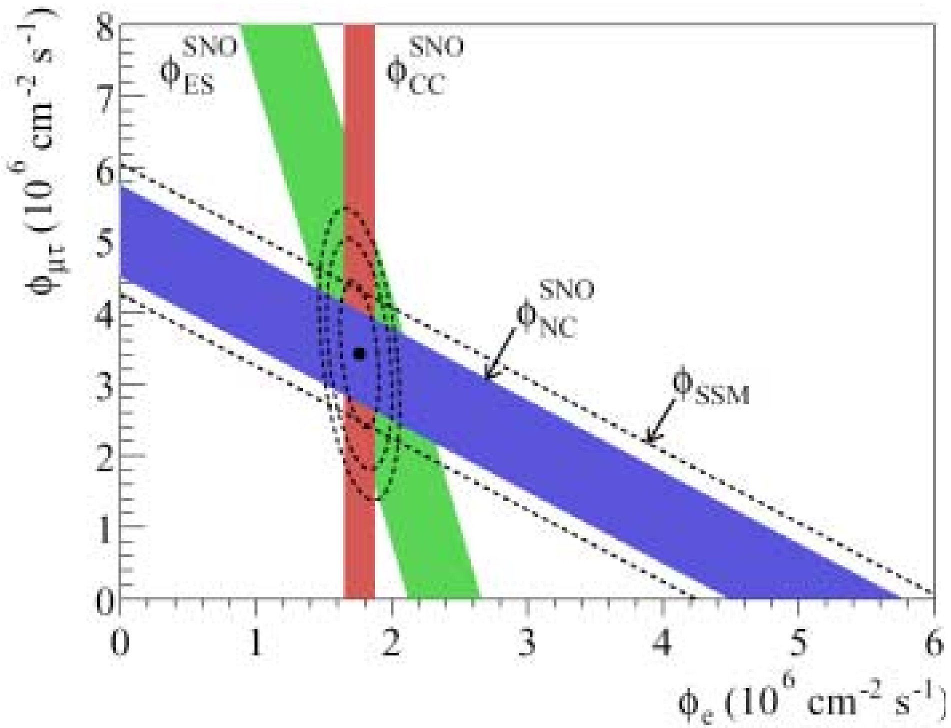
- Extracted values depend on reaction rates for
  - $^7Be(p,\gamma)^8B$, ($S_{17}$)
  - $^3He(\alpha,\gamma)^7Be$
- H. Schlattl, *et al.*, PRD **60,** 113002 (1999)



# Neutral Currents from SNO

## First results (with S-K)

- Ascribe difference in SNO CC rate ($\nu_e$) and S-K ES rate ($\nu_e + \nu_x$) to $\nu_x$
- Extract $\nu_x$ –agrees with Standard Solar Model (SSM)




## New from SNO

Combine all three SNO detection modes CC, NC, ES

## Results

- $\phi(\nu_e) = 1.76 \times 10^6$ cm$^{-3}$sec$^{-1}$; $\phi(\nu_\mu + \nu_\tau) = 3.41 \times 10^6$ cm$^{-3}$sec$^{-1}$
- Good agreement with SSM- solar neutrino problem is no more

# Need Better Nuclear Data

## Why

- Explanation of solar neutrino problem is still imprecise
- Extracted values of $\Delta m^2$ and $\Theta_V$ depend on the cross sections for certain nuclear reactions

## Important cases

- $^3He(\alpha,\gamma)^7Be$
- $^7Be(p,\gamma)^8B$, ($S_{17}$)

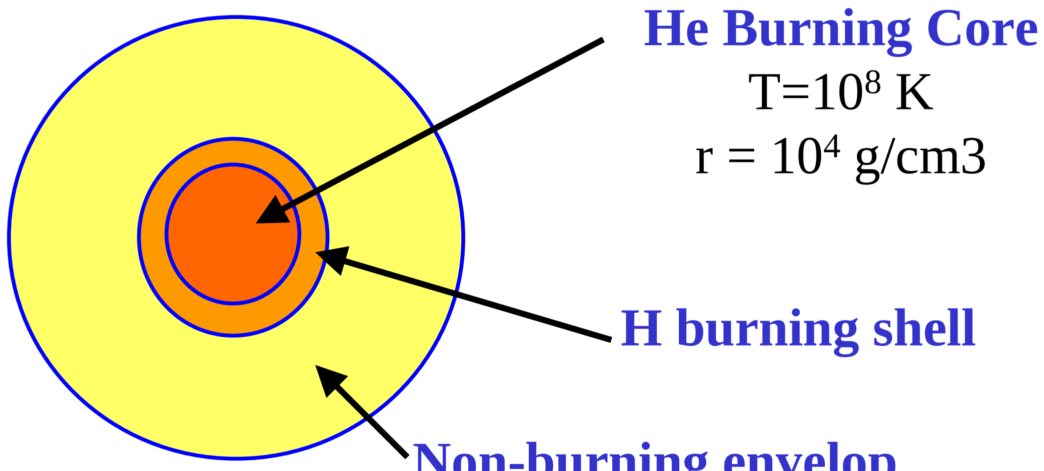
# How the Sun Evolves

**Core hydrogen burning ends**

- Consumed central 10% of sun
- No heat source, pressure decreases, gravity wins
- Core collapses, releases gravitational energy which heats the core

**Core helium burning starts**

- Core hot-allows fusion of two a's (Z=2)
- Helium fuses to $^{12}C$, $^{16}O$
- Hydrogen burns in shell



## What's next for the Sun?

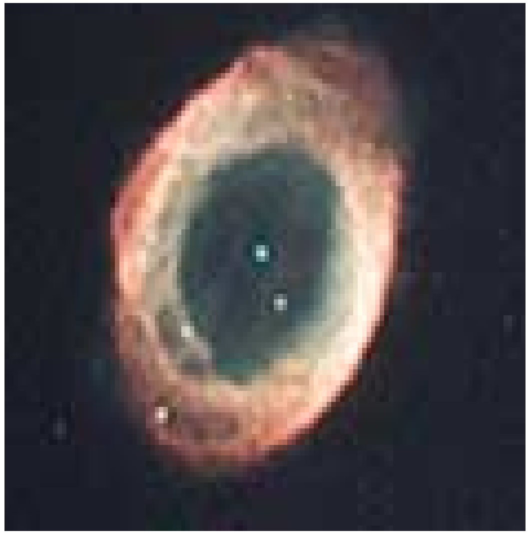
### It's the end of the line

- Helium burning ends after $10^8$ years, C and O core
- Gravitational collapse, BUT, never reach sufficient T to fuse C + C.
- Collapse continues to $10^7$ g/cm$^3$--electron pressure stops collapse

- Shells still burning, unstable, blow off planetary nebula

### Star becomes a white dwarf (e.g. Sirius B).

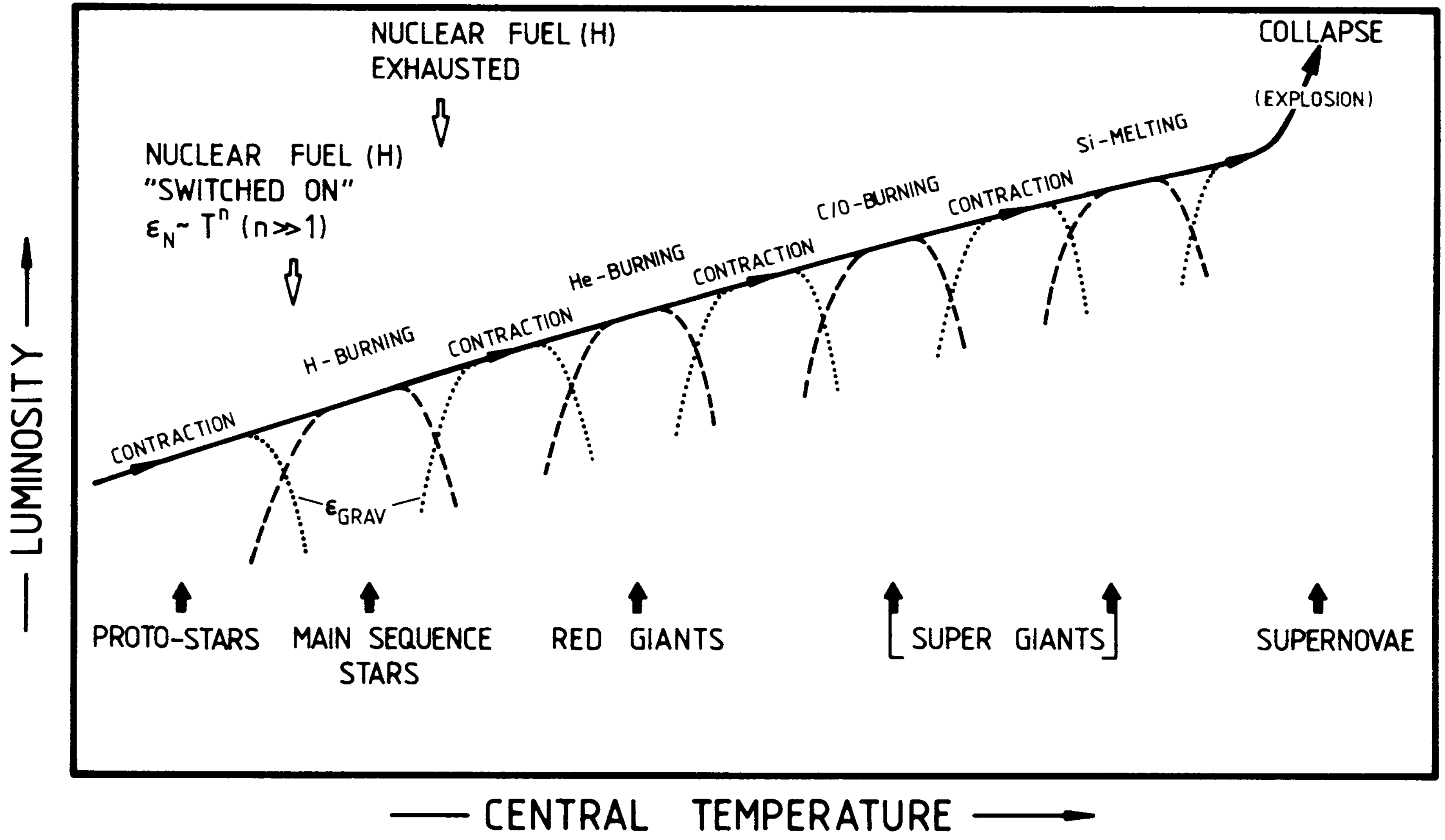
| Property | Earth | Sirius B | Sun |
|---|---|---|---|
| Mass ($M_{sun}$) | $3\times10^{-6}$ | 0.94 | 1.00 |
| Radius($R_{sun}$) | 0.009 | 0.008 | 1.00 |
| Luminosity($L_{sun}$) | 0.0 | 0.0028 | 1.00 |
| Surface T (K) | 287 | 27,000 | 5770 |
| Mean r (g/cm$^3$) | 5.5 | $2.8\times10^6$ | 1.41 |
| Central T (K) | 4200 | $2.2\times10^7$ | $1.6\times10^7$ |
| Central r (g/cm$^3$) | 9.6 | $3.3\times10^7$ | 160 |



**Ring nebula in Lyra-NGC 6720—a planetary nebula**

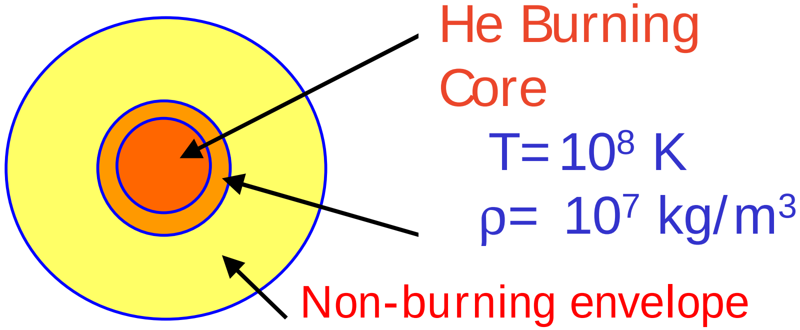
# The Evolutionary Process for Heavy Stars

## With this background can guess what happens for heavier stars



# Heavy Stars--The Stellar Onion

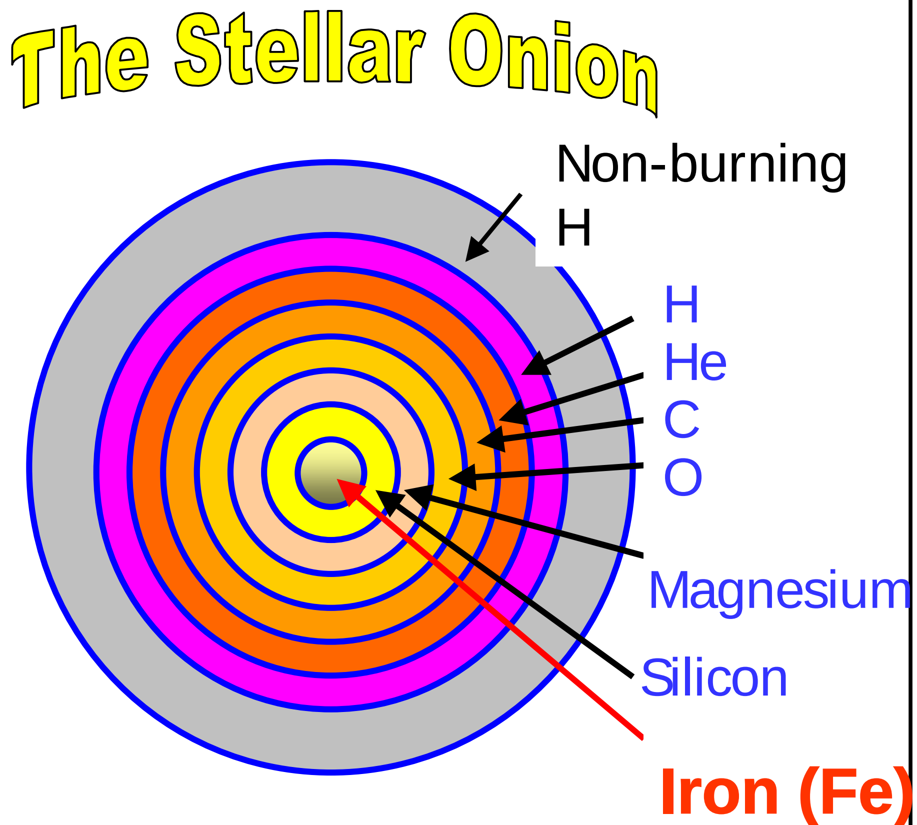
**Starts like the sun:**




But now, when He is exhausted in the core and the core collapses, it does get hot enough to burn carbon and oxygen.

**The successive stages in the core are H → He, gravity, He → C,O, gravity, → C,O → Mg, Si, gravity, Si →Fe.**

## The Result



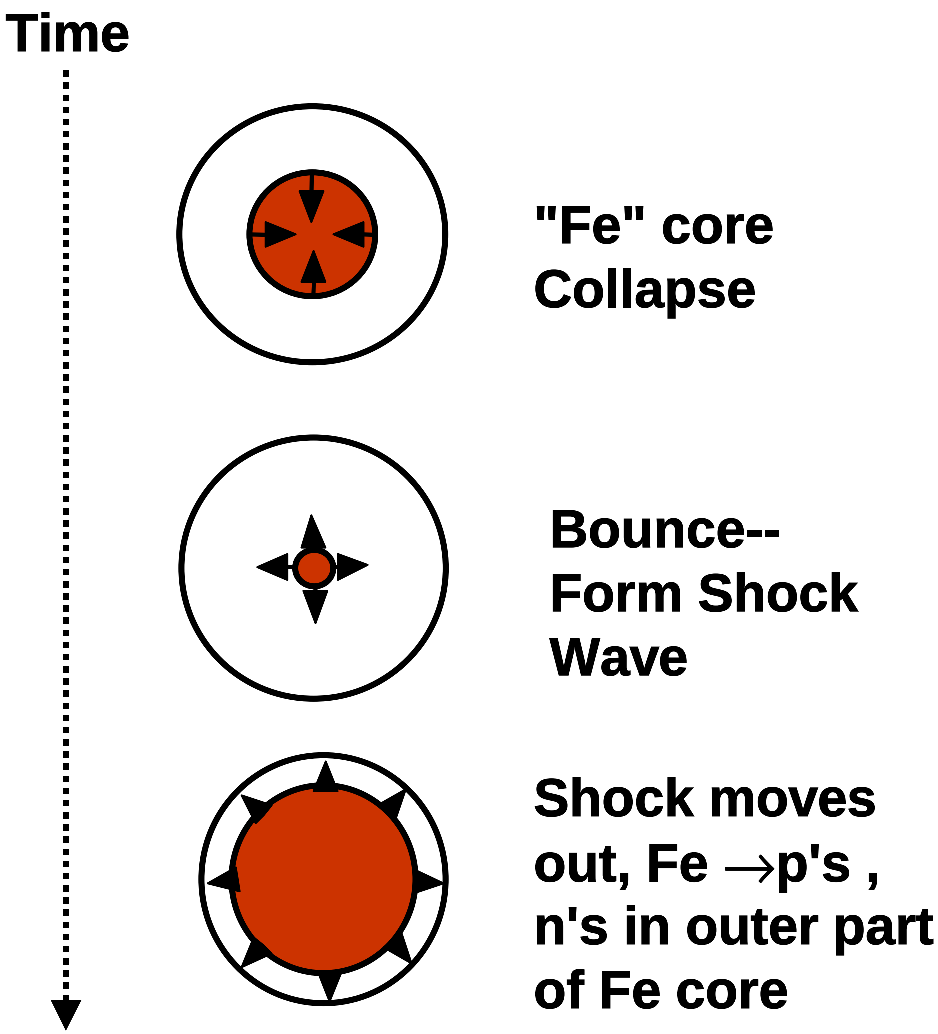

**Attention !!!**

# Supernovae Core Collapse

**Fe (Iron) is special** Core of our stellar onion is "Fe", most tightly bound nucleus. Result of fusing two "Fe's" is heavier than two "Fe's"; costs energy to fuse them. No more fusion energy is available.

**Core collapses,** keeps on collapsing, until reach nuclear density. Then nuclei repel, outer core bounces.

**Outgoing shock wave forms**



## Evolutionary Stages of a 25 $M_{sun}$ Star Weaver et al., 80

| Burning Stage | Time Scale | T(K) x $10^9$ | ρ (g/cm$^3$) |
|---|---|---|---|
| H | 7 x $10^6$ y | 0.006 | 5 |
| He | 5 x $10^5$ y | 0.23 | 700 |
| C | 600 y | 0.93 | 2 x $10^5$ |
| Ne | 1 y | 1.7 | 4 x $10^6$ |
| O | 0.5 y | 2.3 | 1 x $10^7$ |
| Si | 1 d | 4.1 | 3 x $10^7$ |
| Core collapse | Seconds | 8.1 | 3 x $10^9$ |
| Core Bounce | Millisec | 34.8 | 3 x $10^{14}$ |
| Explosive | 0-1-10 sec | 1.2-7.0 | |

# What Next?

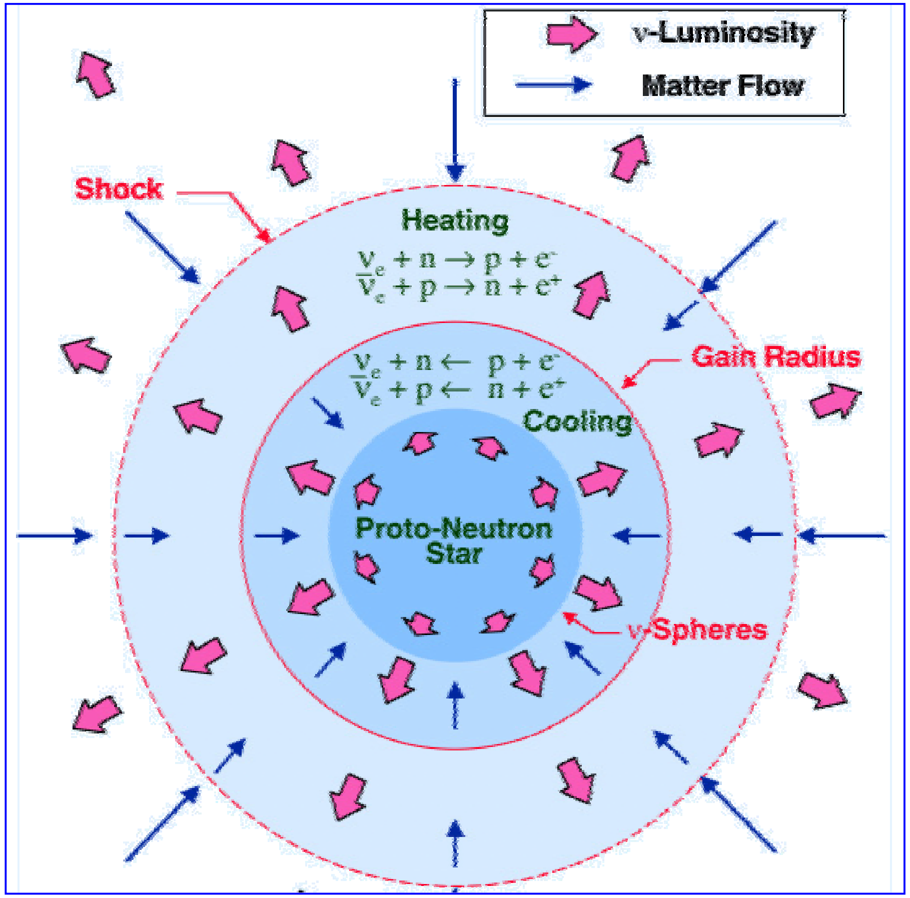
## We know that

- Shock blows off outer layers of star, a supernova
- $10^{51}$ ergs (1foe) visible energy released (total gravitational energy of $10^{53}$ ergs mostly emitted as neutrinos).

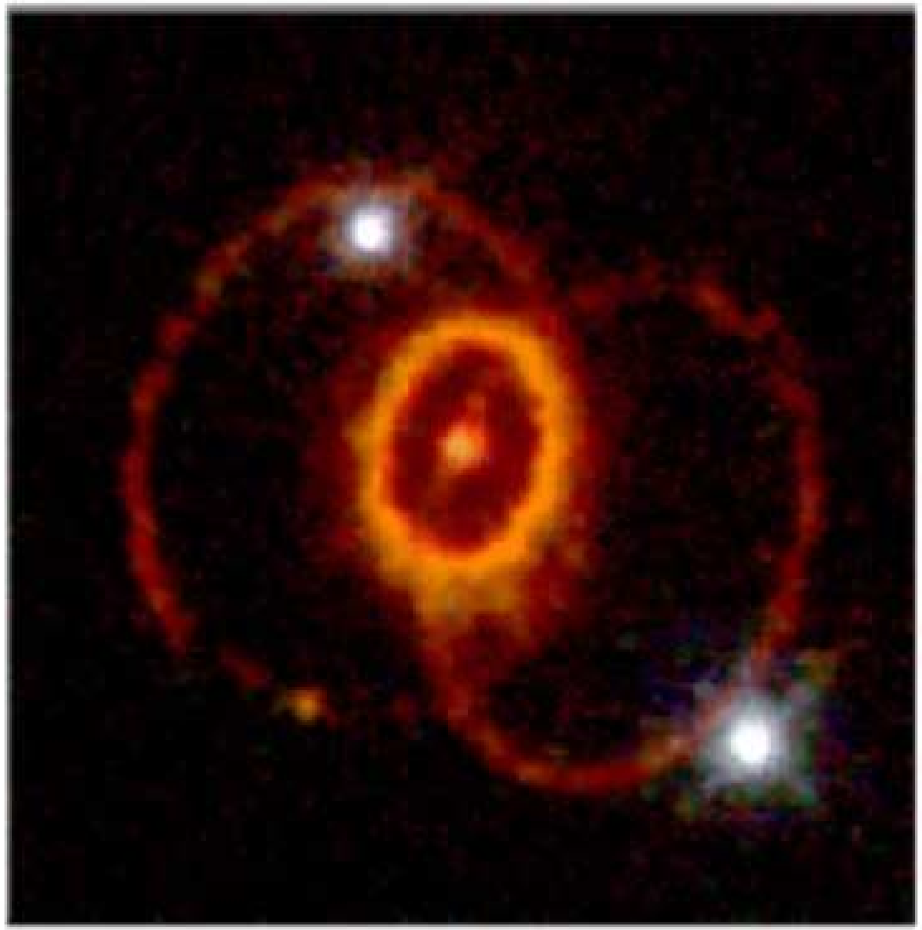
## Theoretically

- Spherical SN don't explode
- Shock uses its energy dissociating "Fe", stalls
- Later, ν's from proto-neutron star deposit energy, restart the shock. Still no explosion.

