Astronomy is much more fun when you're not an astronomer.

Brian May

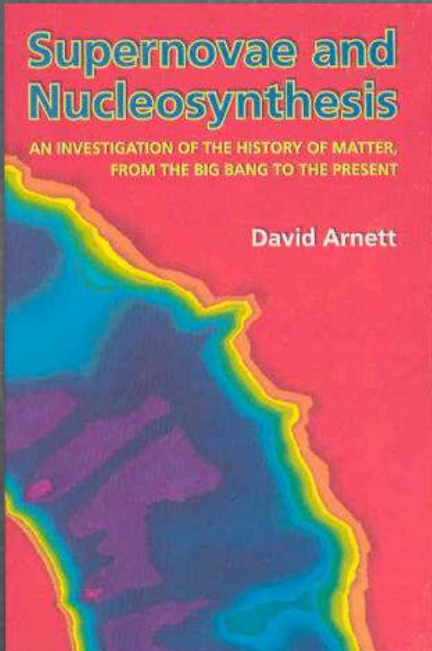
Nuclear Astrophysics: Reaction Networks

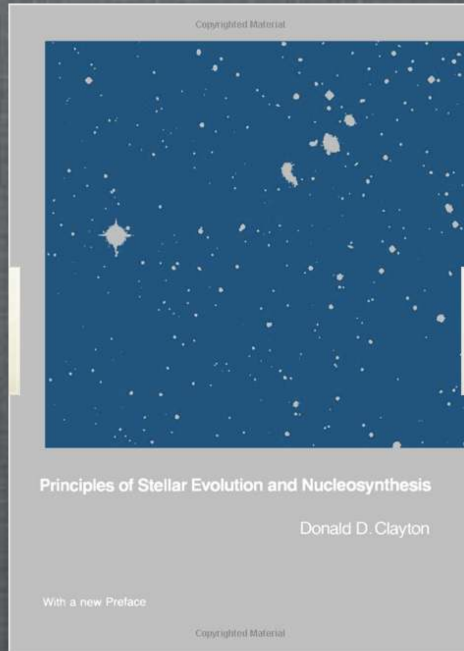
Frank Timmes

Outline for 02Jul2009

1. A general purpose network
2. Past, present, and future of ^{60}Fe & ^{26}Al

Stuff of the day



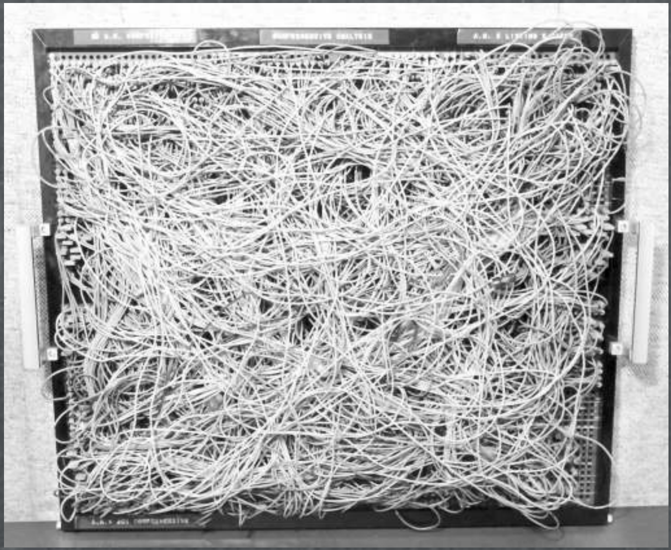


The r-, s-, and p-processes in nucleosynthesis
cococubed.asu.edu/papers/meyer94.pdf

A general network

All our previous networks are examples of hardwired networks.

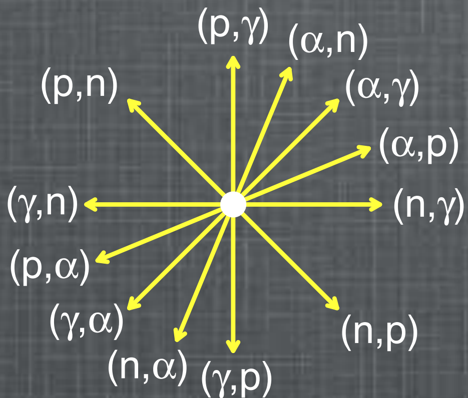
Each is carefully crafted by hand. They have the advantage of being direct and fast, but have the disadvantage of being inflexible.



univac 1004 patchboard

A general network, to do any combination of isotopes, is softwired.

First, connect isotope i with isotope k by reaction type n




```
subroutine naray

! this routine builds the nrr(7,i) array, which specifies
! the location of isotopes coupled to i by various reactions.
! the first index on nrr refers to reactions of the form
! 1=ng 2=pn 3=pg 4=ap 5=an 6=ag 7=b-

! initialize
jz(1) = 0
jz(2) = 1
jz(3) = 1
jz(4) = 1
jz(5) = 2
jz(6) = 2
jz(7) = -1
jn(1) = 1
jn(2) = -1
jn(3) = 0
jn(4) = 2
jn(5) = 1
jn(6) = 2
jn(7) = 1

! isotope i connected to isotope k by reaction type n
do i=ionbeg,ionend
 do n=1,7
  nrr(n,i) = 0
  kz = int(zion(i)) + jz(n)
  kn = int(nion(i)) + jn(n)
  do k=ionbeg,ionend
   if (kz.eq.int(zion(k)) .and. kn.eq.int(nion(k))) nrr(n,i)=k
  enddo
 enddo
enddo
return
end
```

Second, form the ODEs

```
! for every isotope in the network
do j=ionbeg,ionend

! set up y(j)(n,g)y(k) and y(k)(g,n)y(j)
 k = nrr(1,j)
 if (k .gt. 0) then
  b1 = -aan*sig(1,j)*y(j) + sig(2,j)*y(k)
  dydt(j) = dydt(j) + b1
  dydt(in) = dydt(in) + b1
  dydt(k) = dydt(k) - b1
 end if
```

