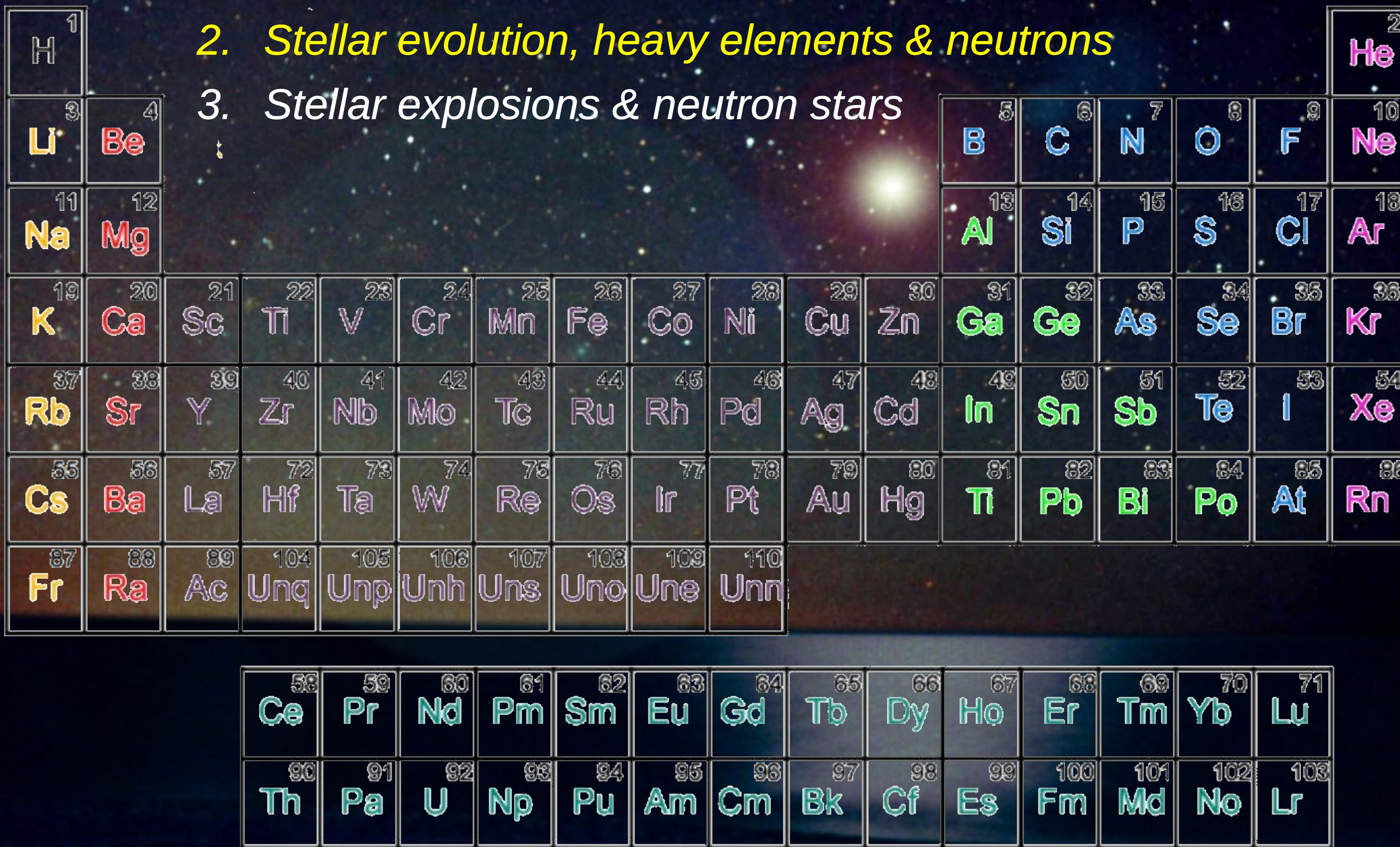
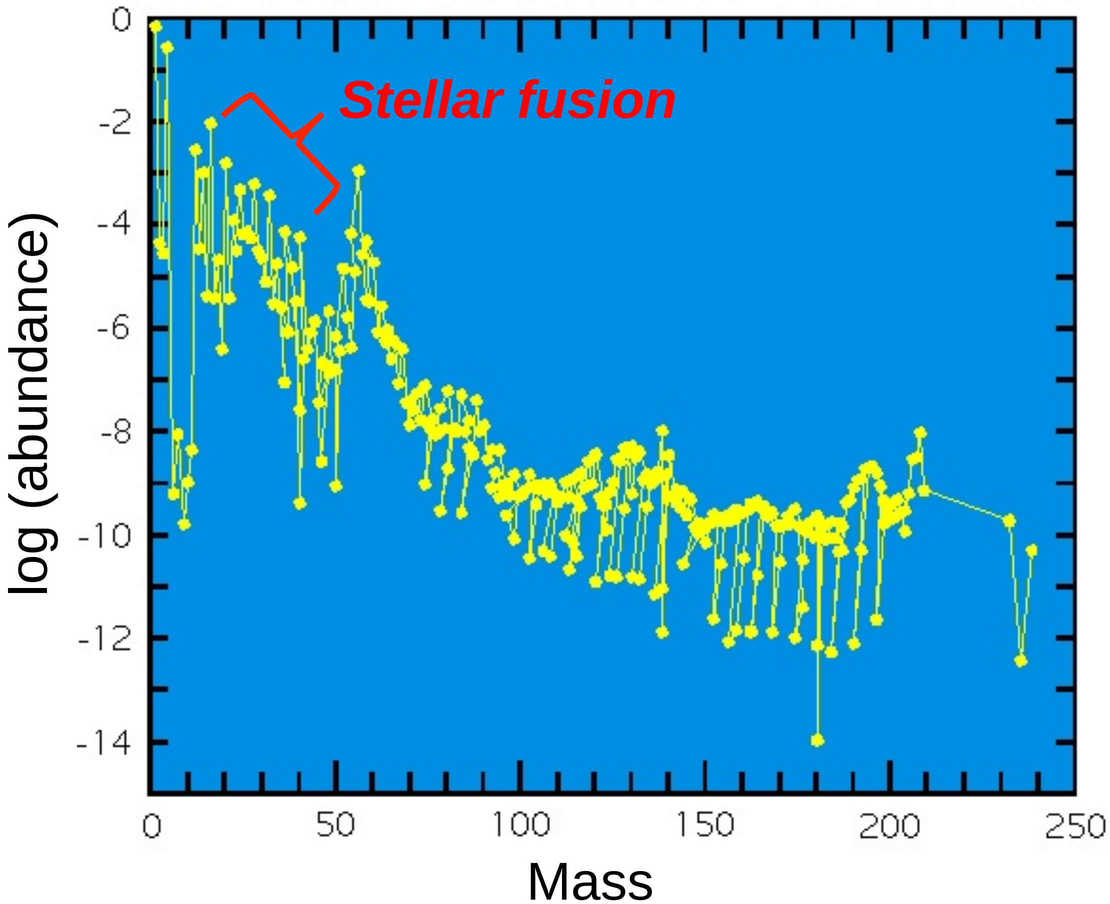
Nuclear Physics in Astrophysics

Jeff Blackmon (LSU)

1. *Introduction, BBN & charged-particle reactions*
2. *Stellar evolution, heavy elements & neutrons*
3. *Stellar explosions & neutron stars*



Solar system abundances



Stellar Structure

Stellar convective zone decoupled from core by radiative heat transport

Large T,P gradient

Hydrostatic equilibrium

$$\frac{dP(r)}{dr} = -\frac{GM_{in}(r)\rho(r)}{r^2}$$

Pressure

$$P(r) = P_{gas}(r) + P_{rad}(r)$$

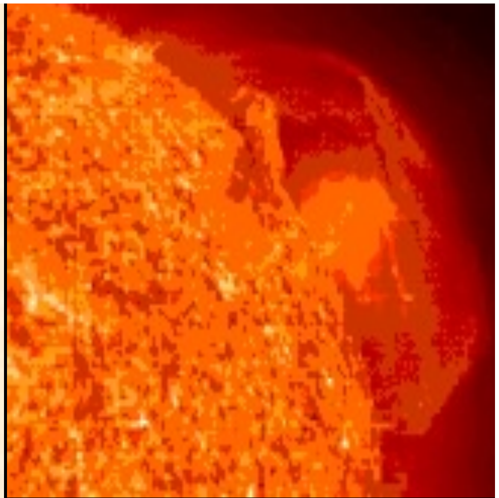
For sun (non-degenerate)

$$P_{gas}(r) = \frac{k}{\langle m \rangle}\rho(r)T(r)$$

$$P_{rad}(r) = \frac{1}{3}aT^4(r) < P_{gas}(r)$$

Opacity: photons absorbed and emitted at shorter λ

Luminosity/opacity/T relationship ➡ $L \propto M^4$



The sun

M=2x10^{30} kg

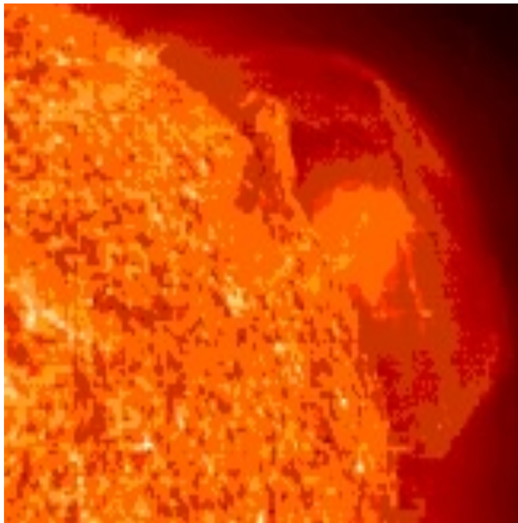
ρ(0)=150 g/cm^3

T(0)=1.5x10^7 K

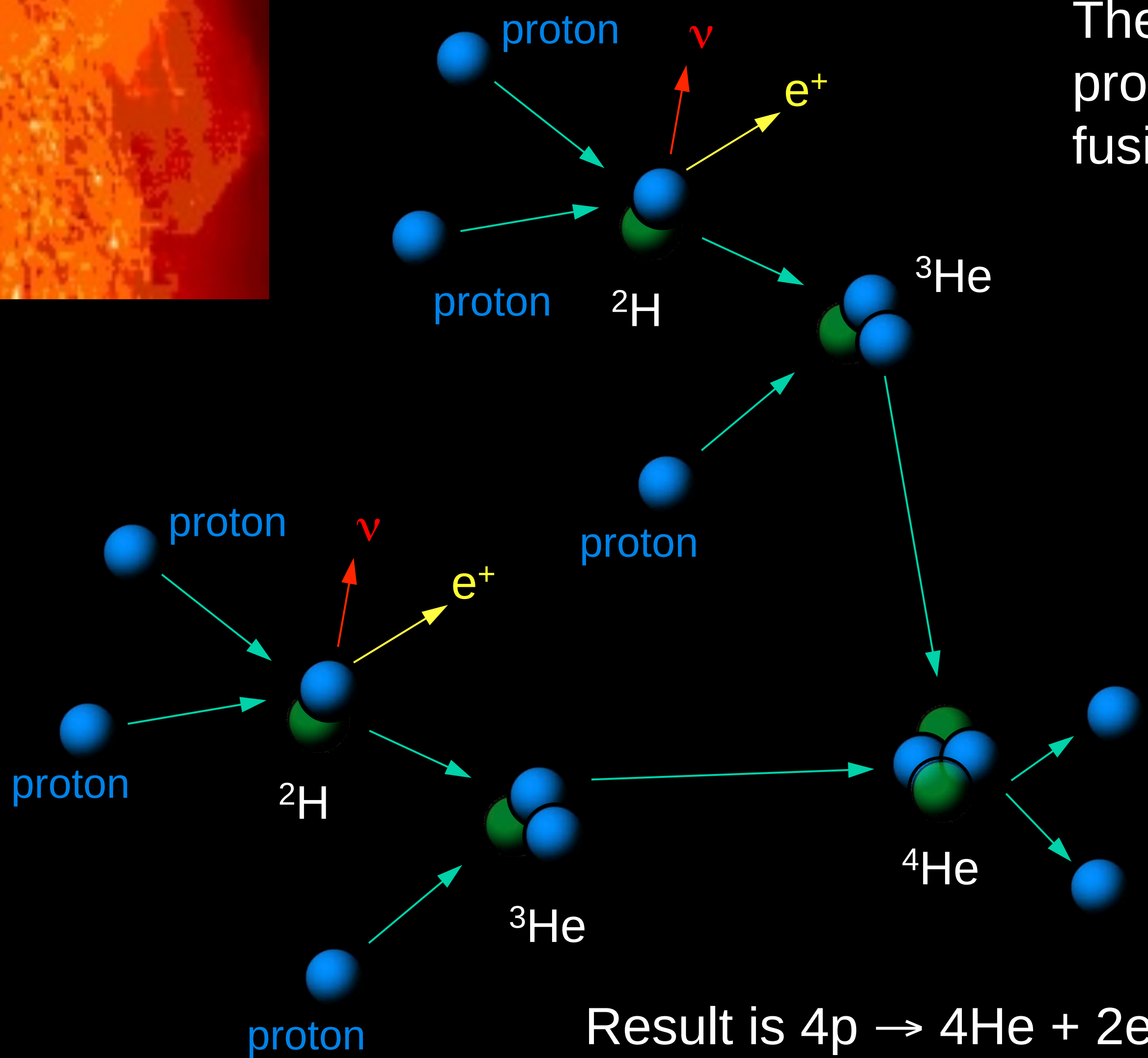
T(surf)=5800 K

L=3.8x10^{26} W

5x10^4 yr for energy produced in sun's core to be reach surface



Solar fusion



The sun's energy is produced by nuclear fusion in its core

T(core)=15 MK

T(surf)=5800 K

Result is $4p \rightarrow 4He + 2e^{+} + 2\nu + 27$ MeV

27 MeV = 4×10^{-12} J * 10^{38} fusions/s = 4×10^{26} Watts

Solar fusion: The pp-chains

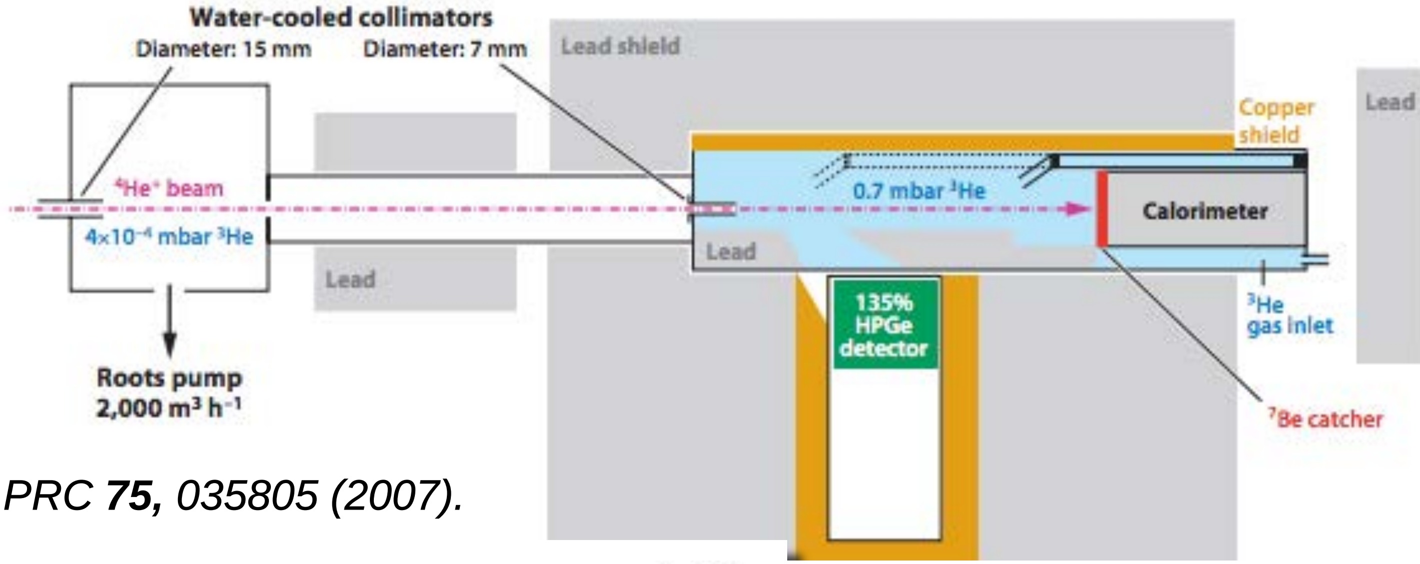
	Uncertainty in reaction rate		Branching
pp-1:	5%	$^{1}H(p,e^{+}\nu)^{2}H$	
	5%	$^{2}H(p,\gamma)^{3}He$	
	7%	$^{3}He(^{3}He,2p)^{4}He$	84.7%
pp-2:	3%	$^{3}He(\alpha,\gamma)^{7}Be$	13.8%
		$^{7}Be(e^{-},\nu)^{7}Li$	13.78%
	13%	$^{7}Li(p,\alpha)^{4}He$	
pp-3:	5-10%	$^{7}Be(p,\gamma)^{8}B$	0.02%
		$^{8}B(\beta^{+}\nu)2^{4}He$	