**1-D model** (T. Mezzacappa)



## The Question—How do we get from here to an explosion?



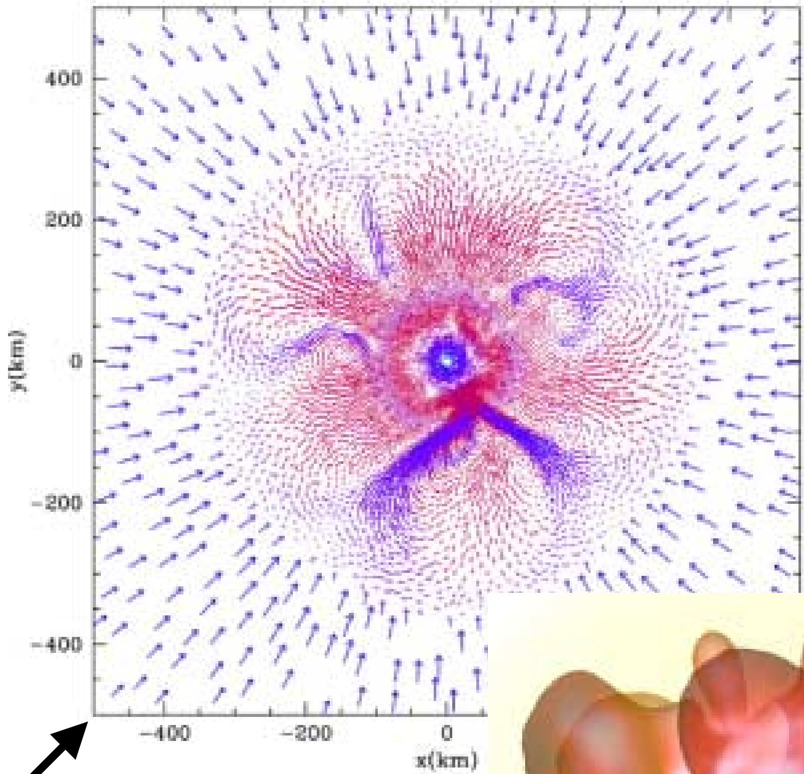
SN 1987a in Large Magallanic Cloud

# Non-Spherical Calculations

## Is sphericity the problem?

- Now have 3-D calculations which explode, but have only a part of the detailed microphysics. Their stability against such changes is not known—we return to this later.
- See, e.g. C. Fryer and M. Warren, Astrophysical Journal, 574:L65-L68
- Find 2-D, 3-D similar

## Two views

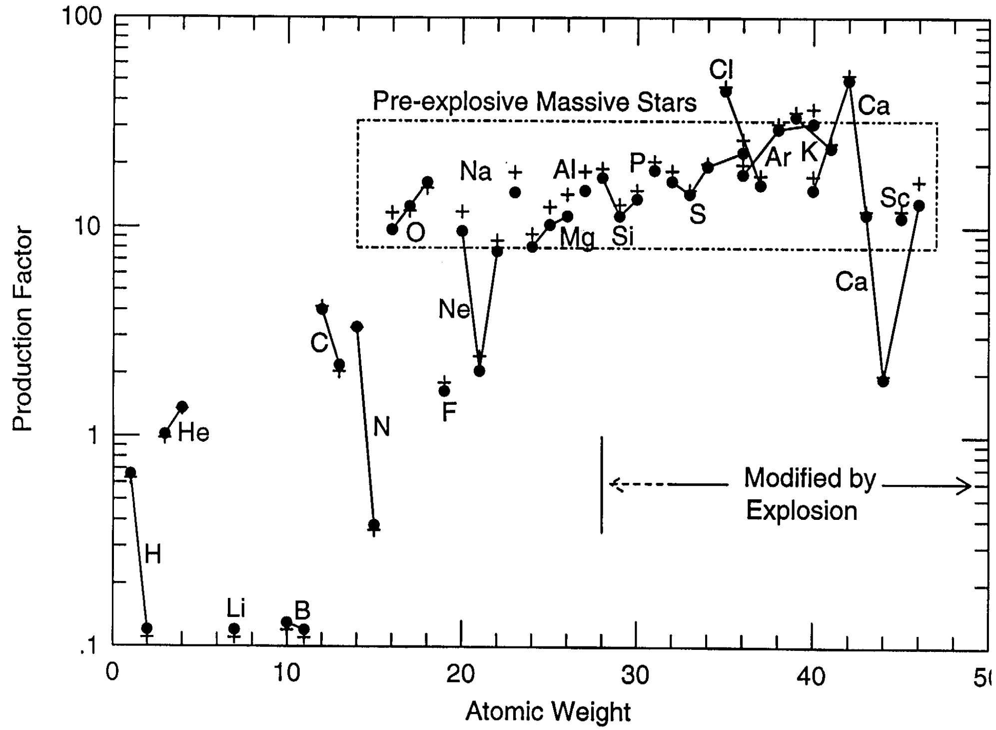



Red upwelling
Blue sinking

# What's Produced in a Supernova

## Model

- Evolve the Pre-SN star
- Put in a piston that gives the right energy to the ejecta (Don't know how explosion really works).
- Calculate what is ejected
- Calculate explosive processes as hot shock passes.
- Example: Wallace and Weaver, Phys. Rep. **227**,65(93)




## Find

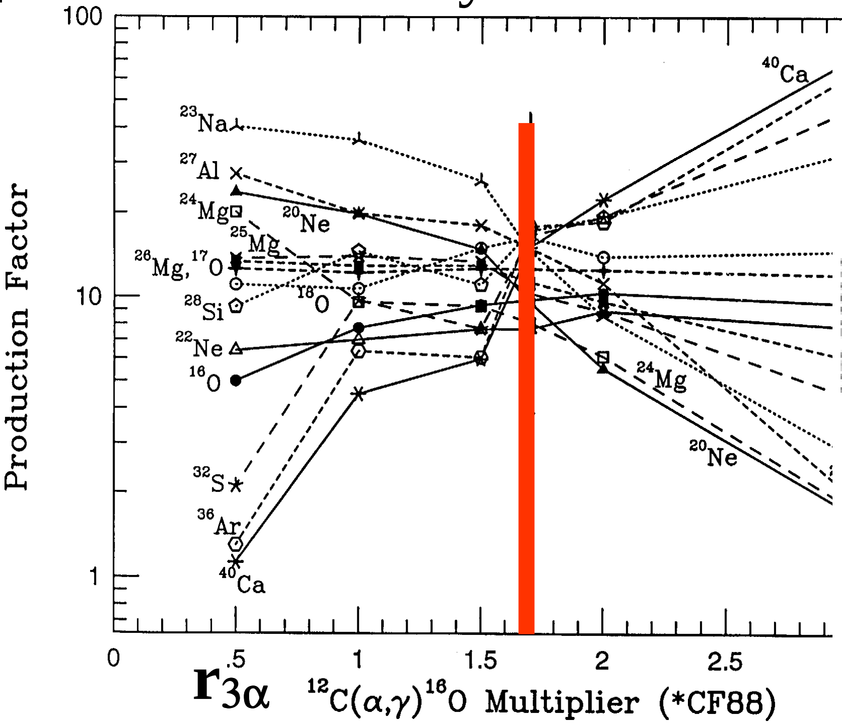
- Elements, mass 20-50, generally reproduced at same ratio to solar.
- Modifications by explosive processes are small

# $^{12}C(\alpha,\gamma)^{16}O$—an Important Reaction

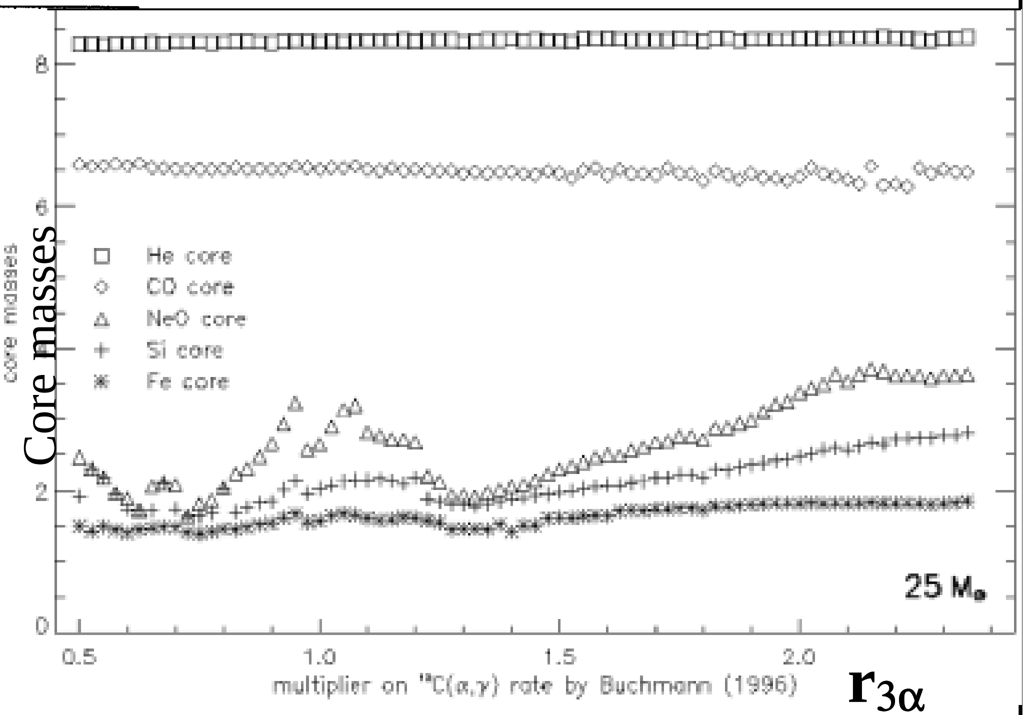
**Helium Burning-** A two Stage Process

- $3\alpha$: $\alpha + \alpha \Leftrightarrow {}^{8}Be^{*} + \alpha \rightarrow {}^{12}C^{*} \rightarrow {}^{12}C$ (gs) Rate known to $\pm$ 12%
- $^{12}C(\alpha,\gamma)^{16}O$ Poorly known (20-30%)
- Ratio affects $^{12}C/^{16}O$ after He burning—important resulting effects

Element Synthesis in SN




Mass of Pre-SN Cores



# Some important Nuclear Rates for SN Synthesis

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

- $r_{3\alpha}$ = 170 ± 20 keV-b (300 keV) describes abundances (last slide)
- Experiment: 100-200, preference near 150, but uncertain.
- **High priority reaction**

**$^{12}C$ + $^{12}C$ for Carbon burning**

**$^{22}Ne(\alpha,\gamma)$, $^{22}Ne$ ($\alpha$, n)**

Production of light slow neutron capture (s-process) nuclides--A= 60=88

**Weak decay rates for gamma line emitters.** E.g. $^{60}Fe$

**Charged particle reactions on N=Z nuclei** for production of p-process nuclei

**For more details**

R.Hoffmann et al. UCRL-JC-146202 and many references at:

http://www.ucolick.org/~alex/nucleosynthesis/

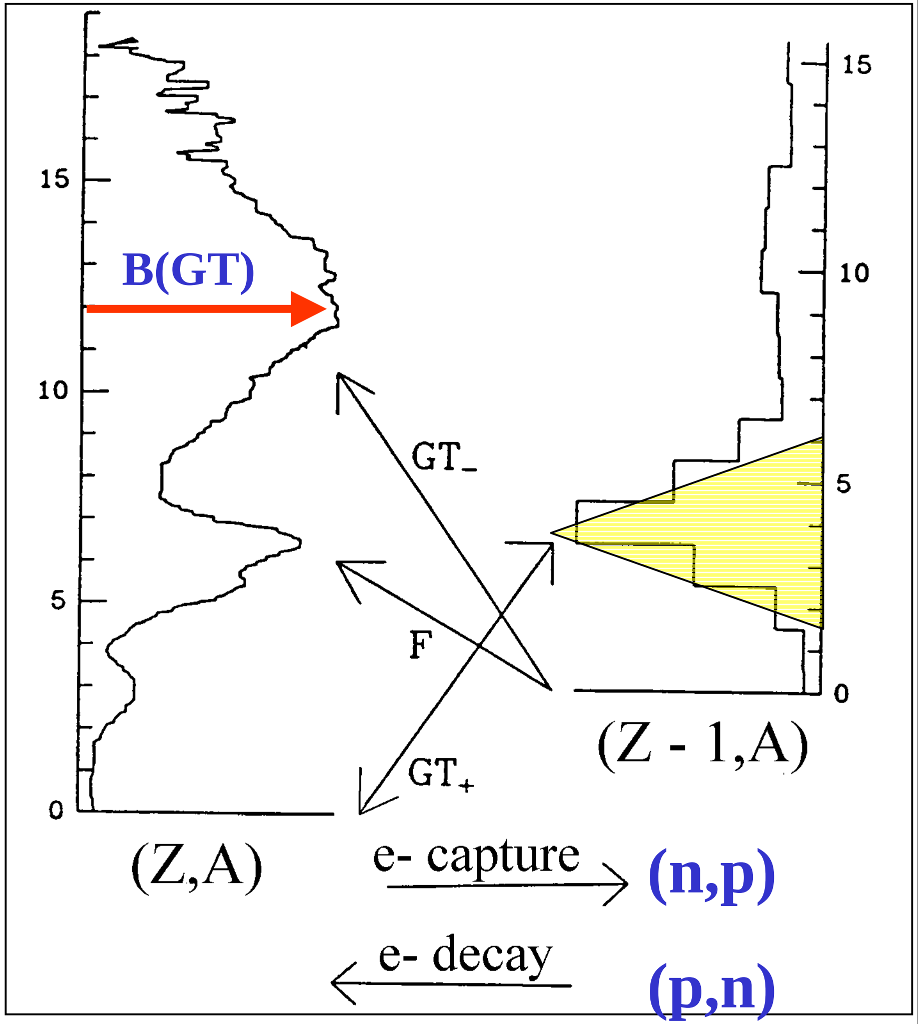
# Weak Strength and Supernovae Core Collapse

## Gamow-Teller (GT) Strength?

- Mediates β-decay, electron capture(EC), ν induced reactions
- GT (allowed) Strength S=1;L = 0, e.g. $0^+ \rightarrow 1^{+}$; $GT^+$,$GT^-$
- Lies in **giant resonances**;

## Situation

- After silicon burning, $T_{core} \approx 3.3 \times 10^9$ K, density$\approx 10^8$ g/cm$^3$. $e^-$ Fermi energy allows capture into $GT_+$.
- At higher T, $GT_+$ thermally populated, $\beta^-$ decays back to ground state. $\beta^- \Leftrightarrow$ E.C.
- $GT^+$ dominates the processes



# How Weak Strength Affects the SN Core

**Core size depends on $Y_e = \langle Z/A \rangle$**

- Starts near 0.5
- Reduced by electron capture
- As $Y_e$ decreases, $\beta^-$ decay becomes important.
- Competition of EC and $\beta^-$ stabilizes $Y_e$ near 0.45
- When EC and $\beta^-$ compete we have the possibility of a cyclic process-the URCA process.

**Urca process** (named after a Casino da Urca in Rio de Janeiro that takes your money slowly but surely)

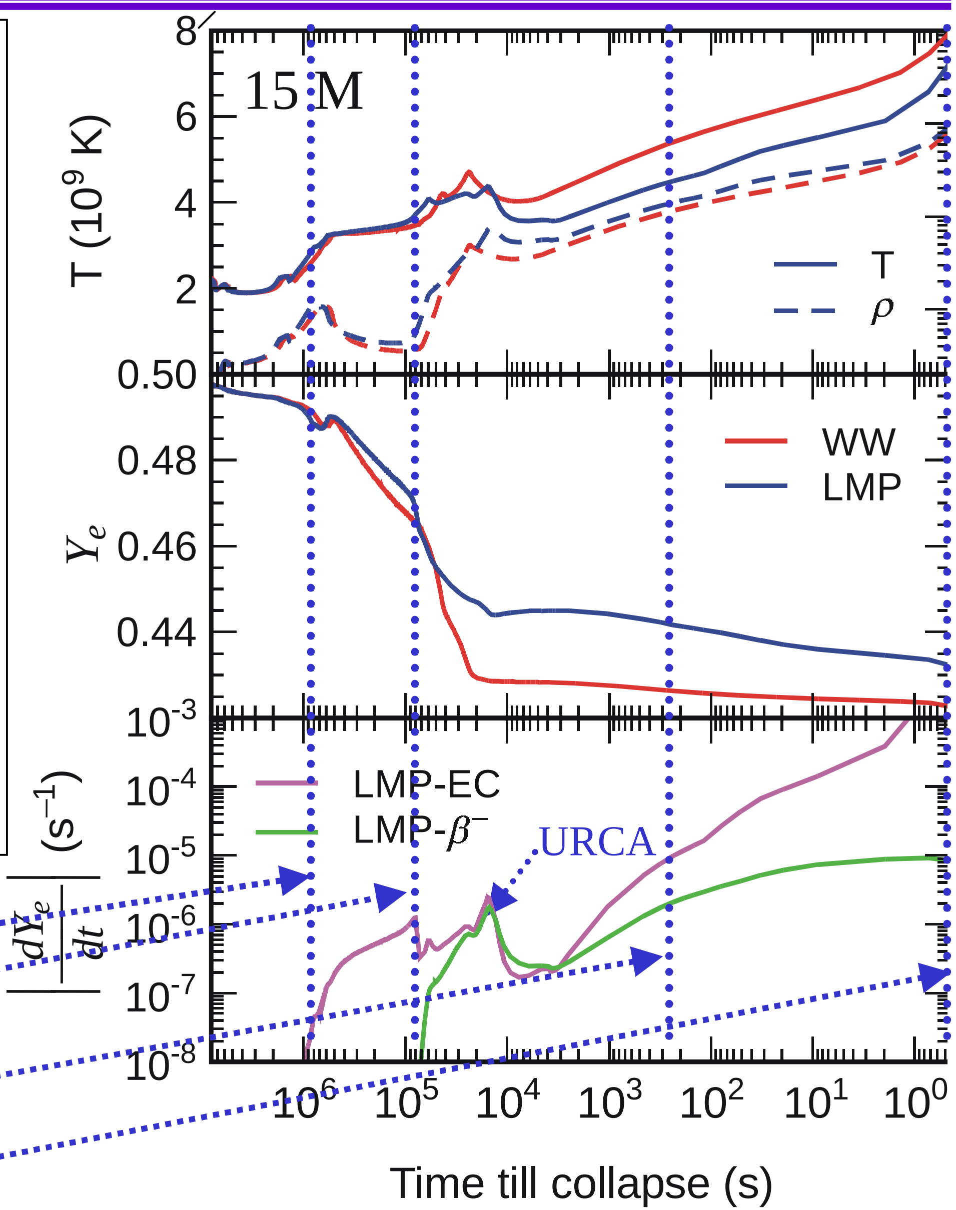
- ${}^{Z}A + e^- \rightarrow {}^{Z-1}A + \nu$

  ${}^{Z-1}A \rightarrow {}^{Z}A + e^- + \nu$
- Net result: production of two neutrinos removes energy from the core
- T reduced

# Effects of Changed Weak Rates-Heger et al. Ap.J. 560 (2001) 307

## Compare WW, LMP rates

- WW standard Wallace-Weaver rates
- LMP-from large basis shell model calculations. Langanke and Martinez-Pinedo, NPA **673**, 481(00)
- Compare results of pre-core-collapse calculations
- Significant differences




Si Ignition
Si depleted
Core contract
Core collapse

# More Weak Interaction Results

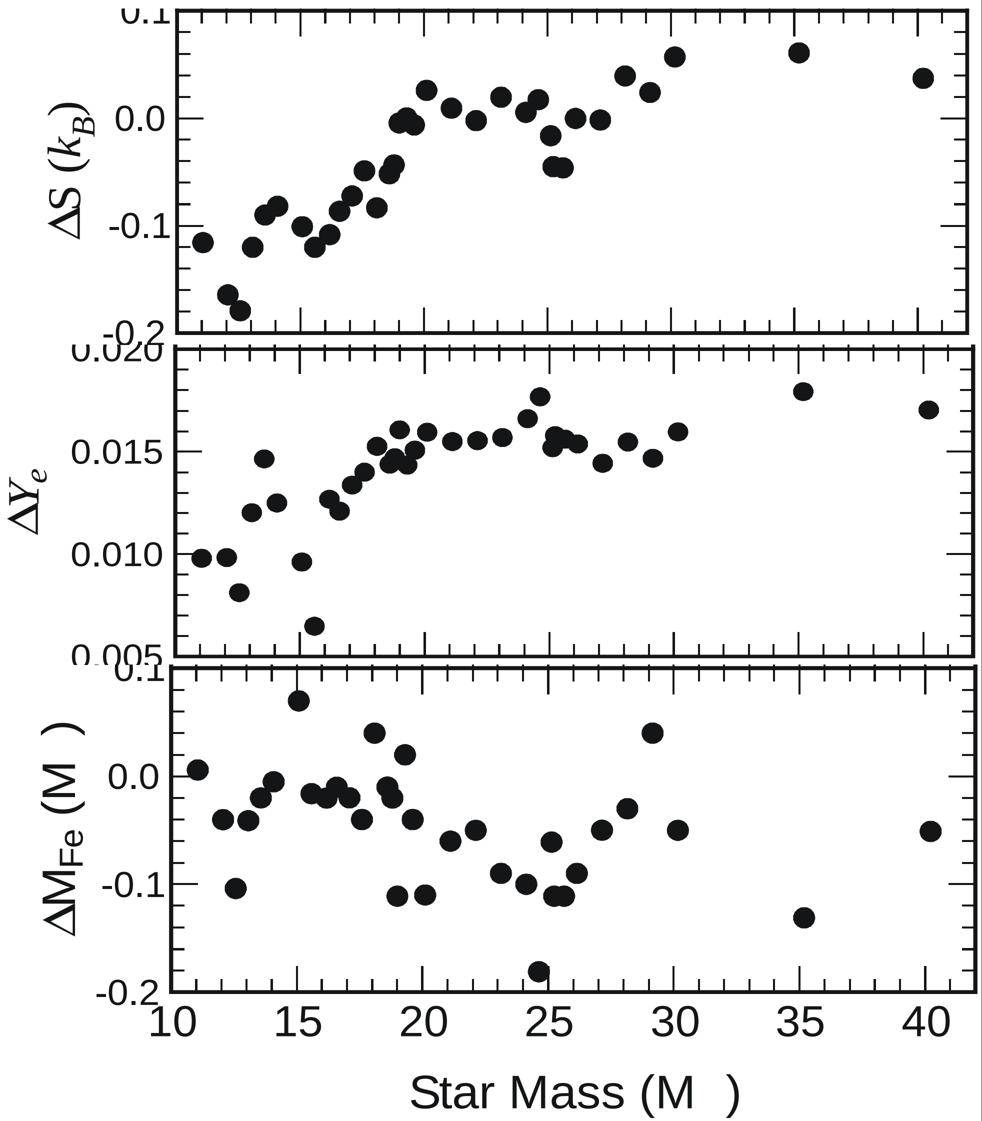
## Effects

- Larger, lower entropy "Fe" pre-collapse core
- More e-'s ($Y_e$ larger), lower T core.
- Larger homologous core

These changes tend to make explosions easier

## How can we improve rates?

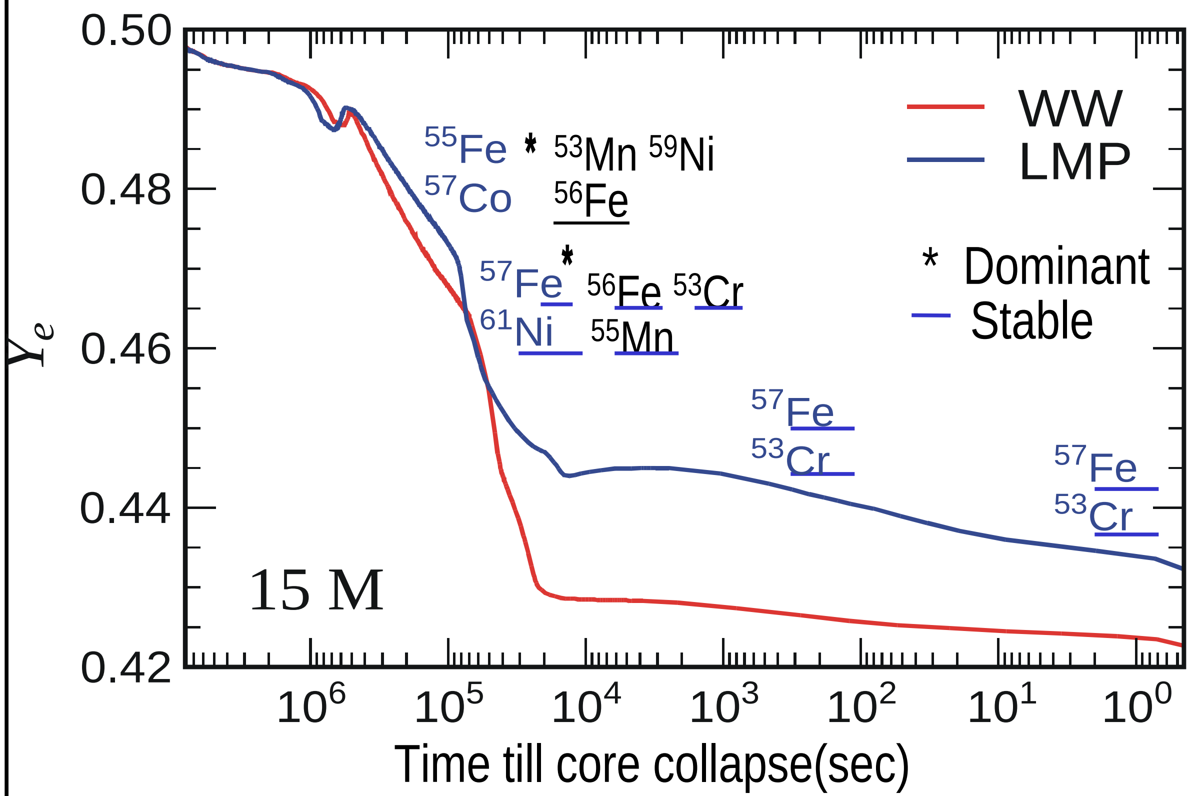
Heger results also determine which nuclei are most important



# Improving Weak Interaction Strengths

**Most important nuclei-**Heger et al.

- Generally closer to stability than predicted earlier.
- Stable and radioactive nuclei important




**Can't rely on exp't**

- Need many rates
- Some transitions are from thermally excited states

**Need**

- Reliable calculations
- Experiments to verify accuracy
- Measurements for the most crucial cases, if possible

# Present Situation

## Experimental data

- (n,p) measurements at TRIUMF
- $^{58,60,62,64}$Ni, $^{54,56}$Fe, $^{51}$V, $^{55}$Mn, $^{59}$Co
- Resolution: 1MeV

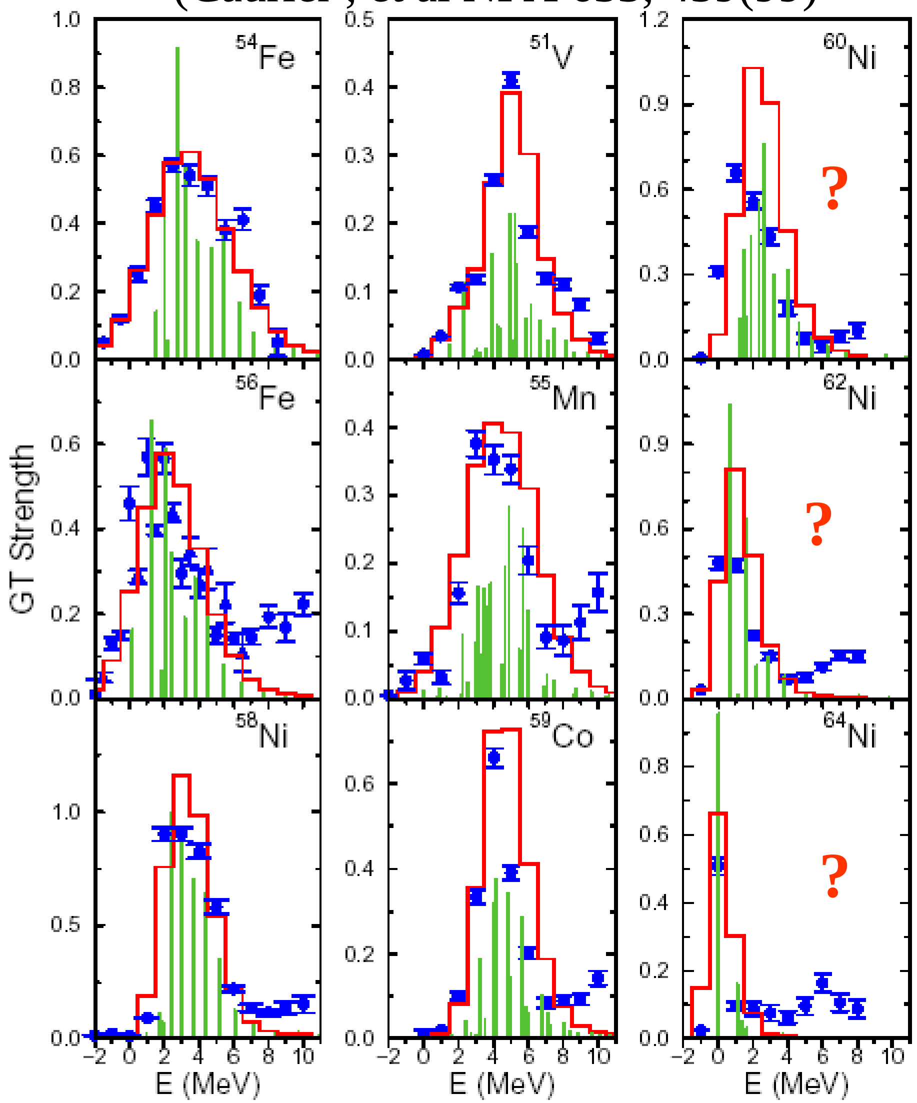
## Compare to Shell Model

Results fairly good, not perfect (?)