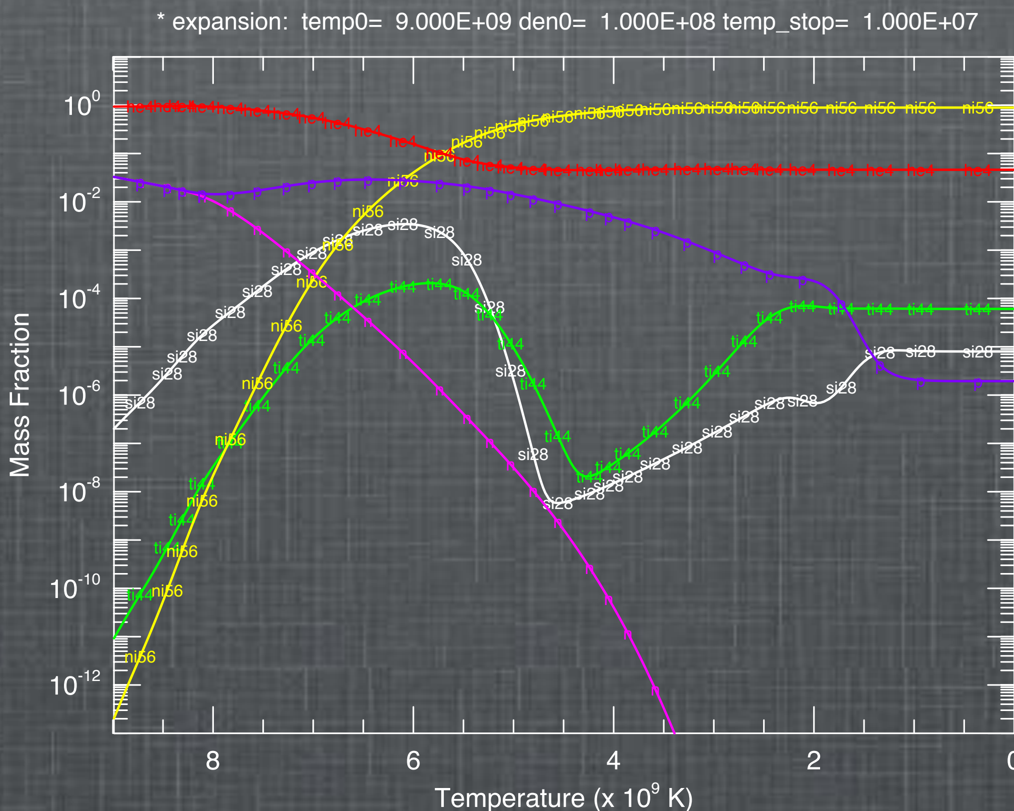
Third, form the Jacobian

```
! for every isotope in the network
do j=ionbeg,ionend

! set up the (n,g) components
 k = nrr(1,j)
 if (k .gt. 0) then
  a1 = sig(1,j) * aan
  a2 = sig(2,j)
  a3 = sig(1,j) * y(j)
  dfdy(j,j) = dfdy(j,j) - a1
  dfdy(j,k) = dfdy(j,k) + a2
  dfdy(j,in) = dfdy(j,in) - a3
  dfdy(k,j) = dfdy(k,j) + a1
  dfdy(k,k) = dfdy(k,k) - a2
  dfdy(k,in) = dfdy(k,in) + a3
  dfdy(in,j) = dfdy(in,j) - a1
  dfdy(in,k) = dfdy(in,k) + a2
  dfdy(in,in) = dfdy(in,in) - a3
 end if
```

Fourth, evolve like our other networks

The nuclear physics data is read from a file named “BDAT”.

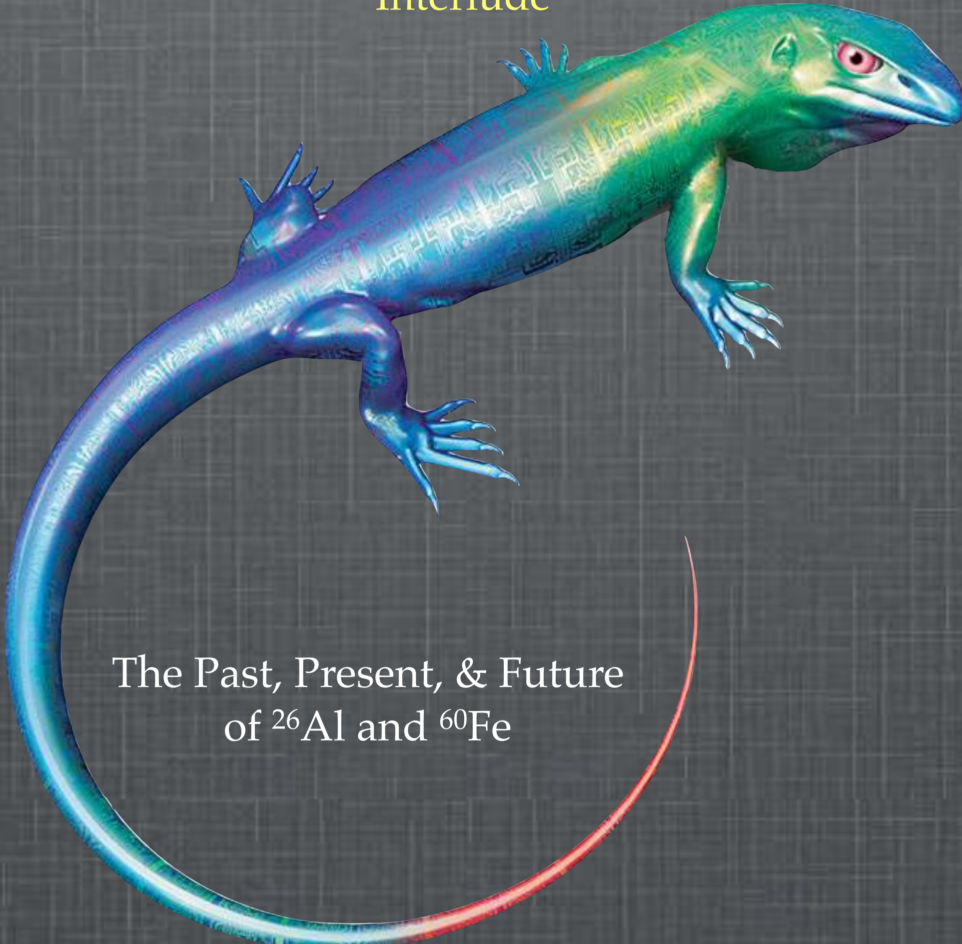


Tasks for the day

Download, compile, and run the torch code from
www.cococubed.com/code_pages/burn.shtml
How do you set which isotopes are in the network?

Run one of the task problems from the previous four days with the torch network. Do you get the same answers?

Interlude

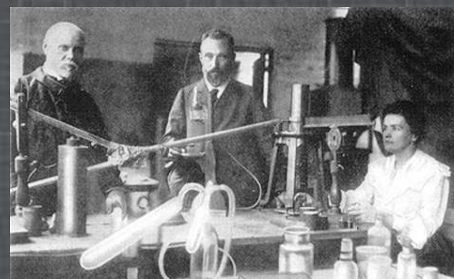


The Past, Present, & Future of ^{26}Al and ^{60}Fe

Radioactivity was discovered a little more than a century ago when Henri Becquerel included potassium and uranium sulfates as part of a photographic emulsion mixture.

He soon found that all uranium compounds were “light sources,” with an intensity proportional to the amount of U present; the chemical combination had no effect.

Two years later, Pierre and Marie Curie coined the term “radioactive” for those elements that emitted such “Becquerel rays.”



