Nuclear Astrophysics

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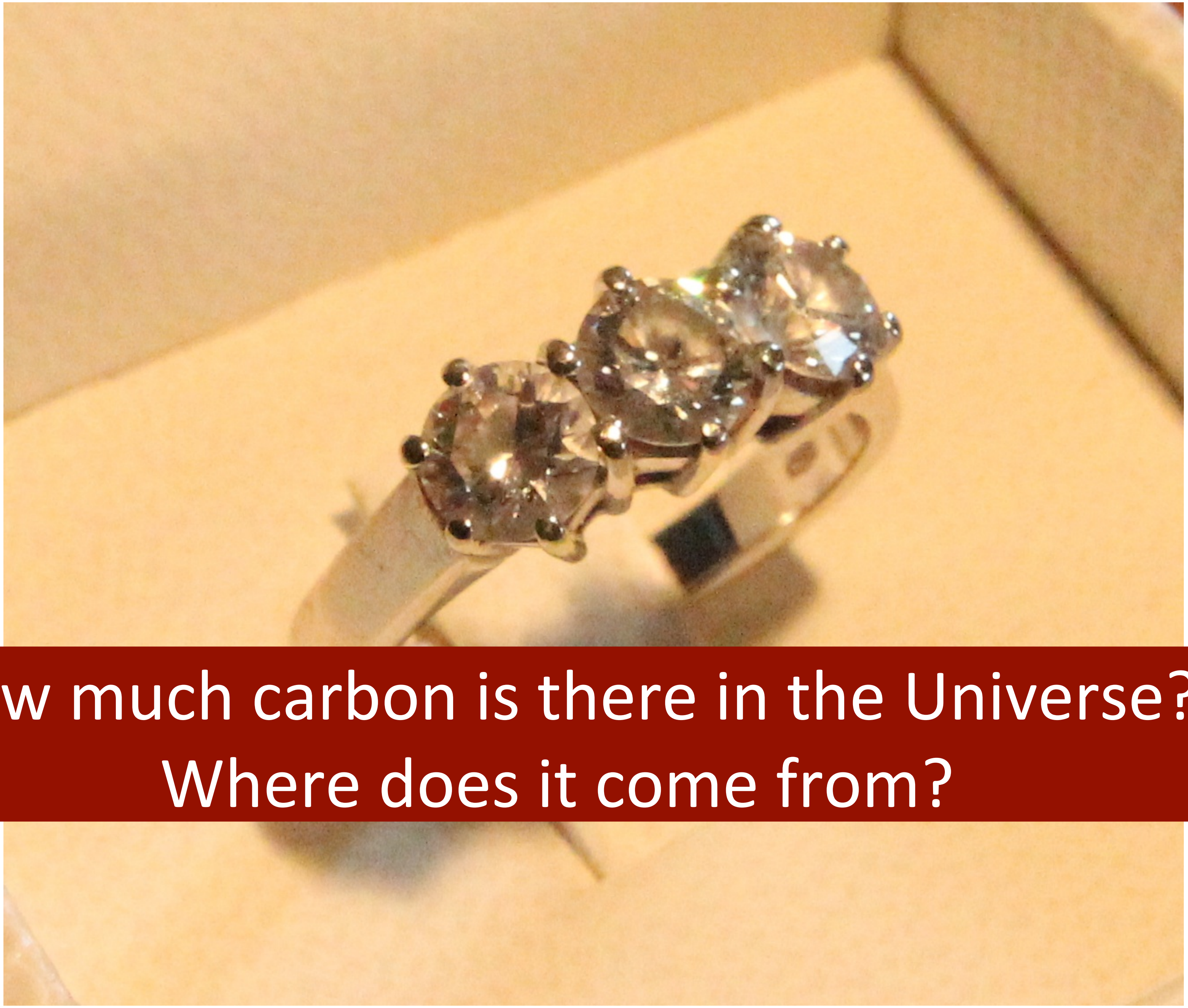
Scottish Universities Physics Alliance

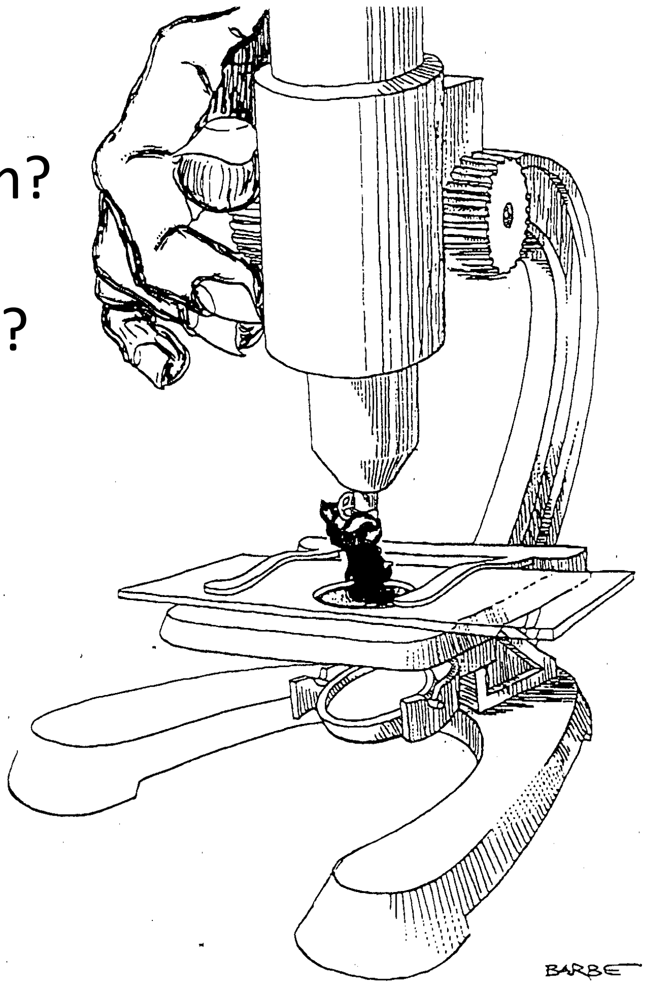
Higgs Workshop, Royal Society Edinburgh – 14 February, 2018



How much carbon is there in the Universe?
Where does it come from?

Nuclear Astrophysics

- Where do all chemical elements come from?
- How do stars and galaxies form and evolve?