## Need

- Data on other nuclei, some radioactive
- Better resolution and detail

(Caurier , et al NPA **653**, 439(99)



# The Experimental Possibilities

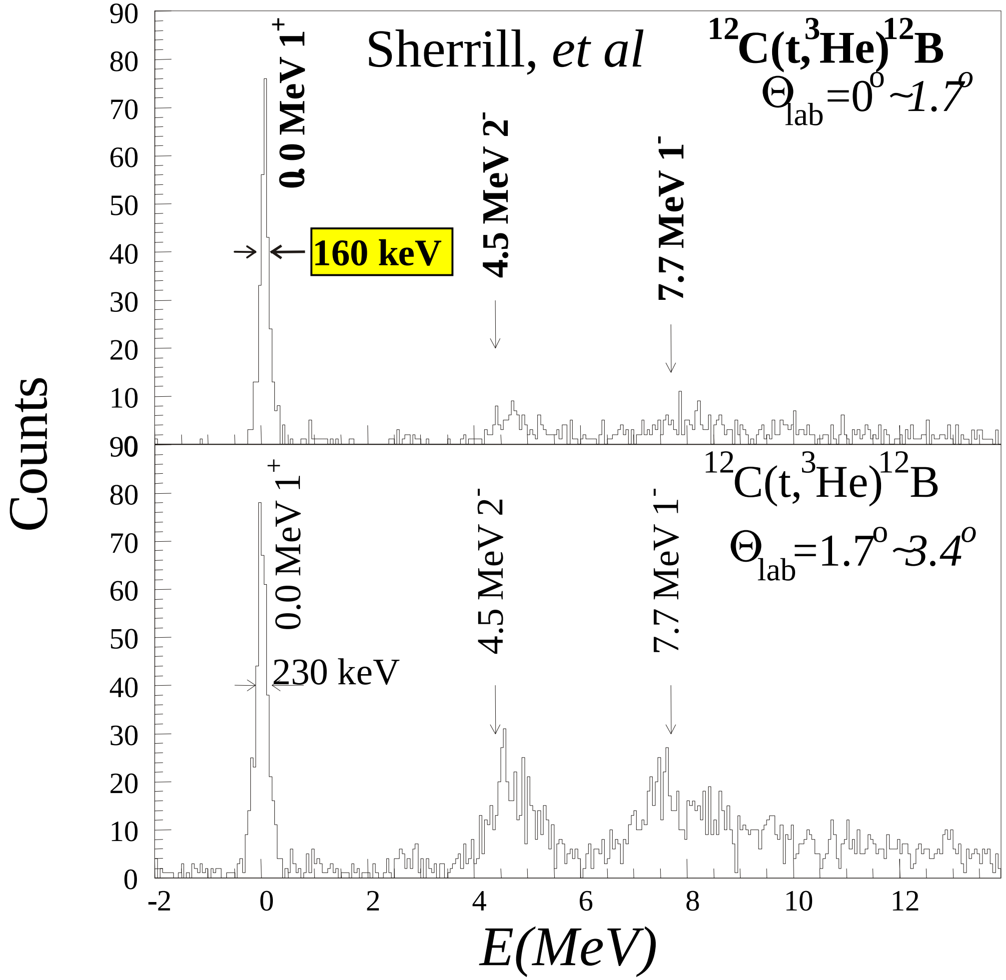
## For stable targets

For EC, (t, $^3$He), (d,$^2$He) best candidate reactions E>120 MeV/nuc desirable

## First (t, $^3$He)

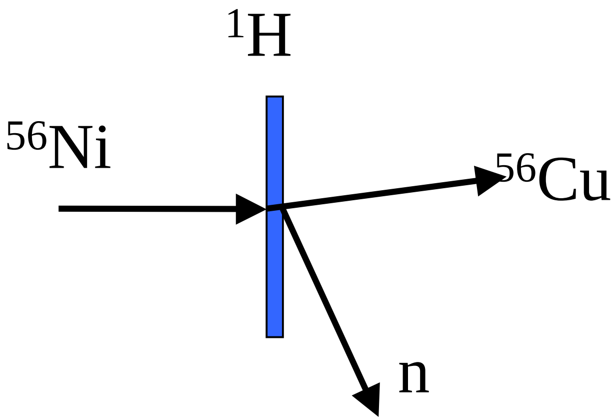
- *secondary* t *beams* $10^6$/sec at MSU/NSCL, Daito et al., PLB **418**, 27(98)
- Resolution: 160 keV, has been achieved at 117 MeV/nuc
- 50 keV resolution possible

**(d, $^2$He)**-KVI, 80 MeV/nuc

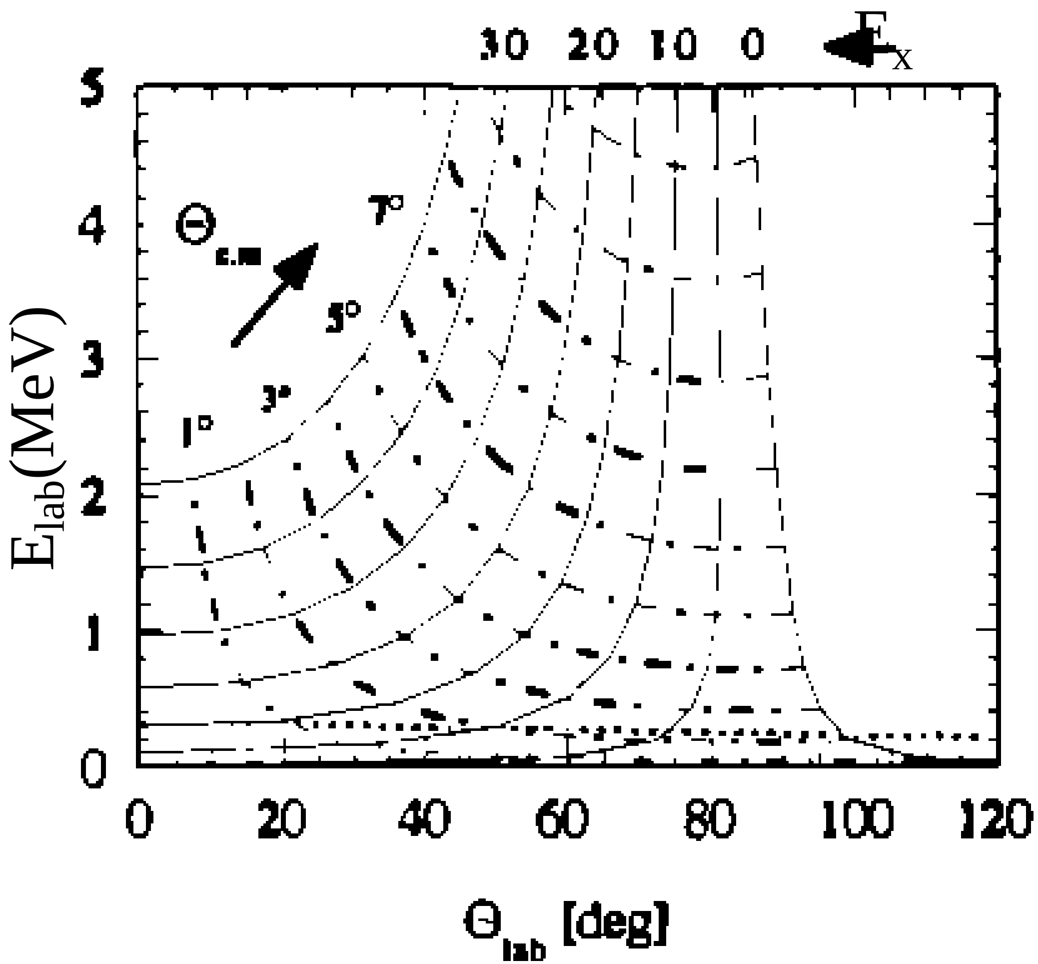


# What About Radioactive Nuclei?

## Use Inverse kinematics




$^{1}H(^{60}Co, n)^{60}Ni$




## Unusual kinematics

- Light particle has low E, few MeV, angle near 90$^{o}$.
- Lab angle => $E_{c.m.}$
- Lab E => $\Theta_{c.m.}$

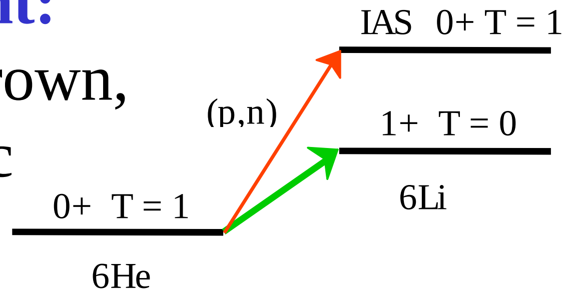
# Some possibilities

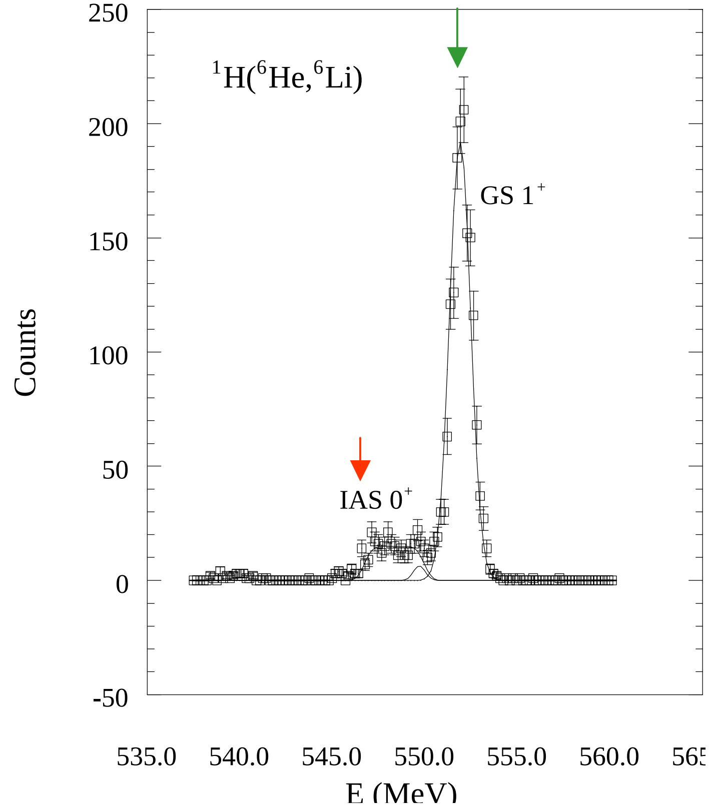
## Some possibilities

- (p,n) expts are feasible. Require many small n detectors for good E resolution.
- EC expts have outgoing charged articles at low E. Detect heavy particle.
- Best possibility: ($^7$Li,$^7$Be) $^7$Li($^{56}$Ni,$^7$Be(1/2$^-$))$^{56}$Co, Coincidence with de-excitation γ-ray => S = 1 (GT).

## First experiment:

$^6$He (p,n)$^6$Li , Brown, et al. 93 MeV/nuc



# Proposed GT Strength Experiments-NSCL

## High Resolution (from γ's)

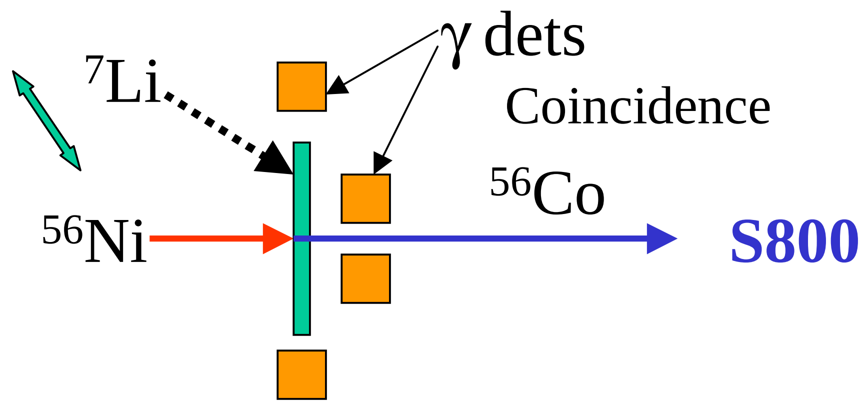
$^{7}Li(^{56}Ni,^{56}Co)^{7}Be(1/2^{-})$ => S=1

- S800 spectograph: ID $^{56}Co$, determine $\Theta_{c.m.}$
- Detect γ's from $^{7}Be$, $^{56}Co^{*}$ de-excitation, to reconstruct the $^{56}Co$ states reached
- 3 x $10^{6}$ $^{56}Ni$/sec-present intensity

## Low resolution

$^{7}Li(^{55}Fe,^{55}Mn)$ $^{7}Be(1/2^{-})$ => S=1

- Complex level structure of $^{55}Mn$ prevents reconstruction of levels reached
- Detect γ's from $^{7}Be$
- S800: ID 55Mn, determine $\Theta_{c.m.,}$ Measure E => thin target



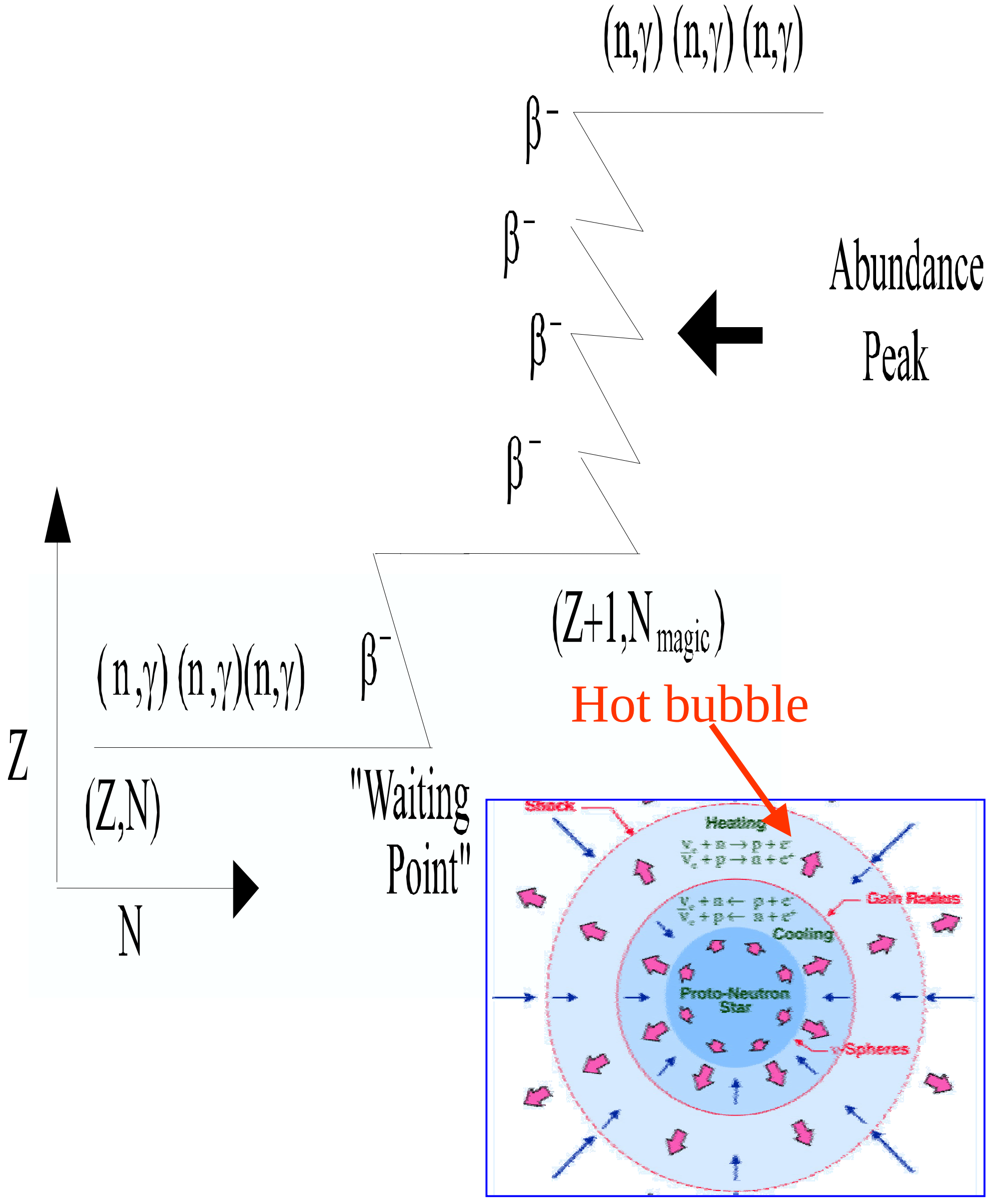
# The r-Process

## What is it?

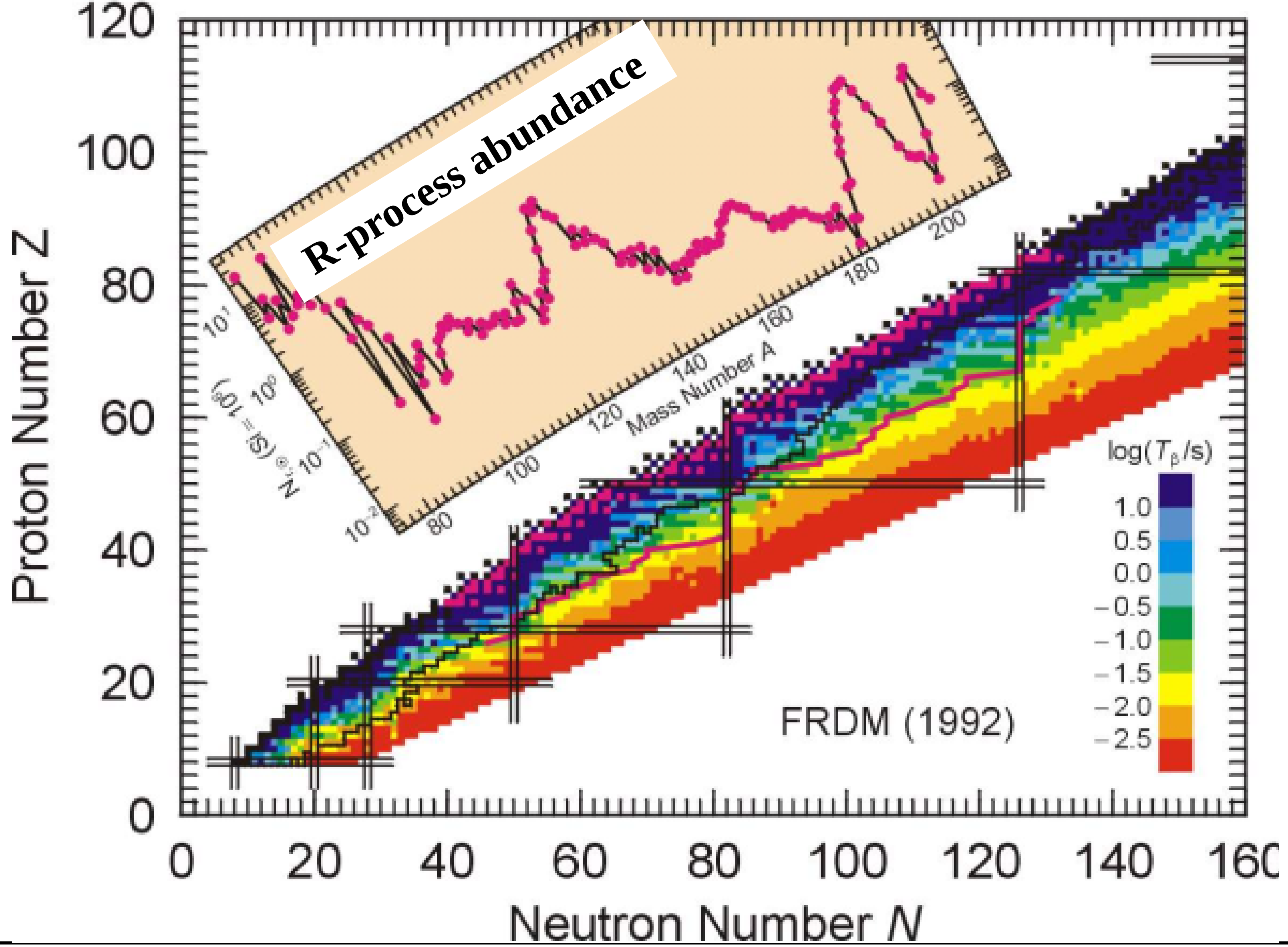
- Heavy elements formed by rapid neutron capture on seed nuclei
- Flow along path near neutron drip line till (n,γ) = (γ,n)
- After explosion, decay back to stable region. **N(Z) ∝ $t_\beta$**

## Where does it occur?

In hot bubble just inside SN shock? Or in fusion of two neutron stars?



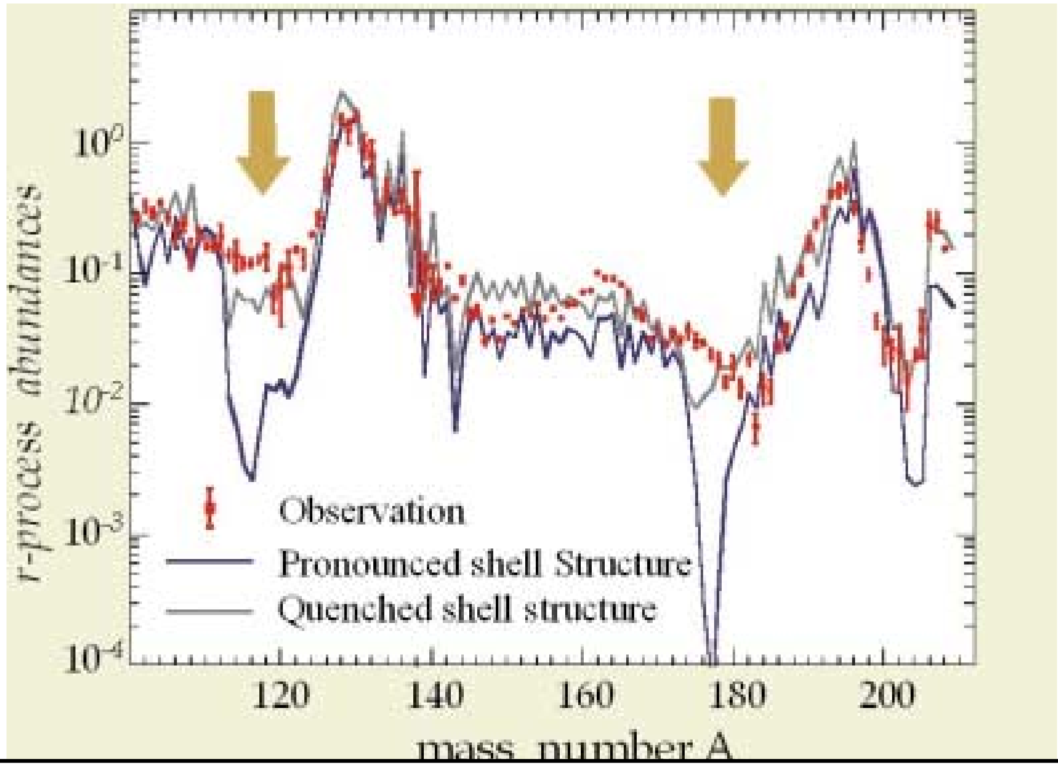
# Properties of R-Process Nuclei



# The r-Process and Nuclear Shells

**Predictions-**(not verified by experiment)

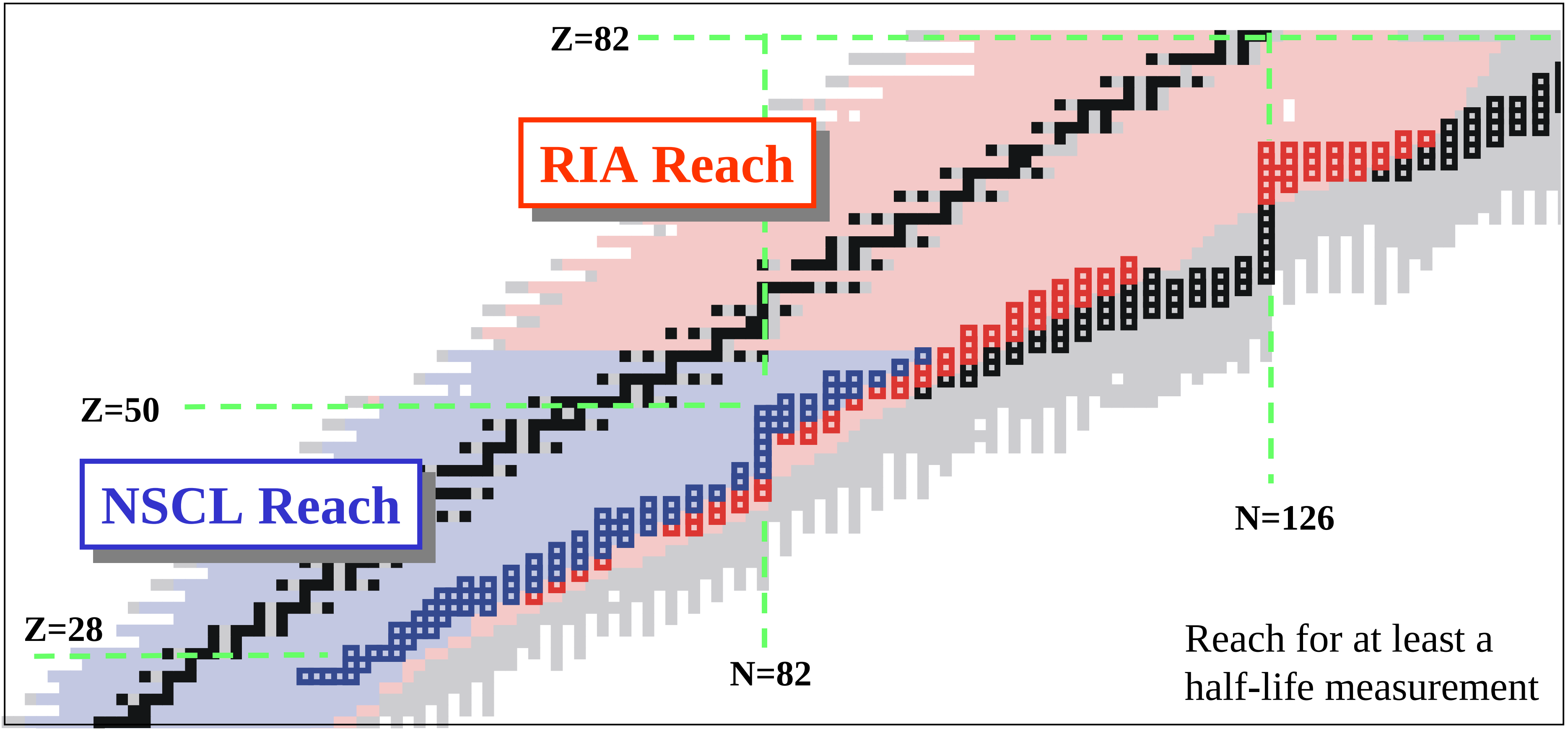
- Shell gaps smaller near drip line
- Changes beta decay lifetimes, masses
- r-process abundance models are sensitive to gaps
- Need measuremnts of $t_\beta$, masses on r-process  path to check