Only ν most experiments measure

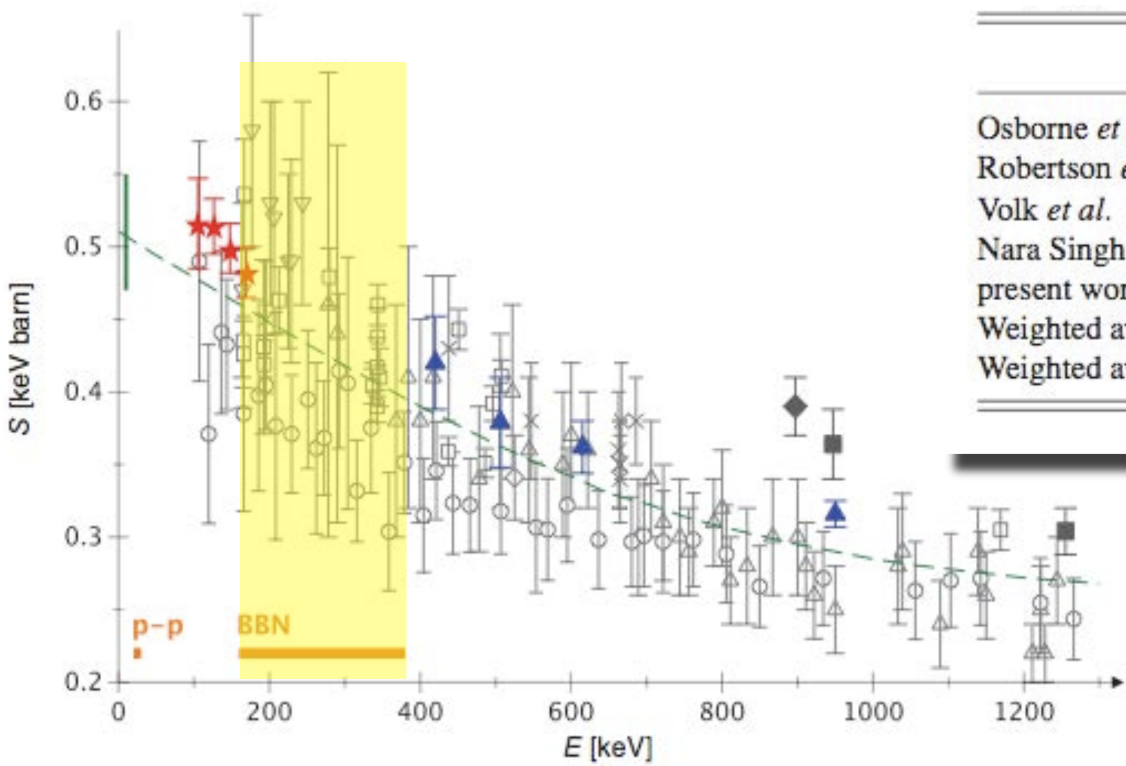
fusion of $4\ ^{1}H \rightarrow 4He + 2e+ + 2\nu e + 26.7$ MeV energy release

$^3He(\alpha,\gamma)^7Be$

Laboratory
Underground
Nuclear
Astrophysics



Gyürky et al., PRC ***75,*** *035805 (2007).*

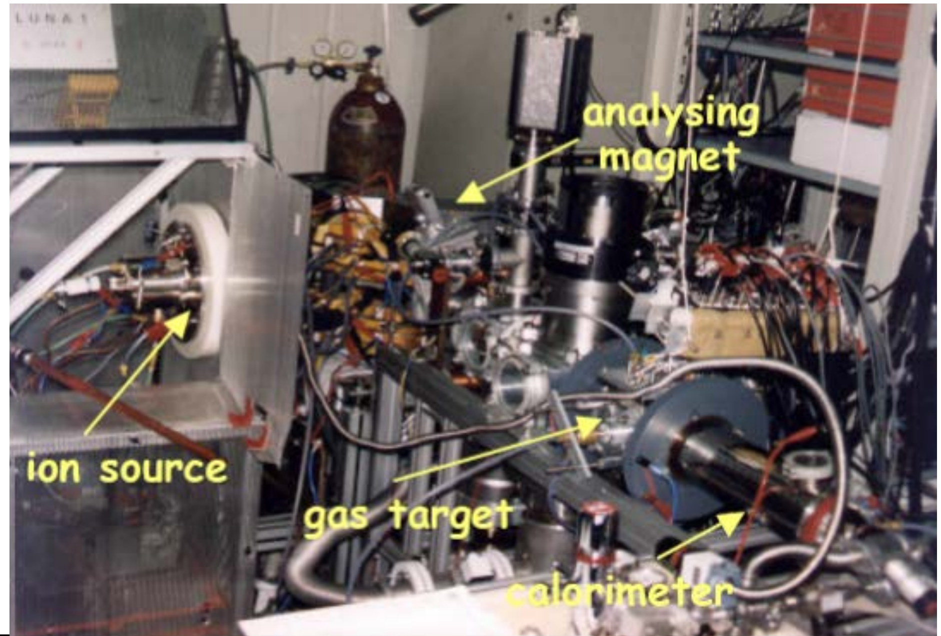


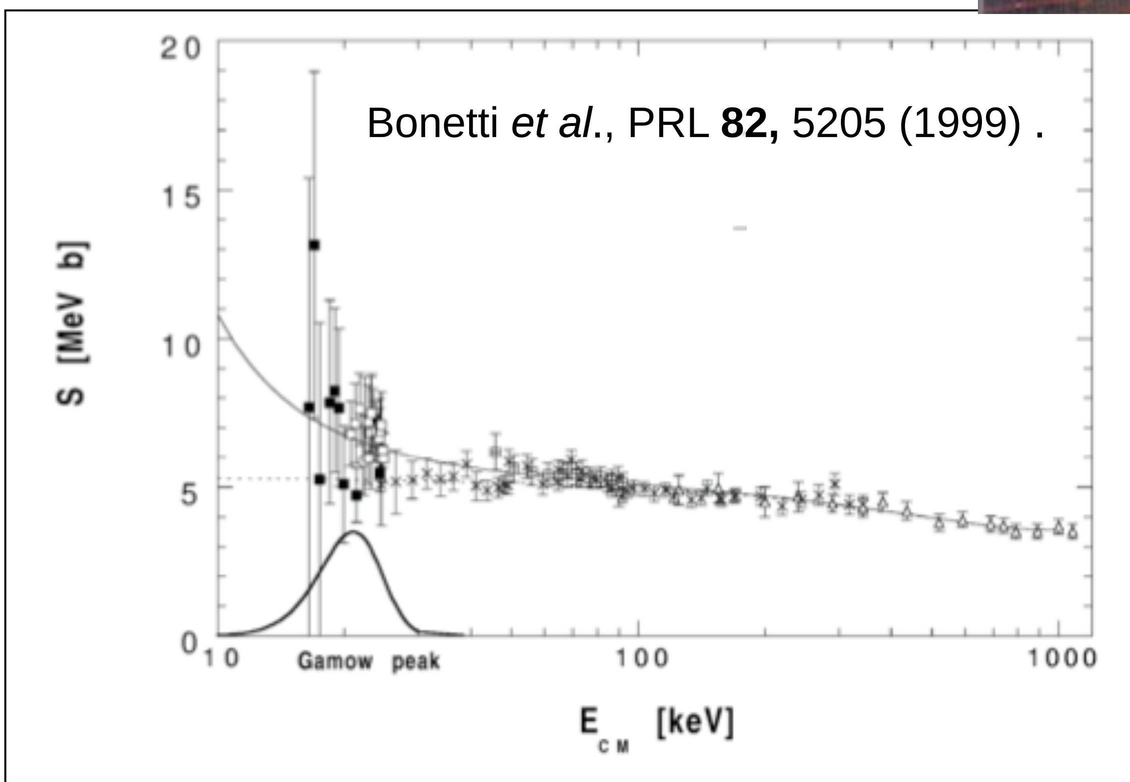
	$S(0)$ (keV b)
Osborne *et al.*	0.535 ± 0.040
Robertson *et al.*	0.63 ± 0.04
Volk *et al.*	0.56 ± 0.03
Nara Singh *et al.*	0.53 ± 0.02
present work	0.547 ± 0.017
Weighted average, all activation studies	0.553 ± 0.012
Weighted average, all prompt-γ studies	0.507 ± 0.016

Laboratory Underground Nuclear Astrophysics

$^{3}He(^{3}He,2p)^{4}He$

- 1999 – First measurement of a pp reaction σ at the ***solar*** Gamow widow
- Somewhat unique situation
  ➨ 2 protons with E_p > 6 MeV



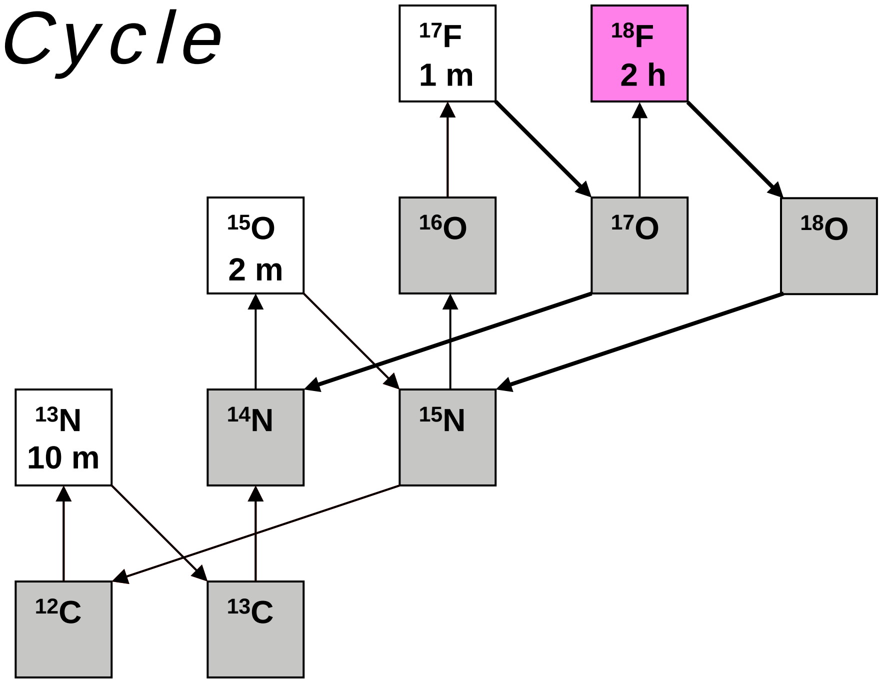


Bonetti *et al*., PRL **82,** 5205 (1999) .

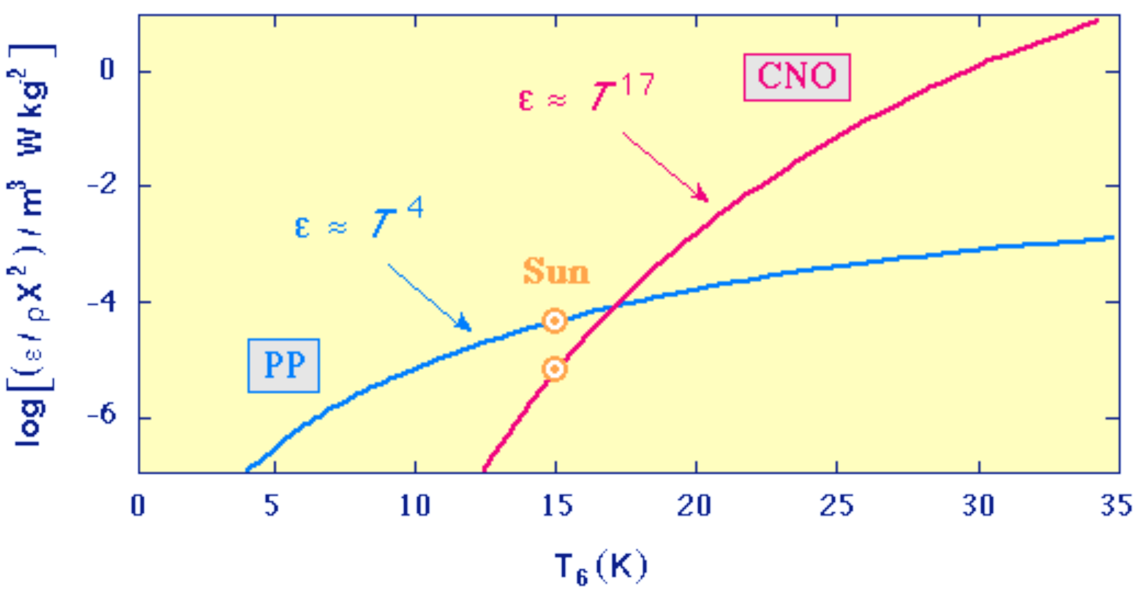
$$I \approx 1\ mA$$

- Windowless ^{3}He gas target
- Coincident 2p detection
- 2 events/month at lowest energy (E_{cm}= 16 keV)
- About 7% uncertainty at solar energies

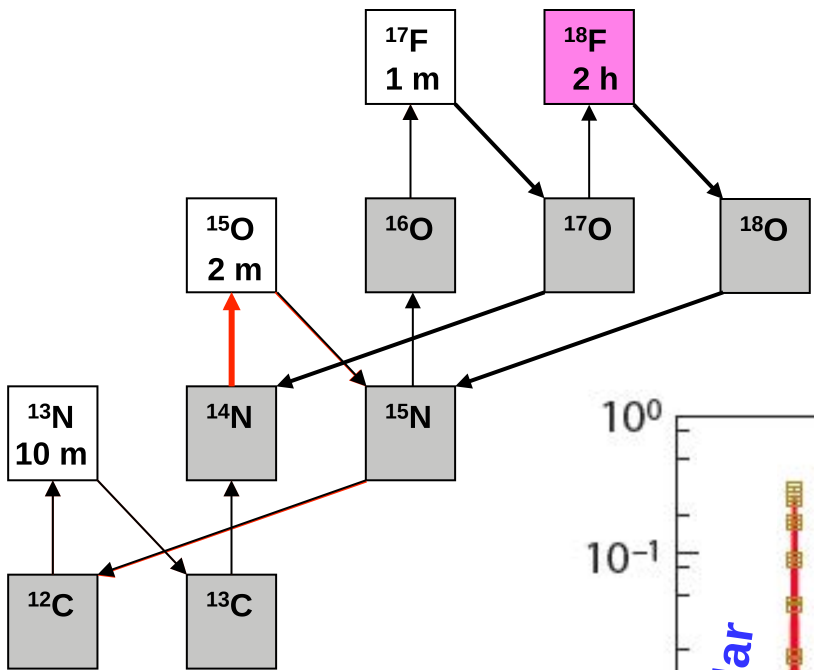
CNO Cycle



- Dominant source of energy generation in stars heavier than the sun
- What is CNO contribution to energy production in the sun? Few% ?
- CNO abundances in sun uncertain
- Stellar photospheric metallicity disagrees with helioseismology