A year later, Ernest Rutherford demonstrated that at least three different kinds of radiation are emitted in the decay of radioactive substances.

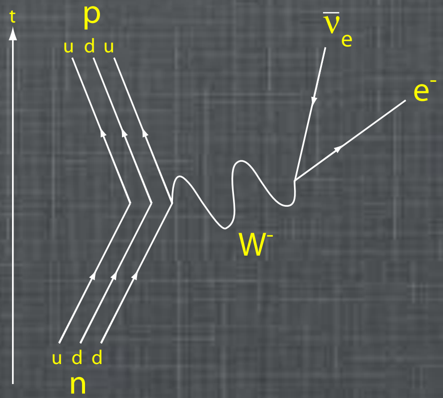
He called these “alpha,” “beta,” and “gamma” rays in increasing order of their ability to penetrate matter.

It took a few more years for Becquerel and Rutherford to show that alpha rays were helium nuclei and beta rays were electrons.

By 1912 it was shown that the γ-rays had all the properties of very energetic photons, but a full appreciation of the physics underlying the measurements took another two decades.

A.H. Compton 1929

We now understand radioactive decay as transitions between different states of nuclei, driven by electroweak interactions.



Measurement of radioactive decay products on Earth forms the basis of high-precision isotopic analysis in tree rings, rocks, and meteoritic samples - to name just a few applications.

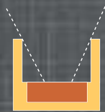
Accelerator mass spectrometer
Institute for Environmental Research Australia

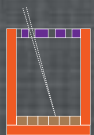
Radioactive material throughout the distant universe may be studied by measuring the γ-ray lines of a specific isotope;
the abundance being proportional to the measured line intensity.

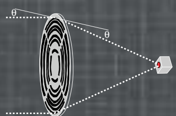
The following γ-ray lines are interesting in astrophysics because they have a decay time larger than the source dilution time and/or have enough produced to overcome instrumental sensitivities.

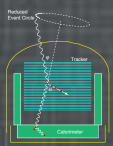
Isotope	Mean Lifetime	Decay Chain	γ-ray Energy (keV)	Source
^{7}Be	77 d	$^{7}Be \rightarrow {}^{7}Li^{*}$	478	Nova
^{56}Ni	111 d	$^{56}Ni \rightarrow {}^{56}Co^{*} \rightarrow {}^{56}Fe^{*} + e^{+}$	158, 812; 847, 1238	Supernova
^{57}Ni	390 d	$^{57}Co \rightarrow {}^{57}Fe^{*}$	122	Supernova
^{22}Na	3.8 y	$^{22}Na \rightarrow {}^{22}Ne^{*} + e^{+}$	1275	Nova
^{44}Ti	89 y	$^{44}Ti \rightarrow {}^{44}Sc^{*} \rightarrow {}^{44}Ca + e^{+}$	76, 68; 1157	Supernova
^{26}Al	1.04×10^{6} y	$^{26}Al \rightarrow {}^{26}Mg^{*} + e^{+}$	1809	Stars, SN, Nova
^{60}Fe	2.0×10^{6} y	$^{60}Fe \rightarrow {}^{60}Co^{*} \rightarrow {}^{60}Ni^{*}$	59, 1173, 1332	Stars, SN
e+	$\sim 10^{5}$ y	$e^{+} + e^{-} \rightarrow Ps \rightarrow \gamma\,\gamma$	511	SN,Nova, ...

By the mid 1970s various international collaborations had launched experiments on stratospheric balloons and space satellites to explore γ-rays from radioactive nuclei.





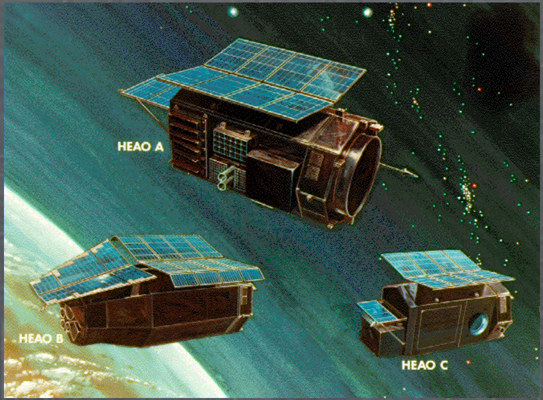




Telescope type	Photon counter	Spatial resolution defined by	Examples
Simple Bucket	Detector array	Shield (= aperture)	HEAO-C, SMM, CGRO-OSSE
Coded Mask	Shadowing mask & Detector array	Mask & Detector element sizes	SIGMA, INTEGRAL
Focussing	Laue lens & Detector array	Lens diffraction and distance	CLAIRE, MAX
Compton	Coincidence setup of position sensitive detectors	Detector's spatial resolution	CGRO-COMPTEL, LXeGRiT, MEGA, ACS

Sensitivity ~ 10^5 ph/cm/s   Angular resolution > 1 degree

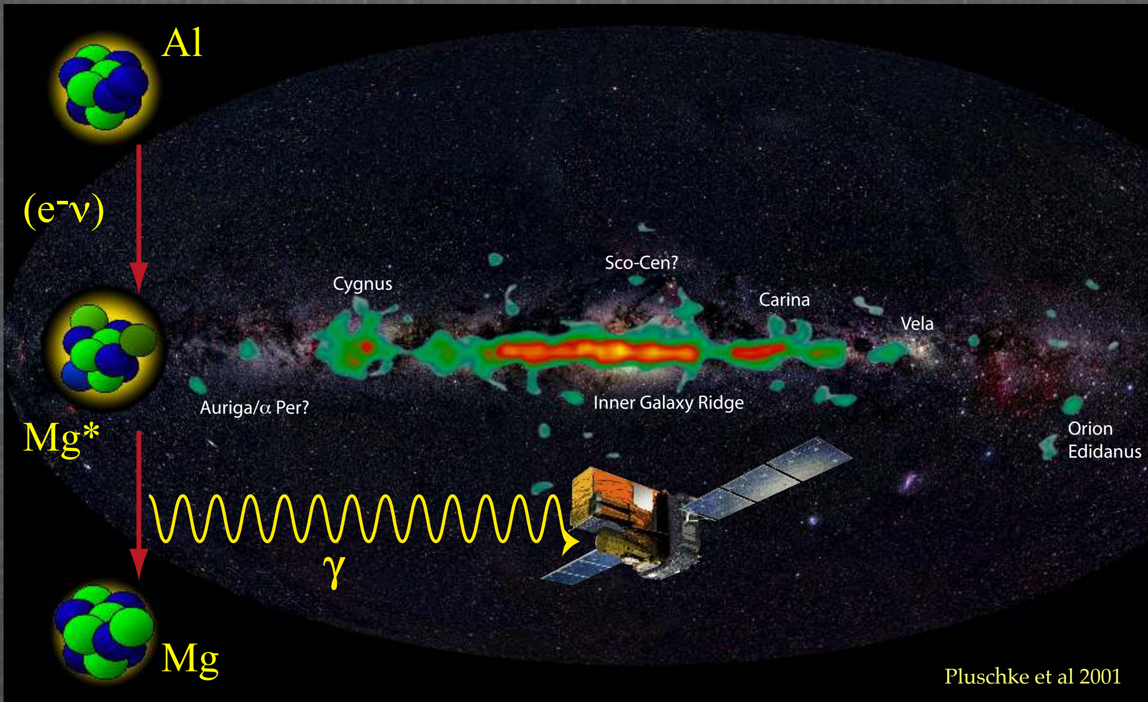
In 1982 ^{26}Al became the first radioactivity detected in the Galaxy through its 1.809 MeV line flux. The measurement by HEAO-C implied ~2 M_{sun} of live ^{26}Al in the central region of the Galaxy.