# Experimental opportunities at Rare Isotope Facilities

Example: fast beams

Need:
- masses
- decay properties
- fission barriers
- neutron capture rates

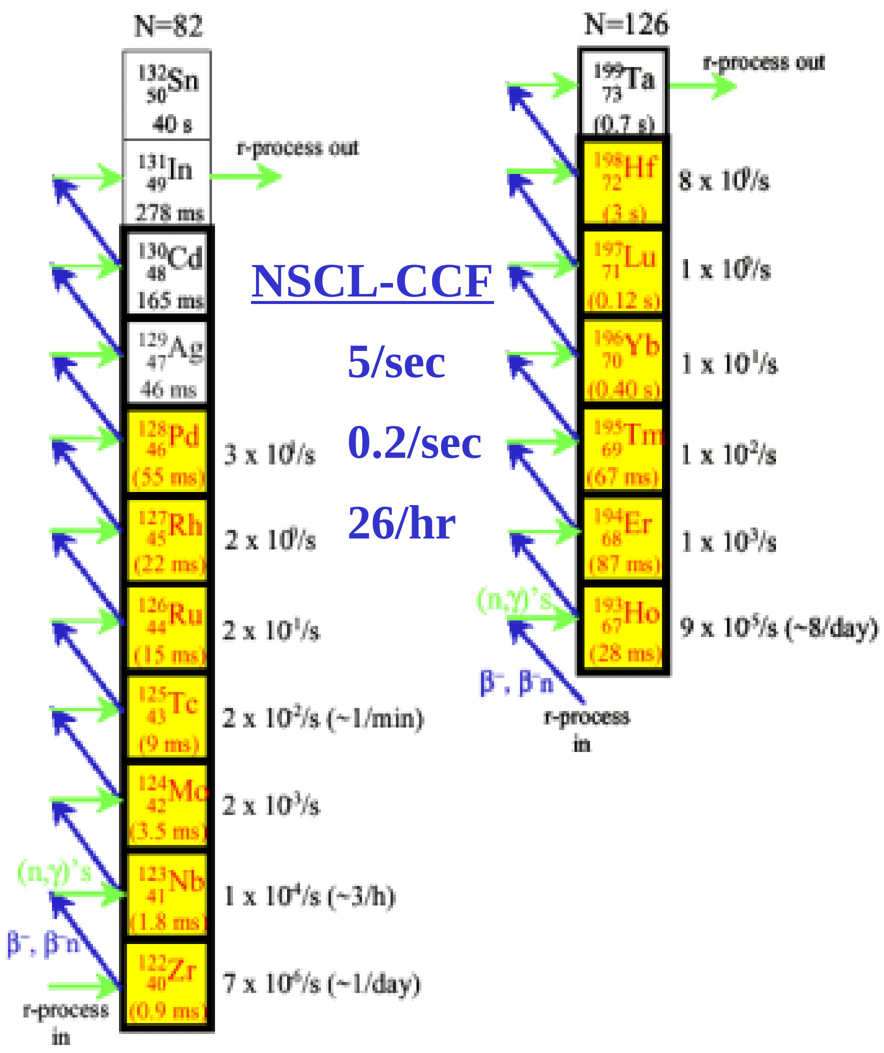


# Waiting Point Lifetimes with Fragmentation Facilities

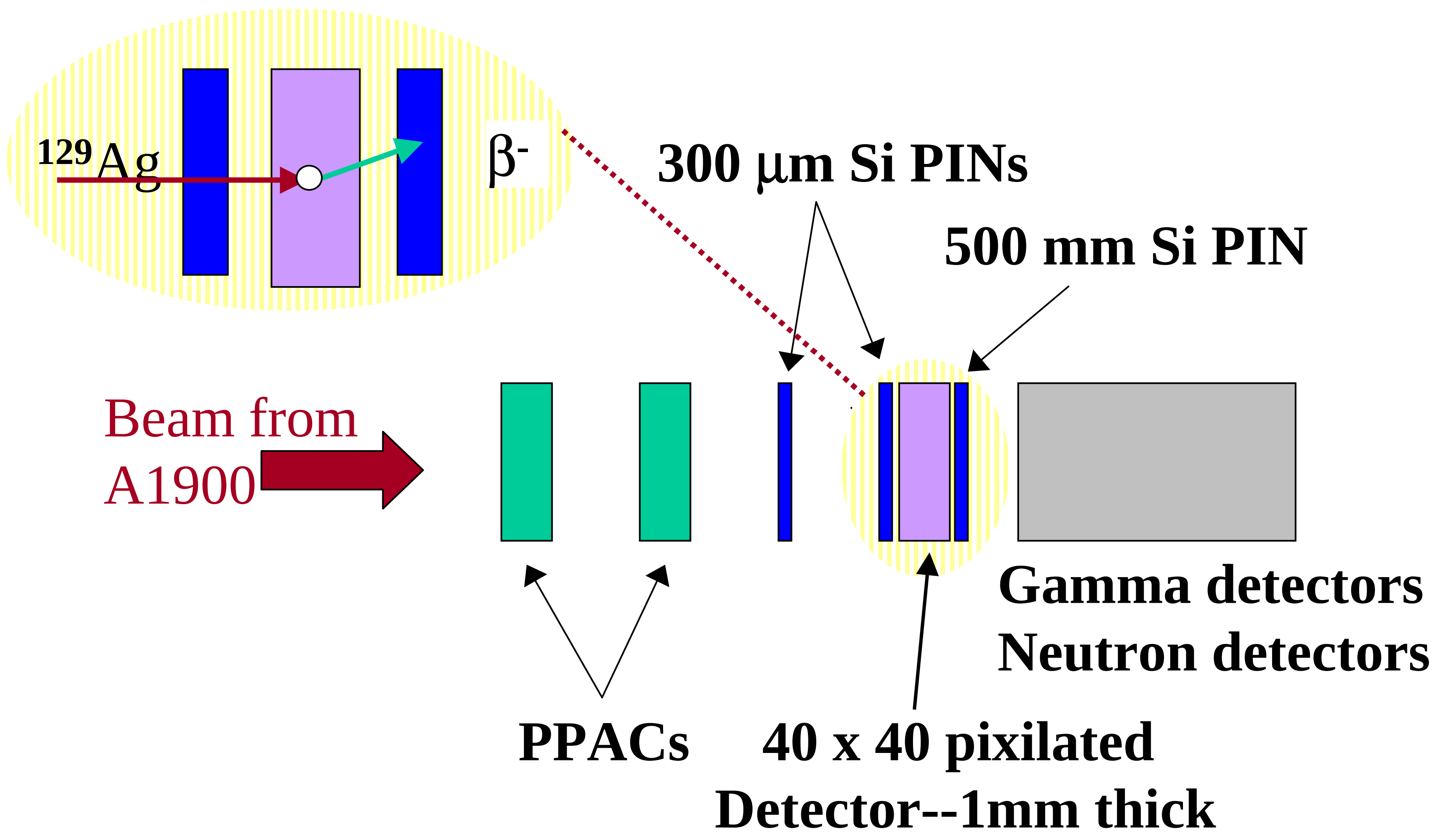
## Why fragmentation?

- Lifetime measurements can be done with beams from low energy facilities
- But, fragmentation facilities have advantages:
    - Use beams of mixed nuclides--Identification on event by event basis
    - Greater reach toward dripline-see figure
    - NSCL,RIKEN, and RIA will cover a large part of r-process path

Beams NSCL, RIA--N = 82,126

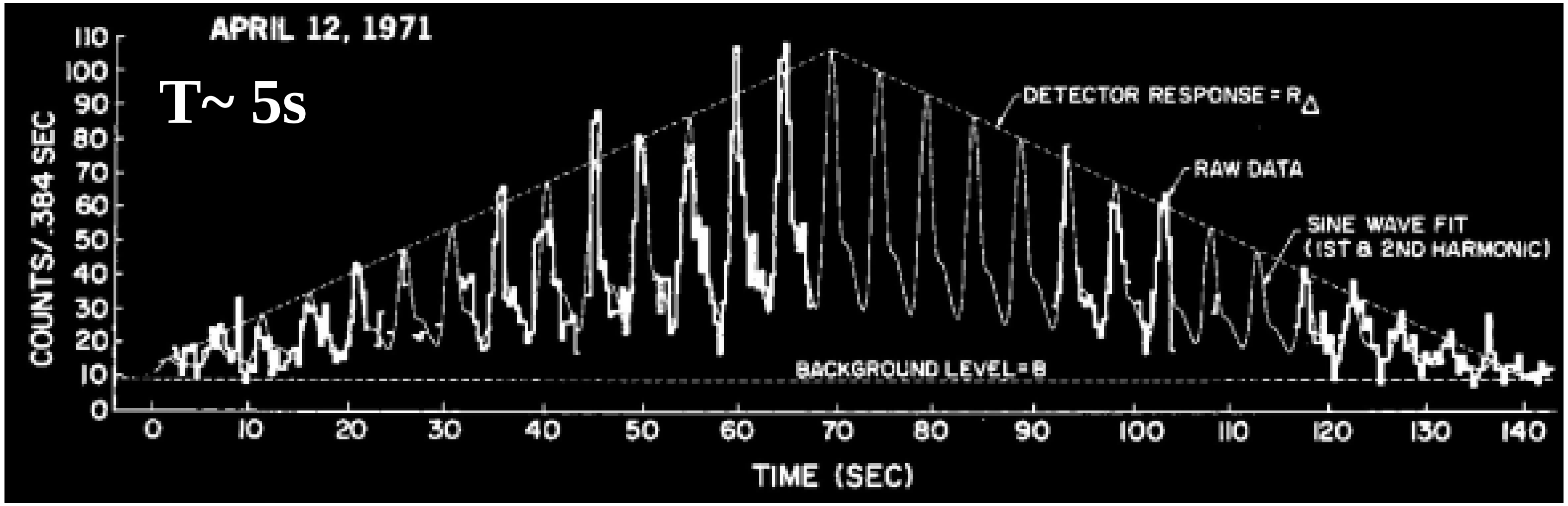


# How to Measure Beta-Decay Lifetimes, Decay Properties



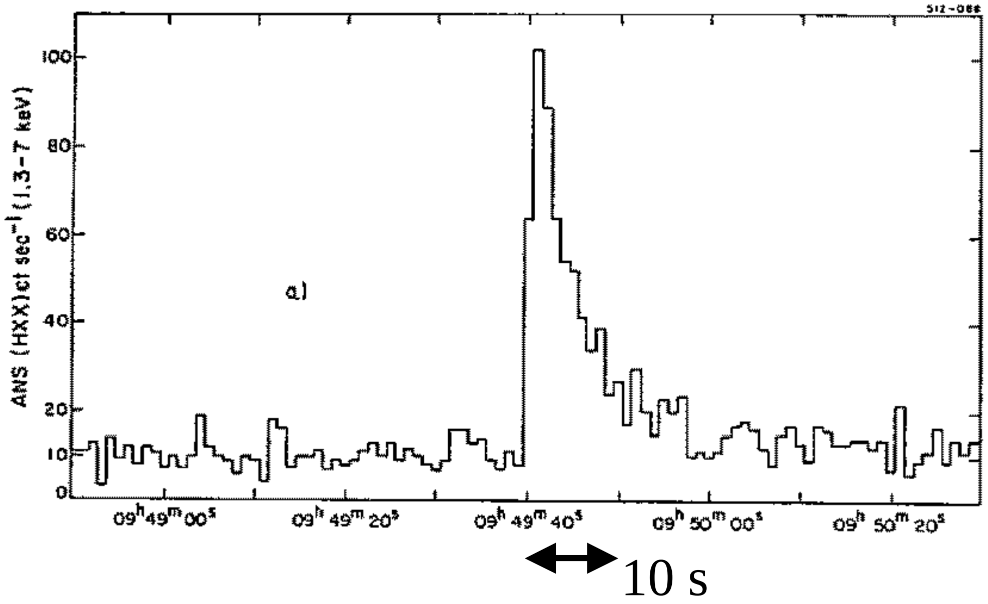
# Explosive Hydrogen Burning-Accreting Binary Systems

First **X-ray pulsar**: Cen X-3 (Giacconi et al. 1971) with UHURU




Today: ~50

First **X-ray burst**: 3U 1820-30 (Grindlay et al. 1976) with ANS

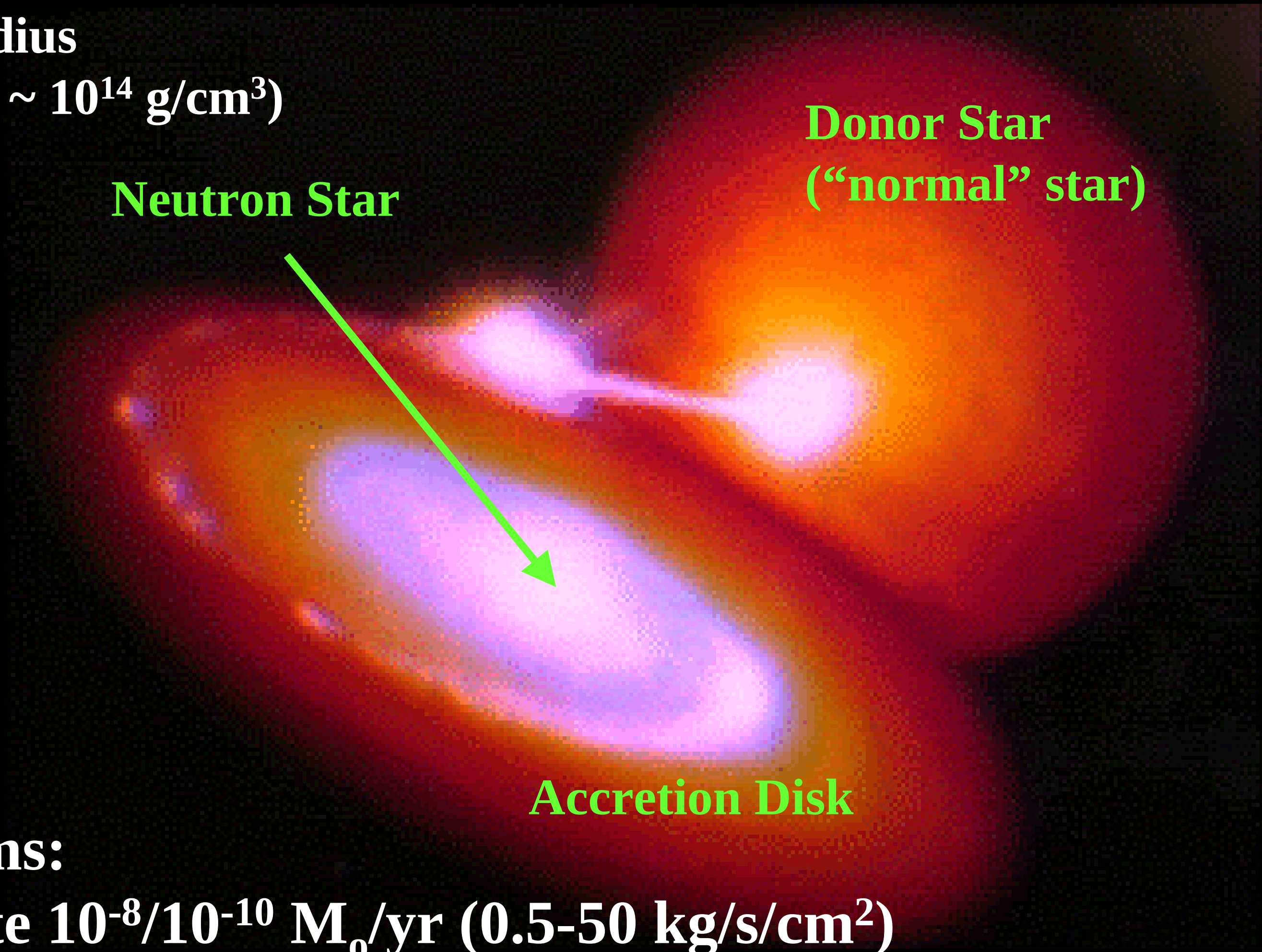



Today: ~40

Total ~230 X-ray binaries known

# The Model

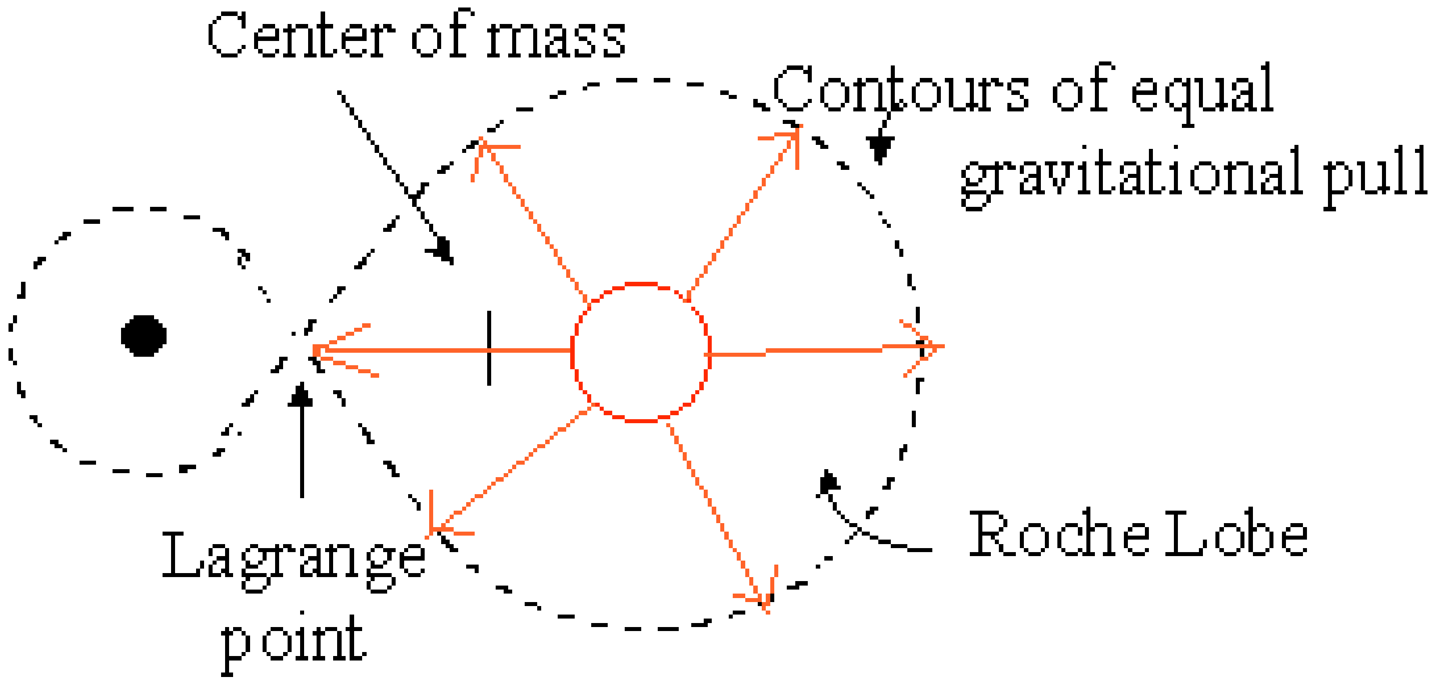
**Neutron stars:**
**1.4 $M_o$, 10 km radius**
**(average density: ~ $10^{14}$ g/cm$^3$)**




**Typical systems:**

- **accretion rate $10^{-8}/10^{-10}$ $M_o$/yr (0.5-50 kg/s/cm$^2$)**
- **orbital periods 0.01-100 days**
- **orbital separations 0.001-1 AU's**

# Mass transfer by Roche Lobe Overflow




Star expands on main sequence.
when it fills its Roche Lobe mass transfer happens
through the L1 Lagrangian point

## Energy generation: thermonuclear energy

$4H \longrightarrow {}^{4}He$ 6.7 MeV/u

$3\ {}^{4}He \longrightarrow {}^{12}C$ 0.6 MeV/u ("triple alpha")

$5\ {}^{4}He + 84\ H \longrightarrow {}^{104}Pd$ 6.9 MeV/u (rp process)

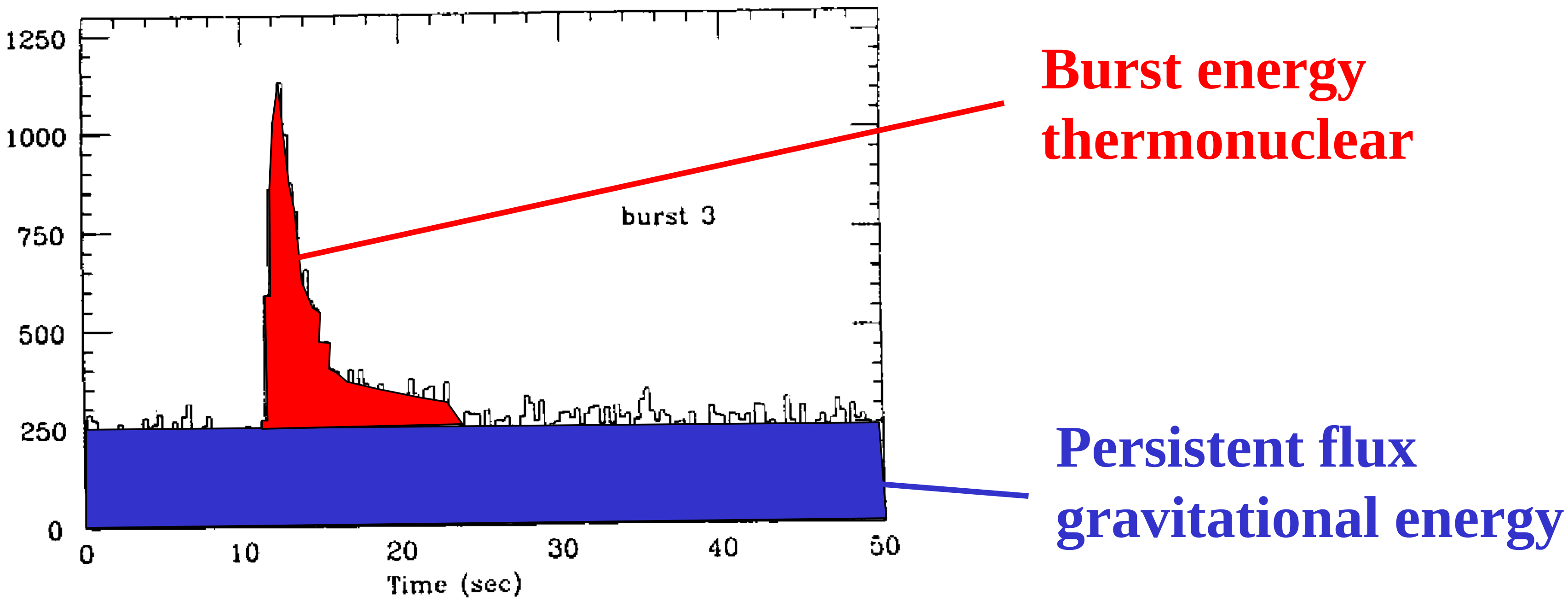
## Energy generation: gravitational energy

$$E = \frac{G\ M\ m_u}{R} = 200\ \text{MeV/u}$$

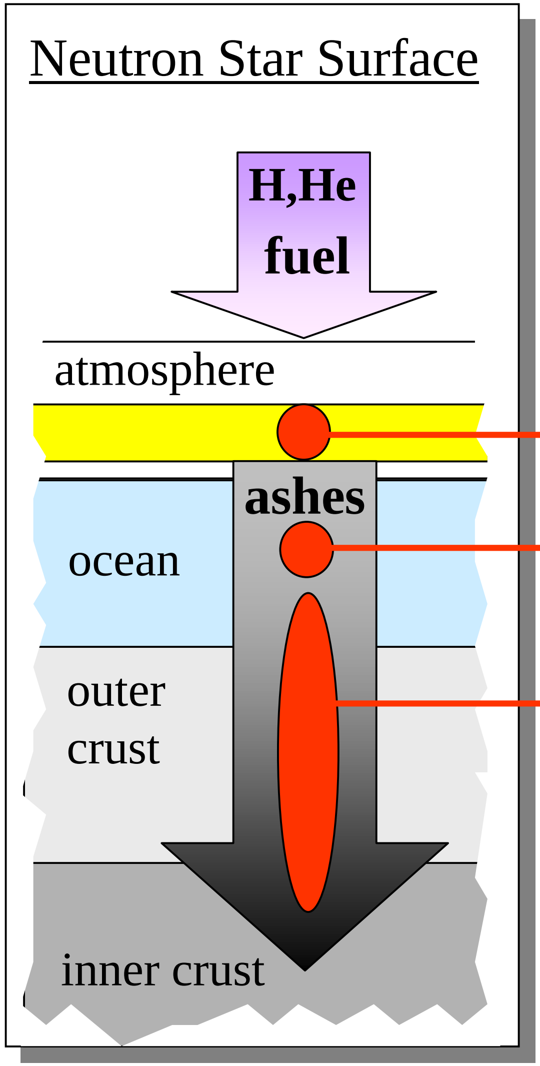
**Ratio gravitation/thermonuclear ~ 30 - 40**

## Observation of thermonuclear energy:

Unstable, explosive burning in bursts (release over short time)



# Nuclear reactions on accreting neutron stars




## Thermonuclear burning (rp process)

- Why do burst durations vary ? (10s – min)
- What nuclei are made in the explosion ?
  - Galactic nucleosynthesis contribution ?
  - Start composition for deeper processes ?

## Deep H, C, … burning

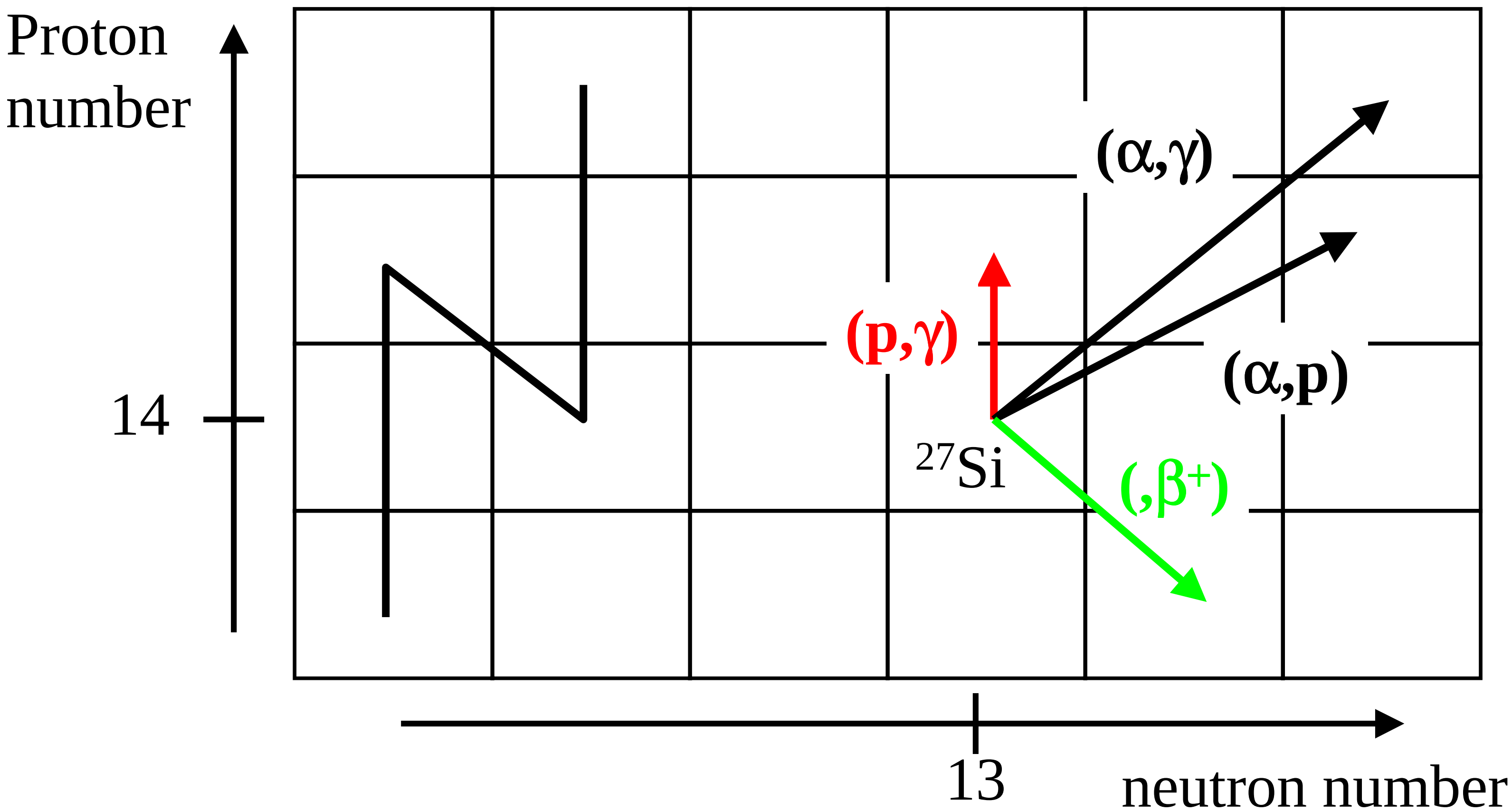
- Origin of Superbursts ? 100X stronger

## Electron captures
## Pycnonuclear reactions

- Gravitational wave emission ?
- Crust heating ?
- Dissipation of magnetic fields ?