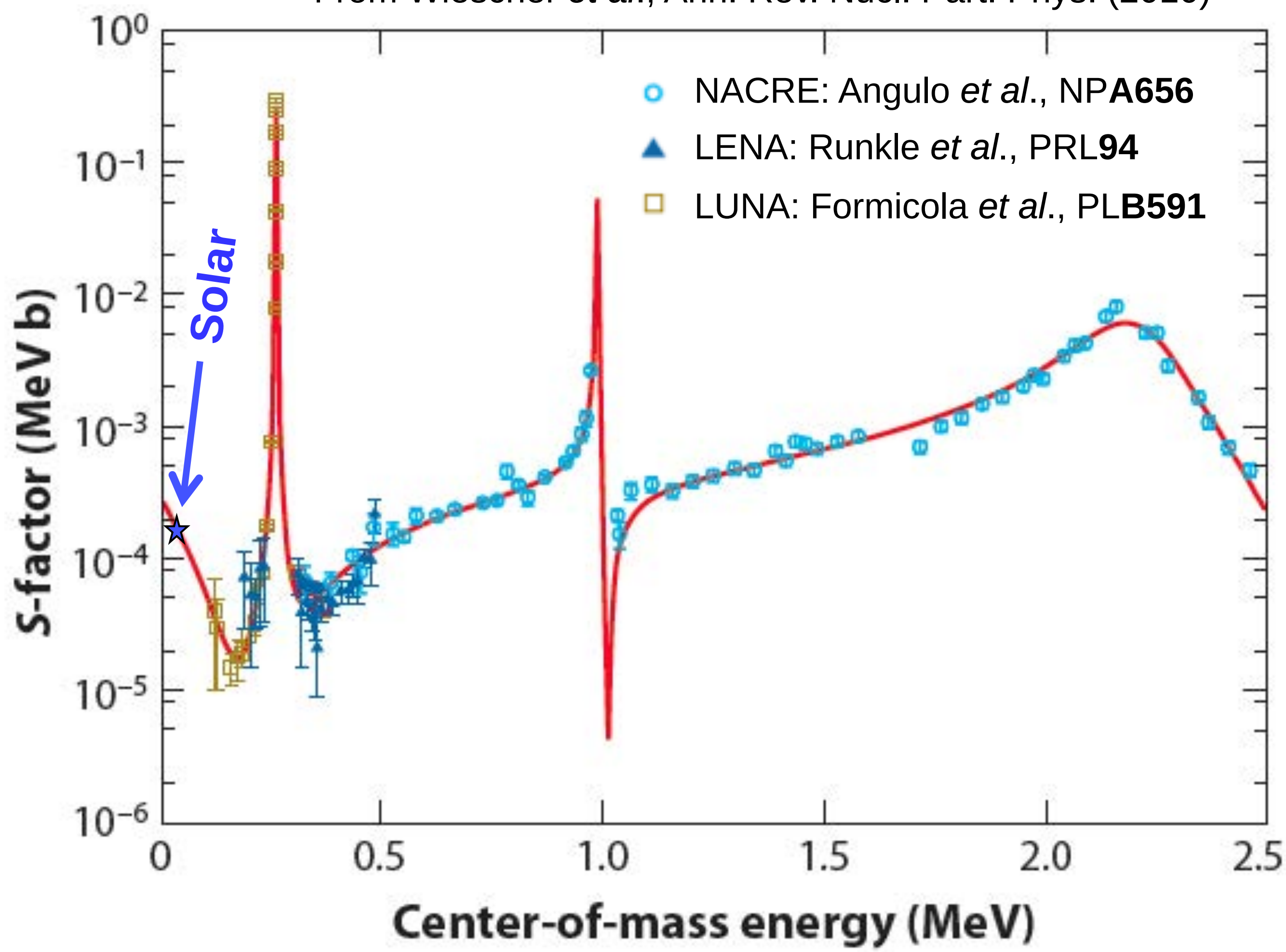


$^{14}N(p,\gamma)^{15}O$



- Slowest reaction in CN cycle
- Determines rate of energy generation and relative abundances

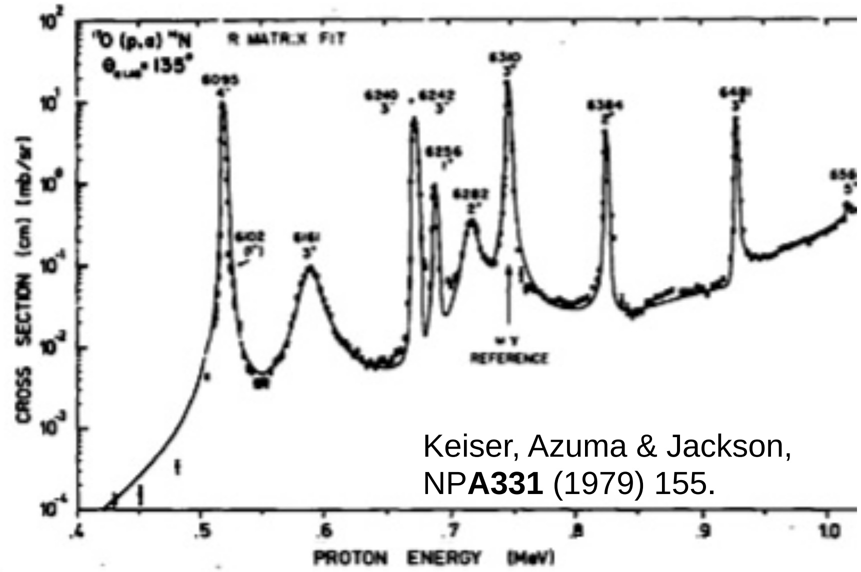
From Wiescher *et al.*, Ann. Rev. Nucl. Part. Phys. (2010)



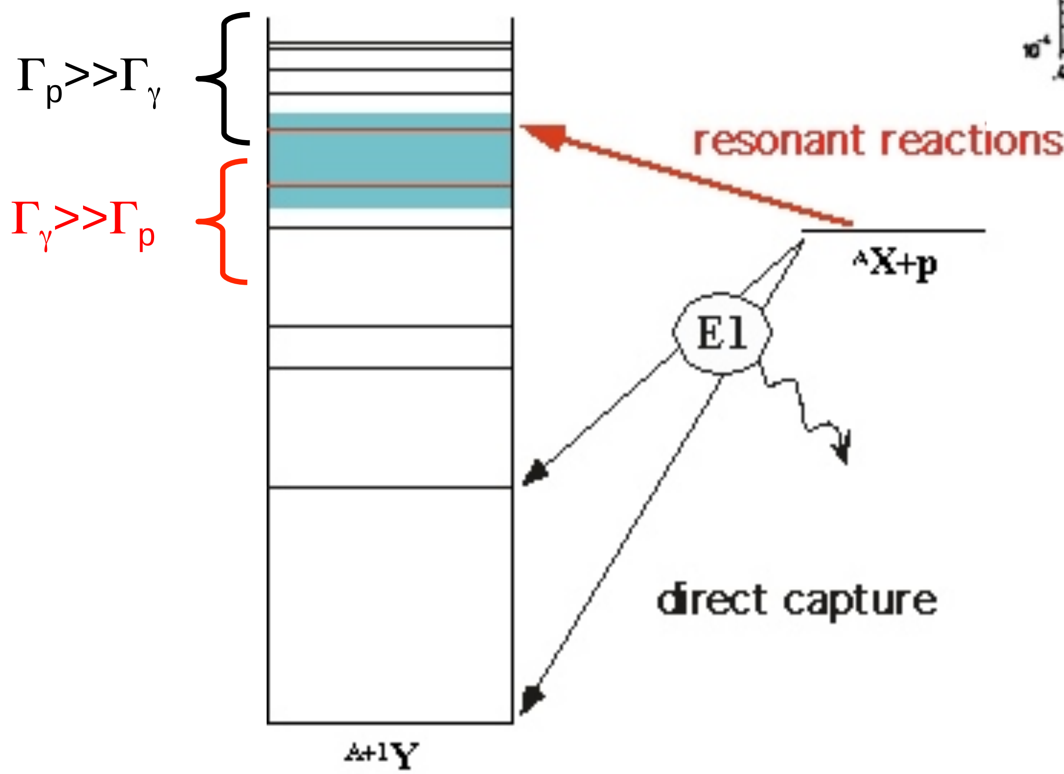
Resonances are important

$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi\mu}} (kT)^{3/2} \int_0^\infty \sigma E e^{-E/(kT)} dE$$

$$\sigma(E) = \pi \lambdabar^2 \frac{2J+1}{(2J_x+1)(2J_y+1)} \frac{\Gamma_x \Gamma_y}{(E-E_r)^2 + (\Gamma/2)^2}$$



Keiser, Azuma & Jackson, NP**A331** (1979) 155.



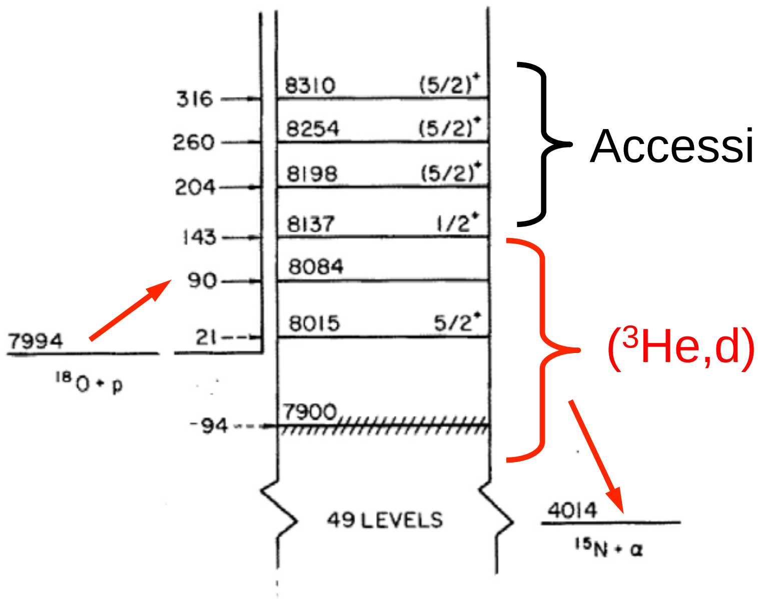
If resonance is narrow

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

$$\omega\gamma = \frac{2J+1}{(2J_x+1)(2J_y+1)} \frac{\Gamma_x \Gamma_y}{\Gamma}$$

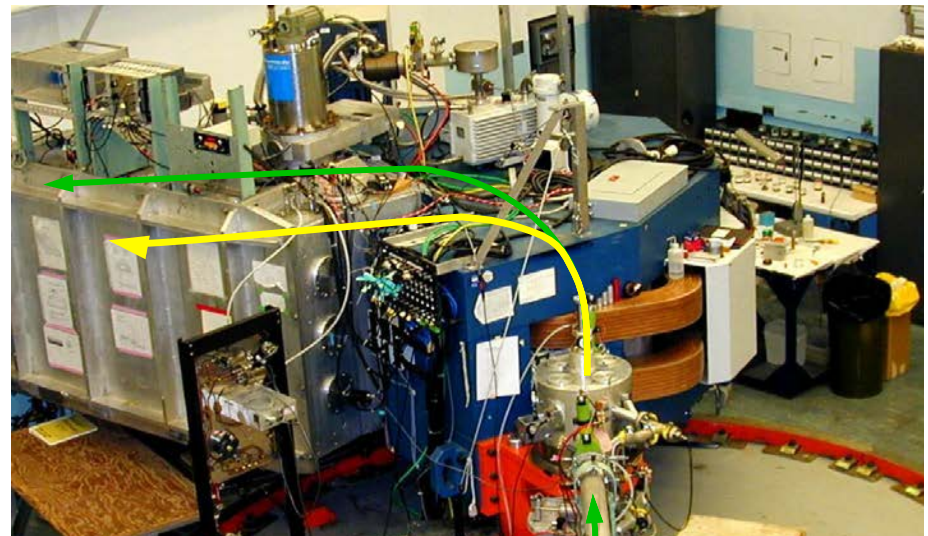
“resonance strength”

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

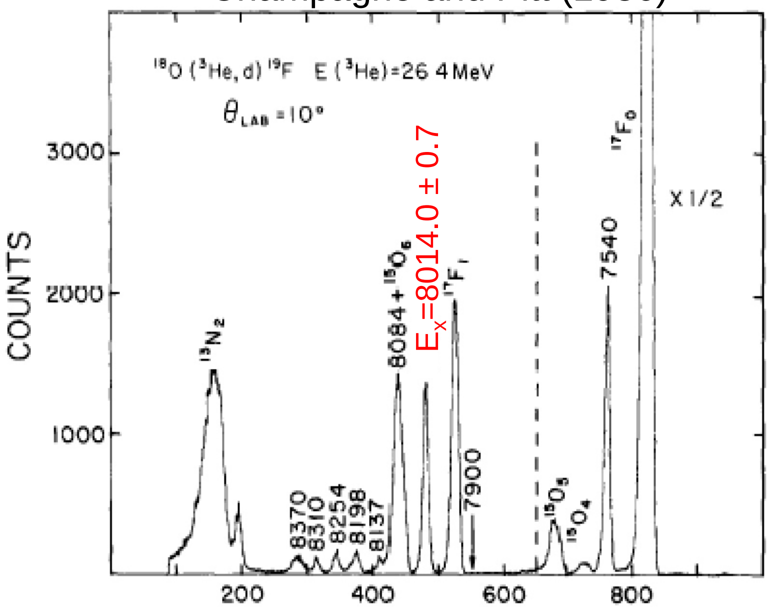


Accessible with high intensity proton beams

Magnetic Spectrograph

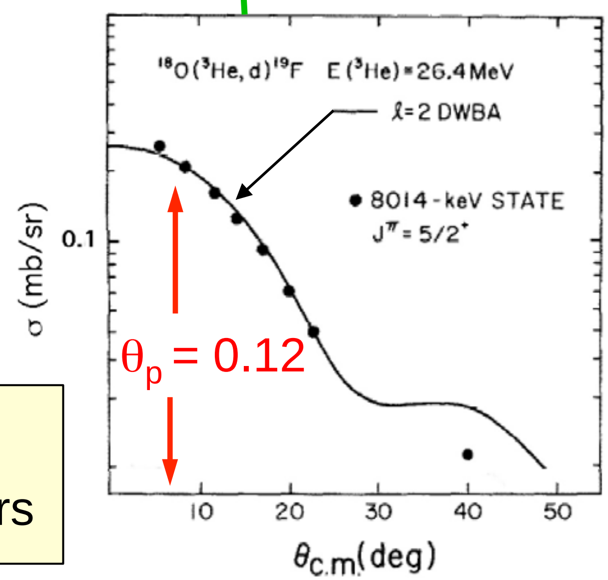


Champagne and Pitt (1986)



- Accurate E_x
- ℓ, J^π inferred

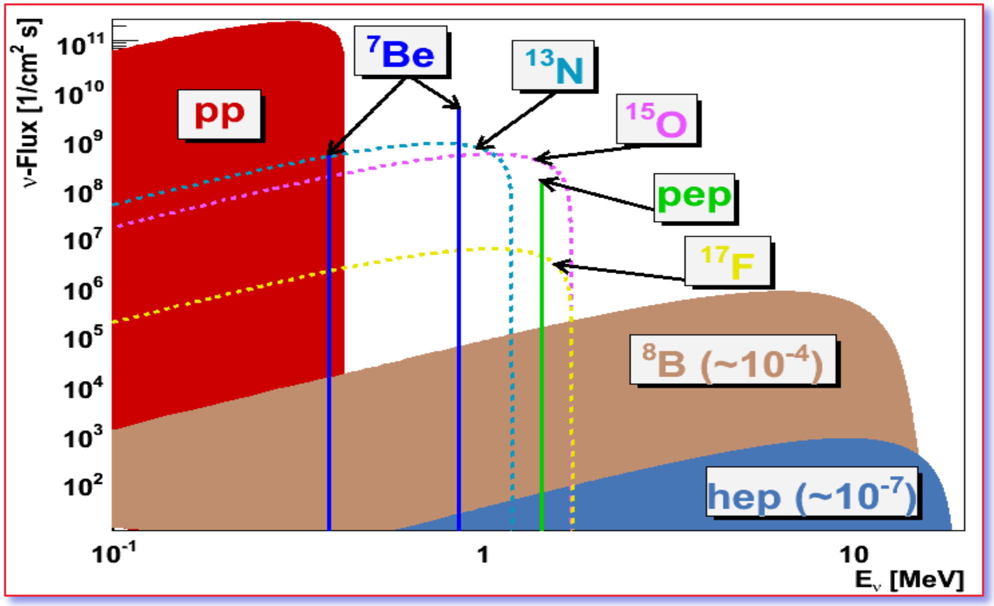
$$\Gamma_p = 2\left(\frac{\hbar^2}{\lambda \mu R}\right)\left(\frac{\theta_p^2}{F_\ell^2 + G_\ell^2}\right)$$



with 1 mA p + ^{18}O

1 event / 3x10^5 years

Why ***still*** measure solar neutrinos?