Courtesy: M. Arnould

Intimate connection between

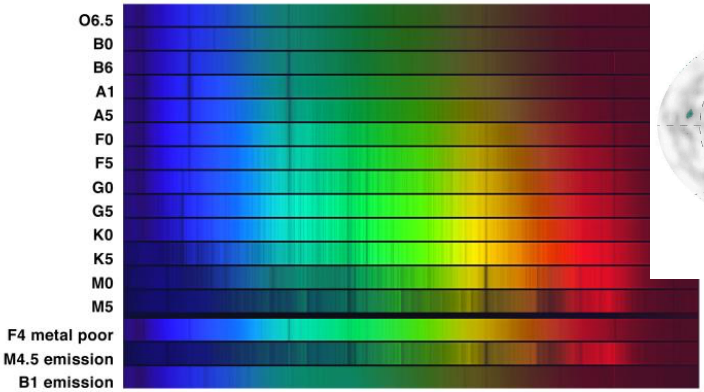
MICRO COSMOS

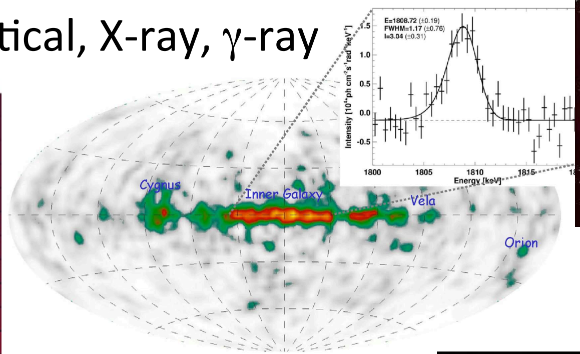
and

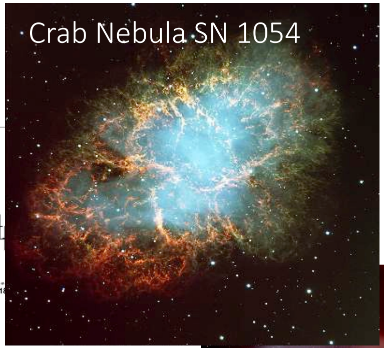
MACRO COSMOS

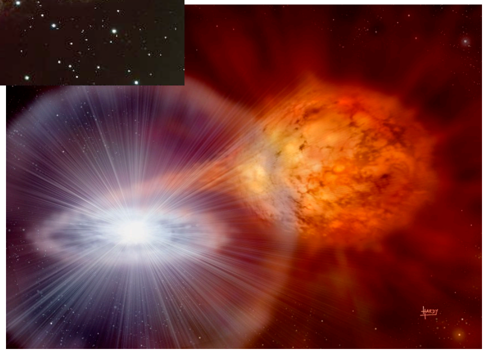
electromagnetic emissions

radio, microwave, infrared, optical, X-ray, γ-ray



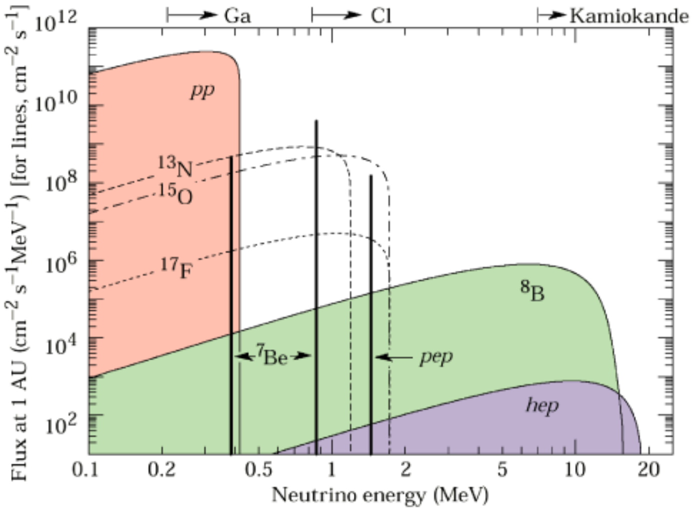


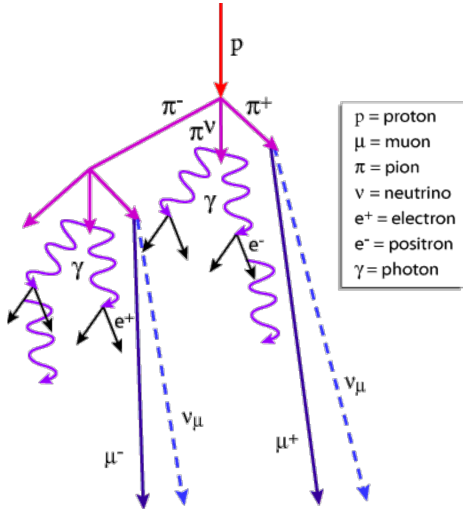




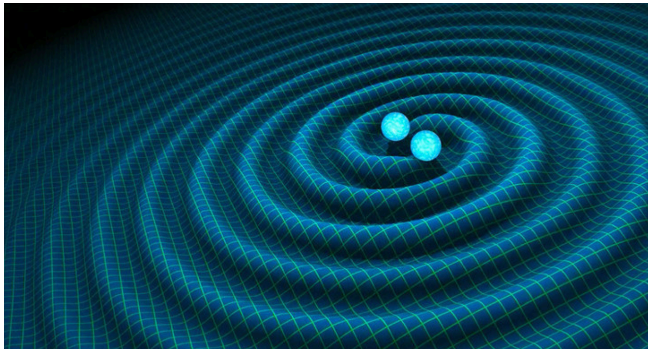
direct messengers

neutrinos, cosmic rays, meteorites, lunar samples, …





gravitational waves



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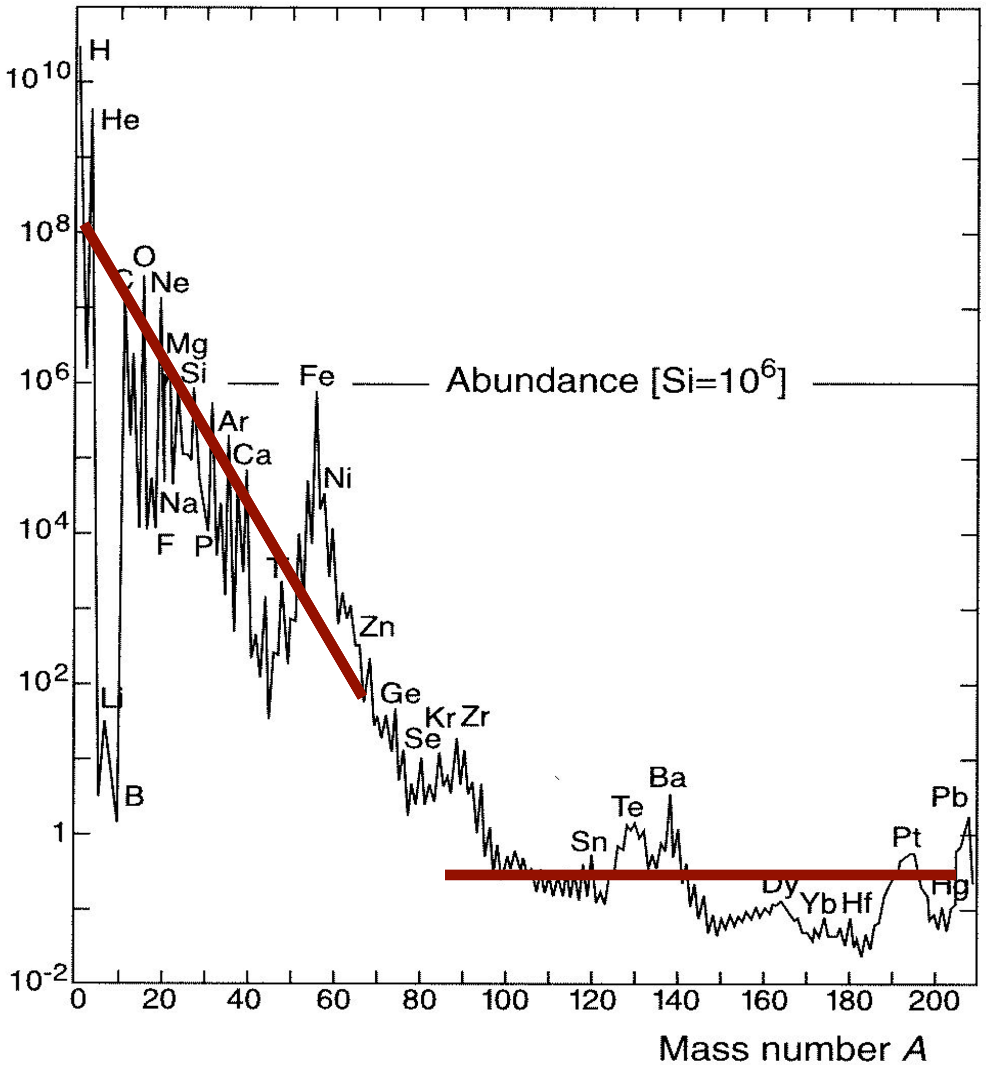
(Solar) Abundance Distribution



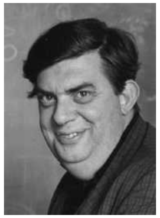
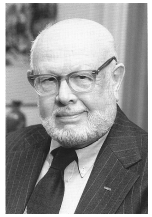
Data sources:

Earth, Moon, meteorites, cosmic rays, solar & stellar spectra…

Features:

- distribution everywhere similar
- 12 orders-of-magnitude span
- H ~ 75%, He ~ 23%
- C → U ~ 2% (“metals”)
- D, Li, Be, B under-abundant
- exponential decrease up to Fe
- nearly flat distribution beyond Fe