Need nuclear physics to answer and to understand observations

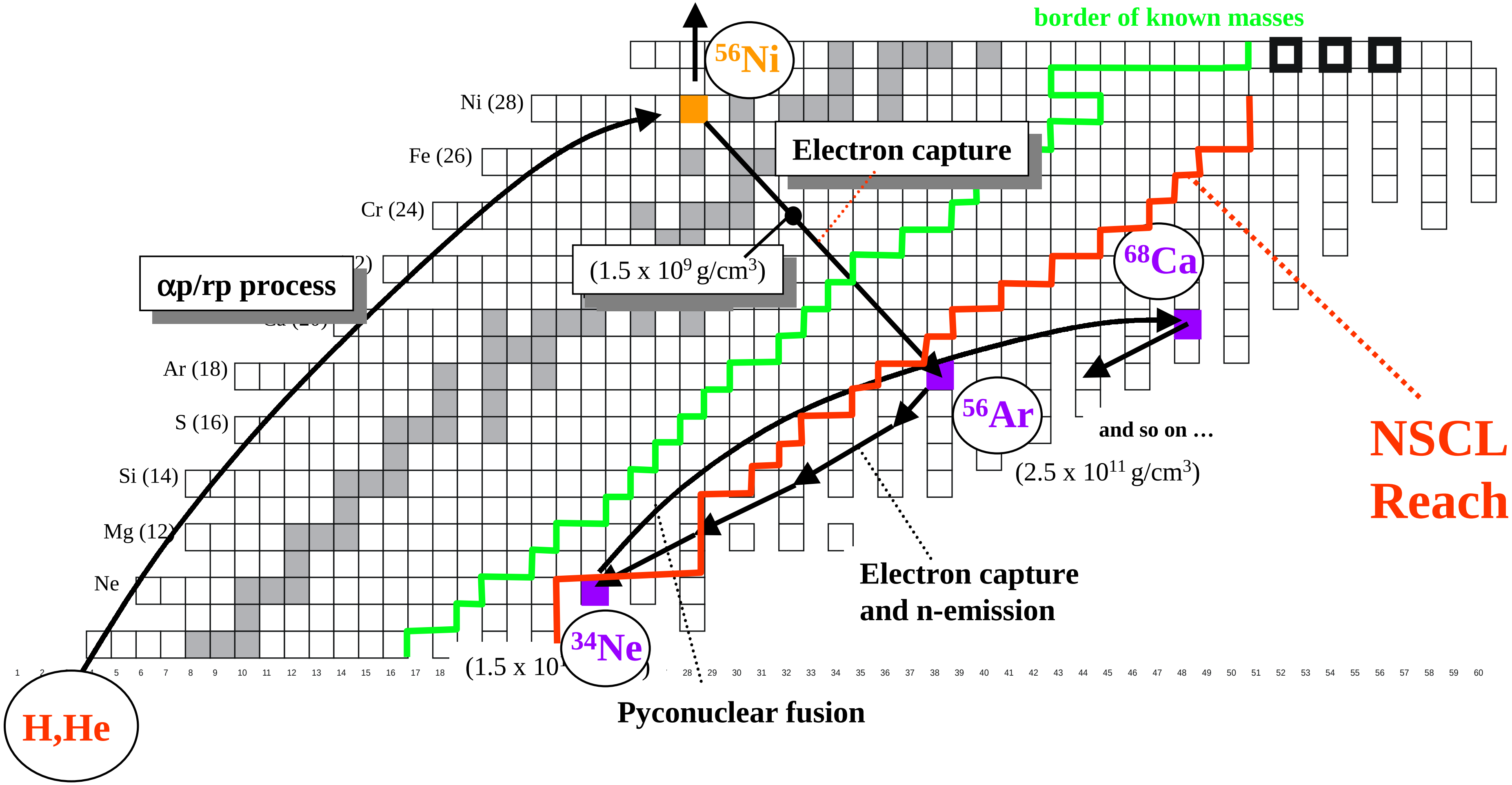
# Visualizing reaction network solutions




Lines = Flow = $$F_{i,j} = \int \left[ \frac{dY_i}{dt}_{i->j} - \frac{dY_j}{dt}_{j->i} \right] dt$$

# Crust reactions in accreting neutron stars

From Haensel & Zdunik 1990




<u>Need to measure:</u>

- Masses **(Exp 1035 Santi, Ouellette at S800)**
- Electron capture rates **(Exp 1038 Sherrill at S800)**

(Charge exchange in inverse kinematics ($^7$Li,$^7$Be) )

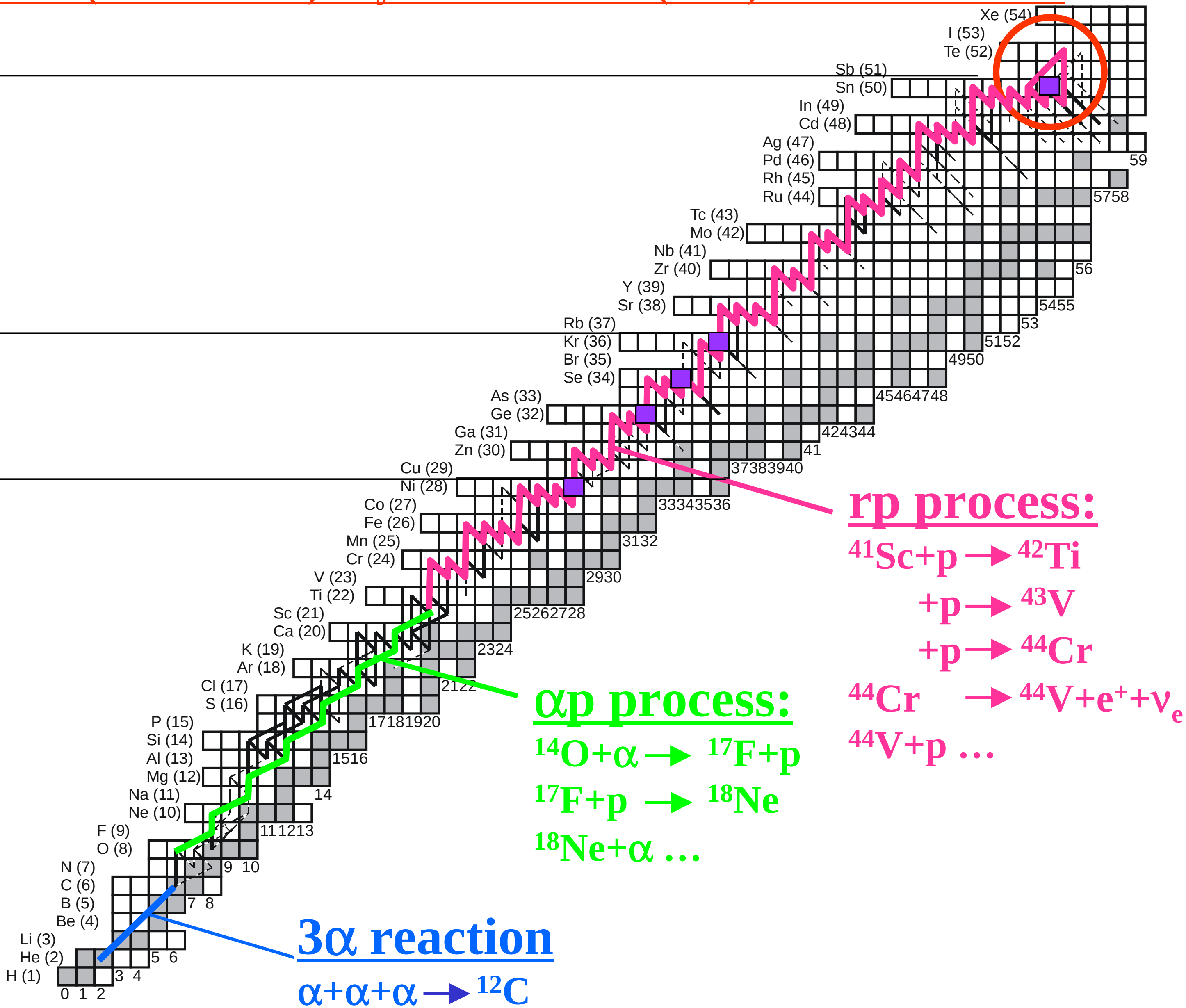
# Models: Typical reaction flows

Schatz et al. 2001 (M. Ouellette) Phys. Rev. Lett. 68 (2001) 3471

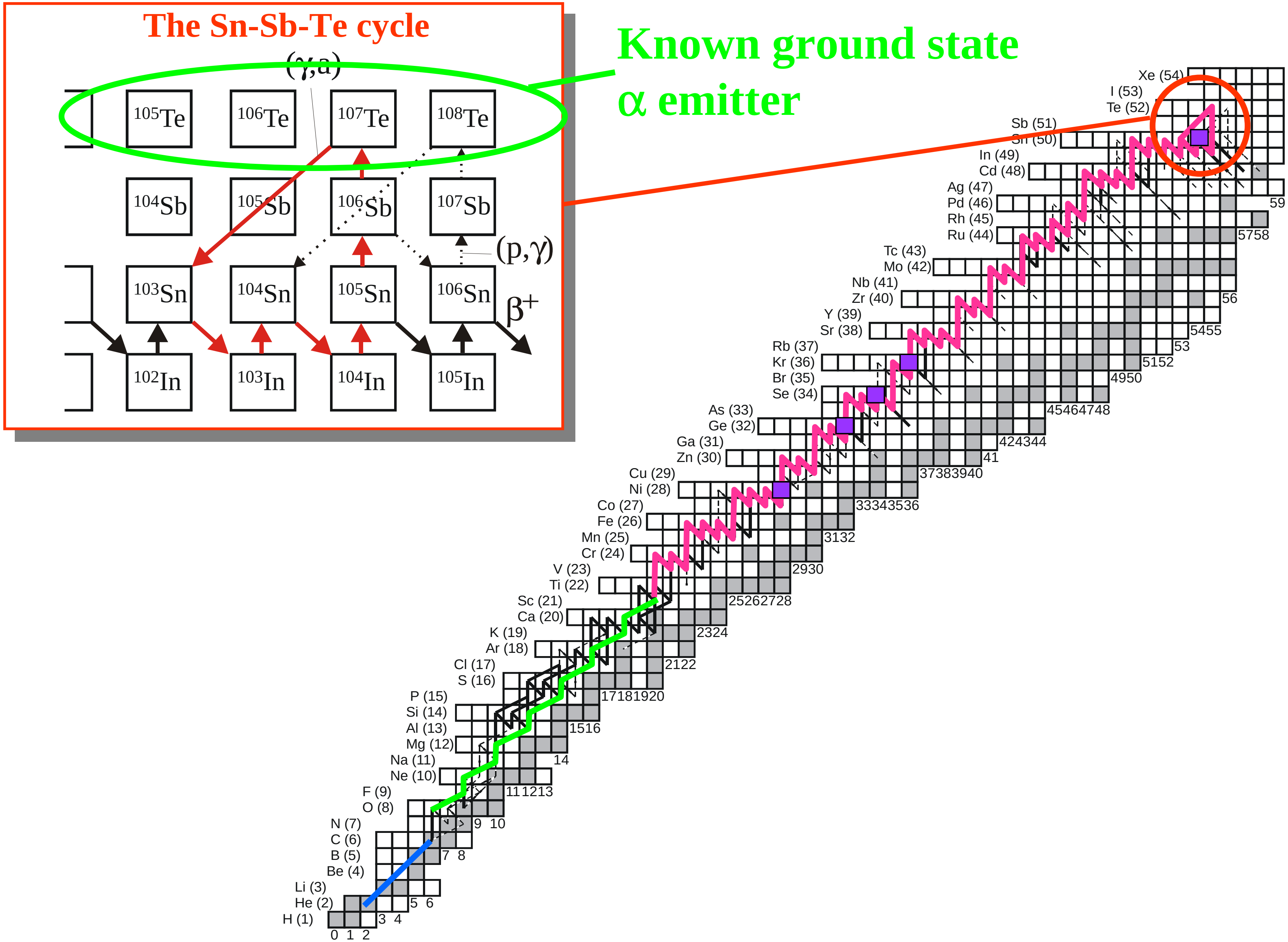
Schatz et al. 1998

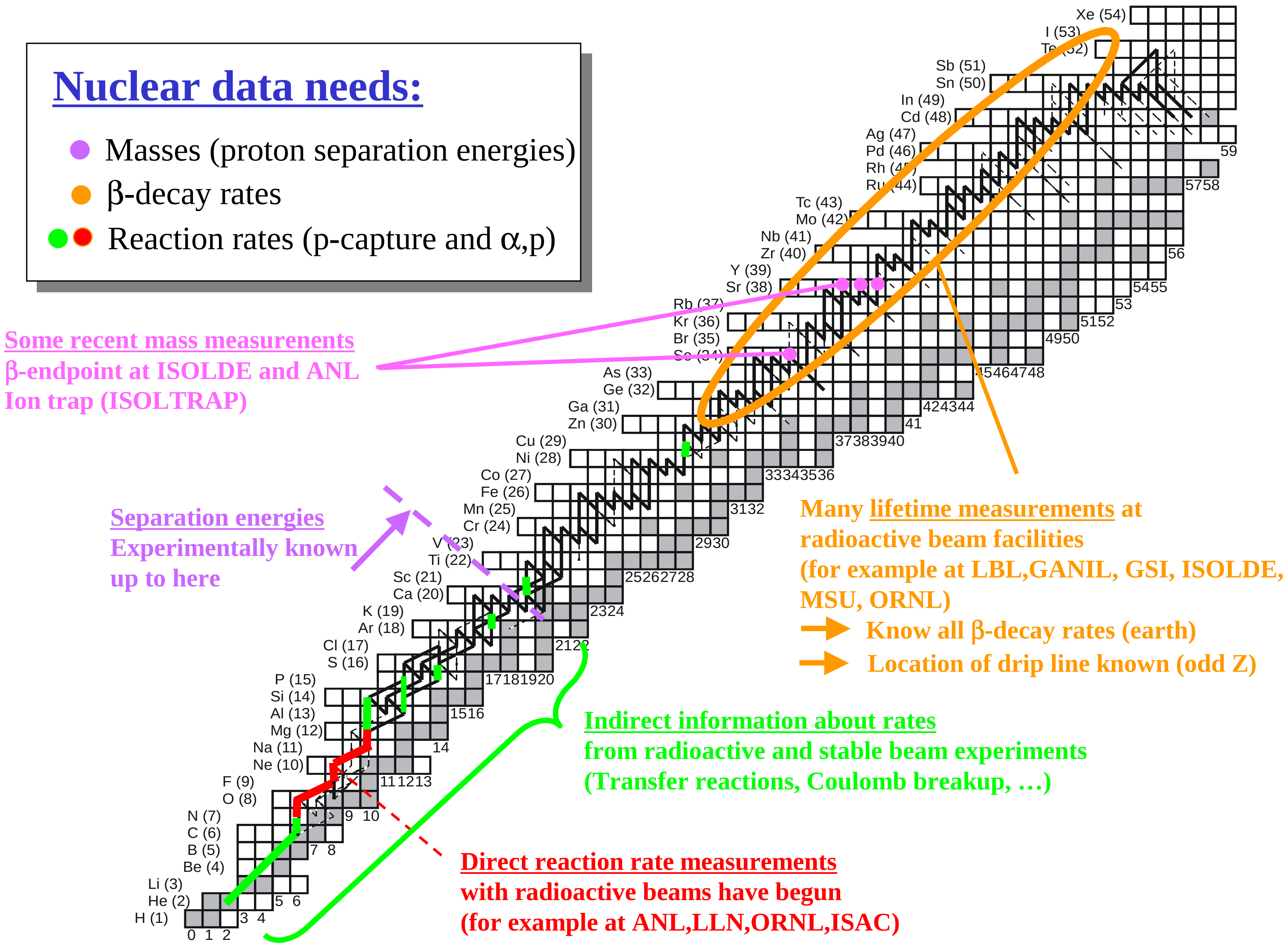
Wallace and Woosley 1981
Hanawa et al. 1981
Koike et al. 1998

Most calculations
(for example Taam 1996)



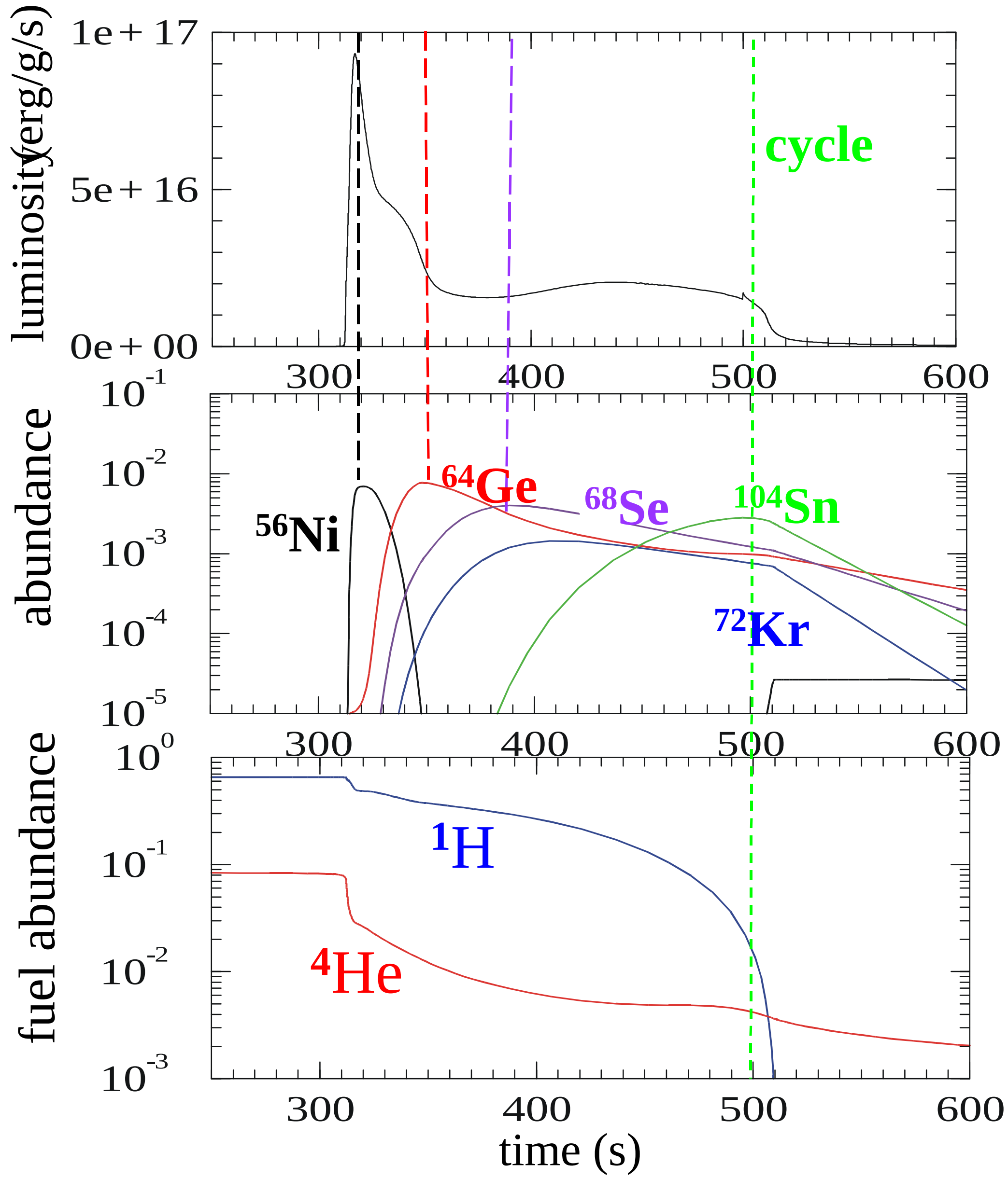
# Endpoint: Limiting factor I – SnSbTe Cycle




Nuclear data needs:
Masses (proton separation energies)
β-decay rates
Reaction rates (p-capture and α,p)
Some recent mass measurenents
β-endpoint at ISOLDE and ANL
Ion trap (ISOLTRAP)
Separation energies
Experimentally known
up to here
Many lifetime measurements at
radioactive beam facilities
(for example at LBL,GANIL, GSI, ISOLDE,
MSU, ORNL)
Know all β-decay rates (earth)
Location of drip line known (odd Z)
Indirect information about rates
from radioactive and stable beam experiments
(Transfer reactions, Coulomb breakup, …)
Direct reaction rate measurements
with radioactive beams have begun
(for example at ANL,LLN,ORNL,ISAC)
H (1)
He (2)
Li (3)
Be (4)
B (5)
C (6)
N (7)
O (8)
F (9)
Ne (10)
Na (11)
Mg (12)
Al (13)
Si (14)
P (15)
S (16)
Cl (17)
Ar (18)
K (19)
Ca (20)
Sc (21)
Ti (22)
V (23)
Cr (24)
Mn (25)
Fe (26)
Co (27)
Ni (28)
Cu (29)
Zn (30)
Ga (31)
Ge (32)
As (33)
Se (34)
Br (35)
Kr (36)
Rb (37)
Sr (38)
Y (39)
Zr (40)
Nb (41)
Mo (42)
Tc (43)
Ru (44)
Rh (45)
Pd (46)
Ag (47)
Cd (48)
In (49)
Sn (50)
Sb (51)
Te (52)
I (53)
Xe (54)

**X-ray burst:** Importance of waiting points-points where the flow is hampered by slow decay or weakly bound nuclei

- Luminosity:
- Abundances of waiting points
- H, He abundance



# What Next?

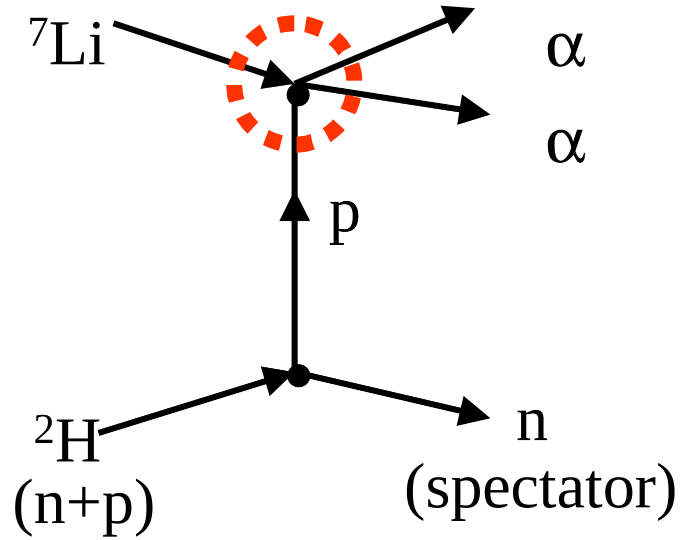
## Several Topics Briefly

- Trojan Horse measurements of low energy cross Sections
- ANCs and S-Factors
- L=1 Forbidden Weak Strength
- Is there a Chance that $\sigma(\mathrm{CEX}) \propto B(L=1)$?
- Coulomb Breakup measurements (more detailed)

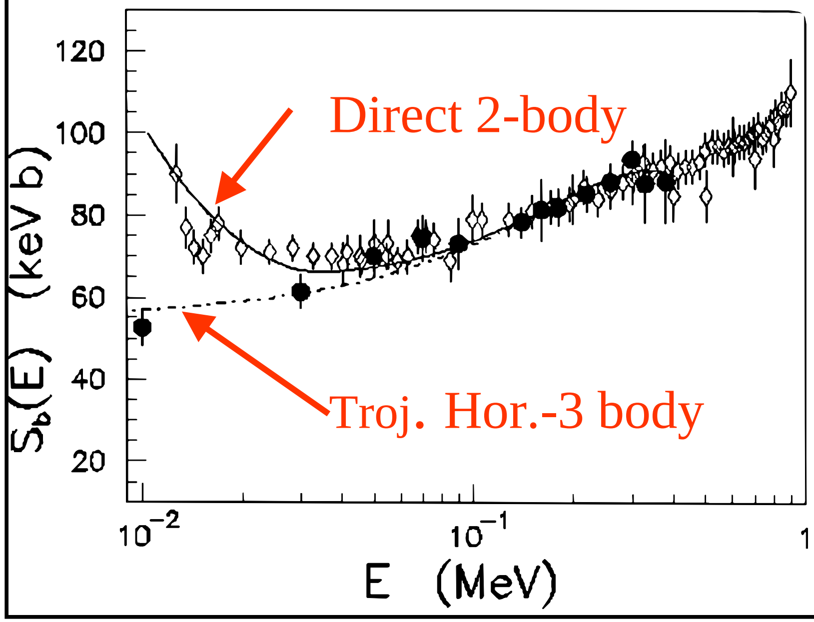
# Trojan Horse Method (Bauer,Typel, Wolter)

## Principle

- Obtain 2-body σ from 3-body reaction
- Example: $^7$Li ( p α)α from $^2$H($^7$Li, αα)n



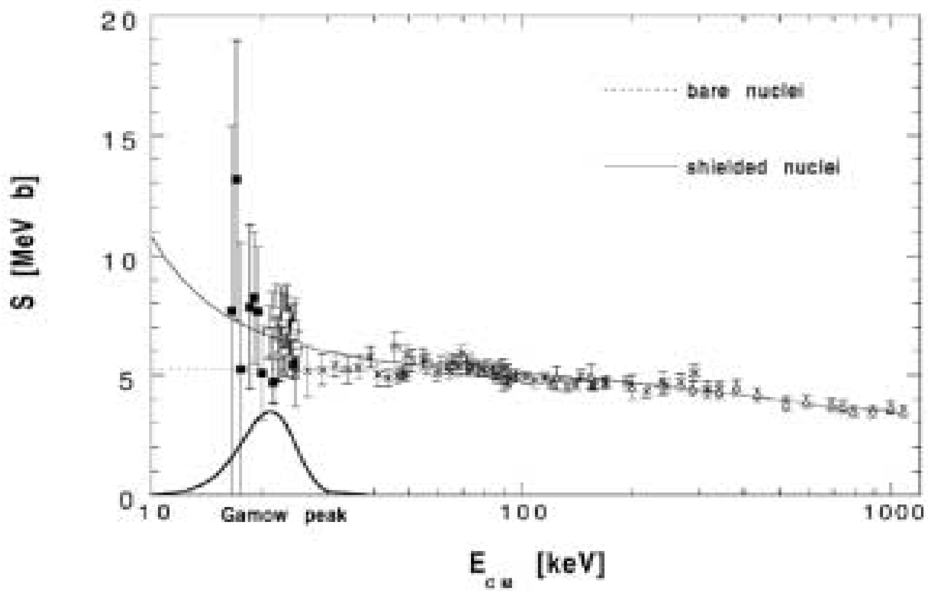

## Results (Lattuada et al., Ap.J. tbp)




## Comments

- Large rates, no screening correction
- Norm to 2-body, extend to low-E
- Compare to direct ⇒ screening correction near 250 eV. Larger than usual theory.