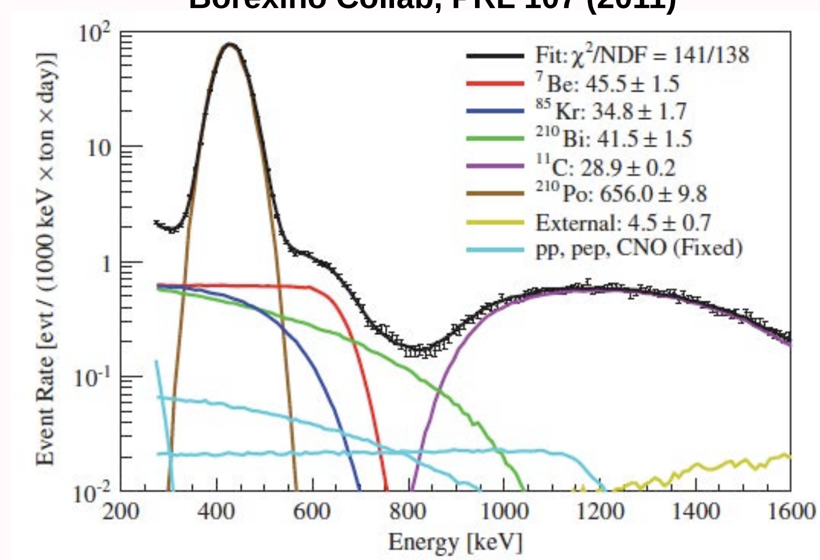
- ^{8}B flux ~4% precision
  →Super-K, SNO, Borexino, . . .
- ^{7}Be flux ~5% precision
  →Borexino
- Others
  →Radiochemical (integral)

- Neutrino flavor oscillation
  →Neutrinos have mass
  →Mass ≠ Flavor eigenstates

- But weak constraints on photospheric luminosity (pp neutrino flux)
- What is contribution of CNO cycle to solar energy generation?
- Is photospheric composition reflective of solar core?

Need precise measure of pp & CNO solar ν flux

Borexino Collab, PRL 107 (2011)



Synthesis of Carbon → Ca

$^4He + p \rightarrow ?$

$^4He + {}^4He \rightarrow ?$

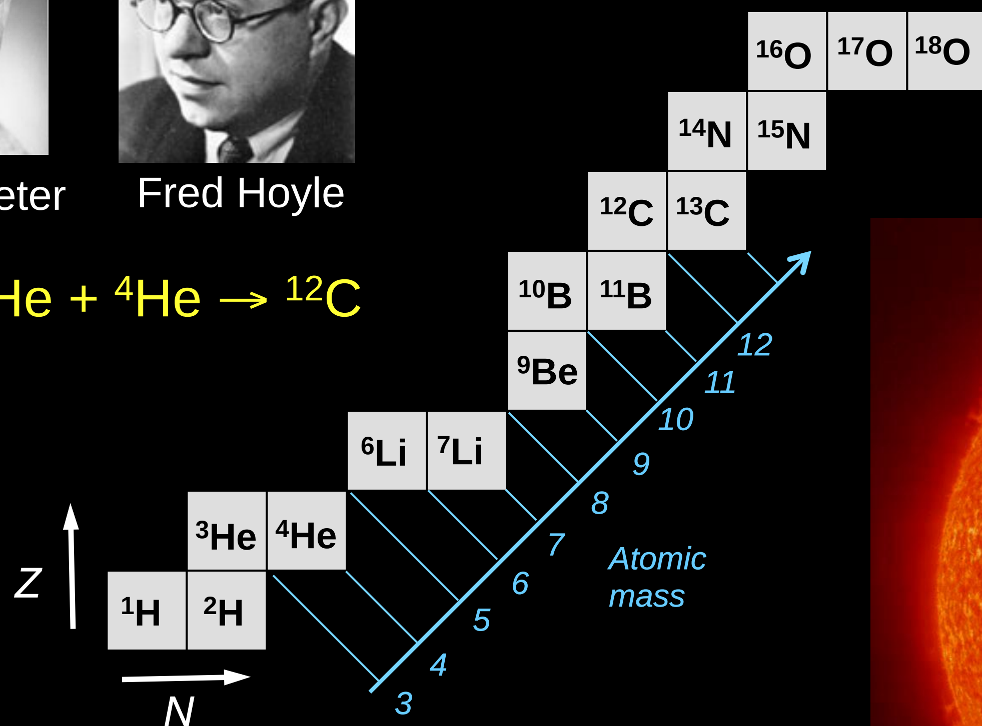
No atoms exist in nature with an A = 5 or 8

^8Be lifetime ~ 10^{-16} s

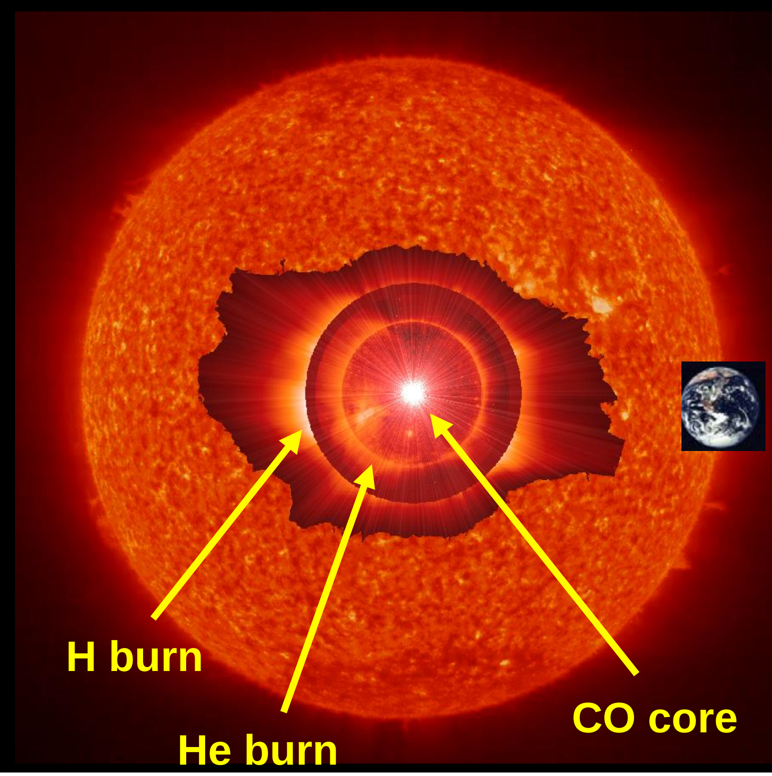
Edwin Salpeter

Fred Hoyle

$^4He + {}^4He + {}^4He \rightarrow {}^{12}C$

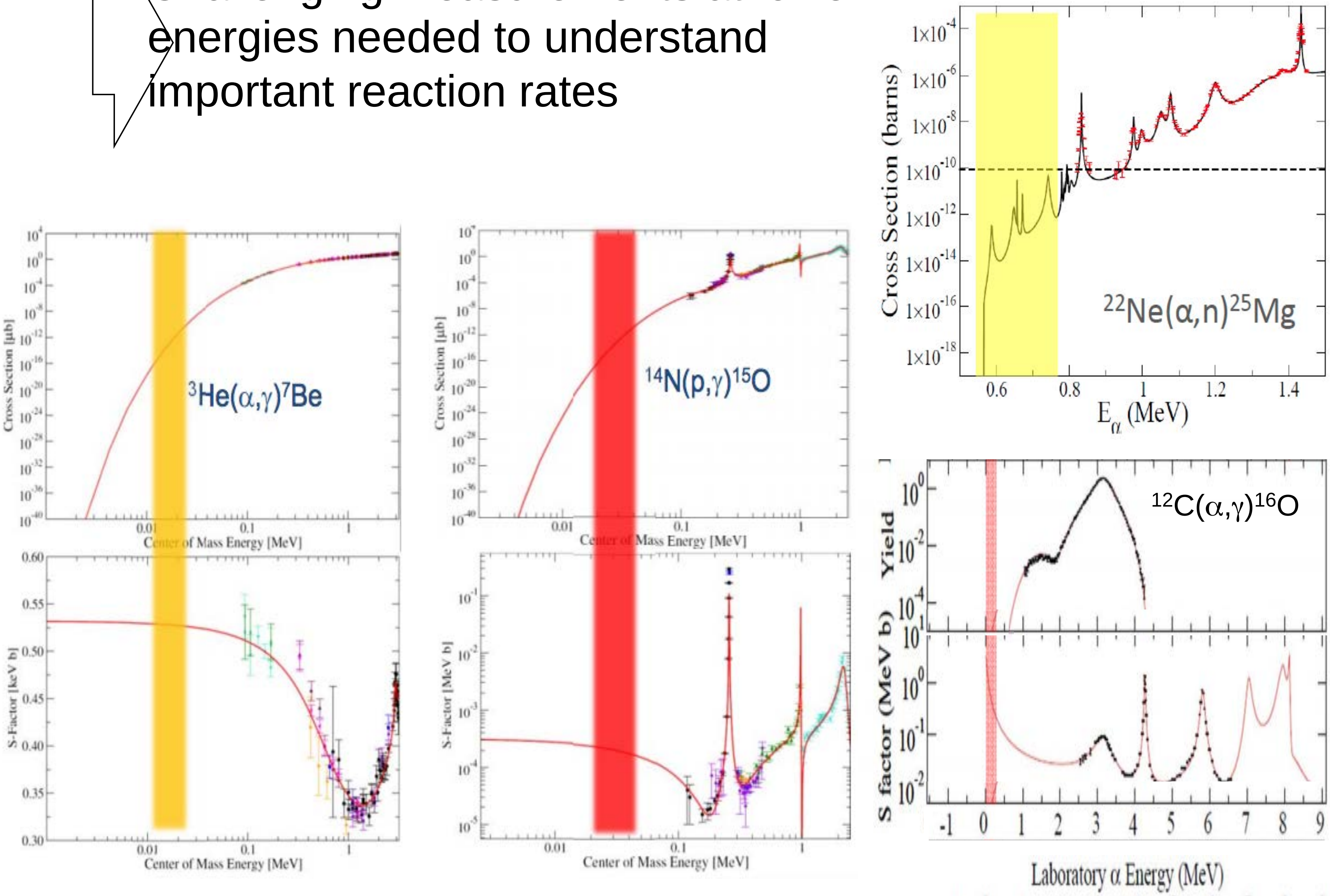


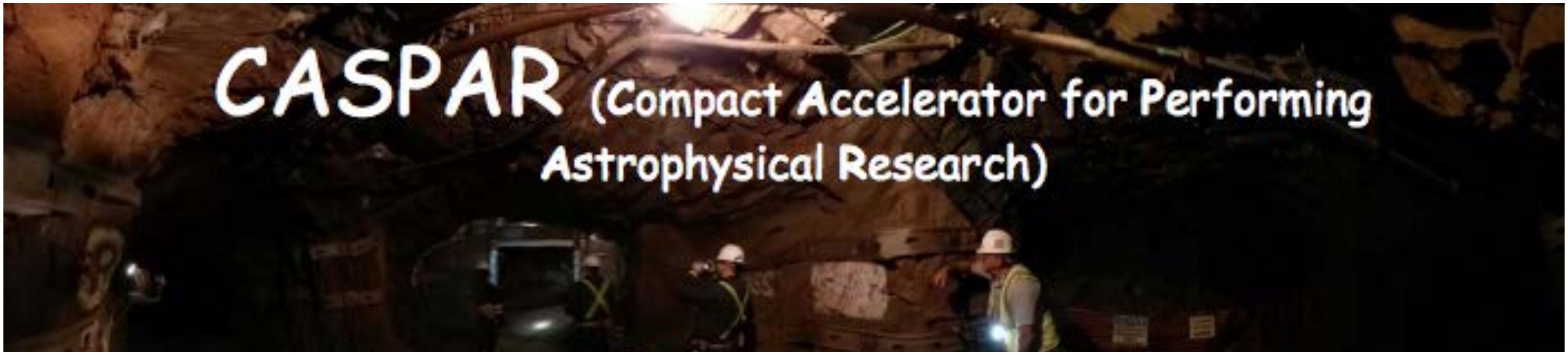
Red Giant Star



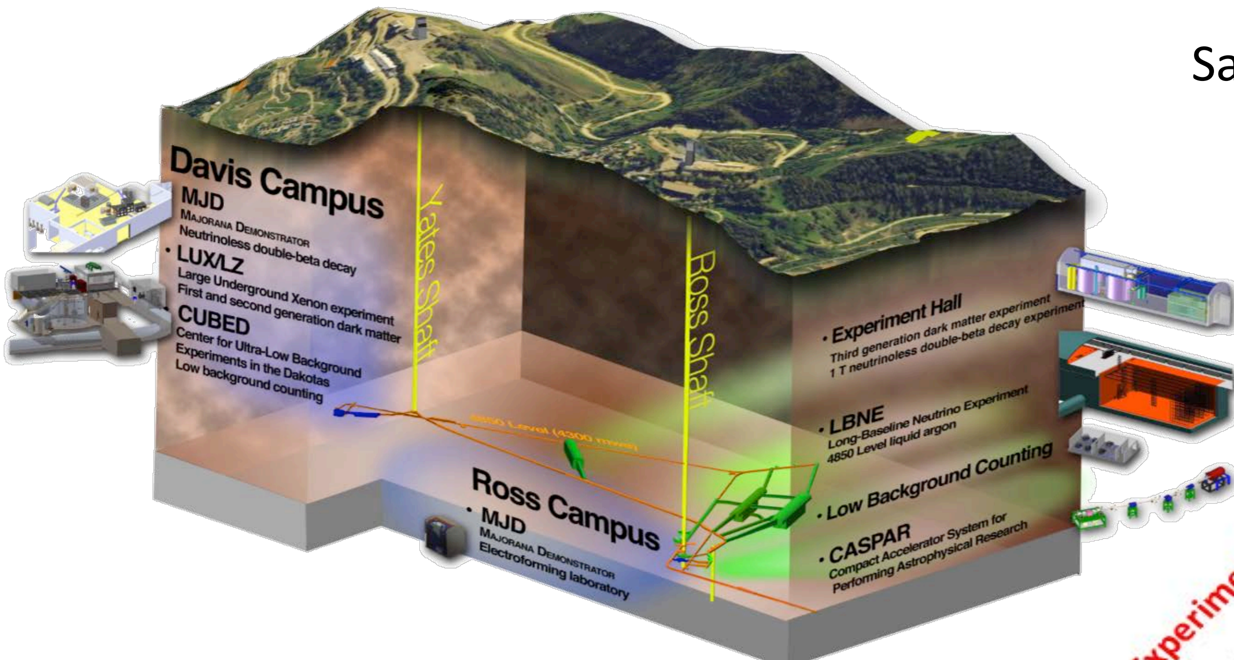
Only possible if ^{12}C has a very large resonance at perfect energy

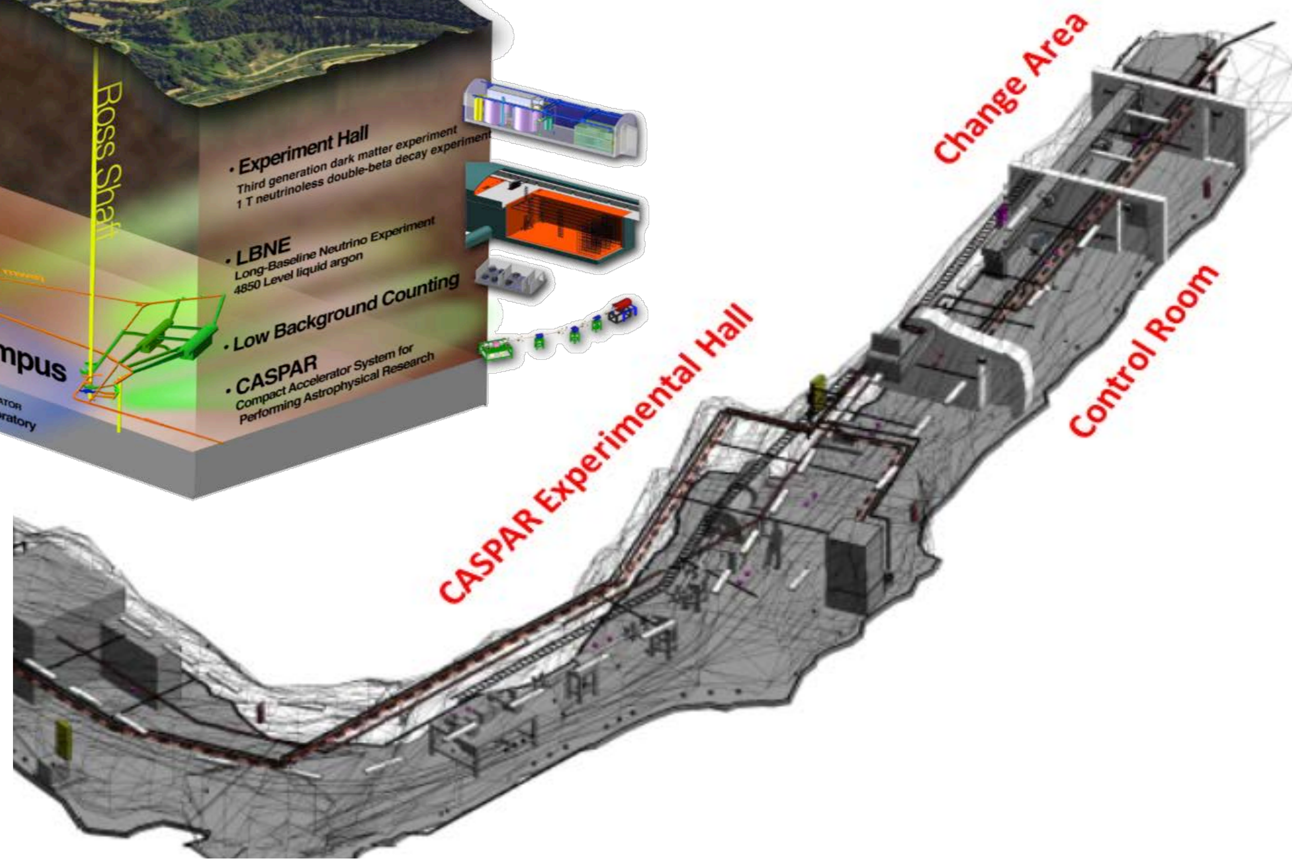
Challenging measurements at lower energies needed to understand important reaction rates