Burbidge, Burbidge, Fowler & Hoyle (B^2FH): Rev. Mod. Phys. 29 (1957) 547

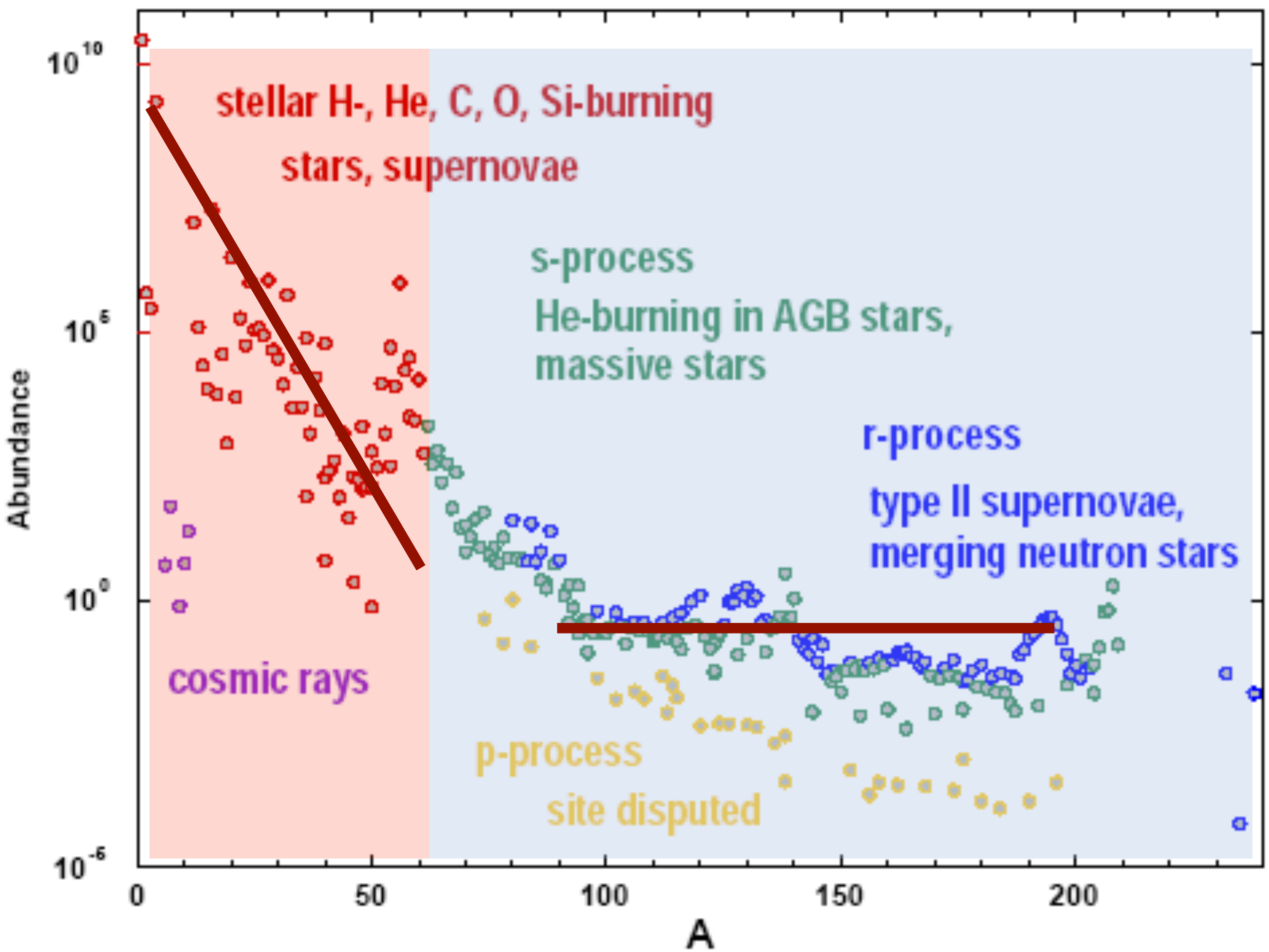

Synthesis of the Elements in Stars*

E. Margaret Burbidge, G. R. Burbidge, William A. Fowler, and F. Hoyle

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

fusion of charged particles

mainly **stable nuclei**



M. Wiescher, JINA lectures on Nuclear Astrophysics

neutron-capture reactions

mainly **unstable nuclei**

The Bigger Picture

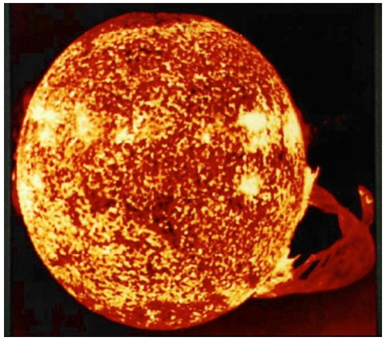
Interstellar medium

BIRTH

gravitational contraction

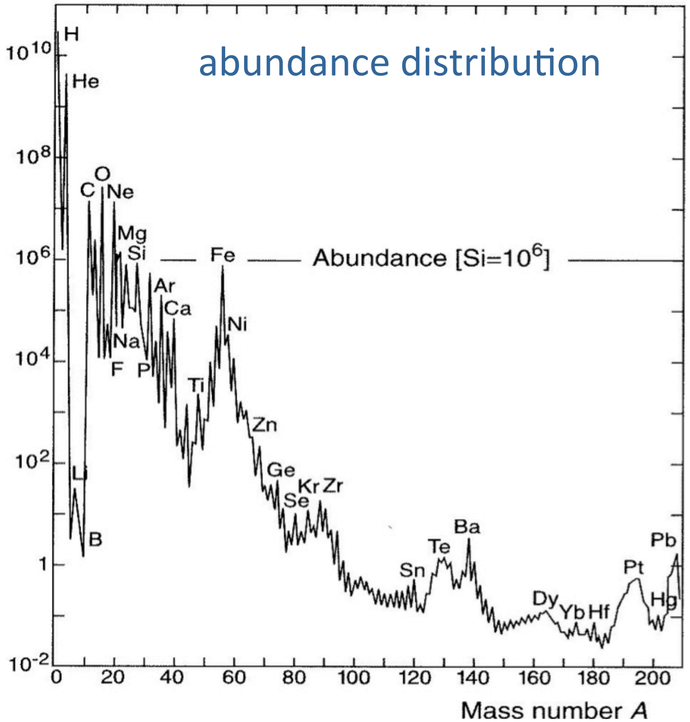
explosion ejection

DEATH



Stars

abundance distribution



- energy production
- stability against collapse
- synthesis of "metals"