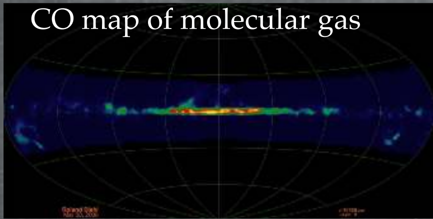


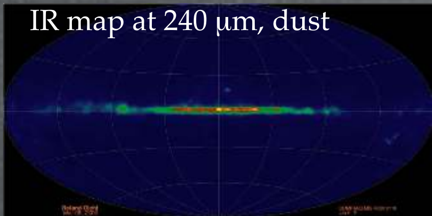
NASA, circa 1979

Modelers subsequently produced numerous calculations of core-collape supernove, Wolf-Rayet winds, Classical Novae, AGB stars, and supermassive stars that, in most cases, all produced the observed ^{26}Al abundance. They all can't be right!

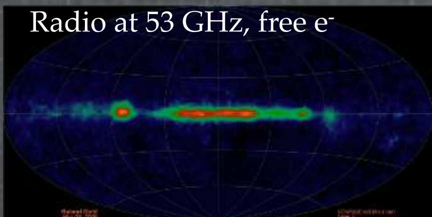
By 1994 images of the central region of the Galaxy in the light of ^{26}Al were being produced by the Compton Gamma Ray Observatory.



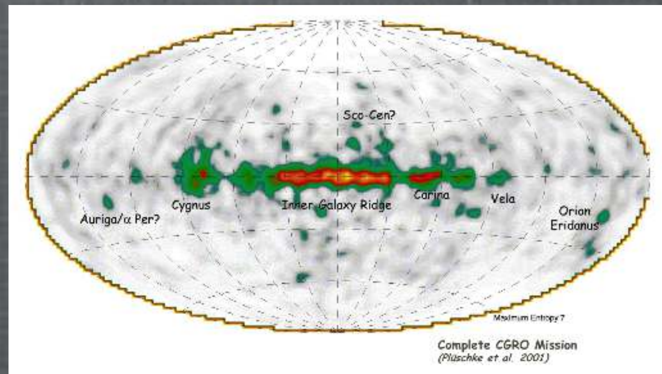




Adapted from Diehl 2000

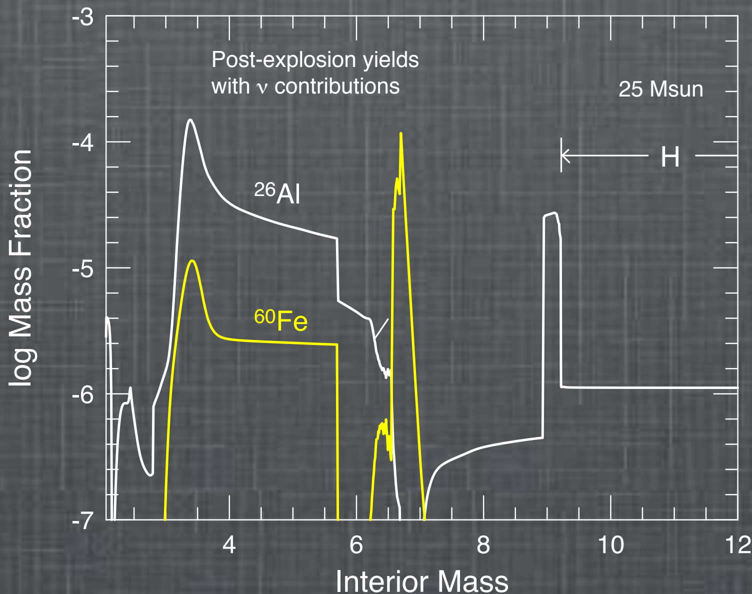


A popular technique for determining the source of ^{26}Al in the mid-1990's was analyzing maps of the Galaxy at other wavelengths.



"Massive stars are the plausible sources as the ^{26}Al map is correlated with star-forming gas, warm dust, diffuse ionized gas, and map the scale height of bright spiral arms."

In 1995 the Santa Cruz group produced a then unprecedented grid of massive star models, 1D without mass loss or rotation, and noticed that ^{60}Fe and ^{26}Al were largely produced at the same location:



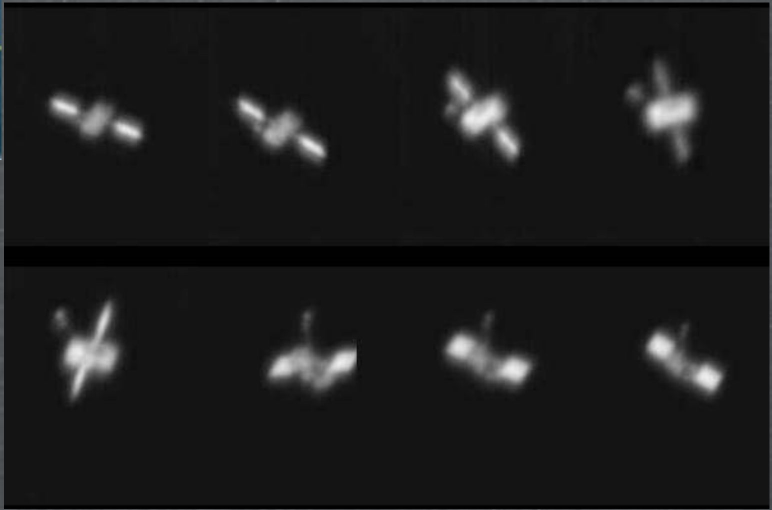
Timmes et al 1995

This led to the idea that ^{60}Fe could be an excellent discriminant of the contested origin site of ^{26}Al since none of the other sources produce significant amounts of ^{60}Fe. Timmes et al 1995 predicted:

1. The ^{60}Fe flux map will be concentrated toward the Galactic center.
2. The ^{60}Fe mass and flux maps will follow the ^{26}Al distributions.
3. The ^{60}Fe and ^{26}Al hot spots will overlap.
4. The ^{60}Fe/^{26}Al flux ratio will be 0.16 ± 0.12.
5. The inferred mass of live ^{60}Fe in the Galaxy will be $0.75 \pm 0.4\ M_{sun}$.