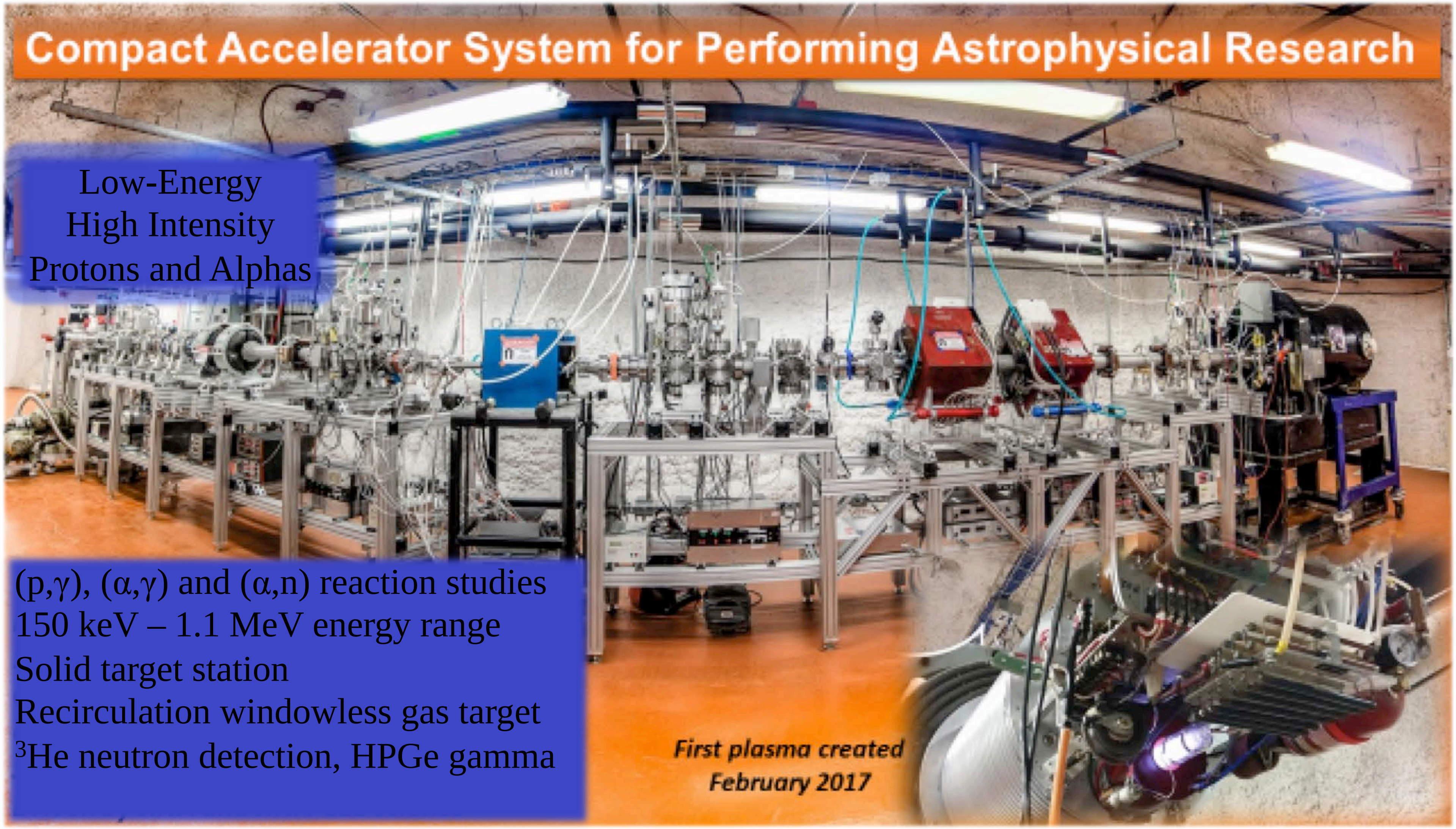




Sanford Underground Research Facility





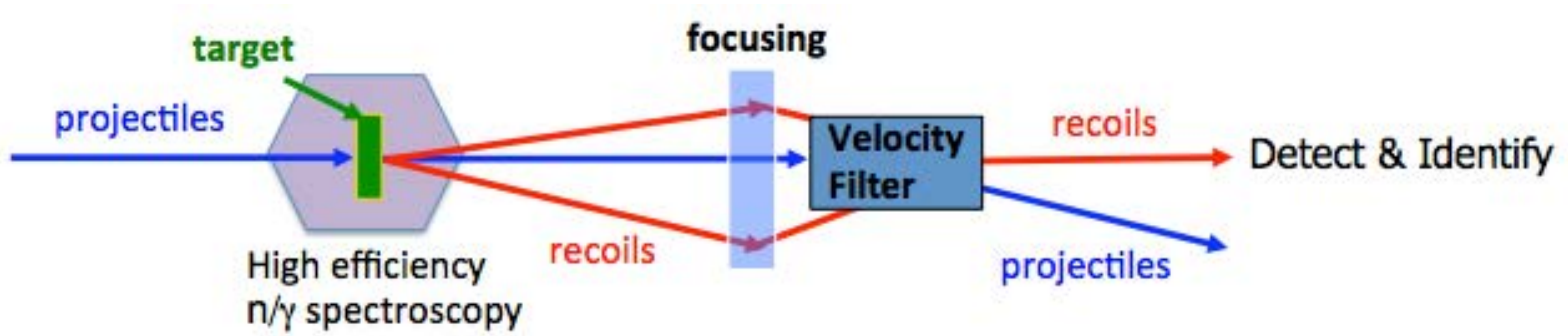


Proposed upgrade (DIANA)

- Increase beam energies and intensities
- Introduction of pulsed beams
- User facility for Nuclear Astrophysics community and beyond
- Planned construction and implementation time line *2019 - 2024*

1 Brute force & 2 Clever approaches

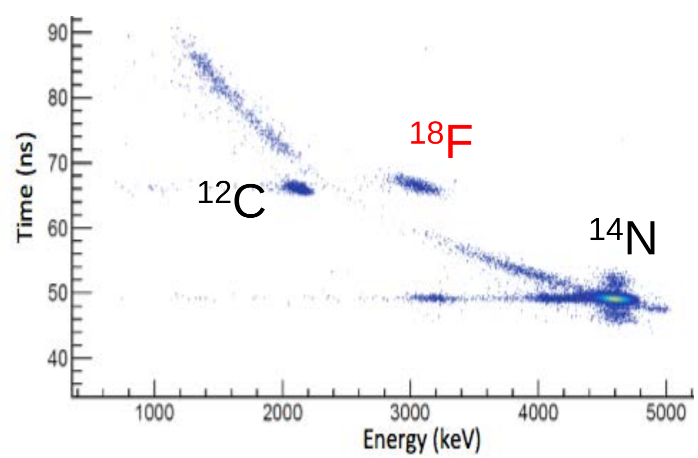
High beam intensities (luminosities) & Selective experimental techniques



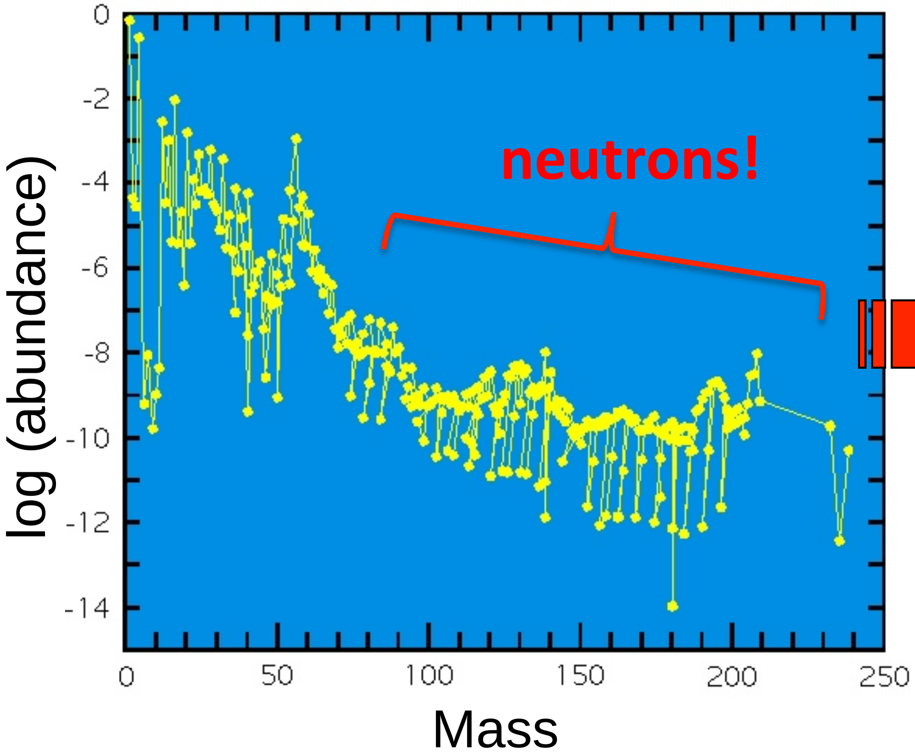
St. George

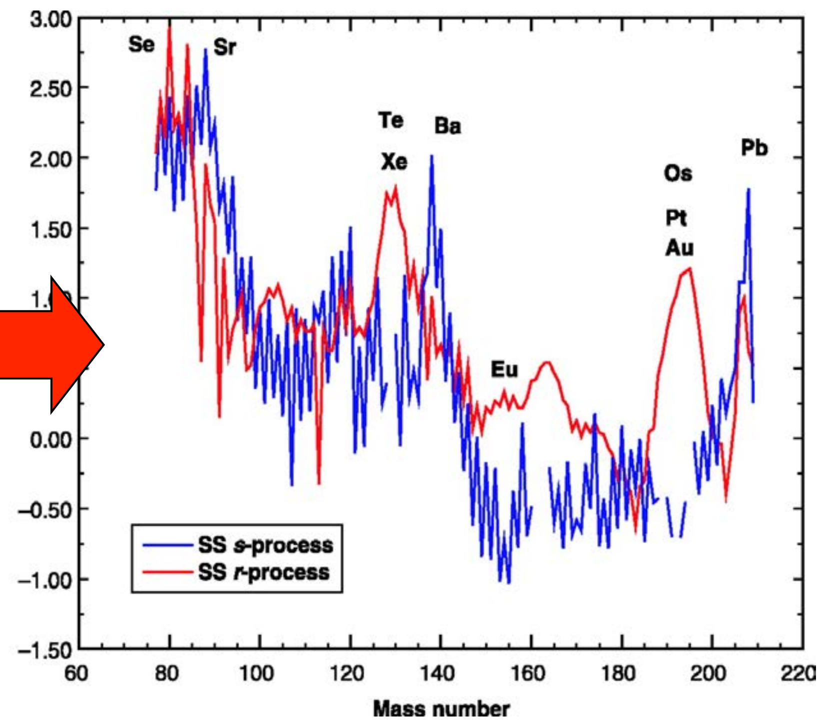
UNIVERSITY OF NOTRE DAME

$^{14}N+\alpha\rightarrow^{18}F$

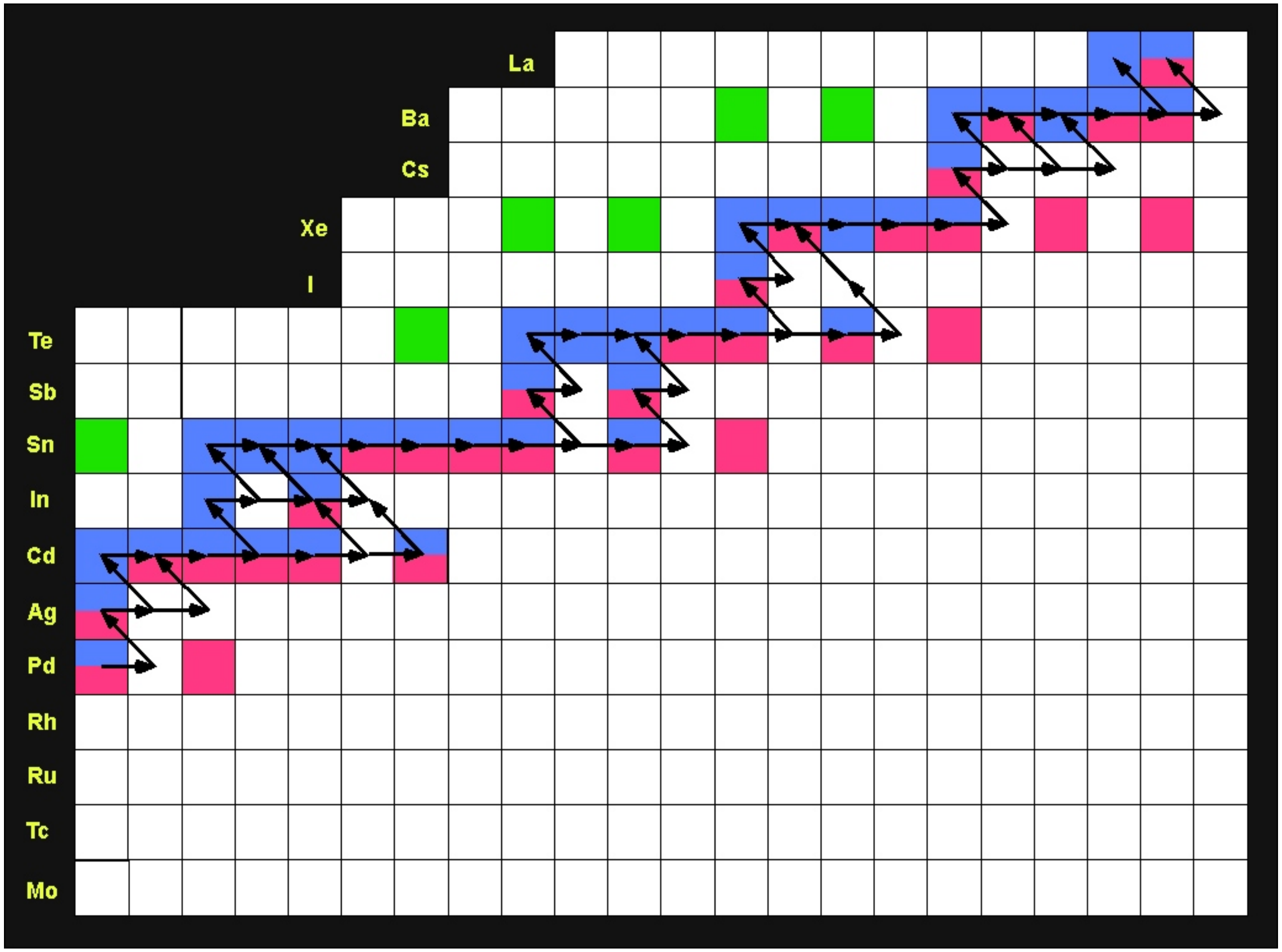


Solar system abundances





Slow neutron capture (s) process



- s process
  - Produces about half of matter that is heavier than iron
  - Series of slow neutron captures
  - Pattern of isotopes produced is generally well understood
  - Most σ's measured