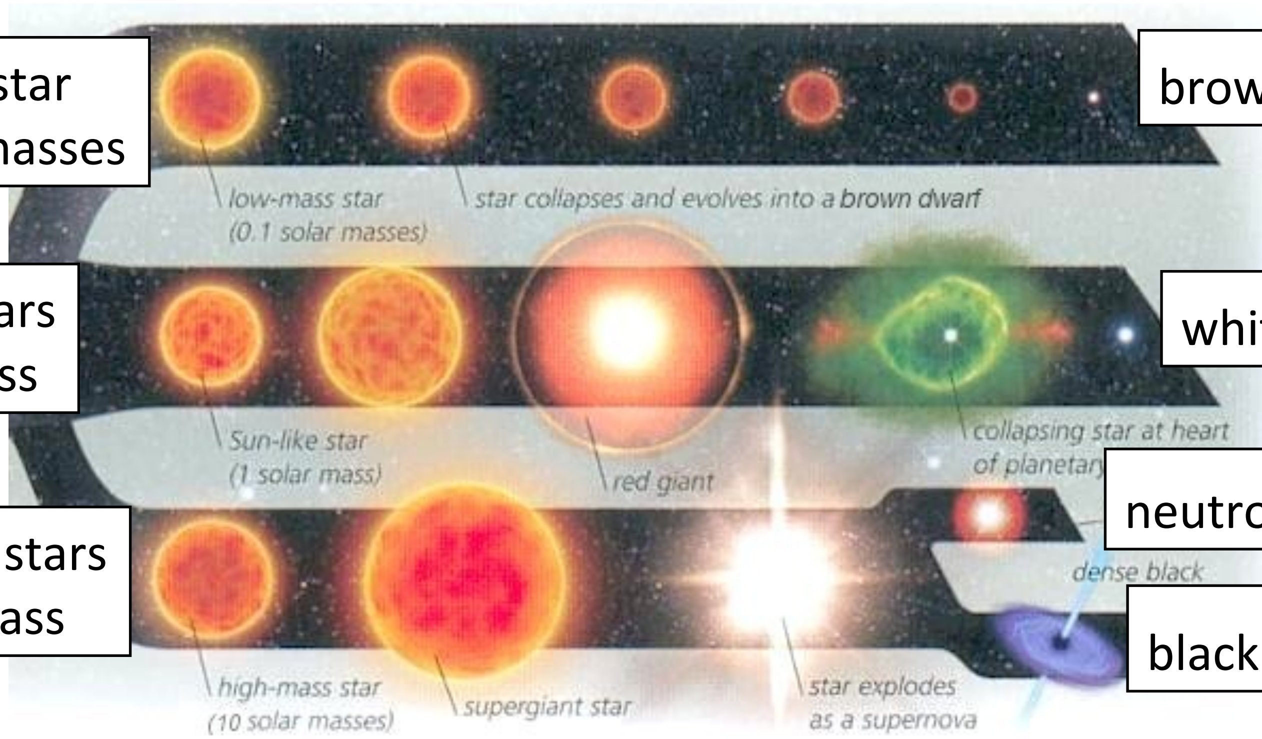
Stellar Evolutionary Paths

birth | evolution | death

low-mass star
0.1 solar masses

sun-like stars
1 solar mass

high-mass stars
10 solar mass



brown dwarf

white dwarf

neutron star

black hole

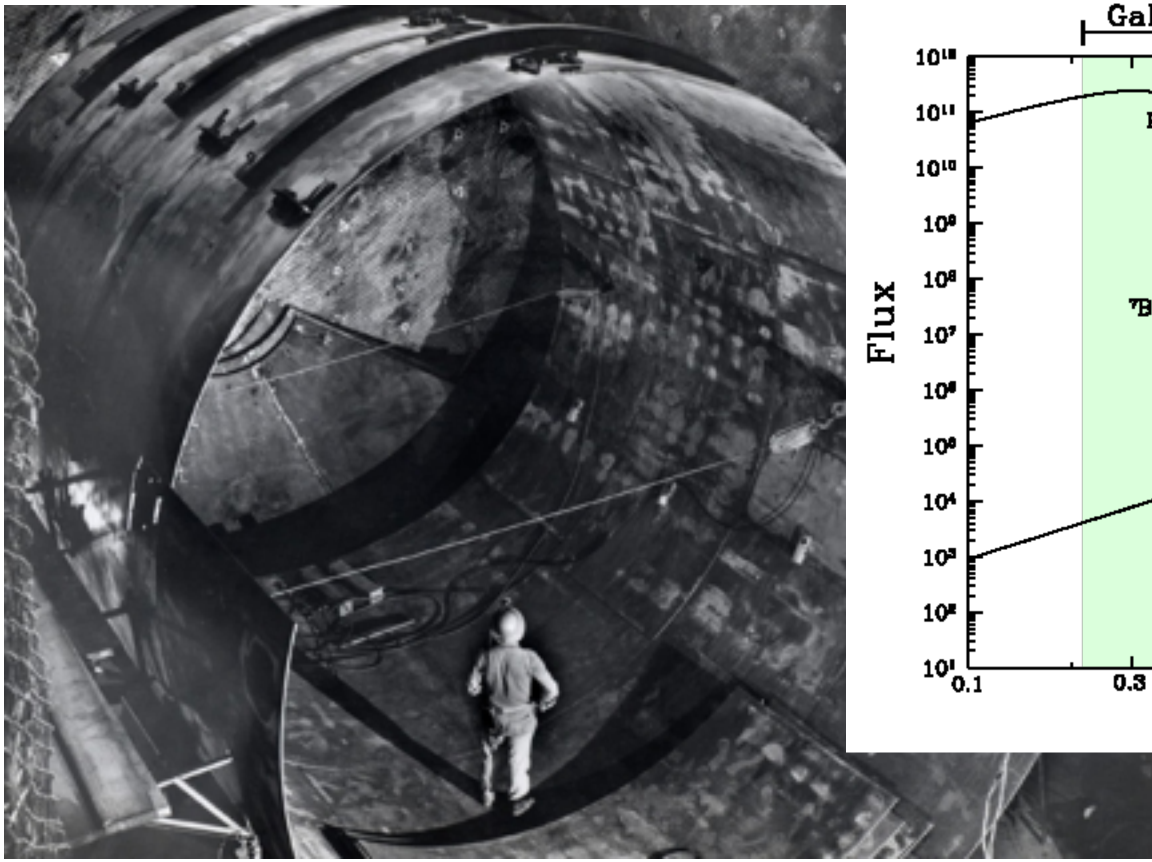
massive stars contribute to **chemical evolution** of the Universe

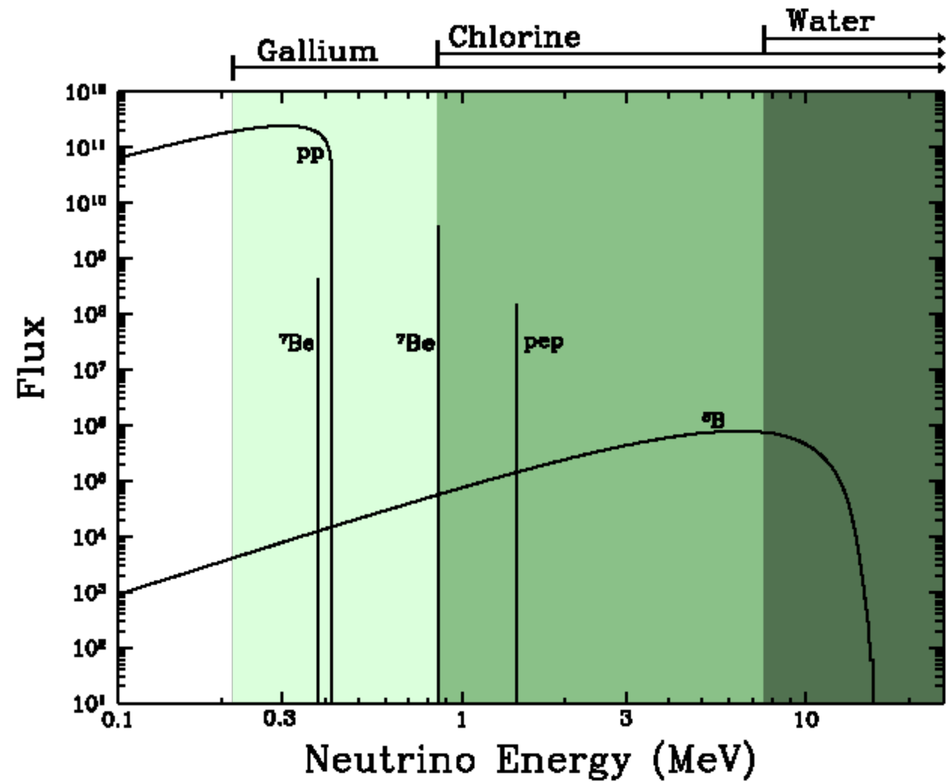
later generation stars form out of enriched material: **more metal rich**

Direct evidence for nuclear reactions in stars?

Solar Neutrino Detection at Homestake in 1960s

http://sanfordlab.org/article/270





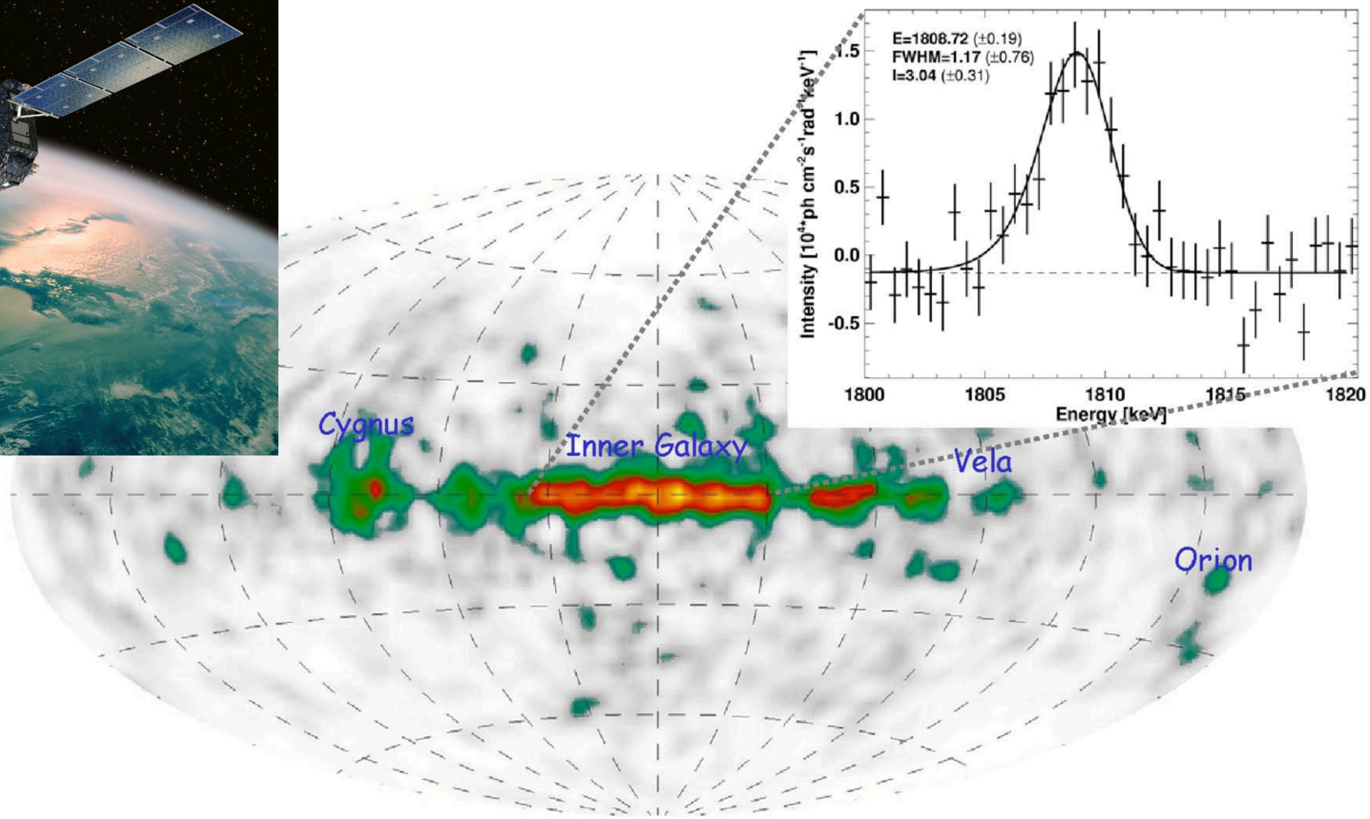
1965: Ray Davis inside chlorine tank that used as for solar neutrino detection
Credit: Anna Davis