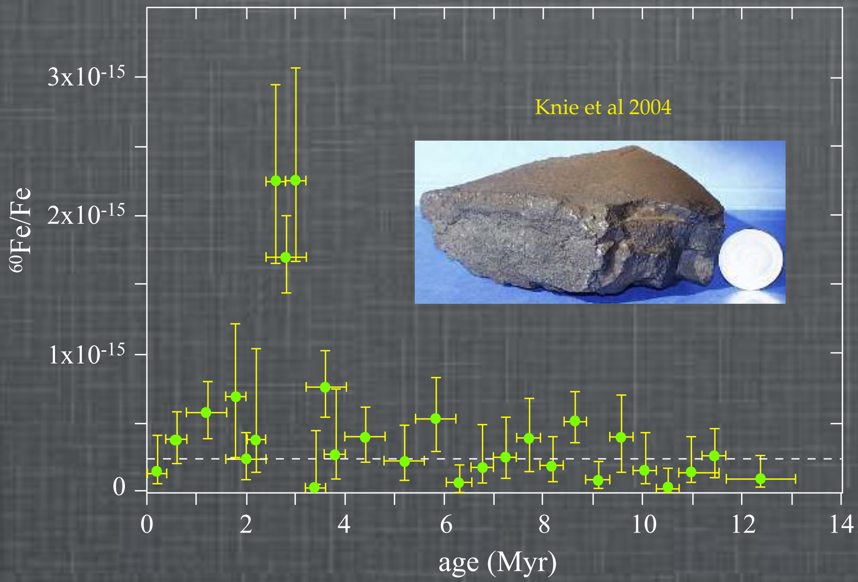
Unfortunately, the predicted $^{60}Fe/^{26}Al$ flux ratio was just below the sensitivity of the Compton Observatory allowing only an upper limit measurement.

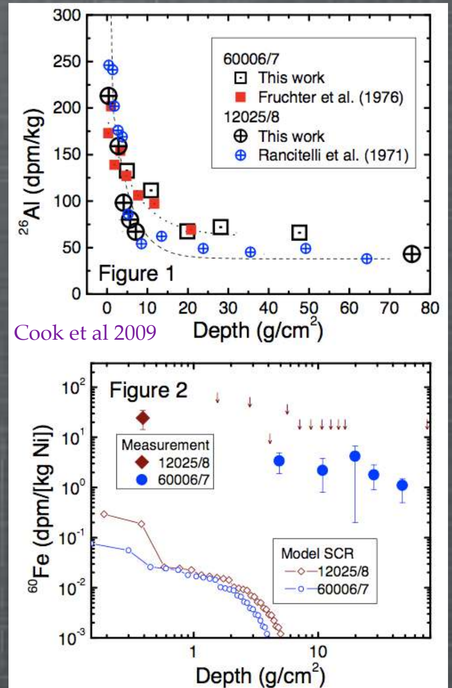
NASA, 2000



CGRO re-entry,
AEOS, April 2000

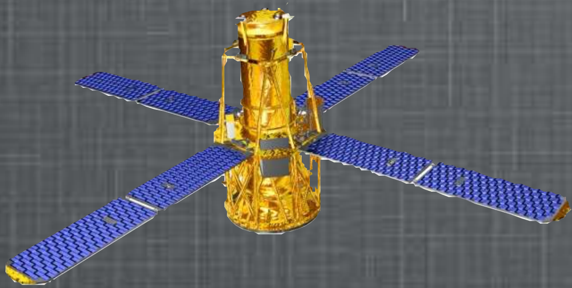
Live ^{60}Fe has been detected in deep Pacific FeMn crust and lunar sample by AMS corresponding to an age of 2.8 ± 0.4 Myr.



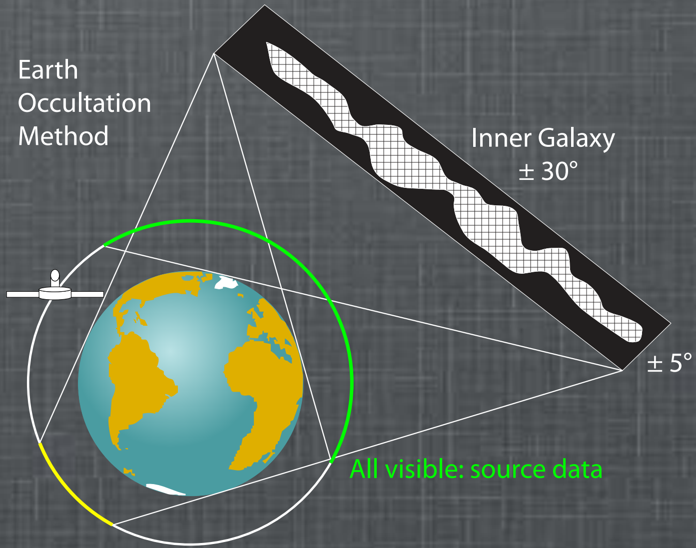


Evidence in other isotopes, extinction or weather records?

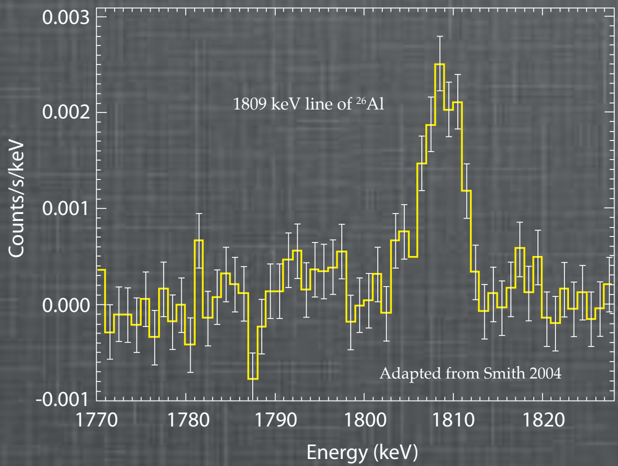
Ramaty High Energy Solar Spectroscopic Imager (RHESSI) Galactic measurements are made using the Earth as an occultator; there is no spatial resolution within the inner Galaxy.

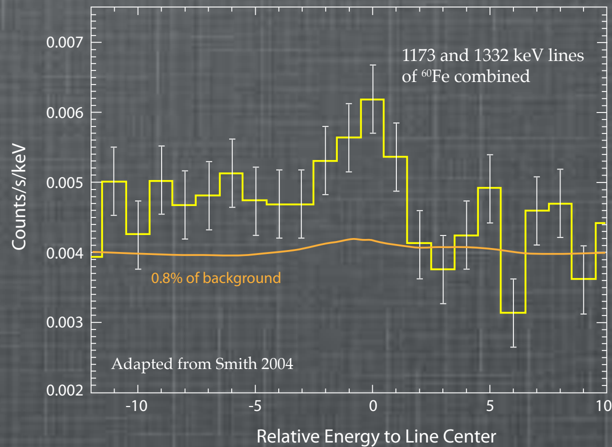


HESSI launch by NASA in February 2002 from the Lockheed L-1011 seconds after Orbital's Pegasus rocket ignited.