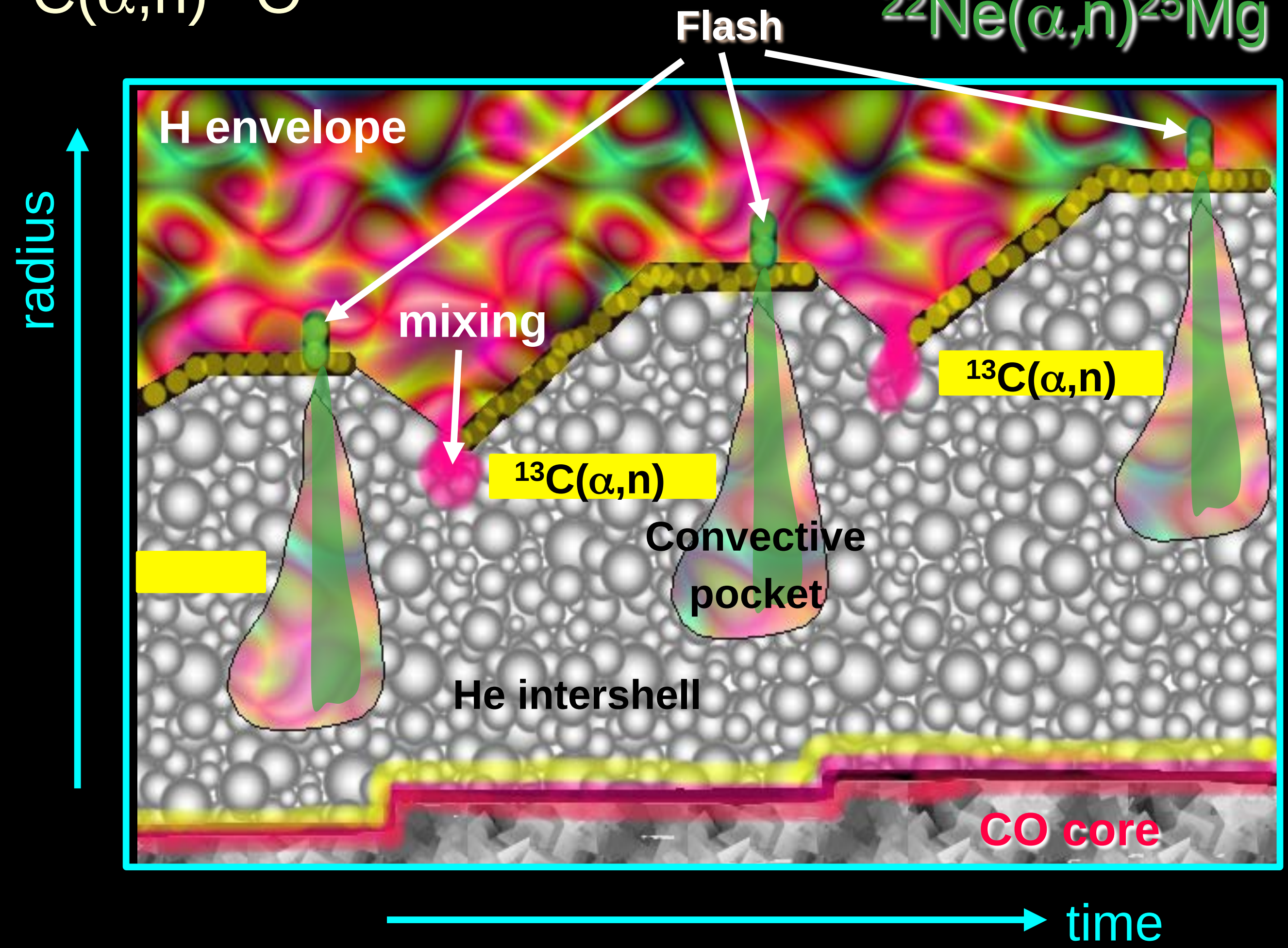
AGB Stars – Fate for M < 8 M⊙

Thermally unstable: mixing, convection, mass loss → nebulae

$^{12}C(p,\gamma)^{13}N(\beta\nu)^{13}C(\alpha,n)^{16}O$

$^{22}Ne(\alpha,n)^{25}Mg$

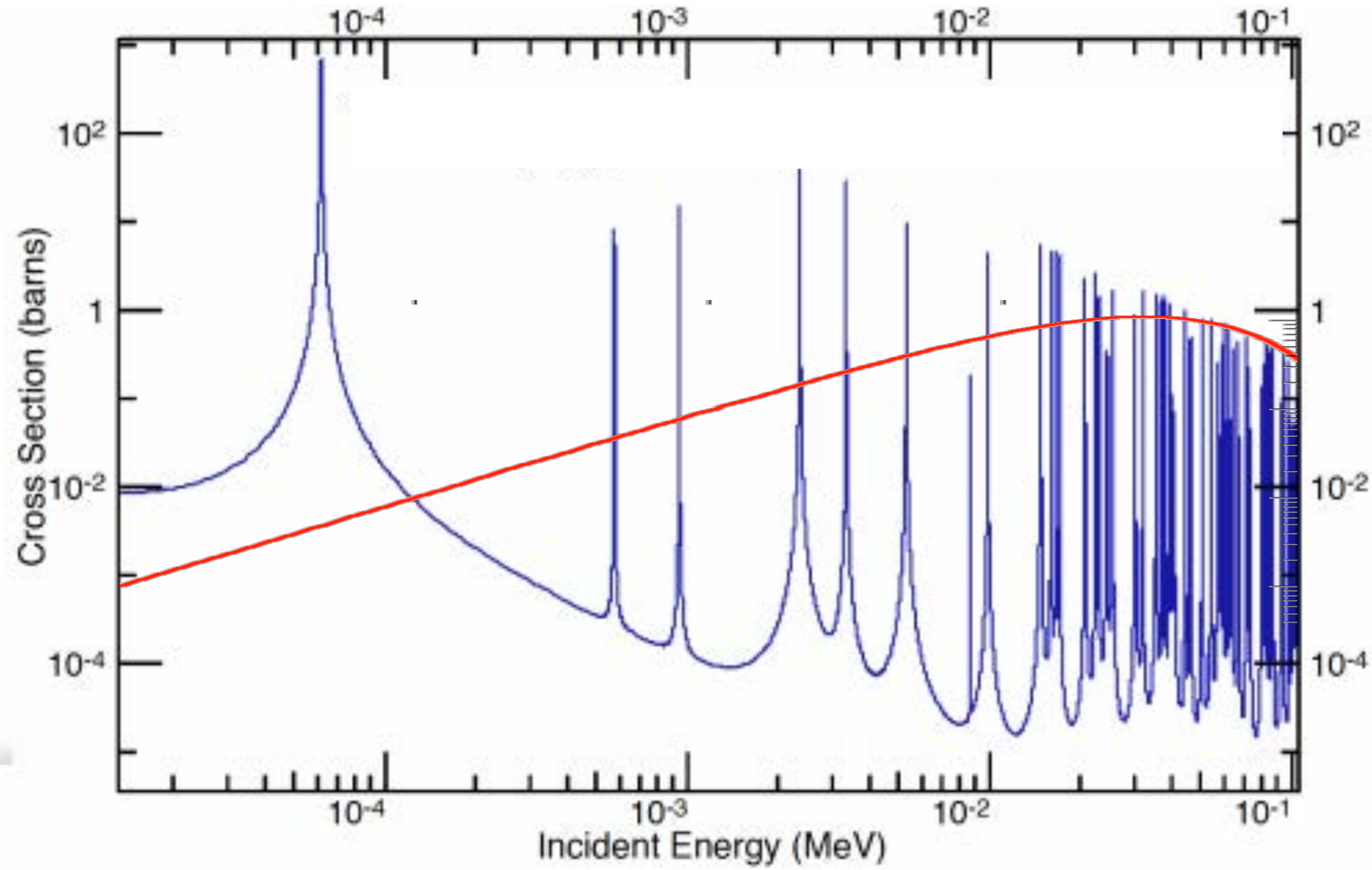
Neutrons drive synthesis of heavy elements



CO core remnant (white dwarf)

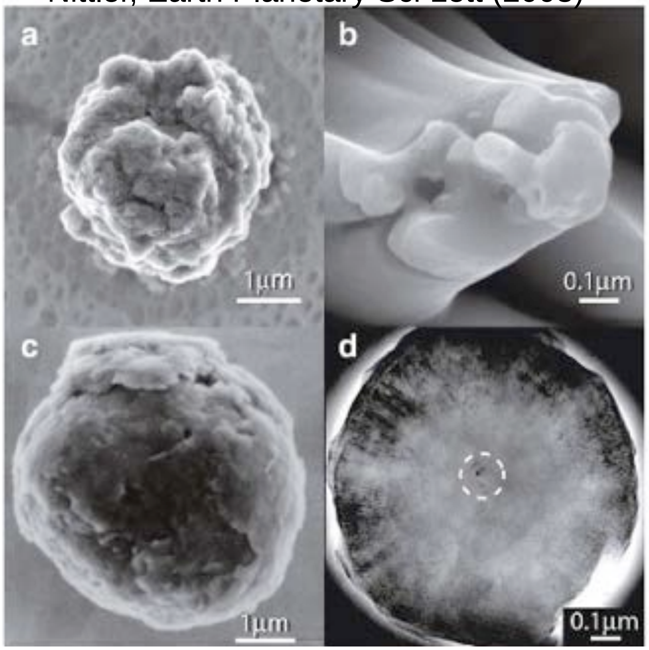
(n,γ) reaction rate (MA cross sections)

Example: $^{124}Sn(n,\gamma)^{125}Sn$ σ —— $Ee^{-E/kT}$ for $(kT = 30keV)$ ——



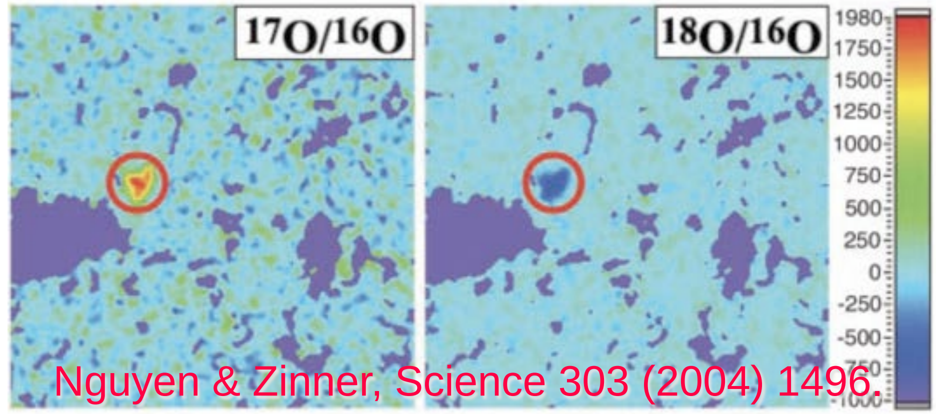
Stardust from AGB stars

Nittler, Earth Planetary Sci Lett (2003)



Tiny grains isolated from meteorites

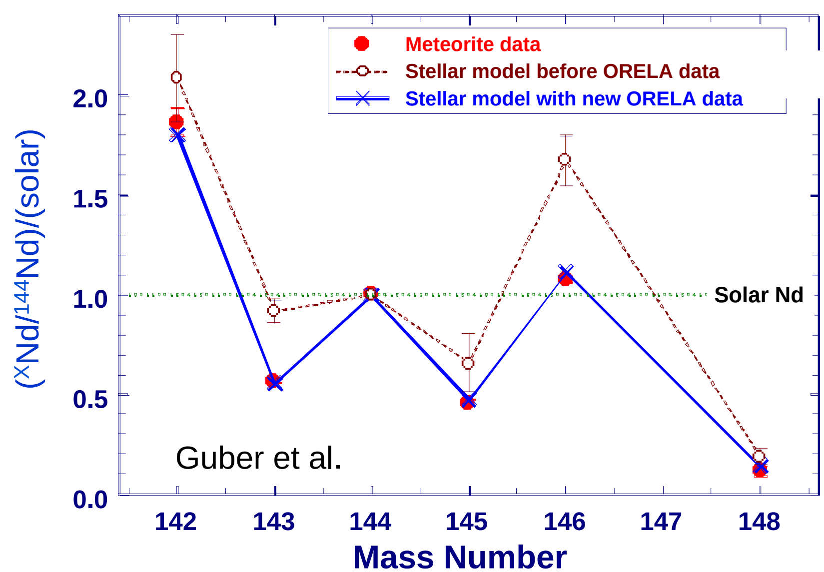
Unusual grains identified with SIMS



Nguyen & Zinner, Science 303 (2004) 1496.

Some grains have preserved isotopic composition from solar environment

Relative abundances for isotopes of a given element from a single AGB star

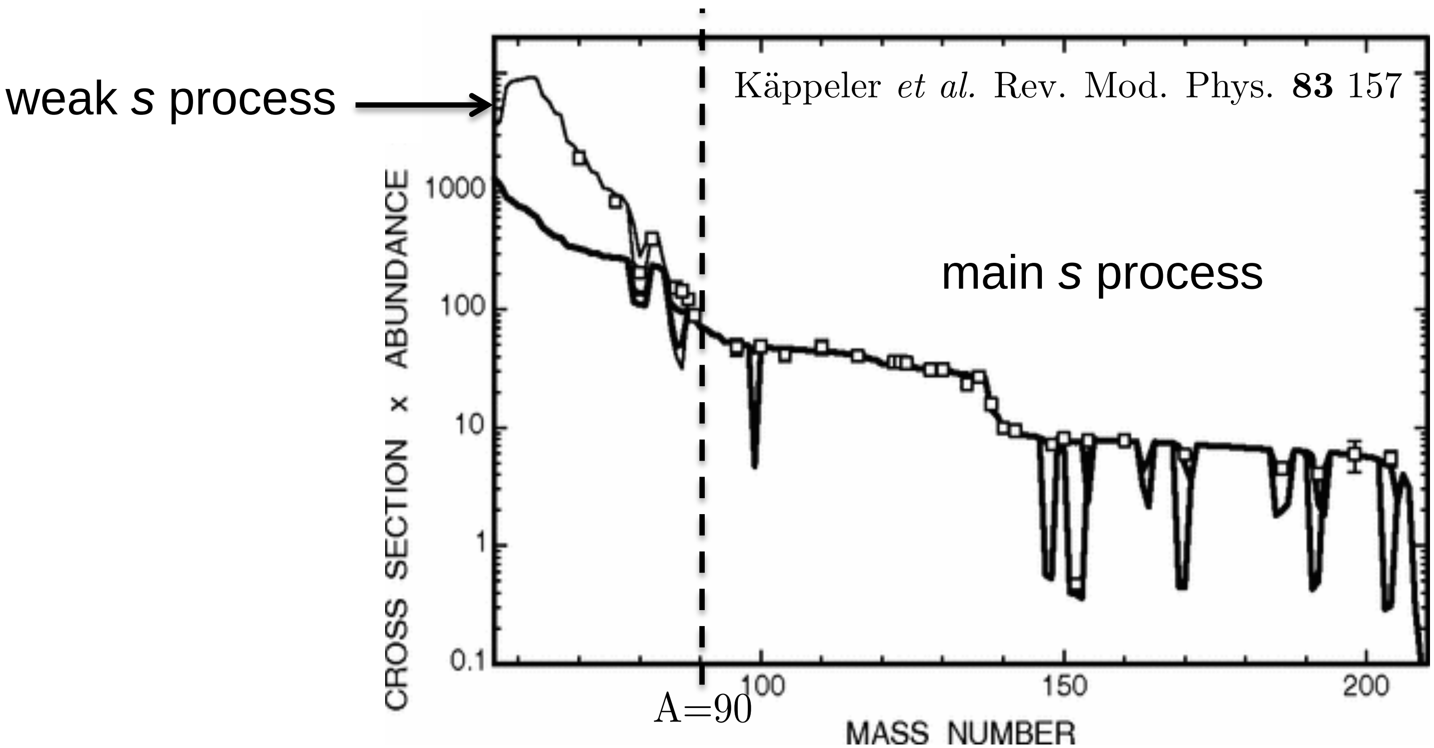


What's new? weak s-process

- Abundance pattern suggests two s process components
- Two different neutron exposures needed