Direct evidence of nucleosynthesis in stars

1982: discovery of 1.8 MeV γ-rays associated with ^{26}Al decay ($t_{1/2}$ = 7x10^5 y)

direct proof of ongoing nucleosynthesis in our Galaxy

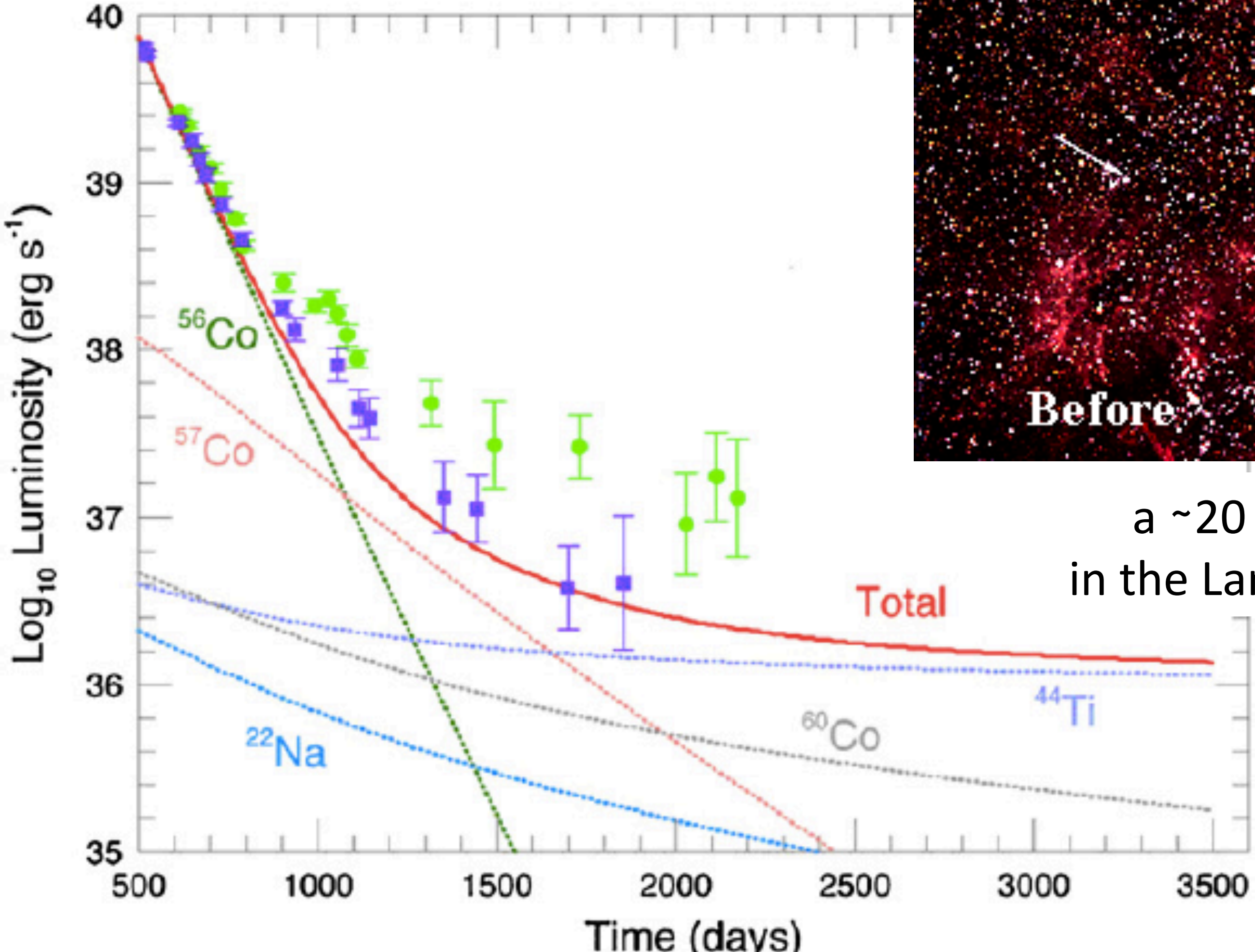
observed with COMPTEL and INTEGRAL



Diehl et al., Nature 439 (2006) 45

Light curves of supernovae explosion powered by radioactive decay

SN1987A



a ~20 $M_\odot$ star explosion
in the Large Magellanic Cloud

$t_{1/2}$ (^{56}Co) = 77d

$t_{1/2}$ (^{44}Ti) = 49 y

Dressler et al, J Phys G: Nucl Part Phys 39 (2012) 105201

Puzzling Facts and Open Questions

- Big Bang Nucleosynthesis: Li problem(s) and the D abundance
- Core metallicity of the Sun
- Fate of massive stars
- Explosive scenarios: X-ray bursts, novae, SN type Ia
- Pre-solar grains composition
- Origin of Heavy Elements
- Astrophysical site(s) for the r-process
- …

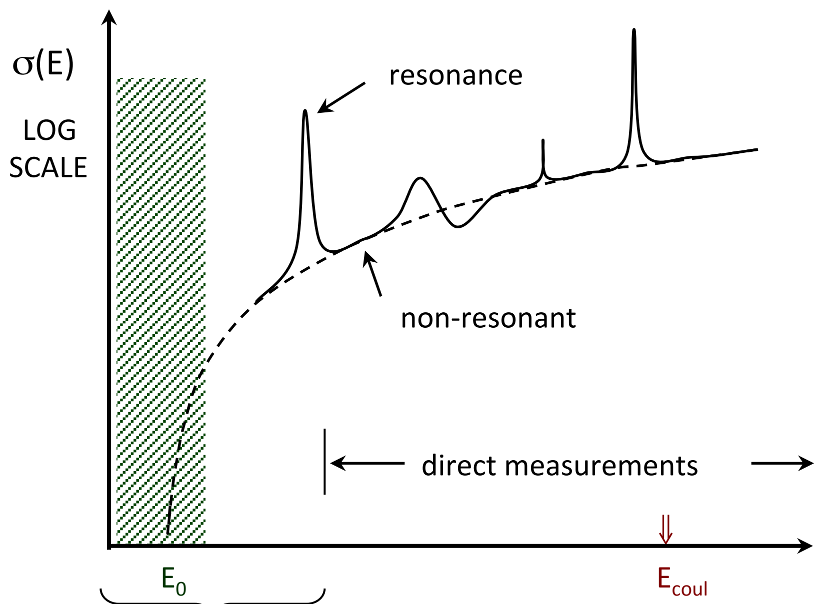
Thermonuclear Reactions in Stars

Gamow peak: energy window where information on nuclear processes is needed

$kT \ll E_0 \ll E_{coul}$ ➔ 10^{-18} barn $< \sigma < 10^{-9}$ barn ➔ Major experimental difficulties

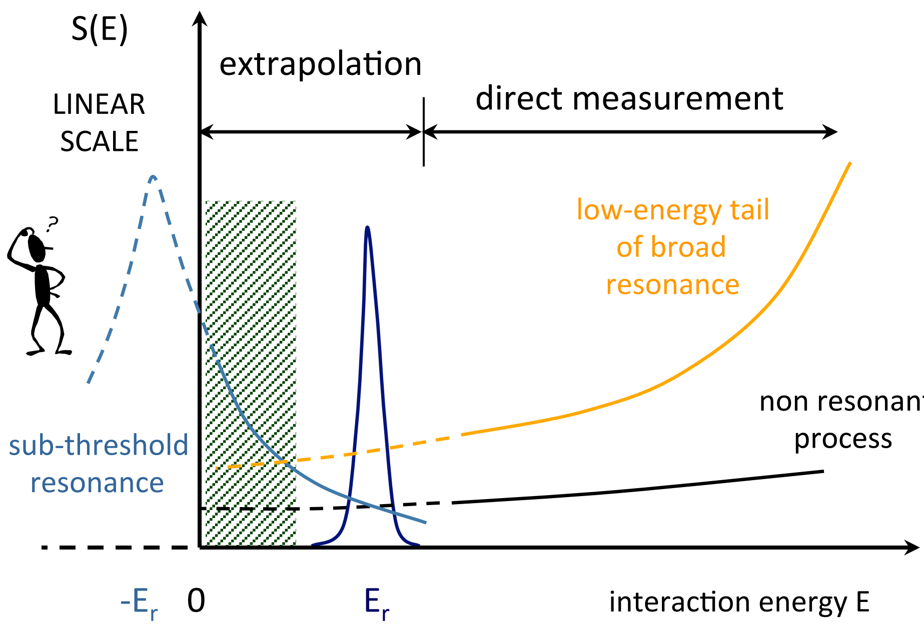
Procedure: measure $\sigma(E)$ over wide energy, then extrapolate down to E_0!