With RHESSI in 2004, Smith measured ^{26}Al and ^{60}Fe line fluxes to derive a ^{60}Fe/^{26}Al flux ratio of 0.17 ± 0.05 (2006 values).





^{60}Fe flux = $3.6 \pm 1.4 \times 10^{-5}$ ph/cm^2/s

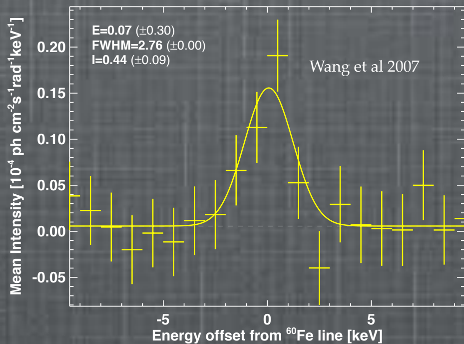
International Gamma-Ray Astrophysics Laboratory (INTEGRAL) is the first space observatory that can simultaneously observe objects in gamma rays, X-rays and visible light.

ESA, 2001

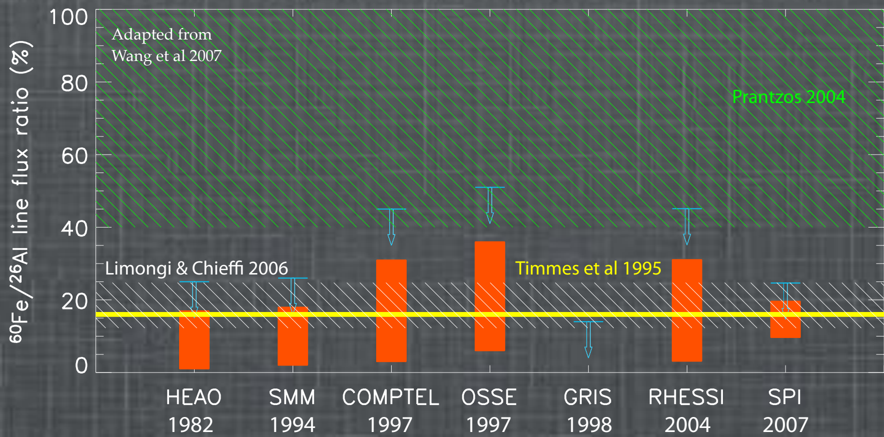
INTEGRAL's coded-mask spectrometer with a 19-element Germanium solid-state detector.

INTEGRAL launched by ESA in October 2002 by a Proton rocket from Baikonur in Kazakhstan.

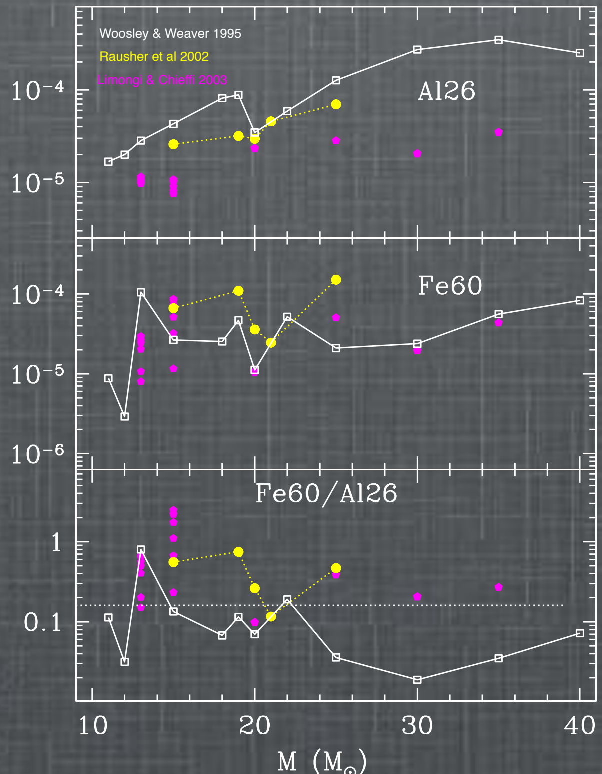
With INTEGRAL in 2007, Wang et al measured the ^{60}Fe line flux and derived a ^{60}Fe/^{26}Al flux ratio of 0.14 ± 0.06, both in excellent agreement with the RHESSI measurements.



^{60}Fe flux = 4.4 ± 0.9 x 10^{-5} ph/cm²/s



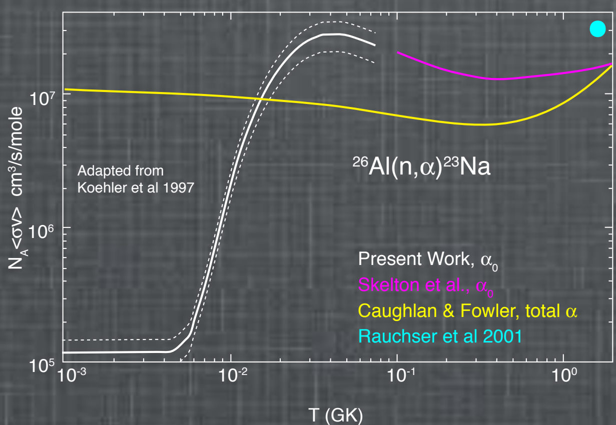
Since the 1995 predictions, “improved” stellar models and nuclear physics gave smaller amounts of ^{26}Al and larger amounts of ^{60}Fe. What happened?!