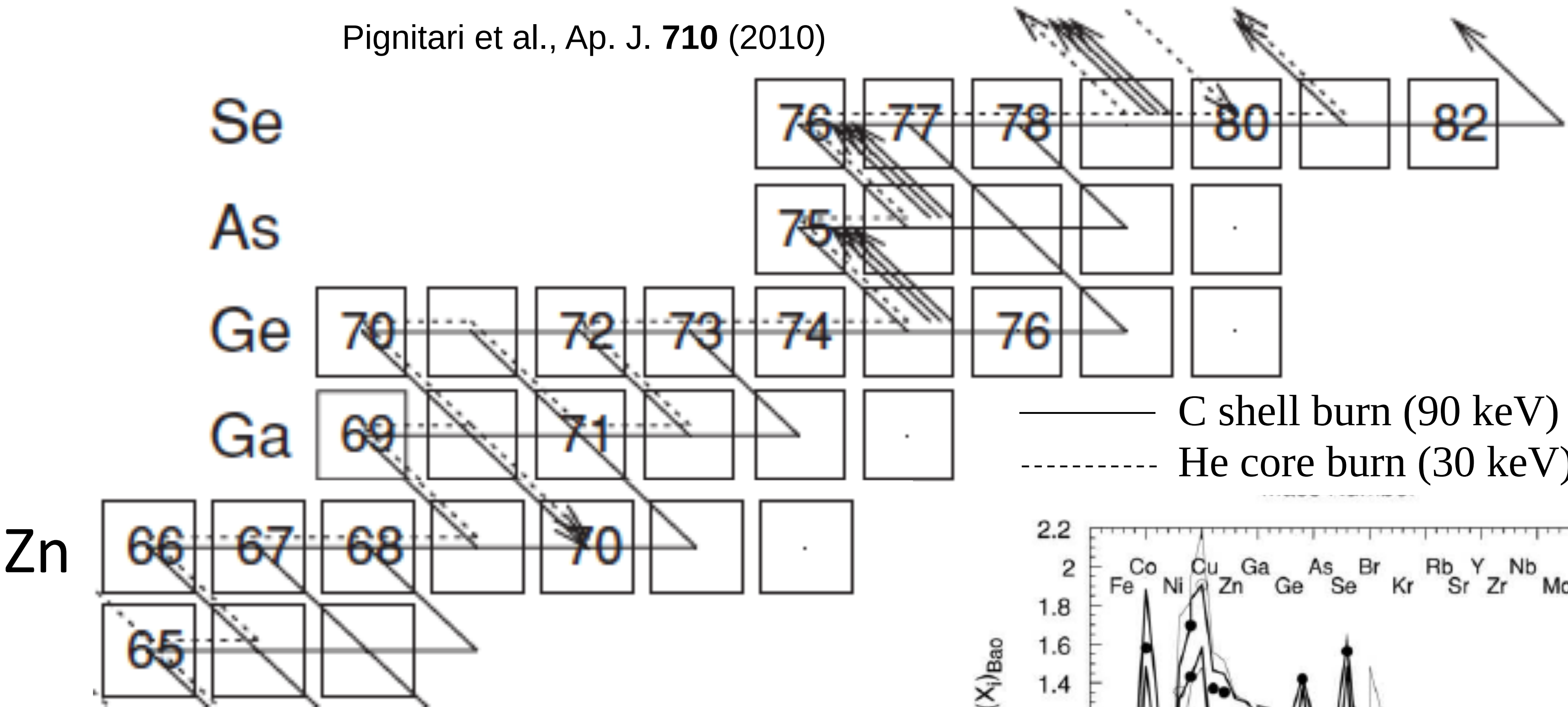
$$\begin{cases} main & (\tau_0 \approx 0.3 \text{ cm}^{-2}) & 1.5 < M_\odot < 3 \\ weak & (\tau_0 \approx 0.07 \text{ cm}^{-2}) & 8 < M_\odot < 25 \end{cases}$$

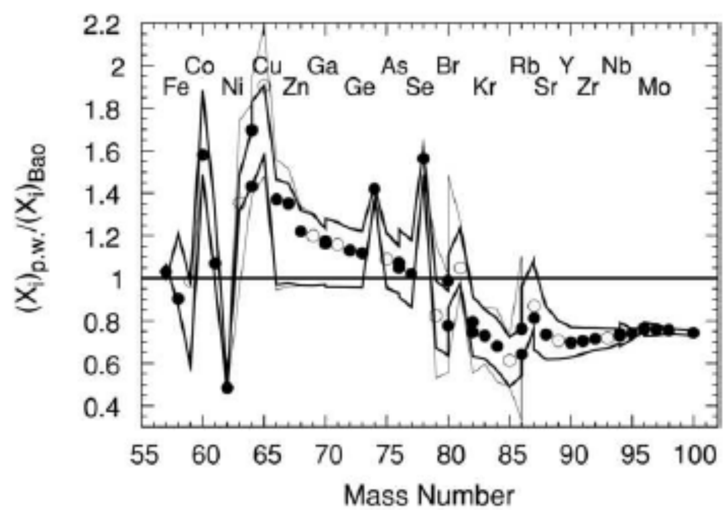
AGB Stars (30 keV)
C burning (90 keV)



Next steps: New neutron capture measurements

Pignitari et al., Ap. J. **710** (2010)

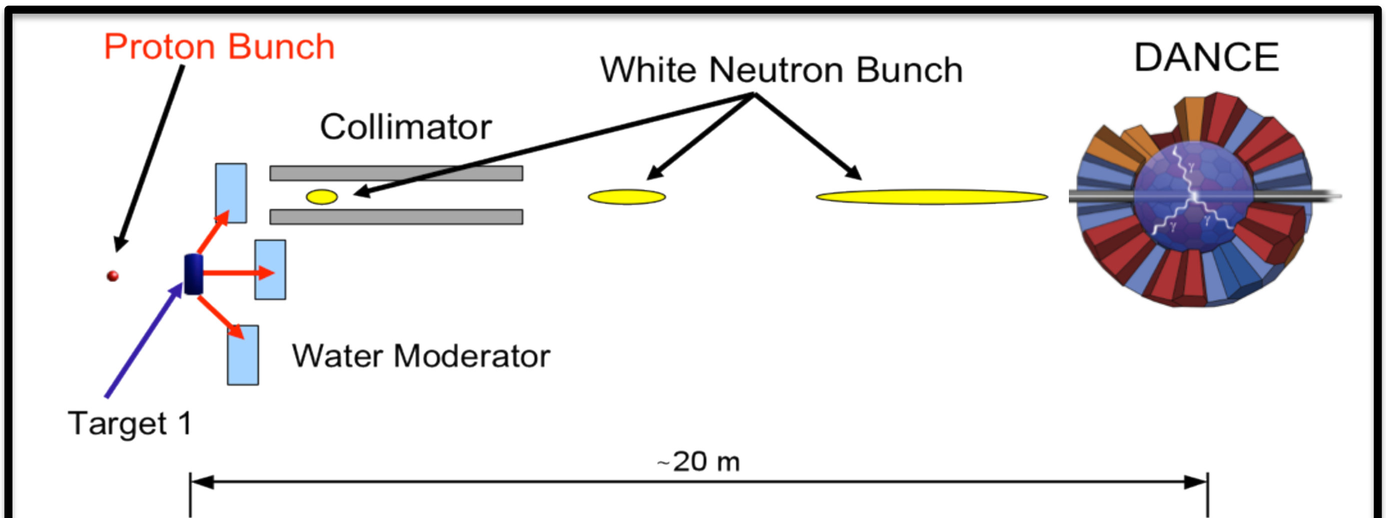




- Recent measurements and models show:
  - Significant changes in abundances
  - Uncertainties larger than previously believed
  - New measurements in the region are importan

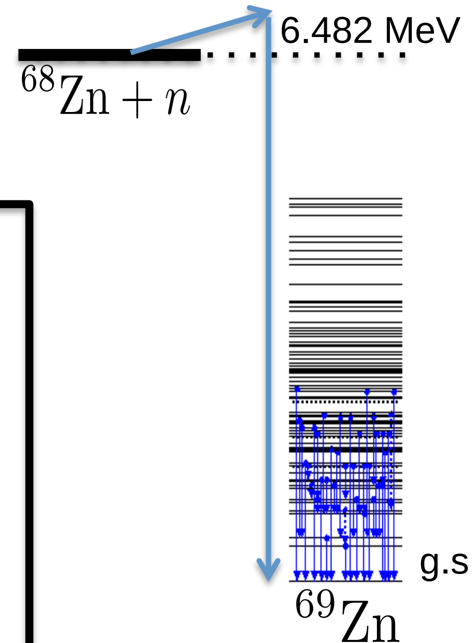
^{67,68}Zn(n,γ) with DANCE

- Detector for Advanced Neutron Capture Experiments (DANCE)
  - 4π BaF γ-ray calorimeter (sum all gamma ray energies)
  - Neuton energies by time-of-flight (distance of 20 m)
- ^{208}Pb sample for background from scattered neutrons
- ~15 days of beam on ^{67,68}Zn samples
  - (100 mg with high enrichment)



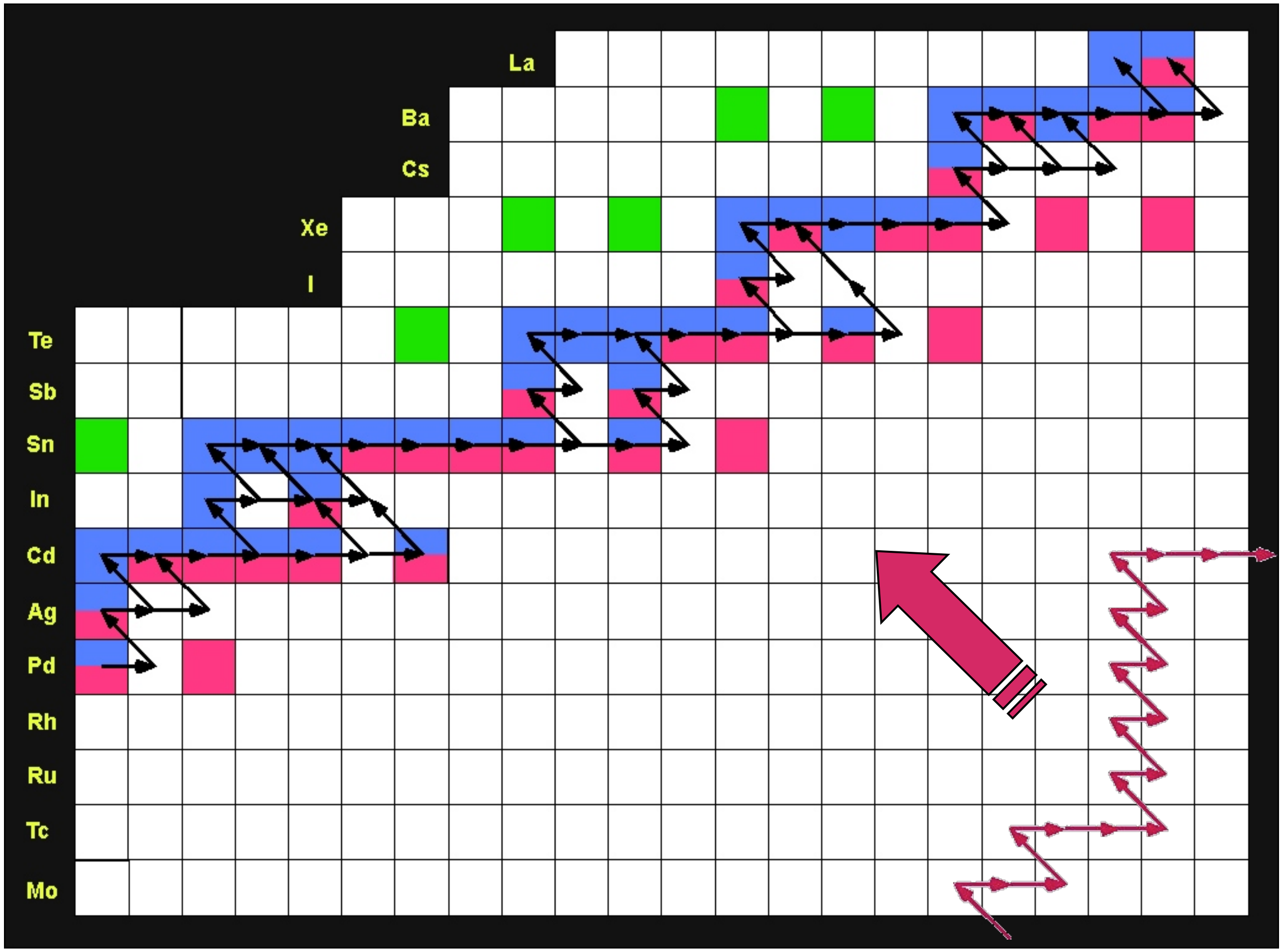
$E_p = 800$ MeV $\quad \nu_p = 20$ Hz $\quad 10$ meV $< E_n < 500$ keV

$\varphi_n = 3 \times 10^5$ n/s/cm^2/decade



	Q-value
^{66}Zn(n,γ)	7.05 MeV
^{67}Zn(n,γ)	10.2 MeV
^{68}Zn(n,γ)	6.48 MeV

Synthesis of heavy elements

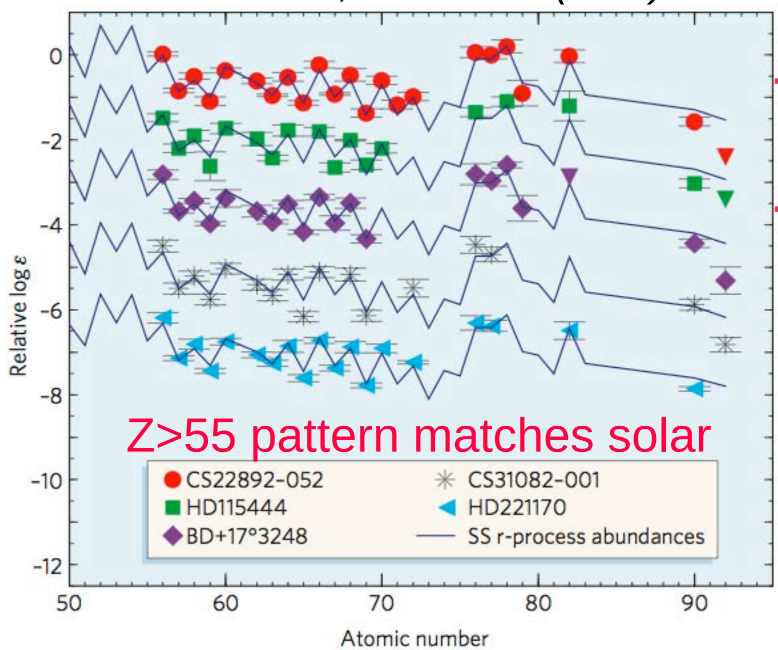


- s process
- r process
  - Produces about half of matter heavier than iron
  - High neutron flux
  - Reactions on unstable isotopes
  - Site unknown

r process in the early Galaxy

New observations of unmixed abundances early in the Galactic halo

Cowan & Sneden, Nature ***440*** *(2006) 1151.*



CS22892-052

Fe/H = (8x10^{-4}) solar = very old

r/Fe = 50 solar

Only 2 known in 2000

Now extensive surveys

e.g. see Frebel et al., ApJ ***652*** *(2006) 1585*

SEGUE (Sloan DSS)