CROSS SECTION



S-FACTOR

$$\sigma = E^{-1} \exp(-2\pi\eta)\, S(E)$$



DANGER OF EXTRAPOLATION !

Reaction Yields and Cross Sections

$$Y = N_p\, N_t\, \sigma\, \eta$$

N_p = number of projectile ions

typically, stable beam intensities 10^{14} pps (~100 μA)

N_t = number of target atoms

typically, 10^{19} atoms/cm^2

σ = reaction cross section (given by nature)

typically, 10^{-15} barn (1 barn = 10^{-24} cm^2)

η = detection efficiency

typically, 100% for charged particles

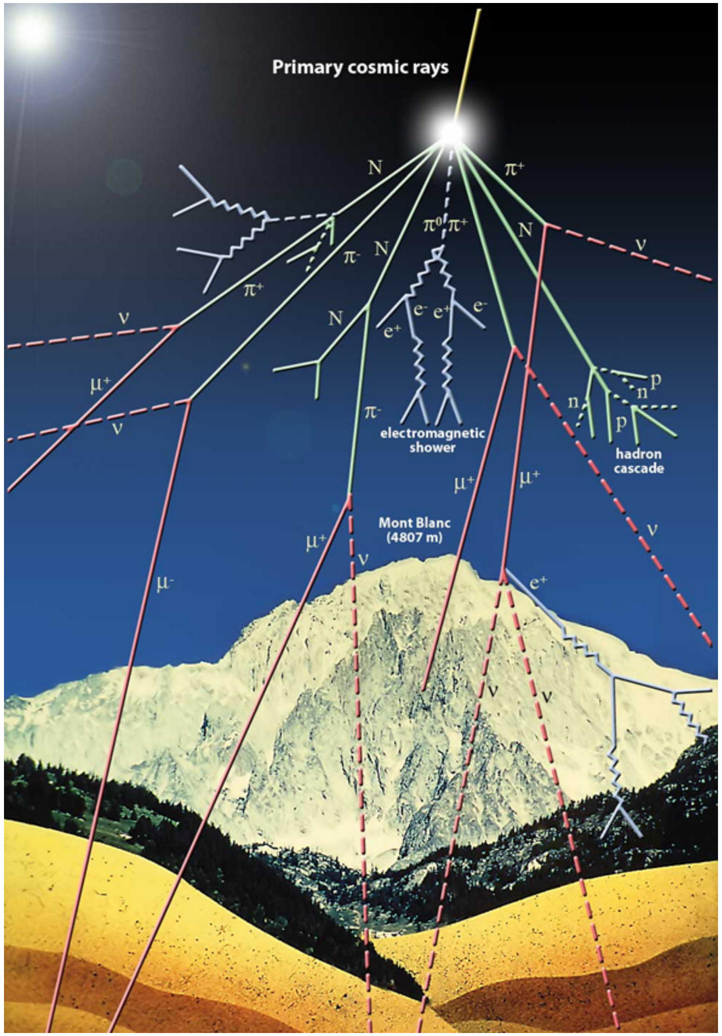
~1% for gamma rays

Y = 0.3-30 counts/year

~ 1.2-220 counts/PhD

maximising the yield requires:

- improving "signal" (e.g. high beam currents, high target density, high efficiency)
- reducing "noise" (i.e. background)
- combination of both



ideal location: underground + low concentration of U and Th

Nuclei in the Cosmos I, 1990 – Baden/Vienna, Austria

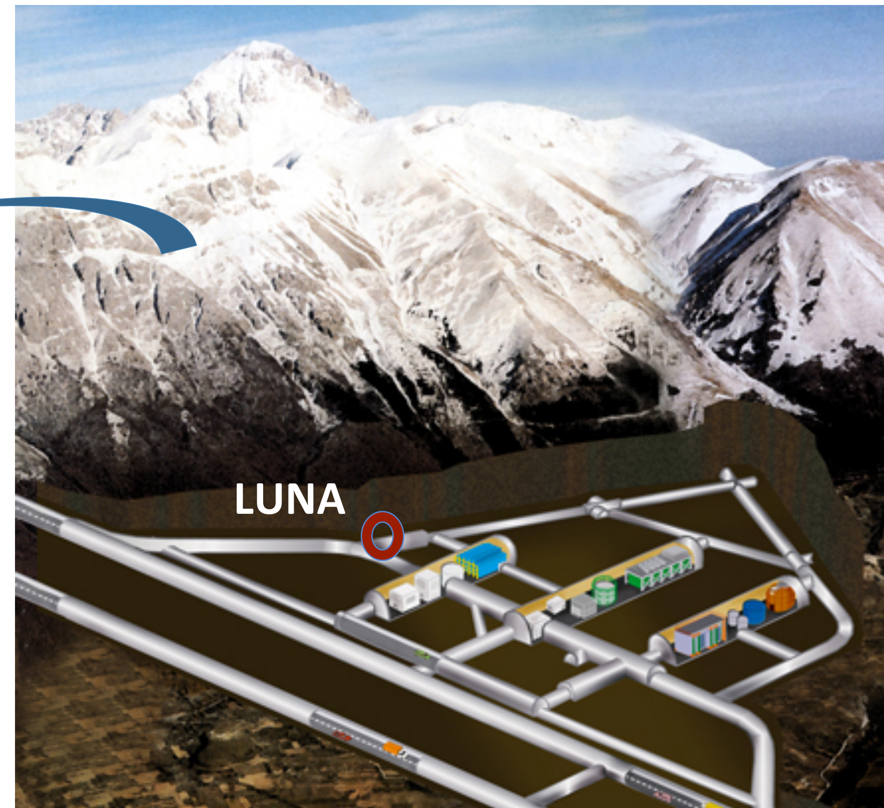
"Some people are so crazy that they actually venture into deep mines to observe the stars in the sky" *Naturalis Historia – Pliny, 44 A.D.*

Gran Sasso Underground Laboratory in Italy

LUNA: Laboratory for Underground Nuclear Astrophysics

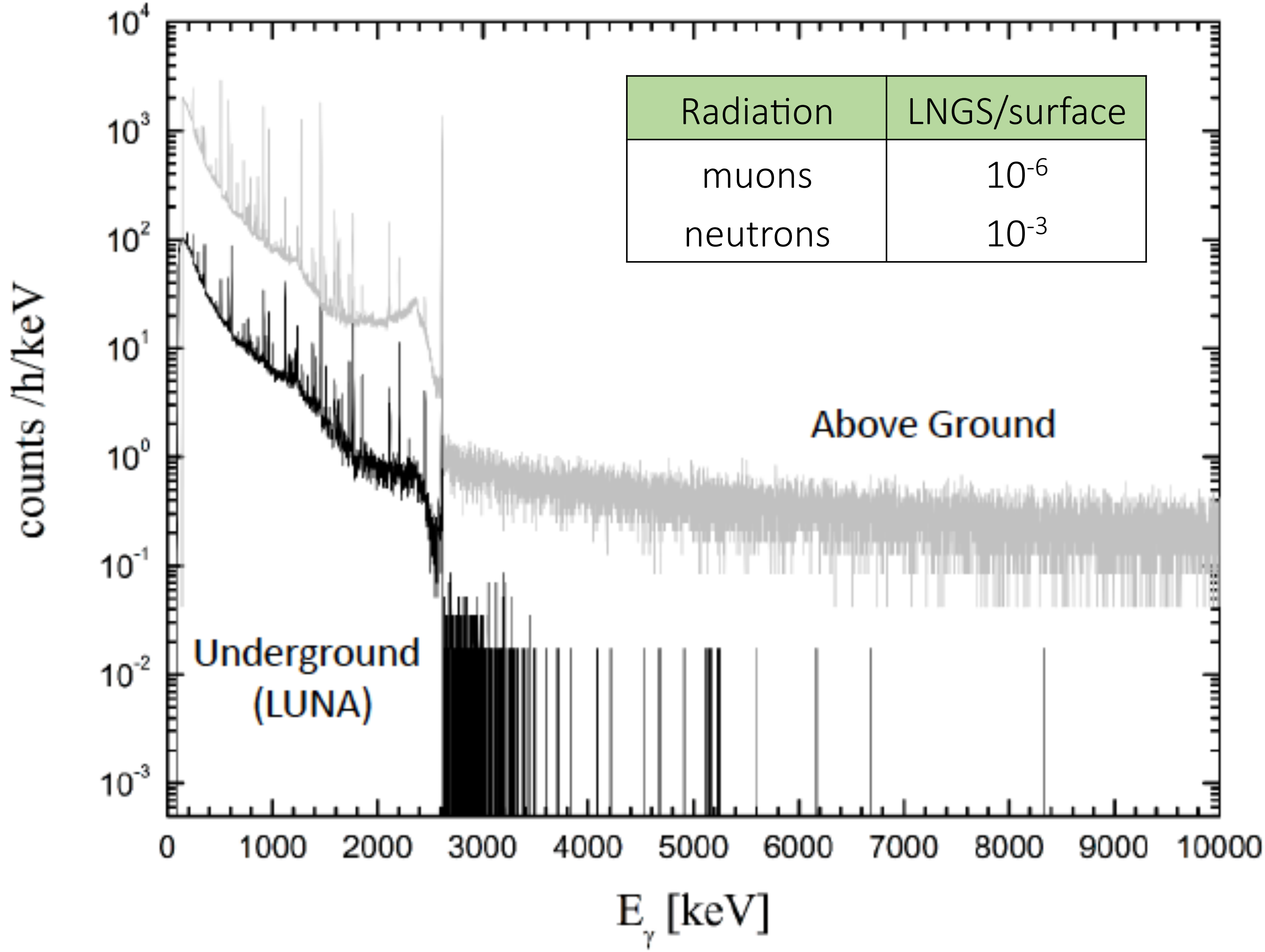
first underground accelerator in the world