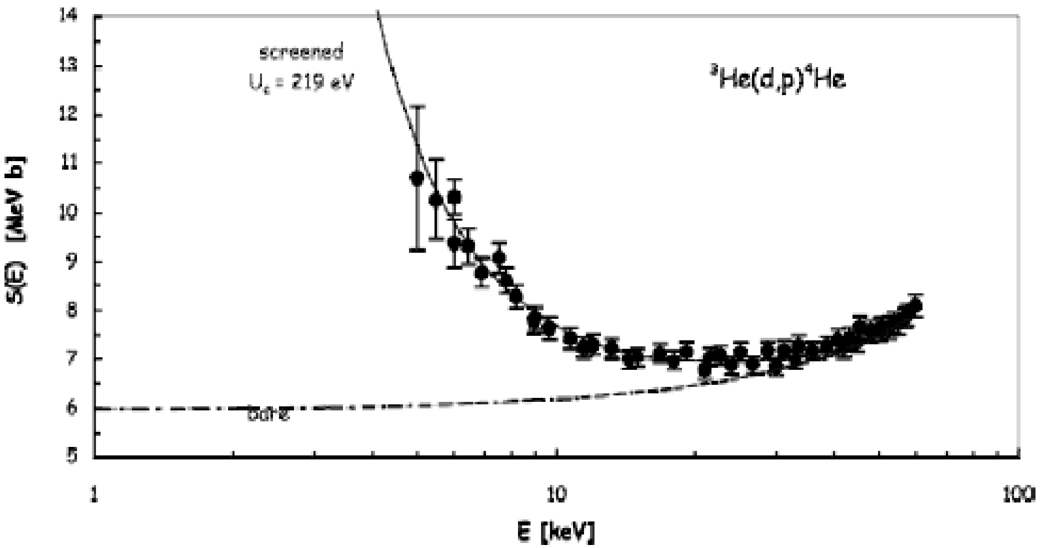
# Low Energy Measurements




R. Bonetti, *et al.*, PRL **82**, 5205 (1999)

Find: $U_e = 290 \pm 47$ eV

Adiabatic: 240 eV




M. Aliotta *et al*. NPA **690**, 790 (2001)

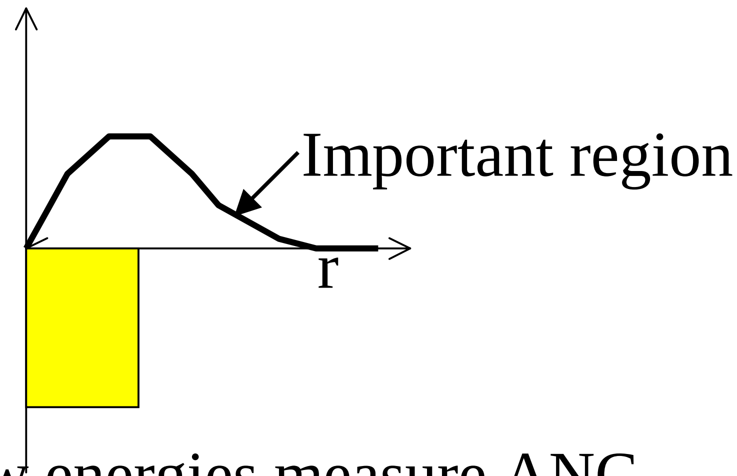
Find: $U_e = 219 \pm 7$

Adiabatic: 120 eV

# ANCs and S-Factors

**Measure ANC** $\Rightarrow$ S(E =0) for (p, $\gamma$), ($\alpha$, $\gamma$) reactions

**Principle:**




- Low-E (x,$\gamma$) reactions occur far from the nuclear surface
- $\sigma \propto |\psi(\text{large r})|^2 \propto \text{ANC}^2$

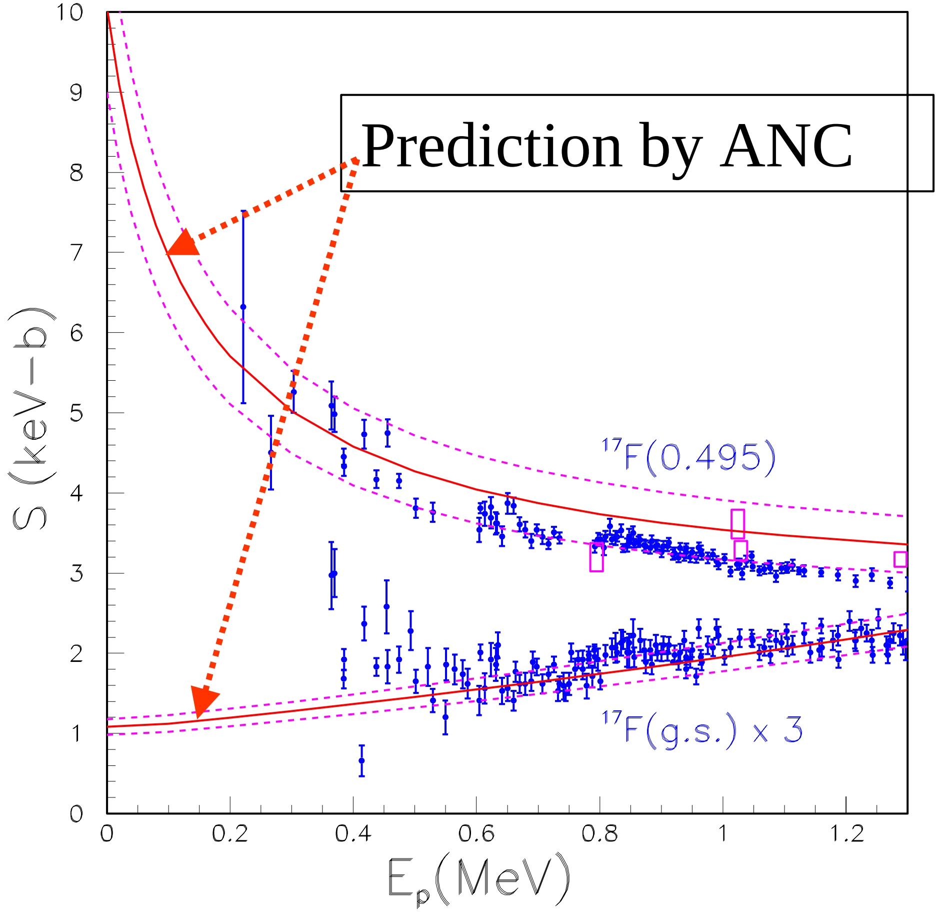
**Experiments:** Transfer reactions at low energies measure ANC

- Detailed work: Texas A&M(Ajhari, Gagliagardi, Mukhamedzhanov, Tribble, *et al.*) $^7$Be(p,$\gamma$)$^8$B, $^{13}$C(p,$\gamma$), $^{16}$O(p,$\gamma$) .
- Issues: Require accurate OM Potentials, limits accuracy to about 10%; checked to 10% against $^{16}$O(p,$\gamma$)
- **Example** $^{10}$B($^7$Be,$^8$B)$^9$Be, $^{14}$N($^7$Be,$^8$B)$^{13}$C at 85 MeV $\Rightarrow$ S($^7$Be(p,$\gamma$)) to 10%, Ogata, 6 Dec.

# S factor for $^{16}O(p, g)^{17}F$—A test of the ANC Method

## Test case-known from Direct Capture

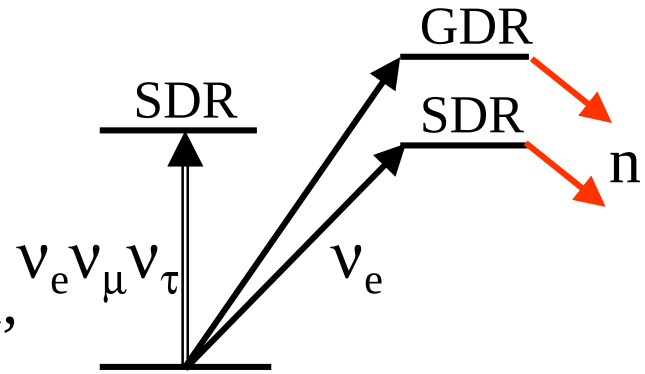
- ANC's for $^{16}O(^{3}He,d)^{17}F$
  - $(C^2)_{gnd} = 1.08 \pm .10$ fm$^{-1}$
  - $(C^2)_{ex} = 6490 \pm 680$ fm$^{-1}$
- Direct Capture data from Morlock, et. Al
- Agree within the relative errors- the 10% level



# Forbidden (L = 1) Strength

## Why we need to know

- Neutrino's excite spin-dipole (L = 1, S =1) resonance--emitted nucleon(s) lead to formation of rare nuclides ($^{7}$Li, $^{11}$B, $^{19}$F…)




- Neutrino reactions modify distribution of r-process nuclides
- Need to calibrate flavor sensitive supernovae neutrino detectors

## What's known?

- For GT (L = 0) transitions, $\sigma$(p, n) $\propto$ B(GT) within, typically, 5-10%. Little similar evidence for L = 1 transitions.
- The maximum strength of the SDR lies below the GDR
- Radioactive beams will permit measurements nearer the dripline

## Is there a Chance that $\sigma$(CEX) $\propto$ B(L=1)?

**Questions we ask (**Dmitriev, Zelevinsky, Austin, PRC**) :**

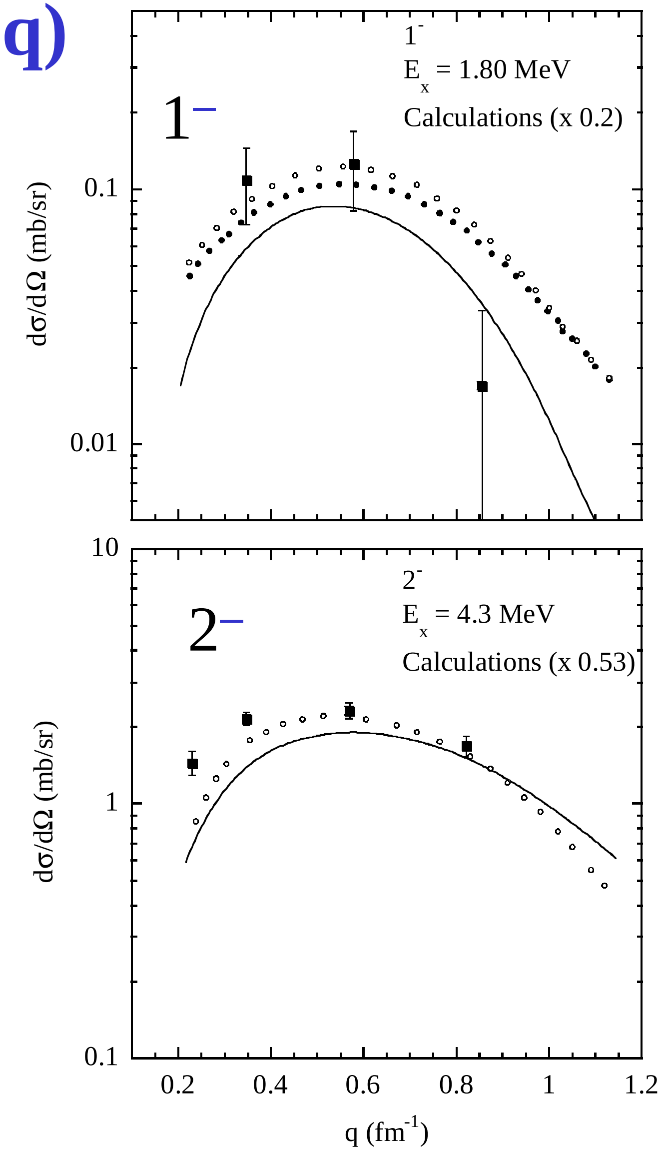
- Is $\sigma$(CEX) $\propto$ B(L=1) when both are calculated with the same wave functions?
- What range of momentum transfer is important in the transition form factor F(q')?

**Sample case:** $^{12}C(p, n)^{12}N$ at $E_p$ = 135 MeV

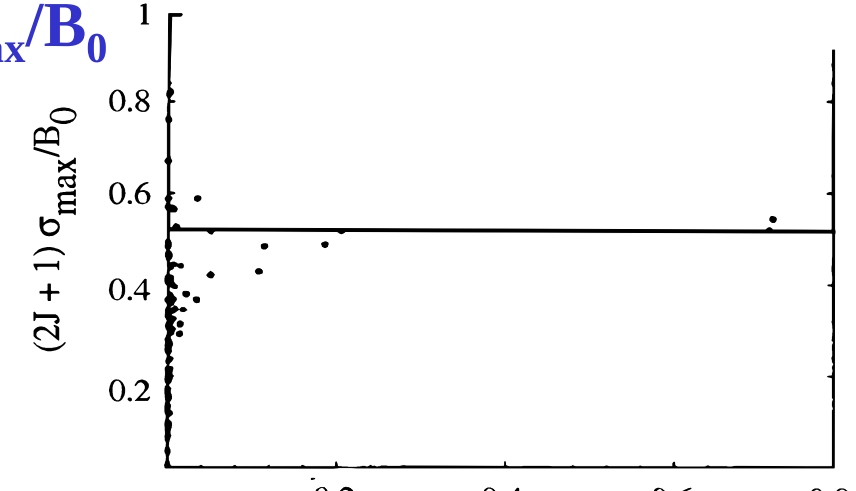
- Eikonal model taking into account real and imaginary parts of OM Potential (Compare to DWIA)
- Define sensitivity function: $T(q) = T_{PW} + \int dq' \, S(q,q') F(q')$
- Characterizes range of q' in F(q') which contribute at a given asymptotic momentum q.

# Cross section vs. B(L = 1, J = 0⁻, 1⁻, 2⁻ )

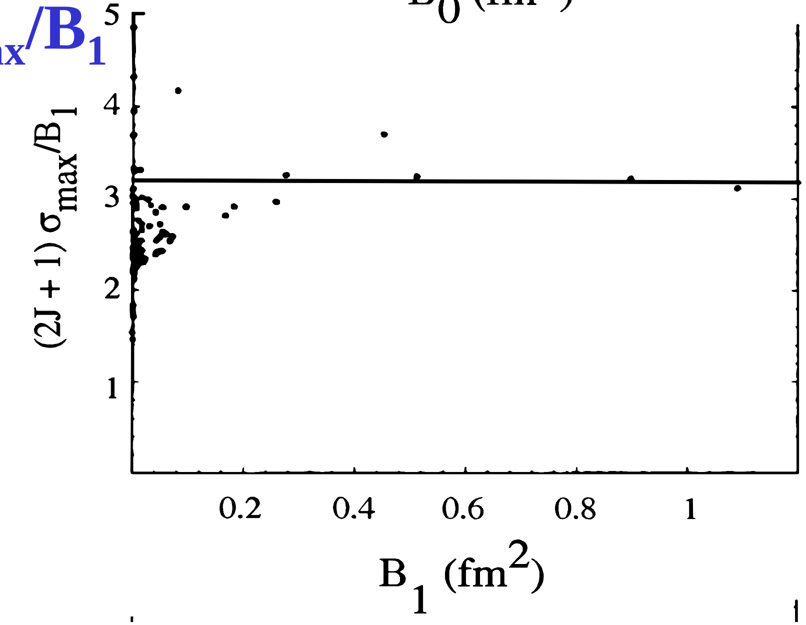
## σ(q)




## $\sigma_{max}/B_0$



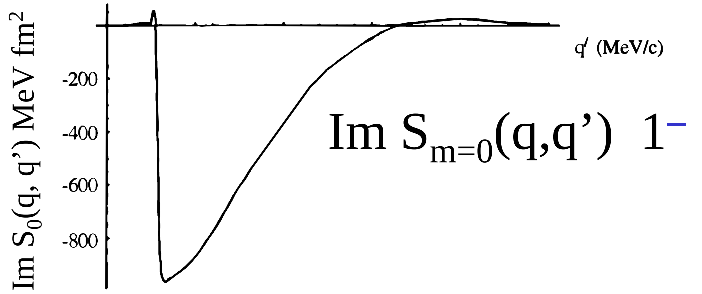

## $3\sigma_{max}/B_1$

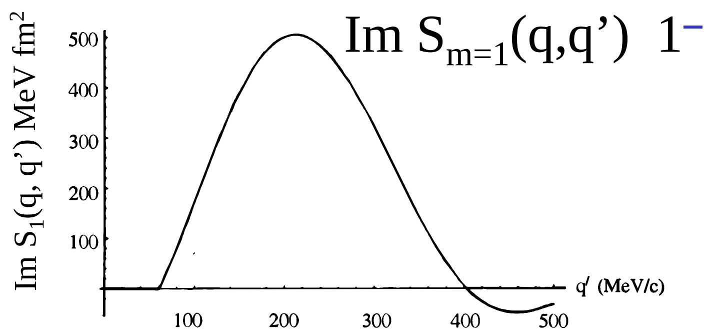


## F(q') and Sensitivity Function

### Results

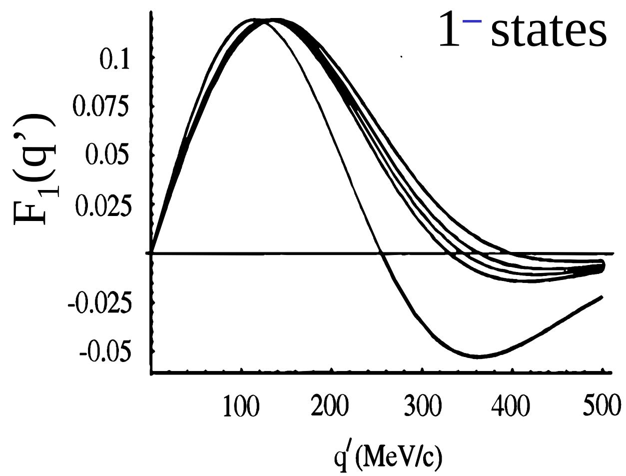
- For $B_J > 0.1\text{fm}^2$, $B_J \propto \sigma(p,n)$ within 10-15%
- Sensitivity function S(q, q') shows main contribution is in range where the transition form factors have the same shape




**To generalize** to other systems

- Are $F_J(q')$ similar for important q'?
- Is S(q, q') localized for heavier nuclei, strongly absorbed probes?



# Coulomb Breakup-Detailed Example

## Principle

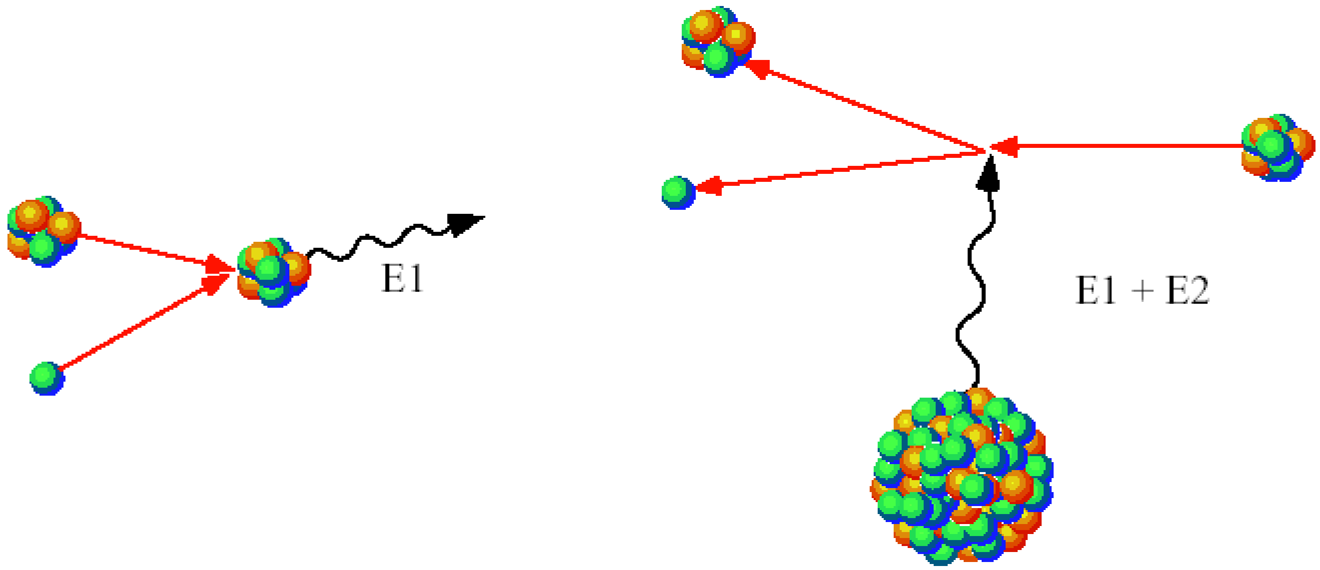
- Breakup of fast projectile by Coulomb field of a high-Z nucleus.
- Inverse of radiative capture. Detailed balance $\Rightarrow$ S-factor for radiative capture. Inverse cross section is larger.
- Advantages-Thick targets, large $\sigma$ $\Rightarrow$ high rates. Universal technique, accuracy probably 5-10%.
- Issues--Nuclear breakup if $E_\gamma$ large, contributions of other multipoles, complex theory.

## Early Experiments

Motobayashi, *et al.*: $^{13}N(p,\gamma)$**$^{14}O$**, $^{7}Be(p,\gamma)$**$^{8}B$**, breakup of **$^{8}B$, $^{14}O$**

GSI, NSCL: $^{7}Be(p,\gamma)$**$^{8}B$**, $^{8}Li(n,\gamma)$**$^{9}Li$**

# Radiative Capture and Coulomb Dissociation



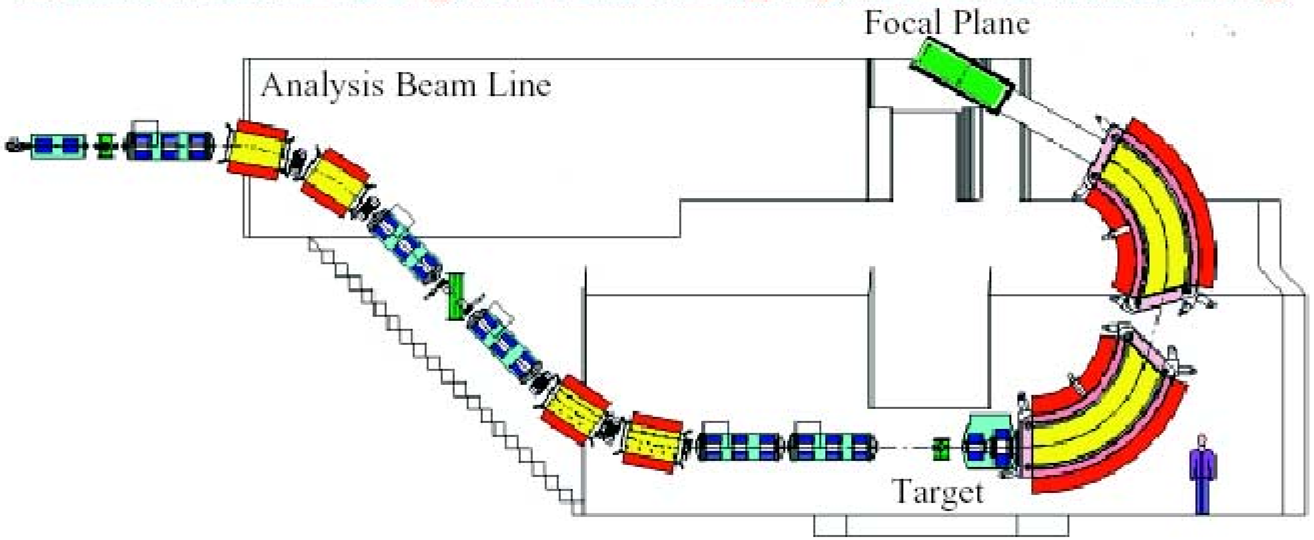

Detailed balance theorem relates Coulomb dissociation and radiative capture cross sections for photons of a given multipolarity

Contributions of E2 and M1 multipolarities must be gauged in order to extract E1 strength from Coulomb dissociation cross section

# Experimental Apparatus

# S800 Spectrometer

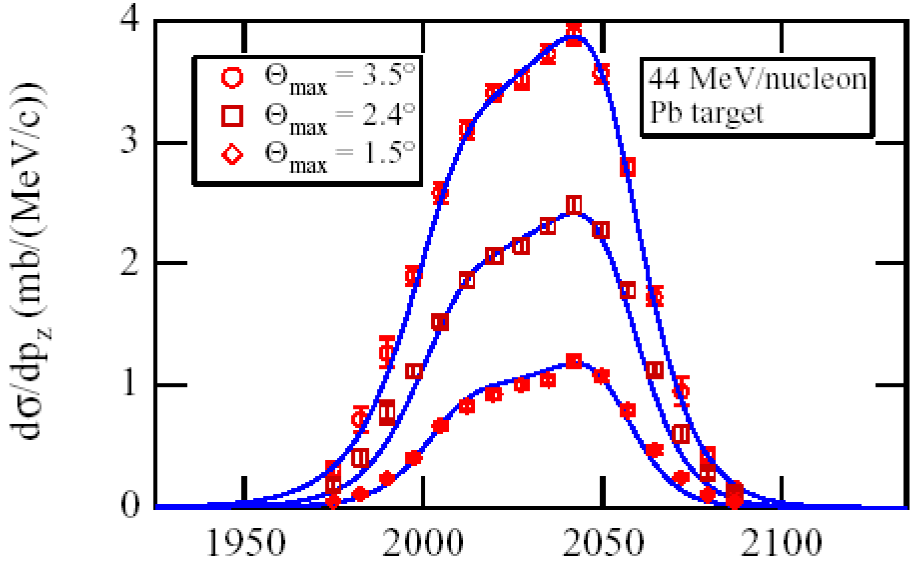
## at the National Superconducting Cyclotron Laboratory