Spectra of >2x10^5 selected halo stars

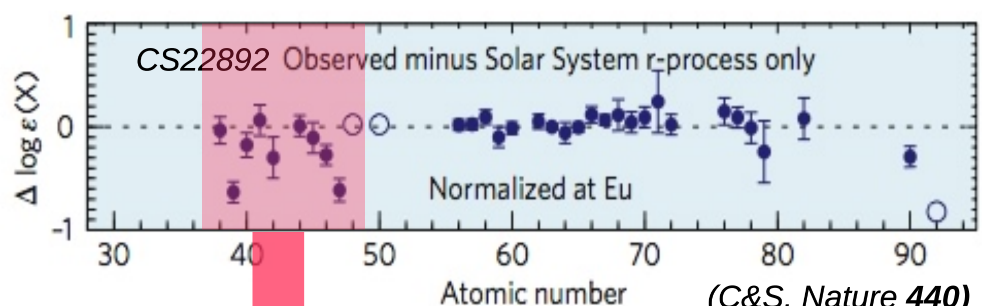
Expect ~ 1% with Fe/H < 0.001solar

~36 known r process stars

11 with r/Fe > 10 solar

Distribution Fe/H puzzling

Lowest Fe/H stars intriguing



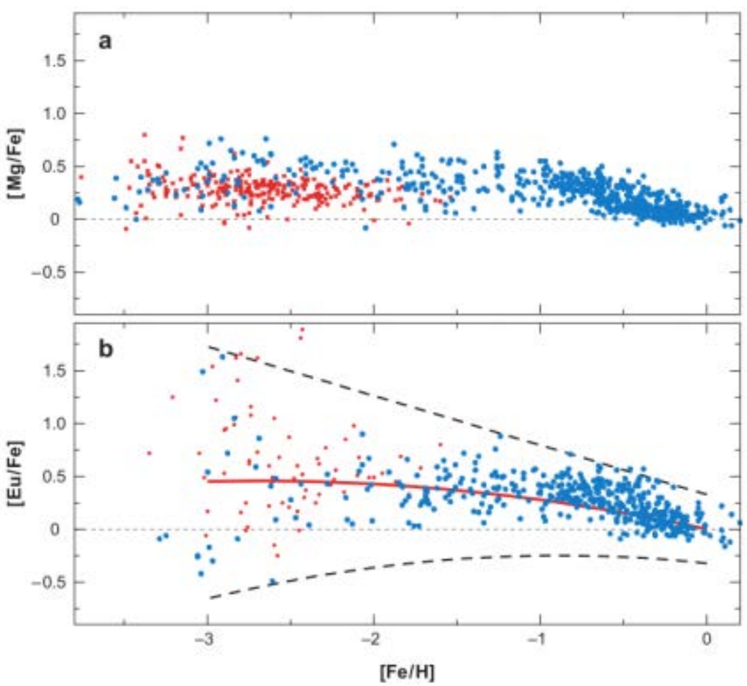
(C&S, Nature ***440****)*

Z<50 abundances vary

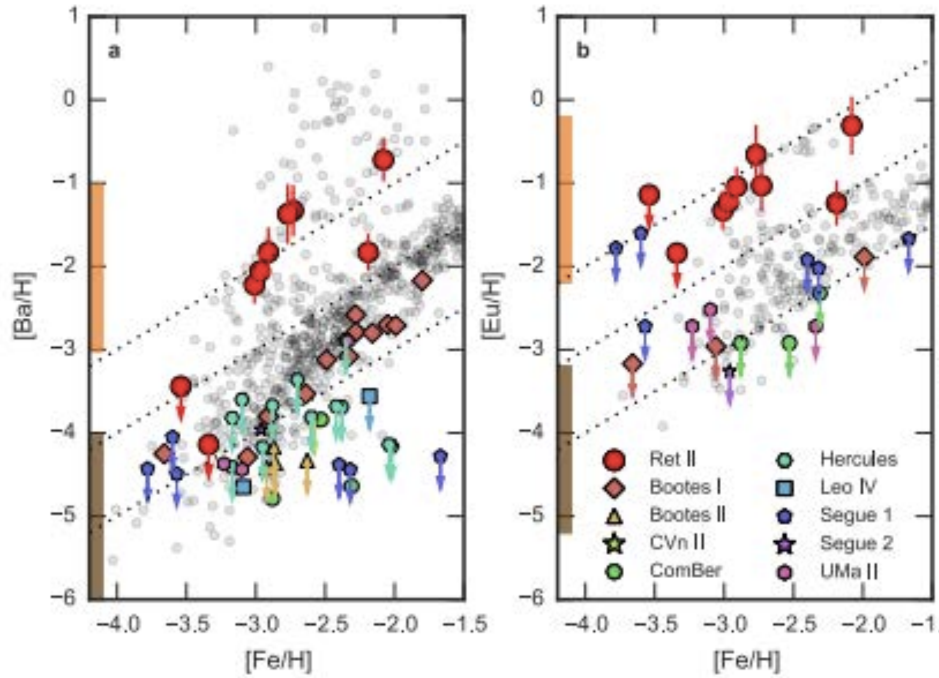
An additional process (besides r/s) must contribute significantly to elements from Fe-Sn

What's new? r process not in supernovae?

- Ultra Faint Dwarf Galaxies
  - Relics of early galactic formation
  - Most have no r process elements
  - Few with large abaundances
  - r process is rare event



Ji, Frebel, Chiti, Simon, *Nature* (2016)

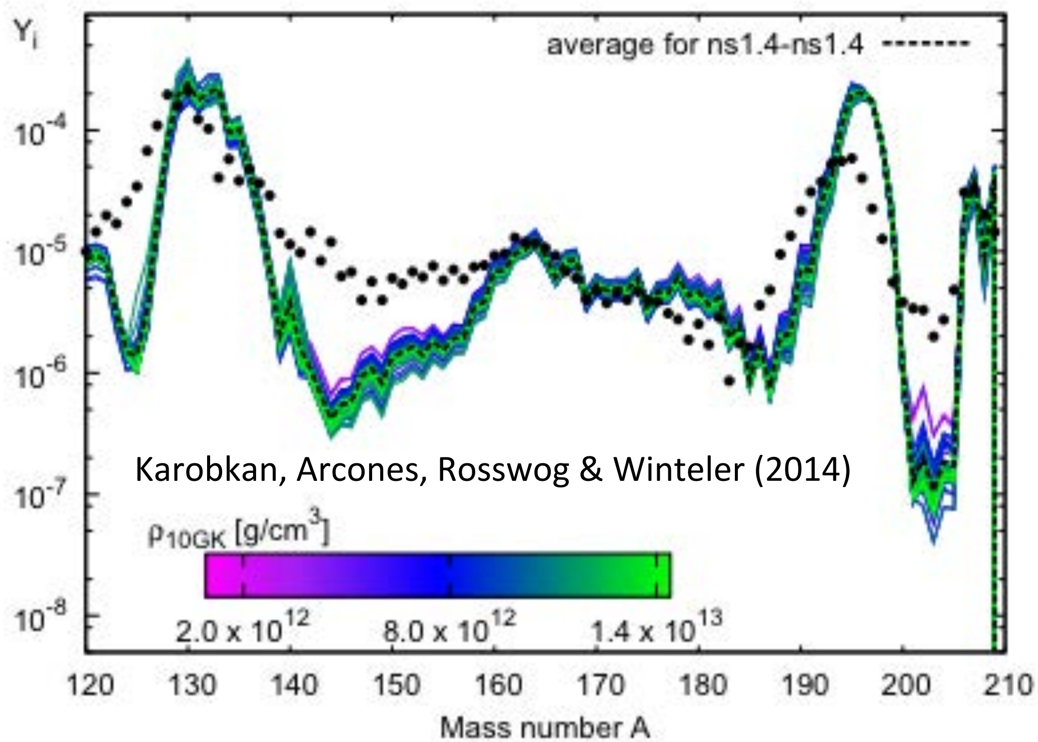


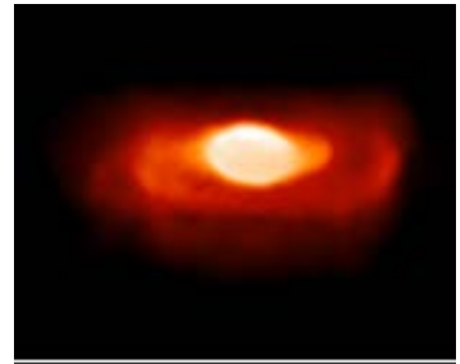
- Heavy elements do not correlate with Fe in metal-poor stars
- Supernova simulations do not produce robust neutron-rich environment
  - Weak r process (lighter masses)?

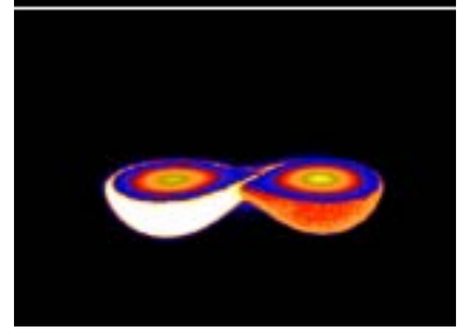
Slide from Blackmon, SURF, May 2017

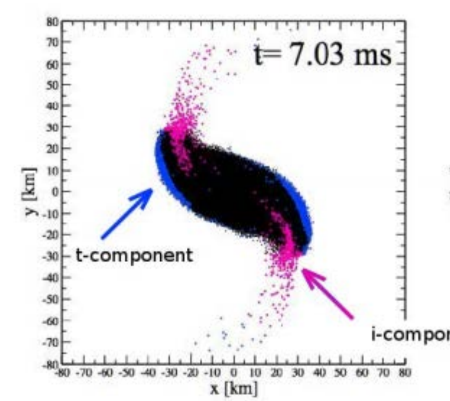
What's new? Neutron-star mergers

- Neutron star mergers produce robust r process pattern *independent of stellar conditions*
  - Sensitive to: masses, $t_{1/2}$, βn branch & fission barriers
- Eject large amounts of r process mateial, but merger rate?
  - Advanced LIGO should have sensitivity to measure the current merger rate









Slide from Blackmon, SURF, May 2017

GW170817 – Aug. 17, 2017

- First observation of neutron-star merger in gravitational waves

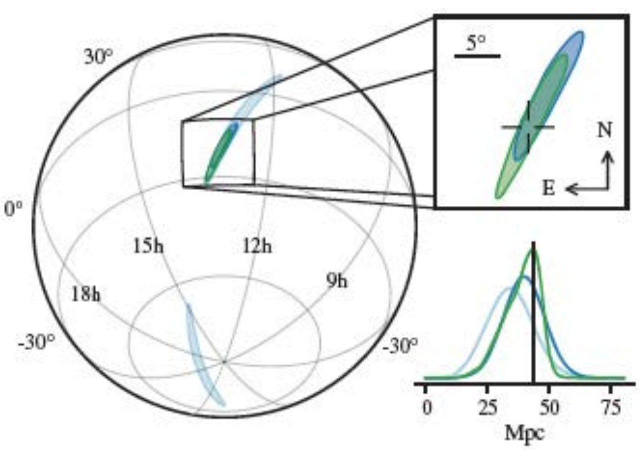
Selected for a Viewpoint in *Physics*
PRL **119**, 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

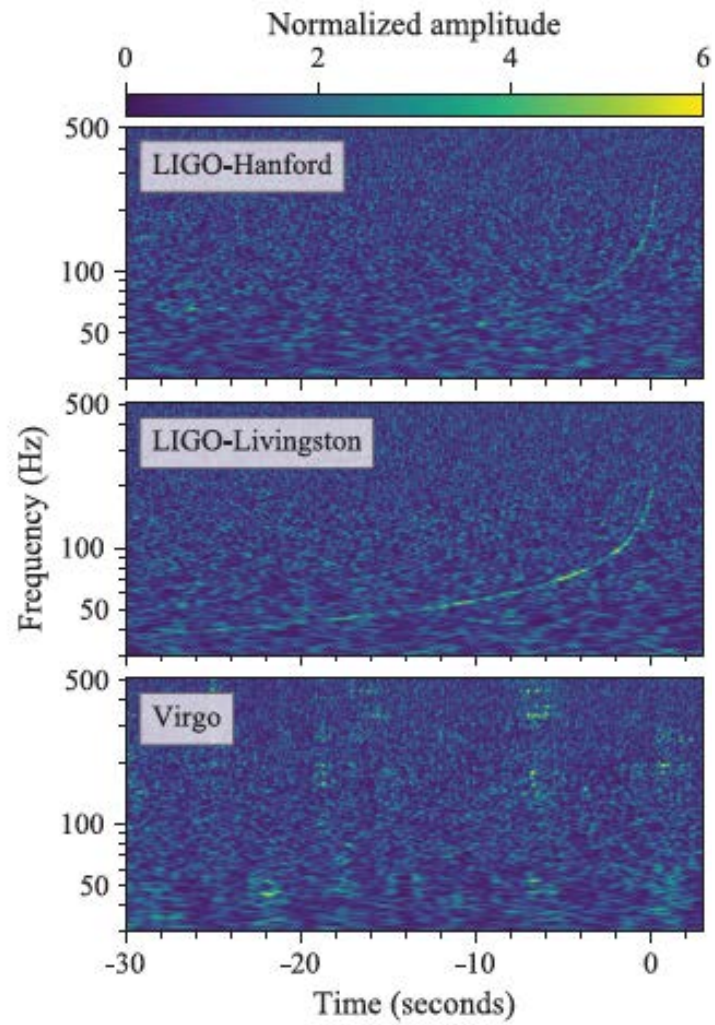
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

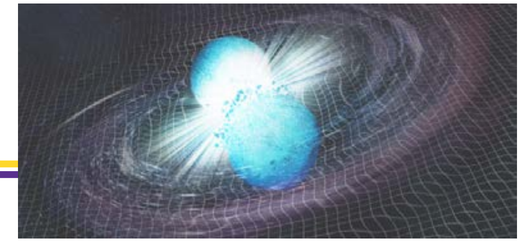
On August 17, 2017 at 12:41:04 UTC the Advanced LIGO and Advanced Virgo gravitational-wave detectors made their first observation of a binary neutron star inspiral. The signal, GW170817, was detected with a combined signal-to-noise ratio of 32.4 and a false-alarm-rate estimate of less than one per 8.0×10^4 years. We infer the component masses of the binary to be between 0.86 and 2.26 $M_{\odot}$, in

- Observation by 3 GW observatories allows good localization



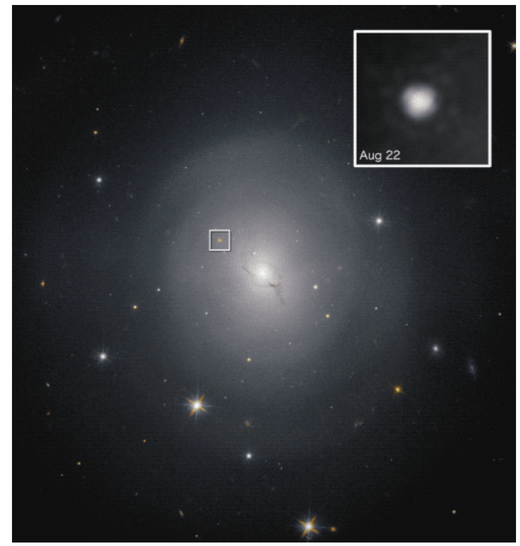


GW170817 = AT2017gfo

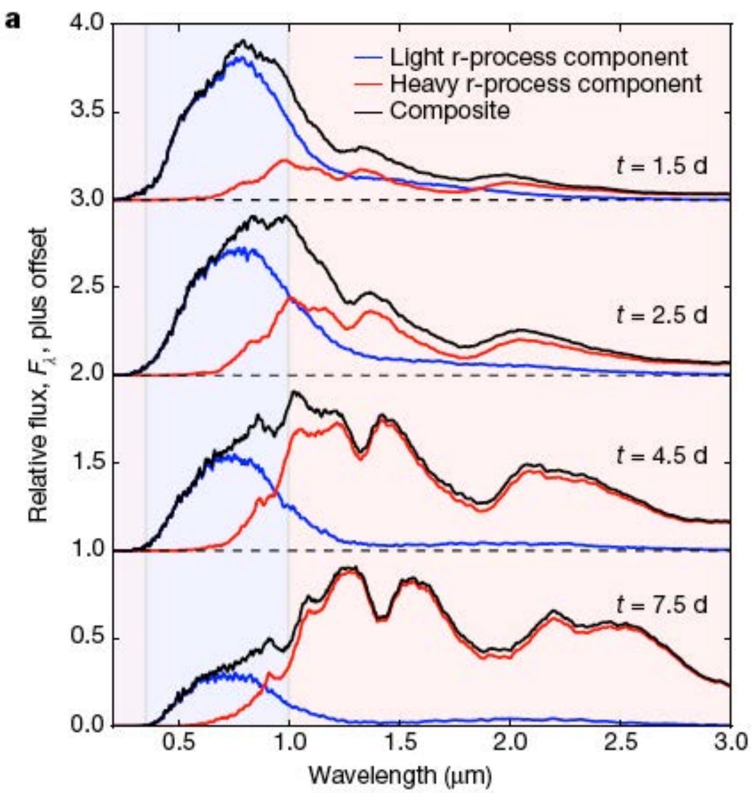


- Multiwavelength (optical, infrared, x-ray, . . .) obserations of kilonova → GW170817

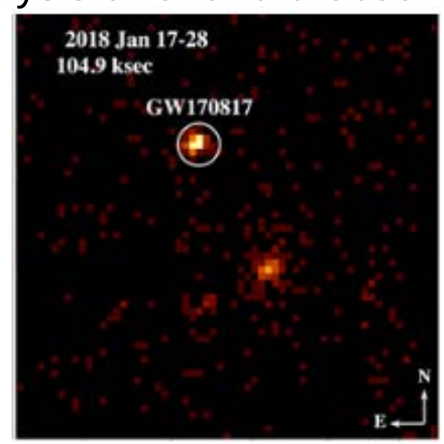
Hubble Timelapse (NASA STSci)



Kasen *et al.*, Nature, Nov. 2017



Pooley *et al.*, Ap. J. Lett, May 2018
Analysis of Chandra observations



- “Smoking gun” evidence for robust r process in n star mergers