1.4 km rock overburden: million-fold reduction in cosmic background



M Aliotta

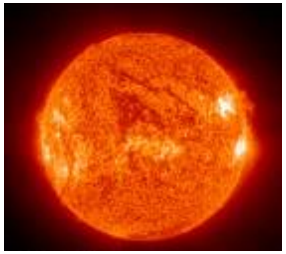
Gamma-ray background: underground vs overground comparison



Radiation	LNGS/surface
muons	10^{-6}
neutrons	10^{-3}

Costantini et al. Rep. Prog. Phys. 72 (2009) 086301

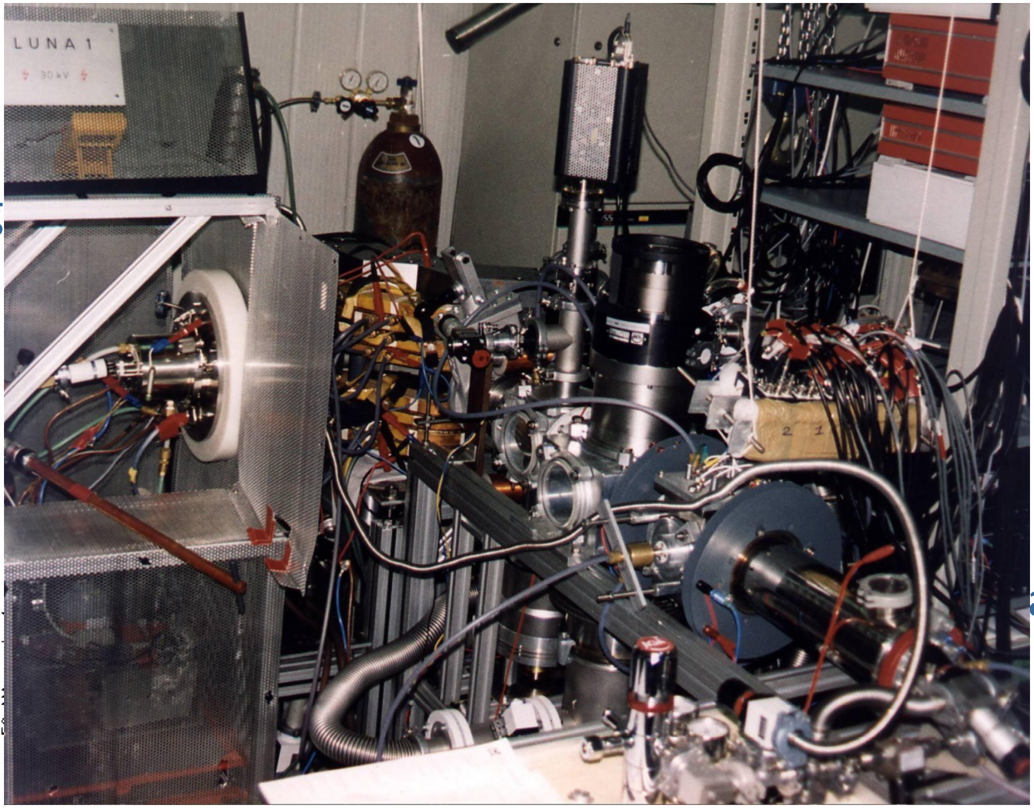
LUNA Phase I (1992-2001): 50 kV accelerator



investigate reactions in solar pp chain

90º analysing magnet

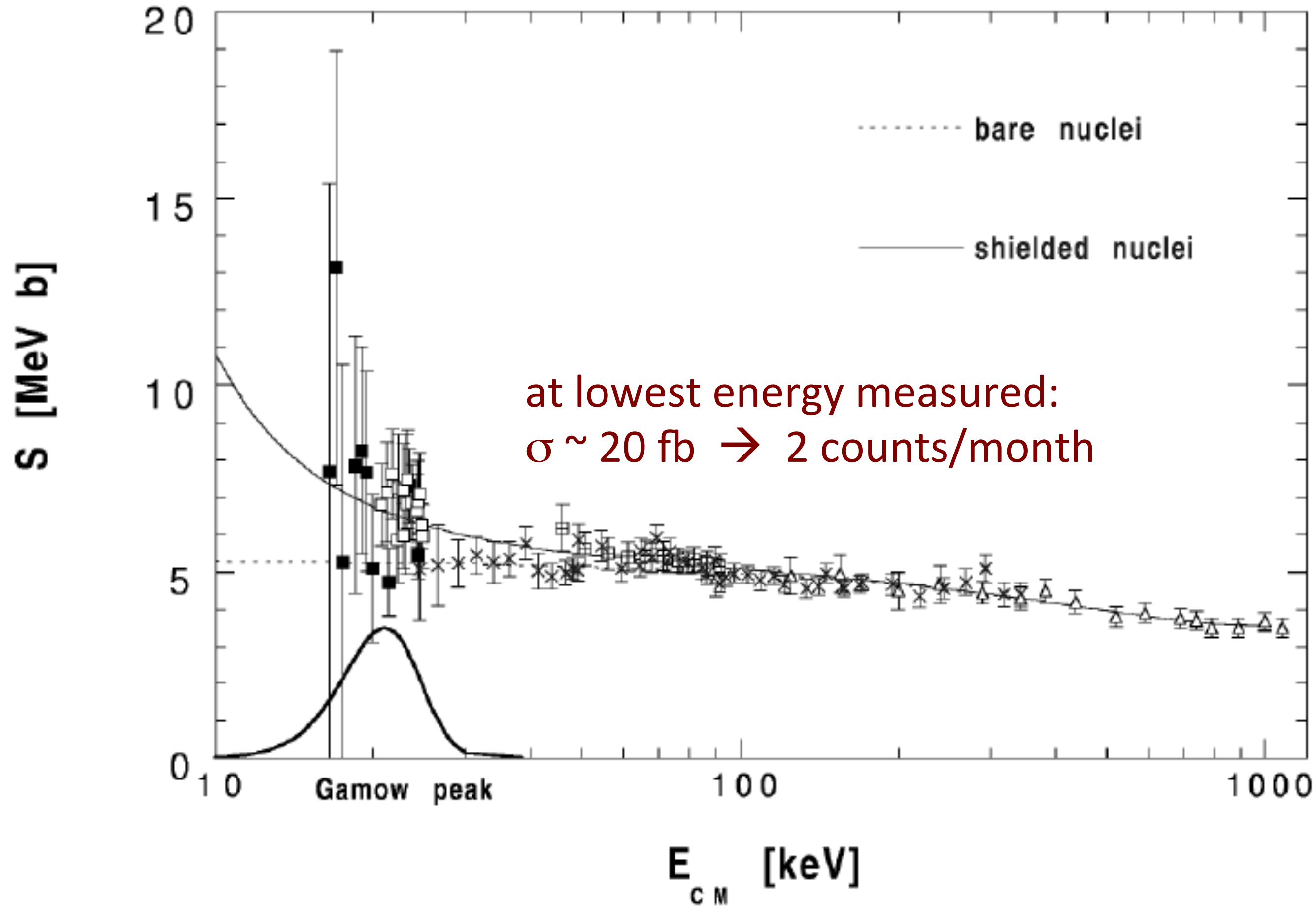
duoplasmatron ion source on 50kV platform



amber

entirely built by students!