Spectrometer set at 0° to detect $^{7}$Be fragments from breakup of

44 and 81 MeV/nucleon $^{8}$B on Ag and Pb targets

# Low Energy Results

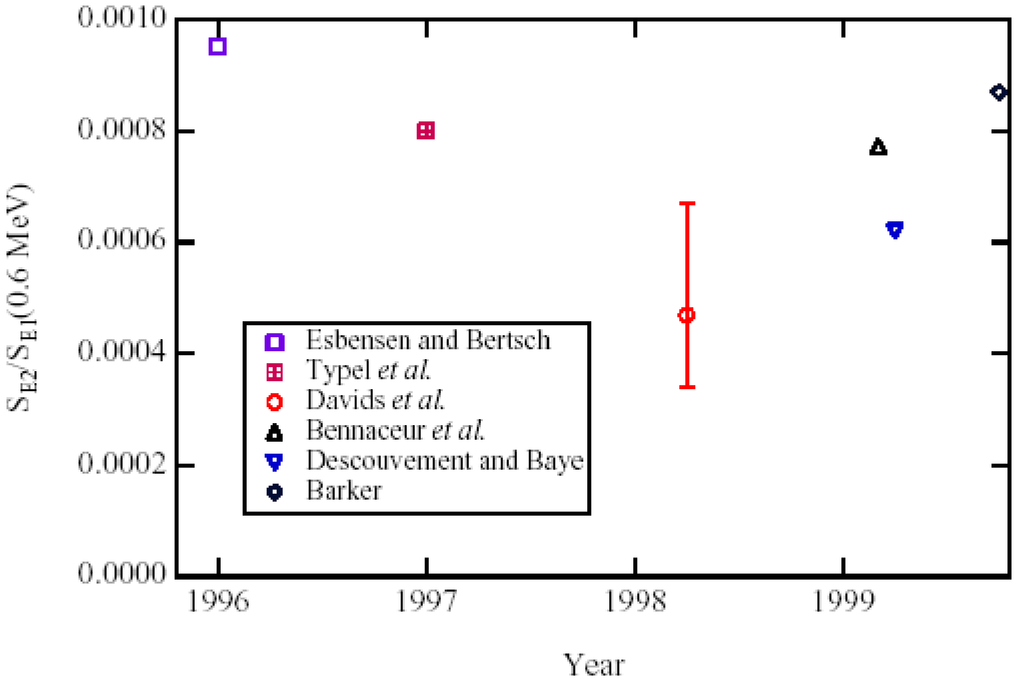



$^{7}$Be Longitudinal Momentum (MeV/c)

Longitudinal Momentum distribution of $^{7}$Be fragments produced in Coulomb dissociation of 44 MeV/nucleon $^{8}$B on Pb target

Curves: 1st-order perturbation theory convoluted with experimental resolution

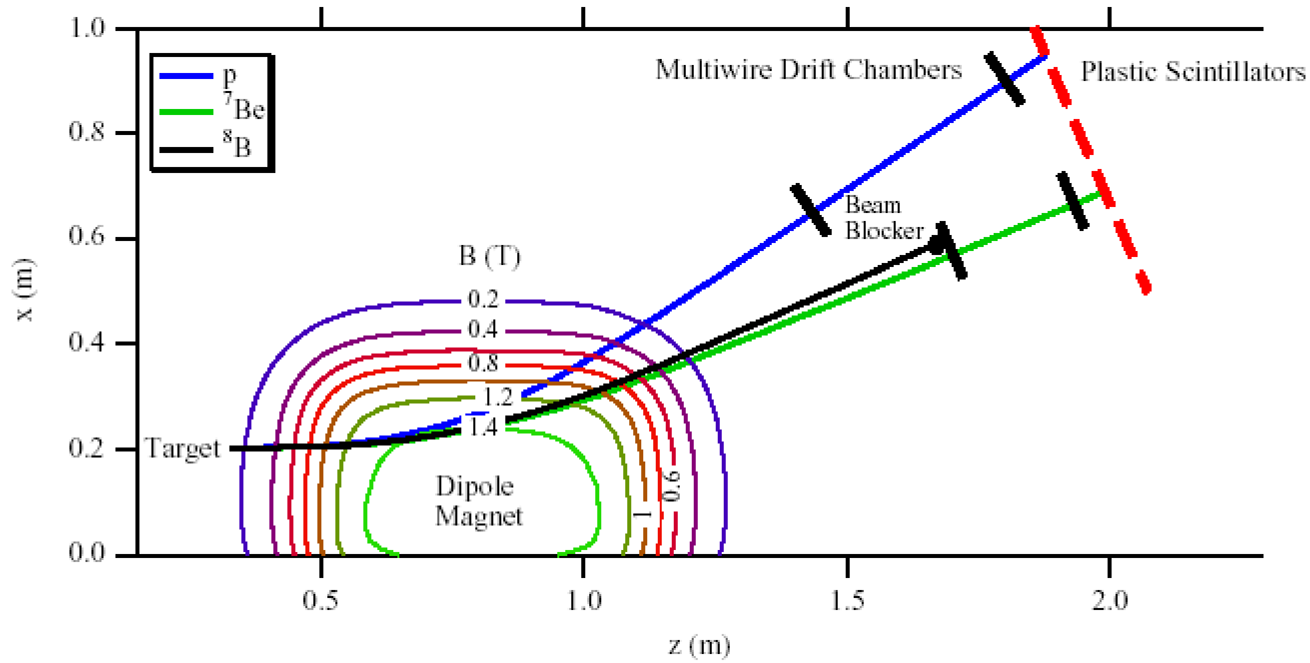
# Conclusions




Results interpreted with 1st-order perturbation theory; if higher-order effects are significant, larger E2 strength required to describe measurement

$S_{E2}/S_{E1} = 4.7\ (+2.0, -1.3) \times 10^{-4}$ at $E_{rel} = 0.6$ MeV

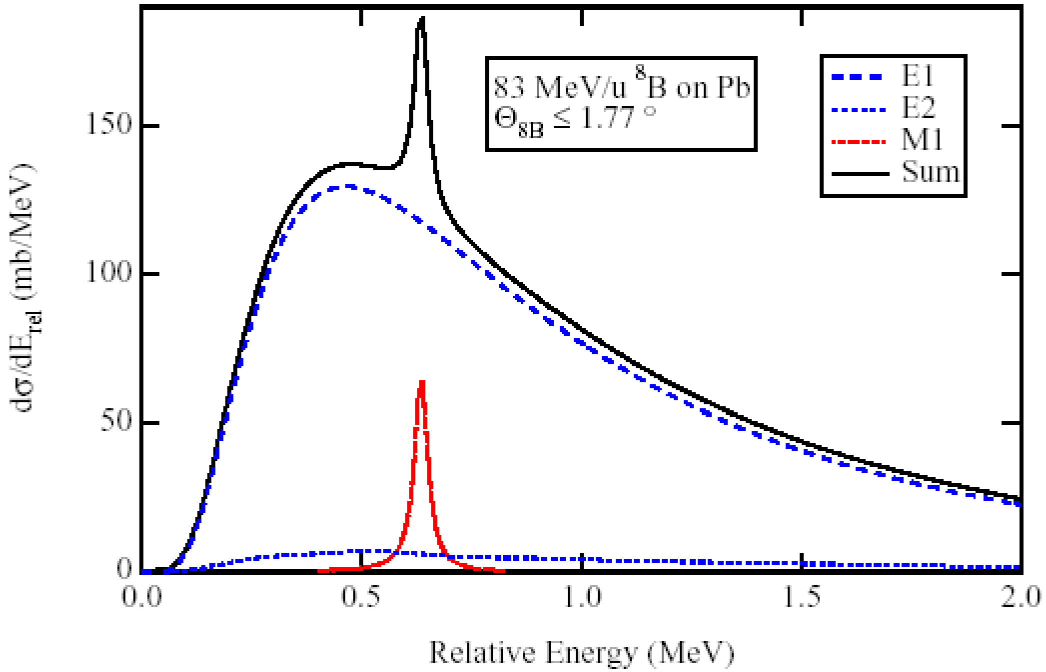
# Exclusive Measurement: Schematic View of Setup




$^7$Be and proton fragments from Coulomb breakup of 83 MeV/u $^8$B on Pb dispersed by 1.5 T dipole magnet, detected in pairs of position-sensitive drift chambers and array of 16 plastic scintillators

Stainless steel plate intercepted direct beam

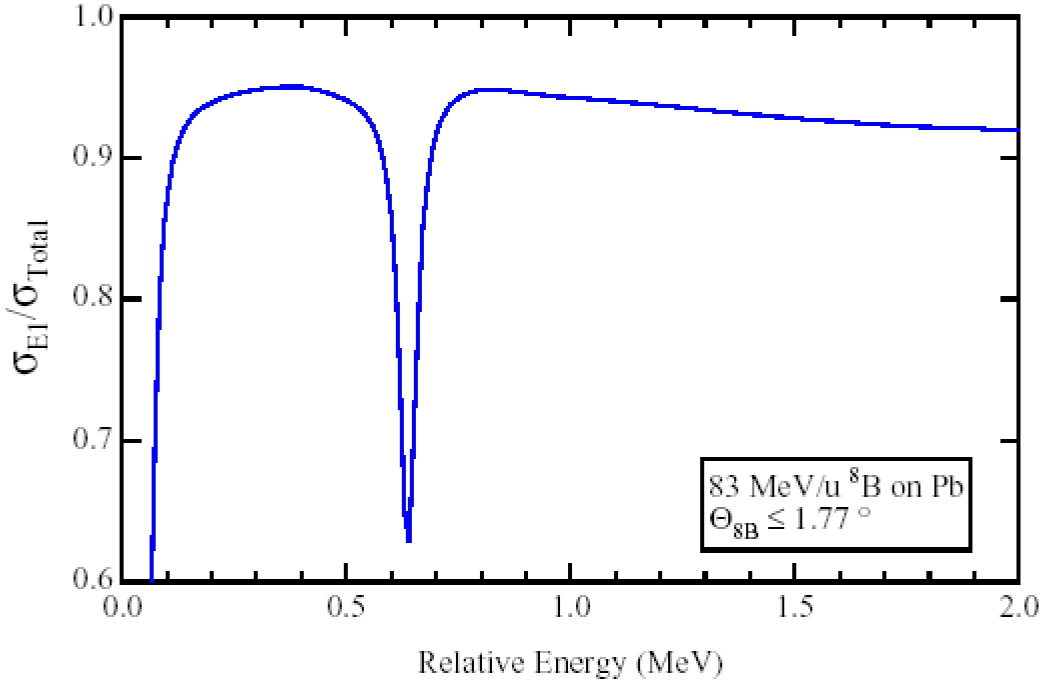
# Theoretical Description of Breakup Energy Spectrum




1st-order perturbation theory calculation of E1+E2 using model of Esbensen and Bertsch with scaled E2 matrix elements, M1 from Filippone measurement

Angular cut corresponds to 30 fm impact parameter: minimizes E2 component, nuclear-induced breakup, and higher-order electromagnetic processes

# E1 Fraction of Total Breakup Cross Section




E1 transitions account for over 90% of cross section between 130 keV and 2 MeV, except near 640 keV M1 resonance

E2 dominates at low relative energies excluded from analysis

# Extracting $S_{17}$—Some Issues

## Reaction Model

•First order perturbation theory--Esbensen, Bertsch

•Continuum Discretized Coupled Channels (CDCC)--Thompson, Tostevin

## E2 Contributions

- Use results from inclusive experiments
- For most of $E_x$ range < 5%, large for $E_x$ < 130 keV

## Nuclear contributions

- From CDCC, less than 4% for $E_x$ < 400 keV

## Continuum Discretized Coupled Channel Calculations

### Basic Picture

- Breakup populates excitations up to $E_{rel} = 10$ MeV
- $E_{rel}$ range divided into bins-discretized
- Bin wavefunctions are orthonormal basis for coupled channels solution of $^{7}$Be+p+target three-body w.f.

### Details

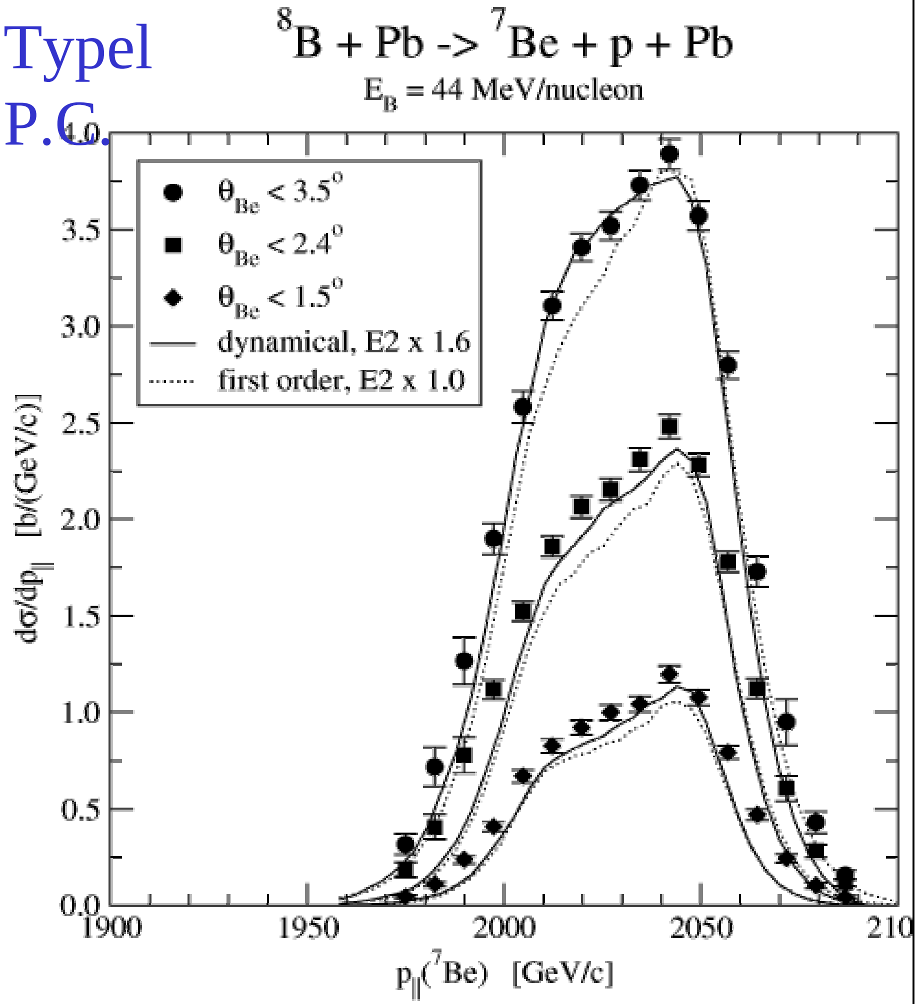
- Partial waves: $L_{max} = 15{,}000$, radii to 1000 fm
- $l_{rel} \leq 3$, $\lambda \leq 2$
- Pure $p_{3/2}$ single particle state ($^{7}$Be inert)
- Consider nuclear interactions

# The Importance of Higher Order Processes-More on L=2

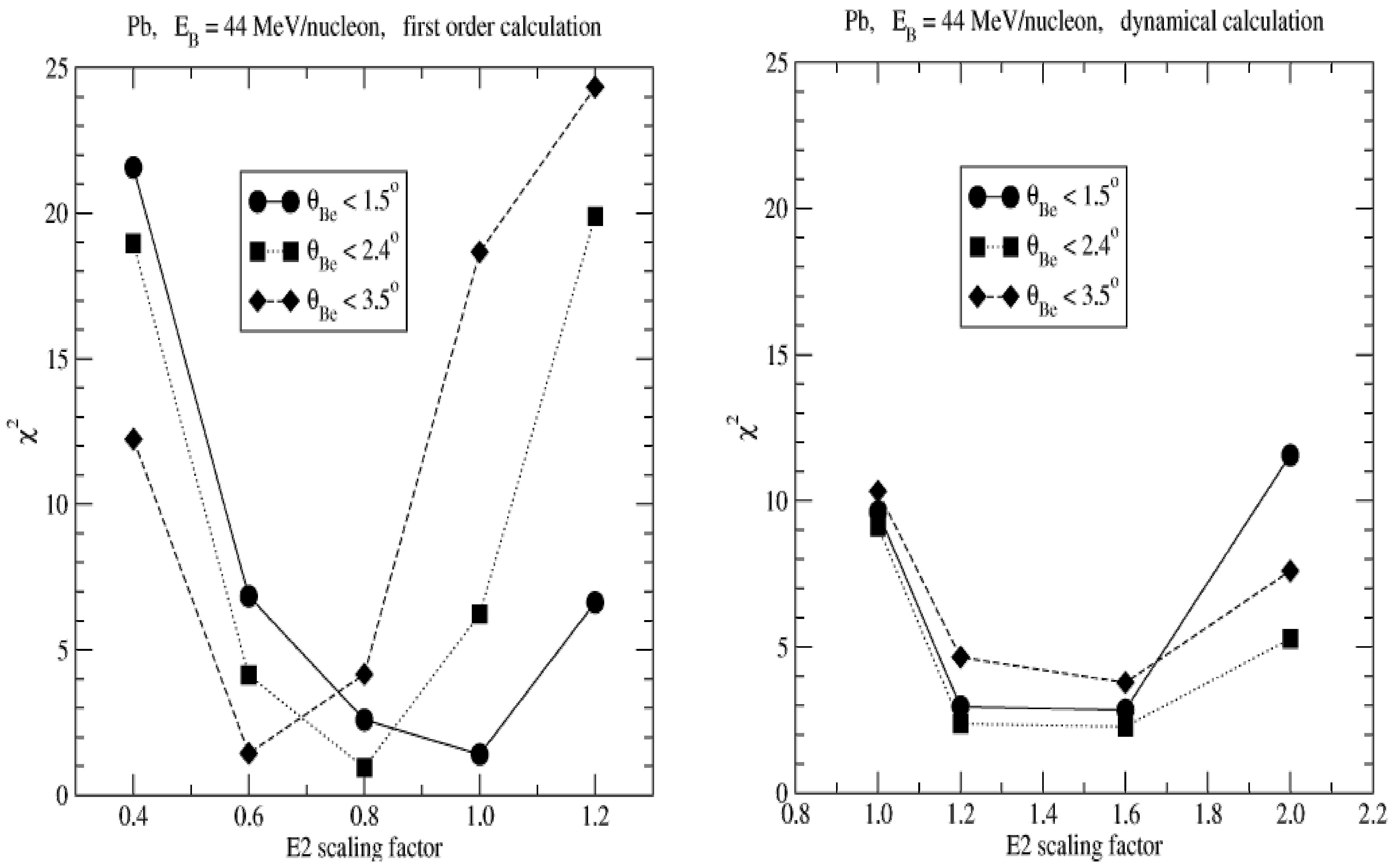
## Beyond perturbation theory

- This analysis done in P.Theory
- Underestimates the E2-strength. (Esbensen-Bertsch)
- Recent calculations by Mortimer et al. in CDCC, find that E2 amplitude must be 1.6 times single particle estimate to fit asymmetries.
- Recent calculations (S. Typel) using the time dependent Schroedinger Eq., find a similar result.

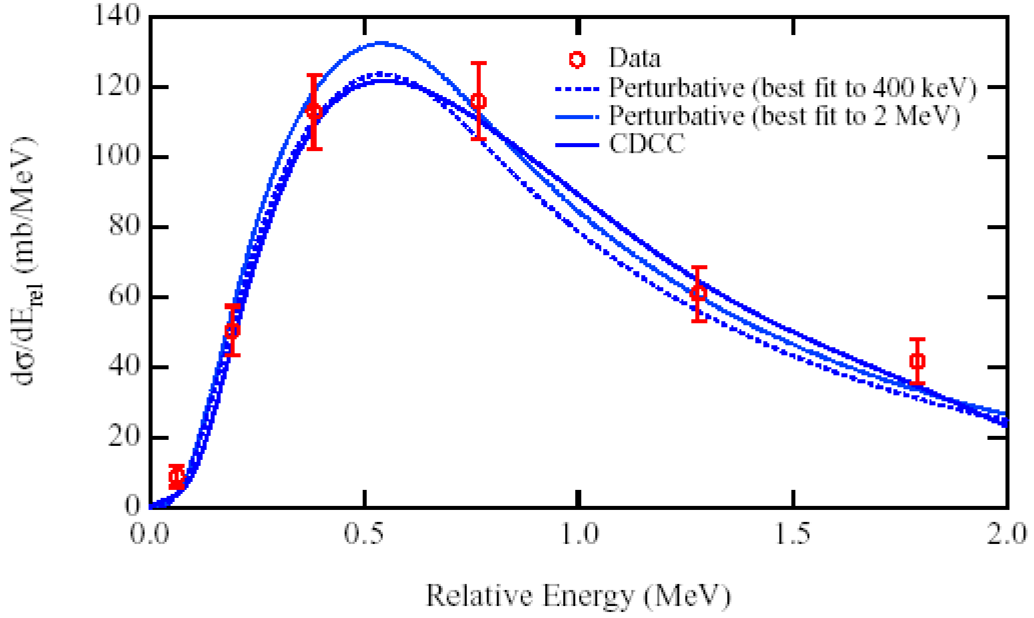
Typel P.C.



# Chi$^2$ for various E2 Scaling Factor



# Measured Coulomb Dissociation Cross Section



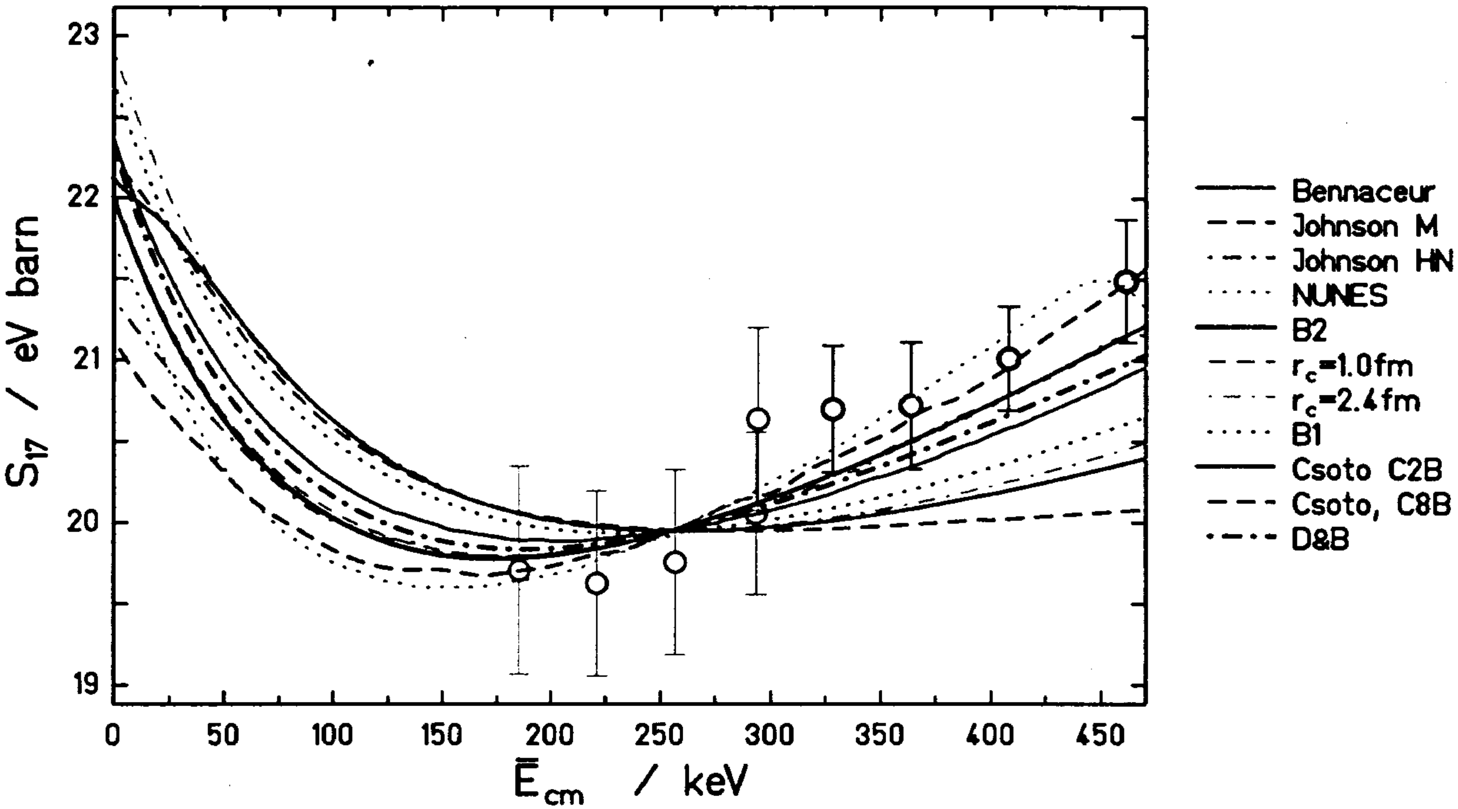

Minimizing $\chi^2$ for the data above 130 keV by varying normalization of E1+E2 calculation in perturbation theory yields best fits for 2 energy ranges

$S_{17}(0) = 17.8\ (+1.4,-1.2)$ eV b

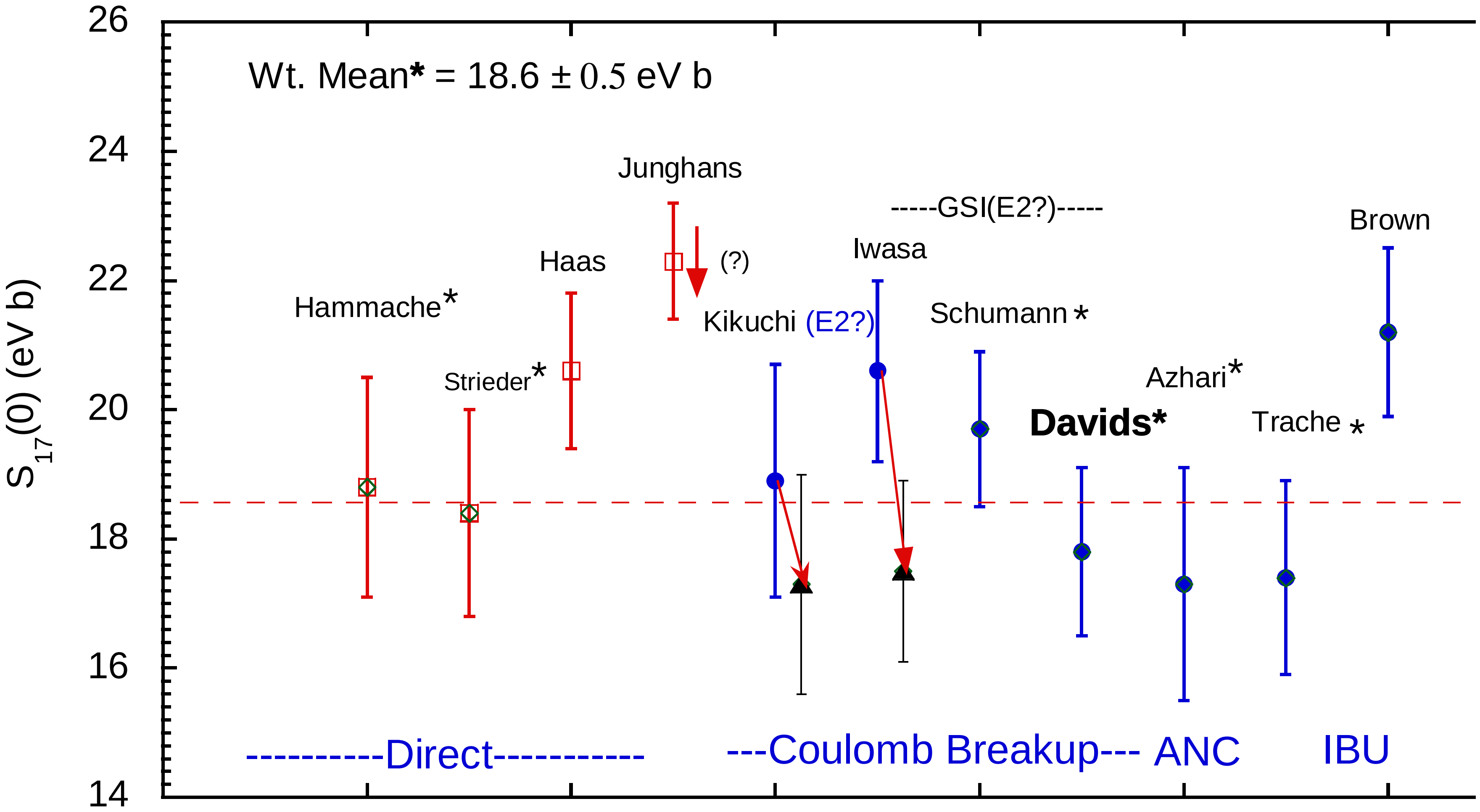
# A Plea to Nuclear Theorists

Theoretical uncertainties for these difficult experiments are now comparable to experimental error even for extrapolations from 250 keV—**can we get a better theory**?