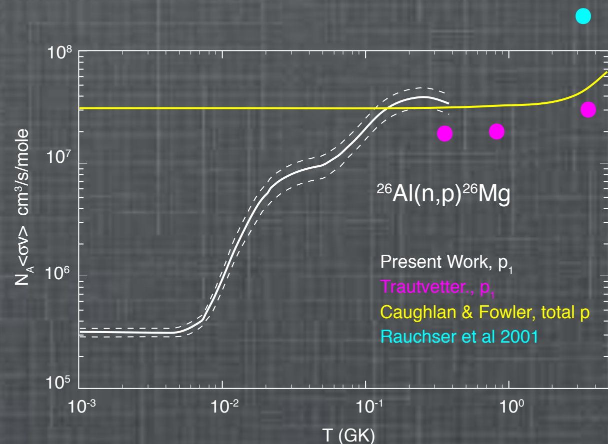


Prantzos 2004

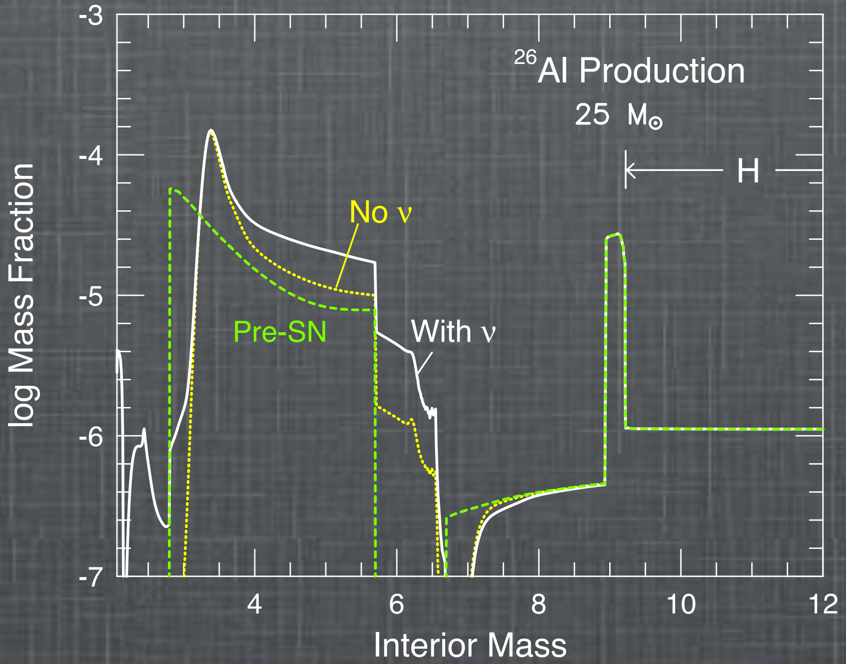
One occurrence was a “perfect nuclear storm” of unsound choices ...

In transitioning to modern data bases, most groups used new Hauser-Feshbach rates for $^{26}Al(n,p)^{26}Mg$ and $^{26}Al(n,\alpha)^{23}Na$ that were 3-5 times larger the experimental determinations by Koehler (1997).



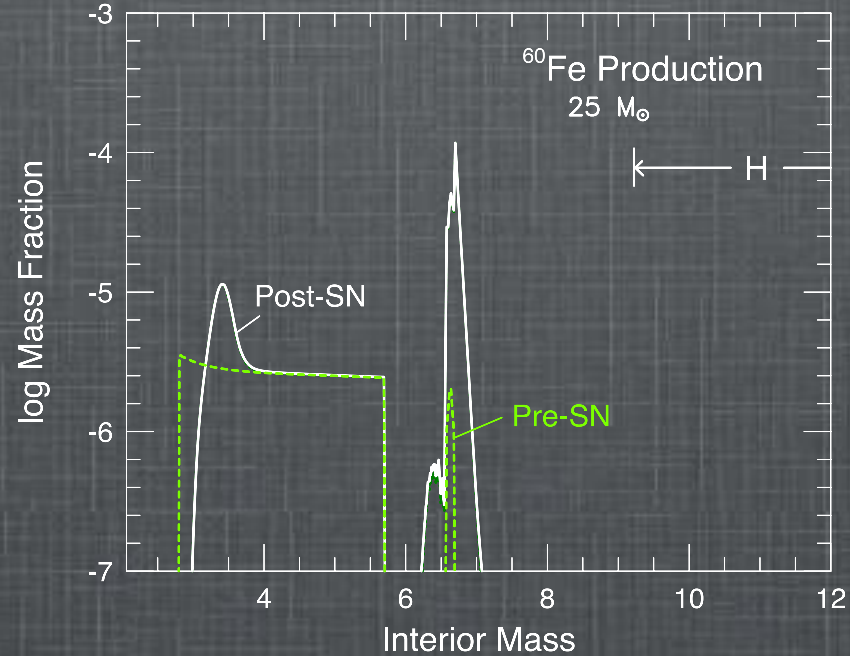


The net effect is to preferentially destroy ^{26}Al in the carbon and oxygen shells of massive stars.



Timmes et al 1995

Cross sections governing the production of ^{60}Fe also changed, with a rate for $^{59}Fe(n,\gamma)^{60}Fe$ half as large and a rate for $^{60}Fe(n,\gamma)^{61}Fe$ twice as large as those used in the 1995 survey. Neither rate is measured. The net effect is to increase ^{60}Fe yields.



Timmes et al 1995

The final nuclear physics uncertainty is $^{22}Ne(\alpha,n)^{25}Mg$, which controls the production of the neutrons used to synthesize ^{60}Fe.

In modern compilations $^{22}Ne(\alpha,n)^{25}Mg$ is larger than what was used in 1995. Reducing this rate further decreases the synthesis of ^{60}Fe.

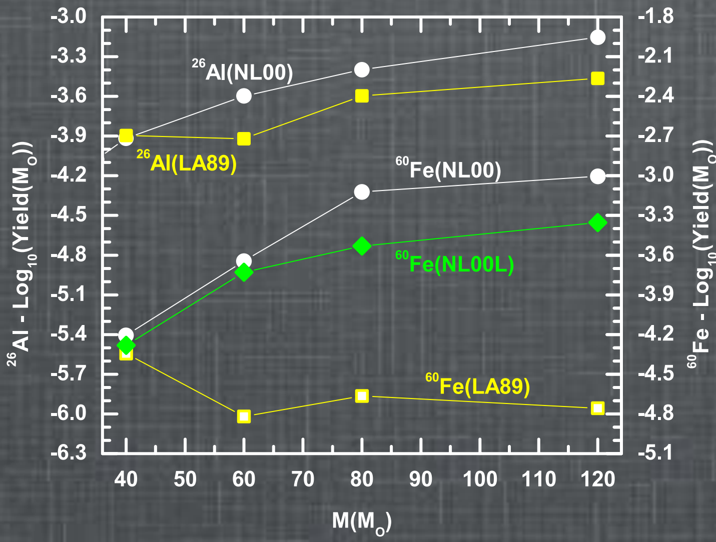
^{26}Al destruction larger
^{60}Fe production smaller
^{60}Fe destruction larger
^{22}Ne destruction larger

Warner Brothers, 2000

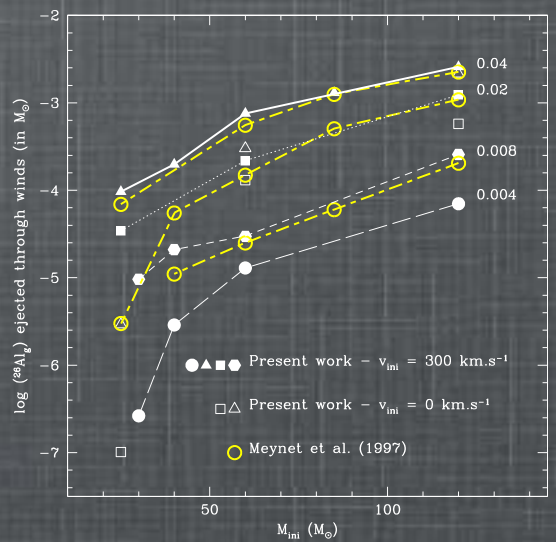
Returning uncertain cross sections to the values they had in 1995, can account for most of the difference between present model calculations and the γ-ray observations.