Tabulation-Junghans, et al.

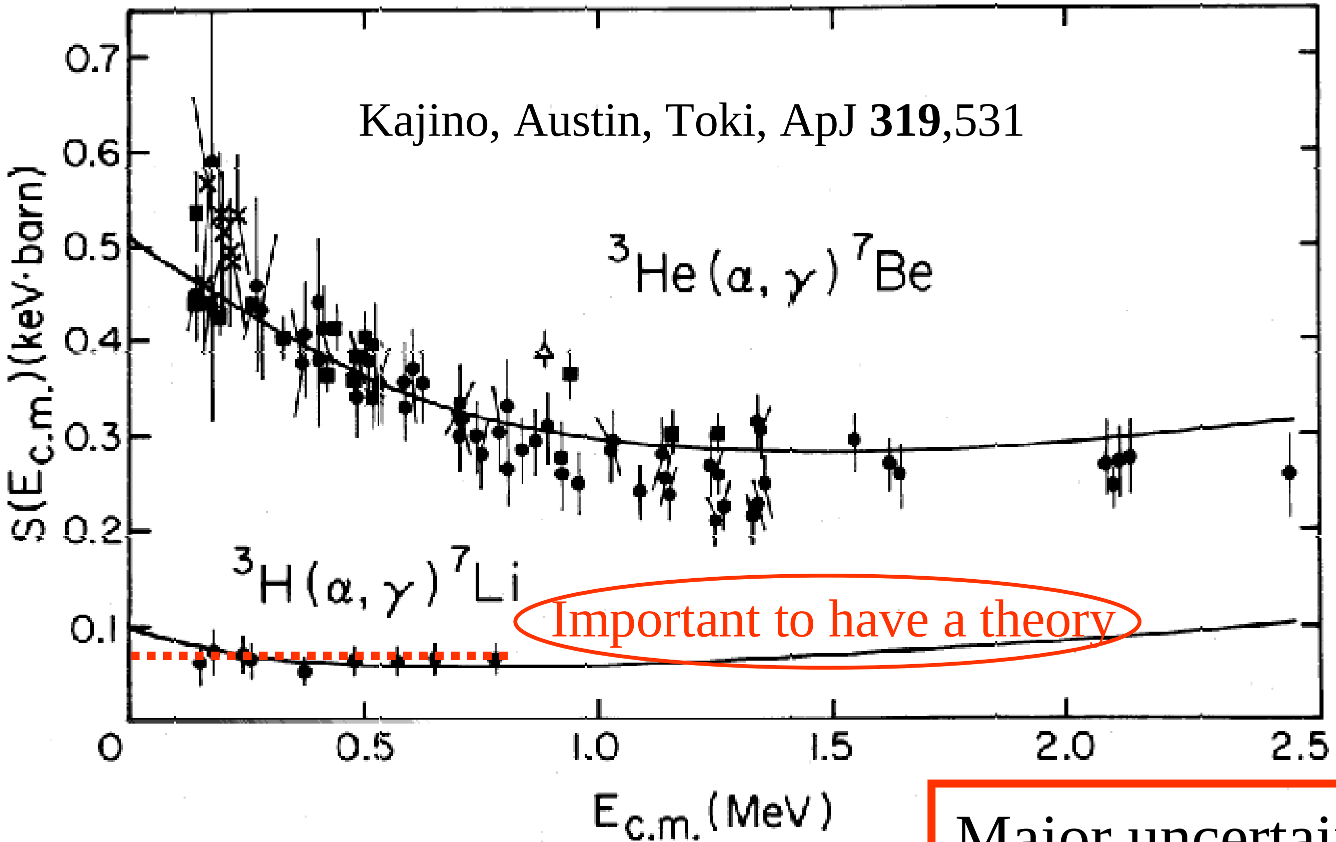


# Summary-Values of $S_{17}$




**Note**: Fit includes * points.

## New Expt-- $^3He + ^4He \rightarrow ^7Be + \gamma$

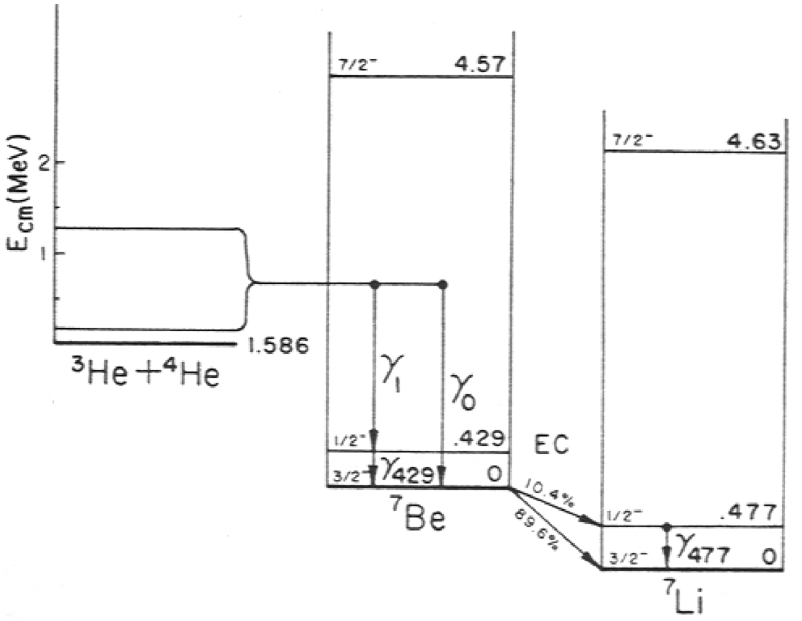


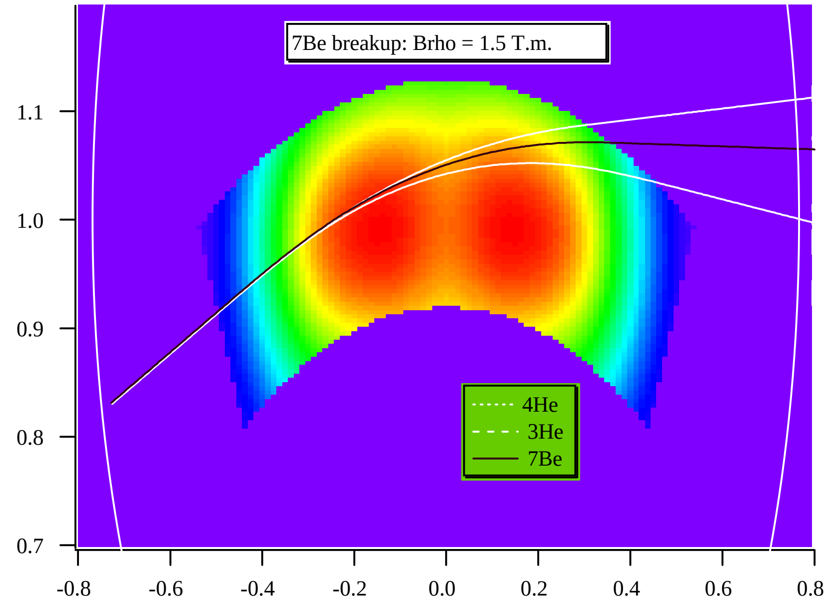

Looks good: BUT

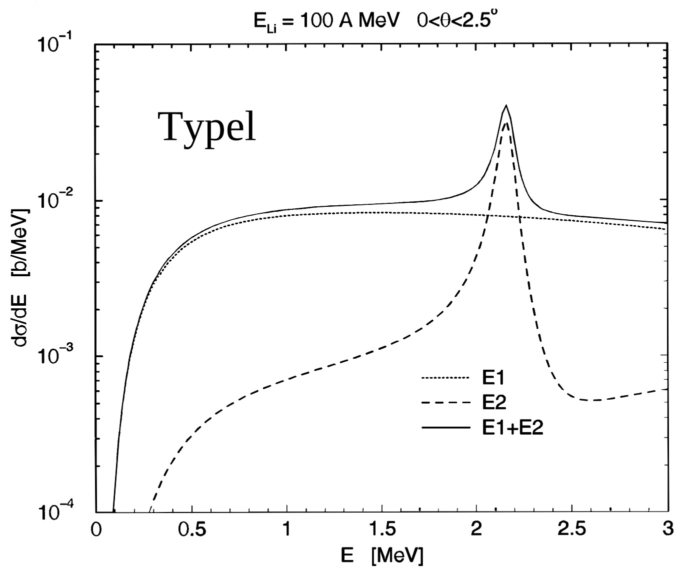
- Counting $\gamma$'s $\Rightarrow$ 0.507 $\pm$ .016 keV b
- Counting $^7Be$ decays $\Rightarrow$ 0.572 $\pm$ 0.026

Major uncertainty (8%) in fluxes of **$^7$Be** and **$^8$B** neutrinos (**SNO**, **SuperK**, **Borexino**). Also $^7Li$ in Big Bang

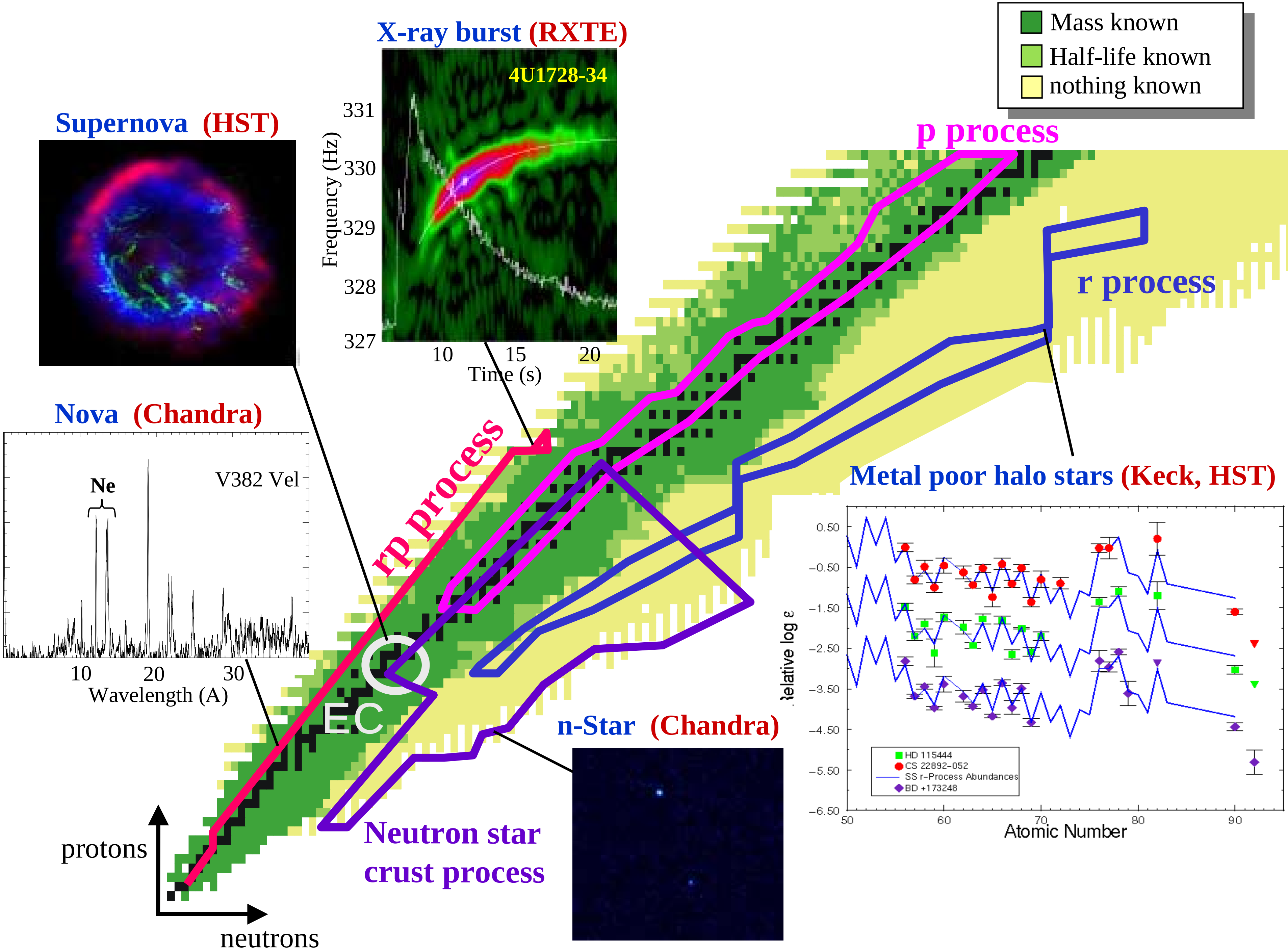
# New Experiment—Coulomb breakup of $^7$Be—Matt Cooper, et al.



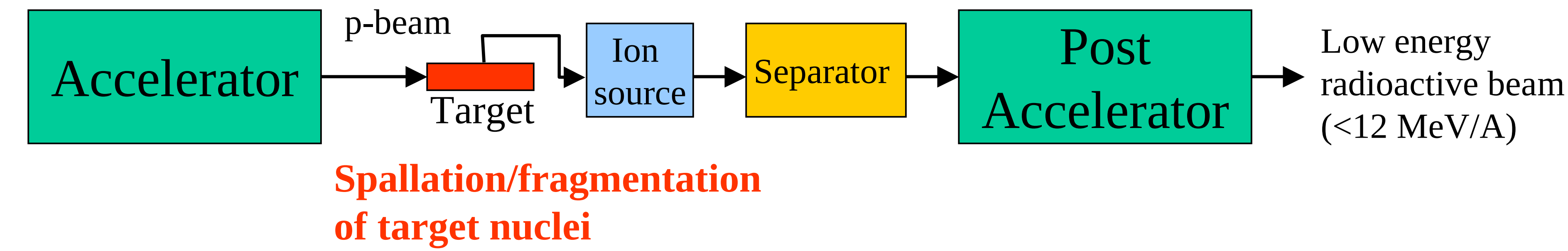

Analysis should be straight forward—E2 cross section small.



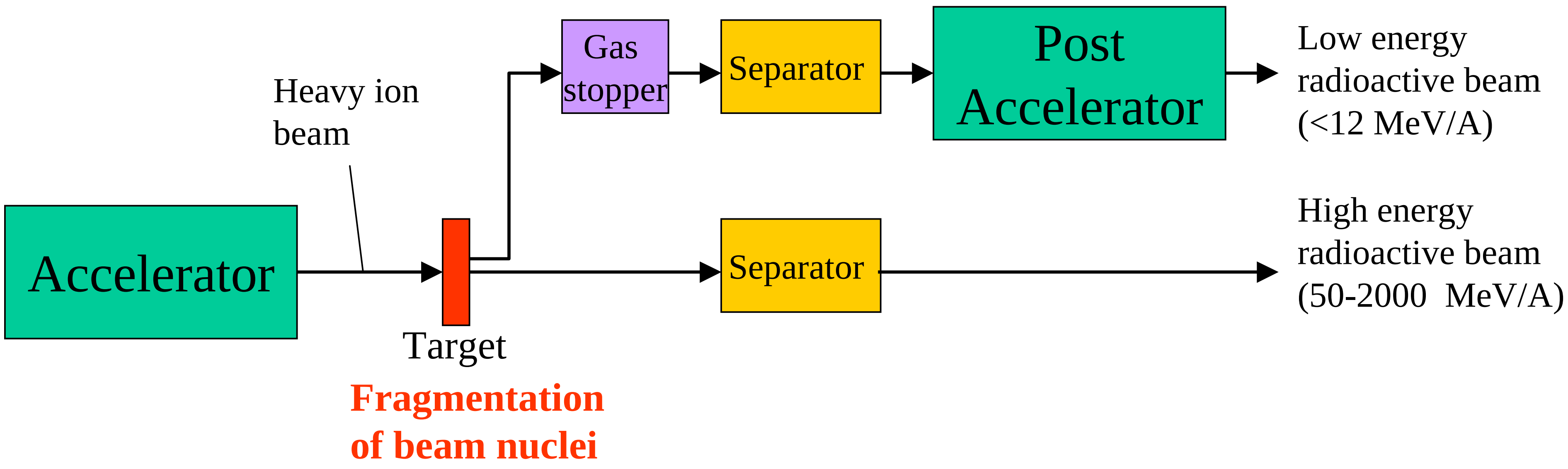
X-ray burst (RXTE)
4U1728-34
Frequency (Hz)
331
330
329
328
327
10
15
20
Time (s)
Mass known
Half-life known
nothing known
Supernova (HST)
p process
r process
Nova (Chandra)
Ne
V382 Vel
10
20
30
Wavelength (A)
rp process
EC
Metal poor halo stars (Keck, HST)
0.50
-0.50
-1.50
-2.50
-3.50
-4.50
-5.50
-6.50
50
60
70
80
90
Atomic Number
HD 115444
CS 22892-052
SS r-Process Abundances
BD +173248
n-Star (Chandra)
Neutron star
crust process
protons
neutrons

# Production of radioactive beams

## ISOL (ISOLDE, ISAC, Oak Ridge, Louvain-la-Neuve, …):




## Fragmentation (NSCL, GSI, RIKEN, GANIL, …):



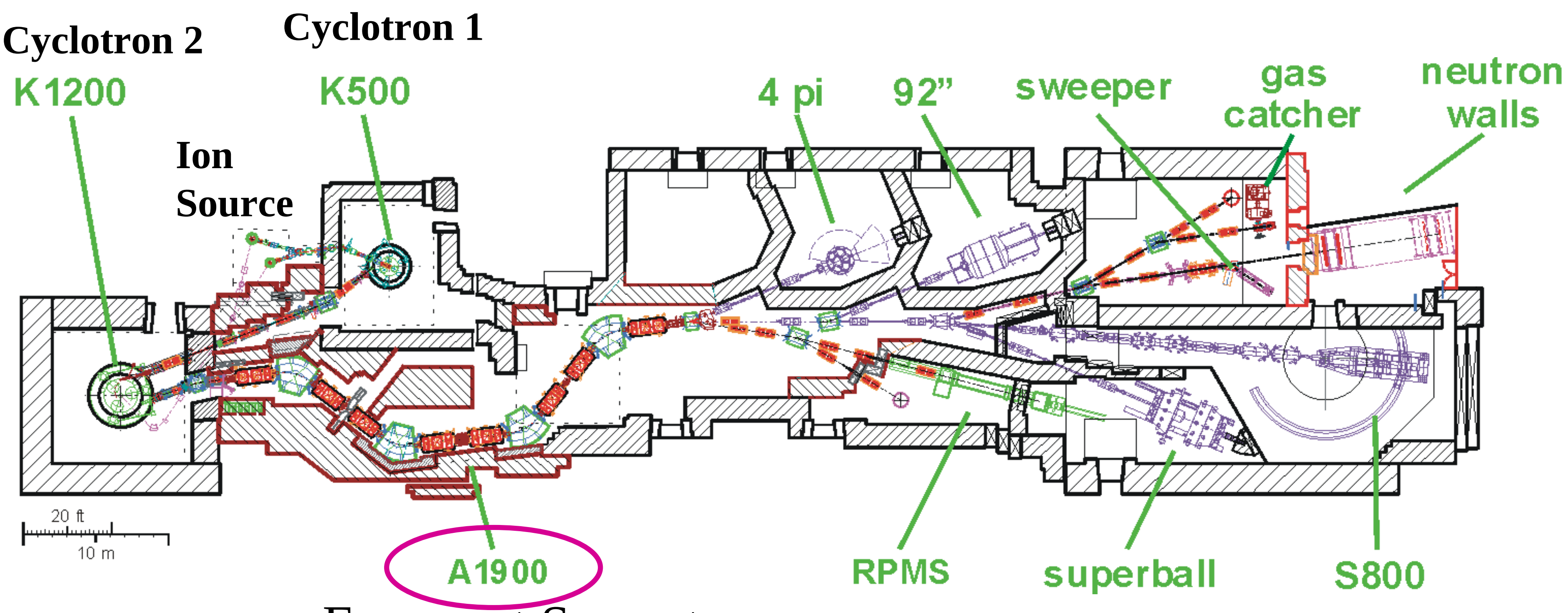
# Summary Fast/Slow beam experiments for nuclear astrophysics

| | slow | fast |
|---|---|---|
| **Direct rate measurements** | **x** | |
| **Half-lives** | **x** | **x** |
| **Bn decay** | **x** | **x** |
| **Masses** | **x** | **x** |
| **Coulomb Excitation** | **x** | **x** |
| **Transfer reactions** | **x** | **x** |
| **Coulomb breakup** | | **x** |
| **Charge exchange** | | **x** |

If both techniques are applicable then consider on case by case basis:

- beam intensity (production cross section, release and transport times)
- target thickness (higher for fast beams)
- selectivity (signal/background) (fast: ~100%, slow: depends)
- method efficiency

# National Superconducting Cyclotron Facility at Michigan State University



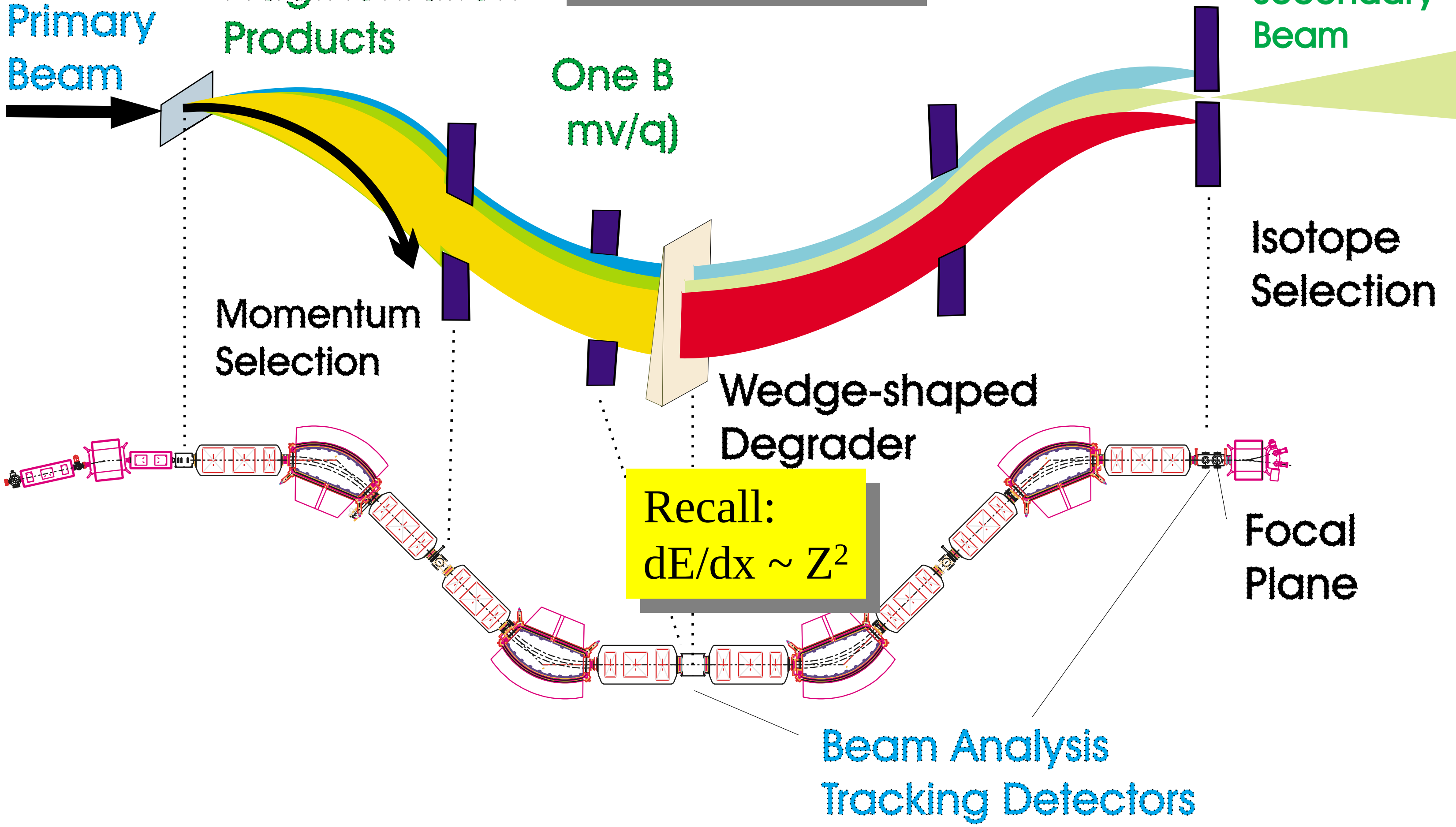

Fragment Separator

- First fully accelerated beams, Oct/00 !
- First Radioactive Ion Beams, Jun/01
- First PAC experiment, Nov/01

Installation of D4 steel, Jul/2000

# Fragment Separators

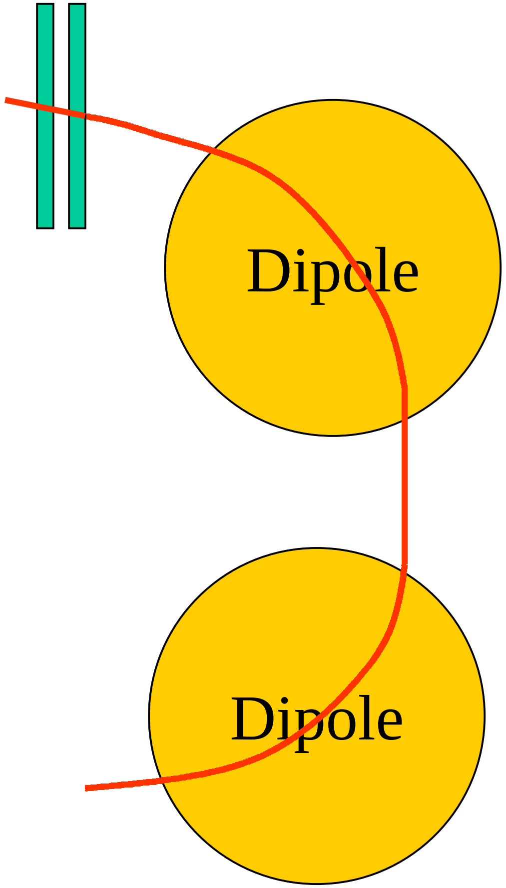
Recall in B-field:
r=mv/qB




Recall:
dE/dx ~ $Z^2$

NSCL S800 Spectrometer

dp/p ~ $10^{-4}$ possible




SPEG GANIL achieved
mass measurements at $10^{-5}$ level