There are also uncertainties in the stellar models. Mass loss, metallicity, rotation, convection and the IMF all play major roles.

Limongi & Cheiffi 2006

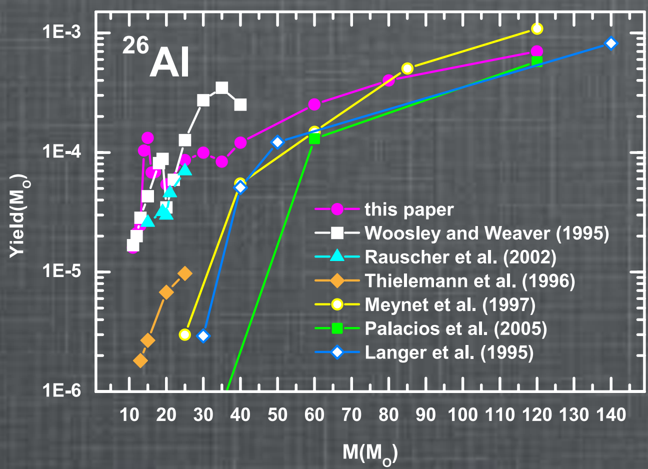


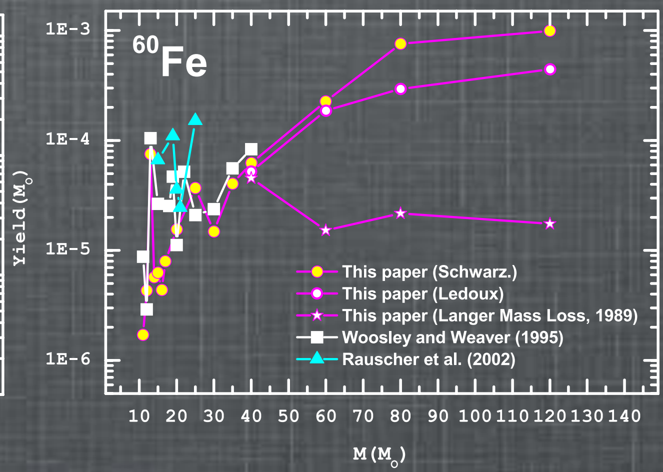
Palacios et al 2005



Even with relatively "standard" reaction rates there are wide differences in various investigators results for ^{26}Al and ^{60}Fe.

Limongi & Cheiffi 2006





Conclusions

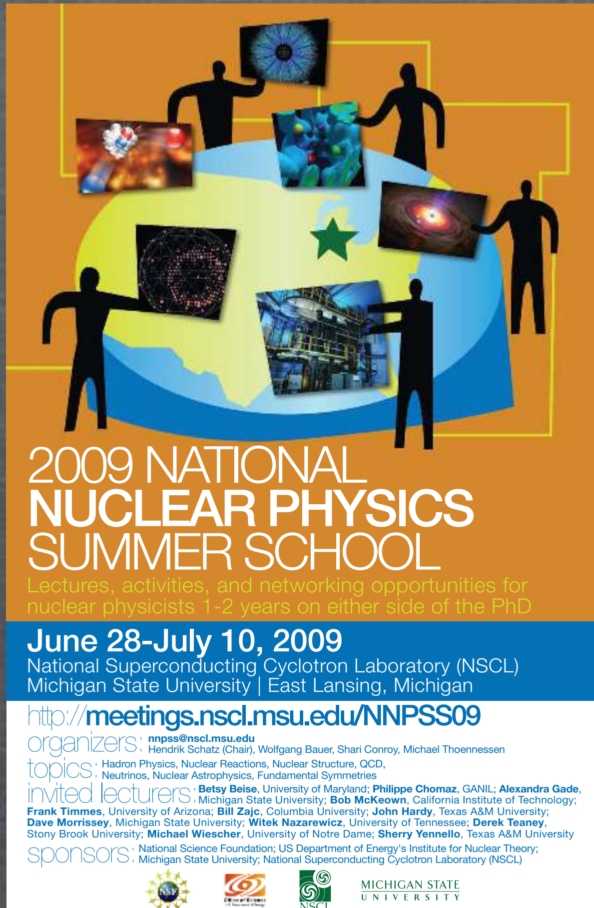
The abundances of ^{26}Al and ^{60}Fe inferred from γ-ray astronomy is now an important constraint on stellar models, and one that is largely independent of the core collapse mechanism.

Progress depends upon more accurate measurements of critical nuclear physics:

^{26}Al(n,p)^{26}Mg	^{26}Al(n,α)^{23}Na
^{59}Fe(n,γ)^{60}Fe	^{60}Fe(n,γ)^{61}Fe
^{22}Ne(α,n)^{25}Mg	^{59}Fe(e^{-} ν_e)^{50}Co

New missions such GRASP and GRI that may be able to image the inner Galaxy in the light of ^{60}Fe hold promise for an exciting future in γ-ray astronomy.

Thank You


2009 NATIONAL
NUCLEAR PHYSICS
SUMMER SCHOOL
Lectures, activities, and networking opportunities for nuclear physicists 1-2 years on either side of the PhD
June 28-July 10, 2009
National Superconducting Cyclotron Laboratory (NSCL)
Michigan State University | East Lansing, Michigan
http://meetings.nscl.msu.edu/NNPSS09
organizers: nnpss@nscl.msu.edu
Hendrik Schatz (Chair), Wolfgang Bauer, Shari Conroy, Michael Thoennessen
topics: Hadron Physics, Nuclear Reactions, Nuclear Structure, QCD, Neutrinos, Nuclear Astrophysics, Fundamental Symmetries
invited lecturers: Betsy Beise, University of Maryland; Philippe Chomaz, GANIL; Alexandra Gade, Michigan State University; Bob McKeown, California Institute of Technology; Frank Timmes, University of Arizona; Bill Zajc, Columbia University; John Hardy, Texas A&M University; Dave Morrissey, Michigan State University; Witek Nazarewicz, University of Tennessee; Derek Teaney, Stony Brook University; Michael Wiescher, University of Notre Dame; Sherry Yennello, Texas A&M University
sponsors: National Science Foundation; US Department of Energy's Institute for Nuclear Theory; Michigan State University; National Superconducting Cyclotron Laboratory (NSCL)
NSF
NSCL
MICHIGAN STATE UNIVERSITY