The $^{3}He(^{3}He,2p)^{3}He$ Reaction and the Solar Neutrino Puzzle



at lowest energy measured:
σ ~ 20 fb → 2 counts/month

Bonetti *et al*. Phys. Rev. Lett. 82 (1999) 5205

first measurement within solar Gamow energy!
no extrapolation needed; no new resonance found

LUNA: 400 kV accelerator

LUNA

VOLUME 82, N... ...AL REVIEW ... 28 JUNE 1999

A&A 420, 625–629 (2004)
DOI: 10.1051/0004-6361:20040981
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PHYSICS LETTERS B

PRL 117, 142502 (2016) ... ending ...MBER 2016

nature astronomy

LETTERS

PUBLISHED: 30 JANUARY 2017 | VOLUME: 1 | ARTICLE NUMBER: 0027

Origin of meteoritic stardust unveiled by a revised proton-capture rate of ^{17}O

M. Lugaro[1,2*], A. I. Karakas[2-4], C. G. Bruno[5], M. Aliotta[5], L. R. Nittler[6], D. Bemmerer[7], A. Best[8], A. Boeltzig[9], C. Broggini[10], A. Caciolli[11], F. Cavanna[12], G. F. Ciani[9], P. Corvisiero[12], T. Davinson[5], R. Depalo[11], A. Di Leva[8], Z. Elekes[13], F. Ferraro[12], A. Formicola[14], Zs. Fülöp[13], G. Gervino[15], A. Guglielmetti[16], C. Gustavino[17], Gy. Gyürky[13], G. Imbriani[8], M. Junker[14], R. Menegazzo[10], V. Mossa[18], F. R. Pantaleo[18], D. Piatti[11], P. Prati[12], D. A. Scott[5,†], O. Straniero[14,19], F. Strieder[20], T. Szücs[13], M. P. Takács[7] and D. Trezzi[16]

C. G. Bruno, ... F. Cavanna, ... G. Gervino, ... F. R. Pantaleo, ... H. ... V. Ro...

...olli, ...p, ...ossa, ...ezzi ... J. Cruz ... A. Lemut ... E. Somorjai ... Zavatarelli

solving puzzle on origin of some pre-solar grains

slowest reaction ... years

25 year of Nuclear Astrophysics at LUNA (LNGS, INFN)

- **solar fusion reactions**
  $^{3}He(^{3}He,2p)^{4}He$ $^{2}H(p,\gamma)^{3}He$ $^{3}He(\alpha,\gamma)^{7}Be$
- **electron screening and stopping power**
  $^{2}H(^{3}He,p)^{4}He$ $^{3}He(^{2}H,p)^{4}He$
- **CNO, Ne-Na and Mg-Al cycles**
  $^{14}N(p,\gamma)^{15}O$ $^{15}N(p,\gamma)^{16}O$ $^{22}Ne(p,\gamma)^{23}Na$ $^{22}Ne(\alpha,\gamma)^{26}Mg$ $^{23}Na(p,\gamma)^{24}Mg$ $^{25}Mg(p,\gamma)^{26}Al$
- **(explosive) hydrogen burning in novae and AGB stars**
  $^{17}O(p,\gamma)^{18}F$ $^{17}O(p,\alpha)^{14}N$ $^{18}O(p,\gamma)^{19}F$ $^{18}O(p,\alpha)^{15}N$
- **Big Bang nucleosynthesis**
  $^{2}H(\alpha,\gamma)^{6}Li$ $^{2}H(p,\gamma)^{3}He$ $^{6}Li(p,\gamma)^{7}Be$
- **neutron capture nucleosynthesis**
  $^{13}C(\alpha,n)^{16}O$ (to start soon)

some of the lowest cross sections ever measured (few counts/month)

18 reactions / 25 year ~ 20 months data taking per reaction!

Puzzling Facts and Open Questions

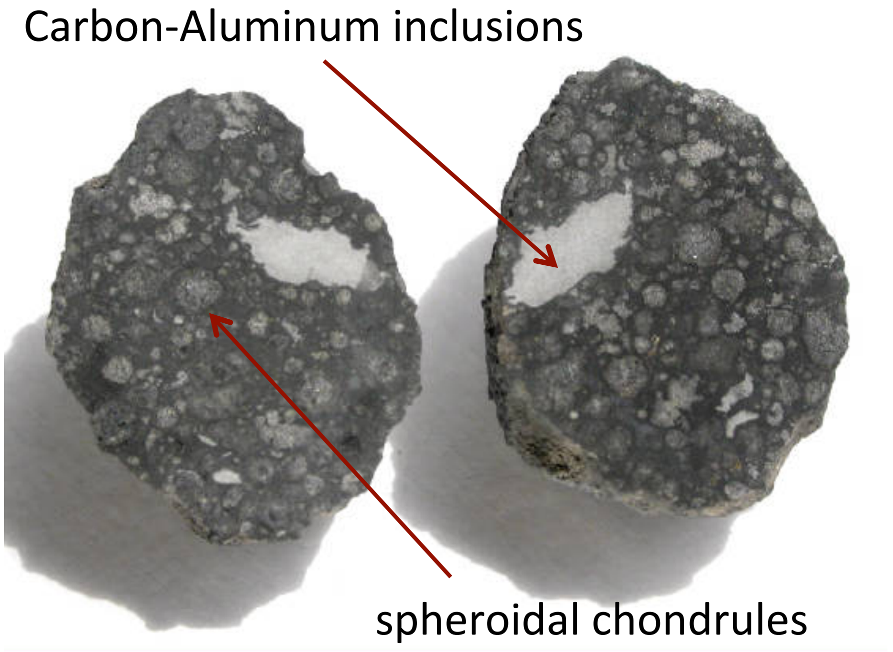
- Big Bang Nucleosynthesis: Li problem(s) and the D abundance
- Core metallicity of the Sun
- Fate of massive stars
- Explosive scenarios: X-ray bursts, novae, SN type Ia
- Pre-solar grains composition
- Origin of Heavy Elements
- Astrophysical site(s) for the r-process
- …

Pre-Solar Grains Composition

Rocks from Space: the Importance of Meteorites

fragment of Allende Meteorite
(named after nearest post office)
8 February 1969 – Mexico

- best known and most studied meteorite in history



isotopic anomalies compared to solar abundances provide evidence for processes that occurred in other stars before Solar System formed

http://www.marmet-meteorites.com/id46.html

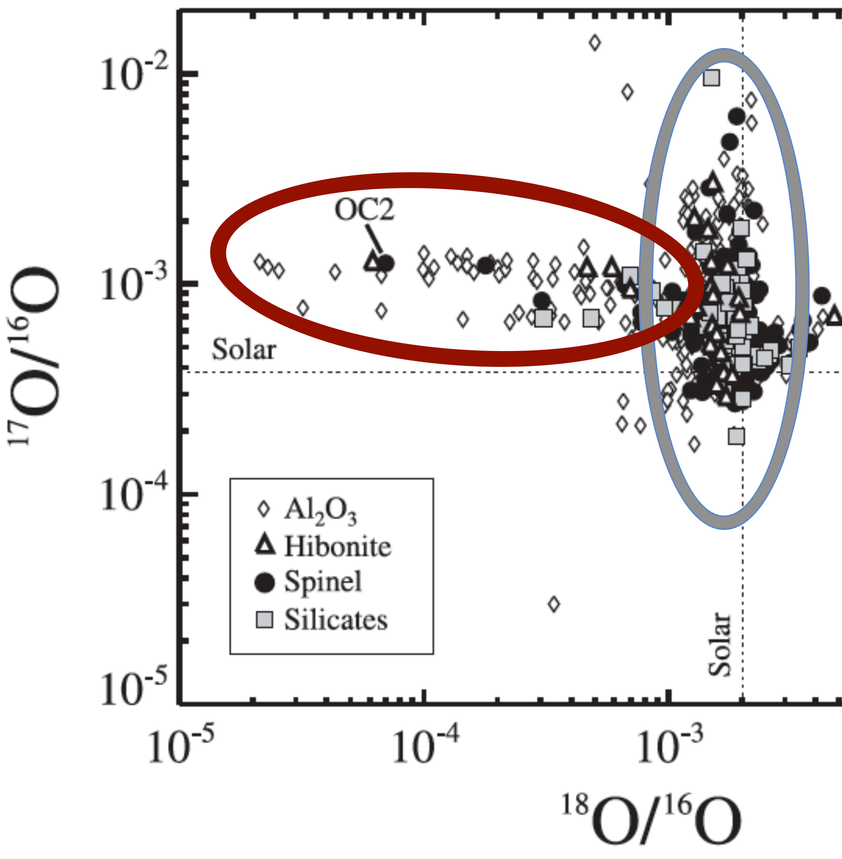
Pre-solar grains in meteorites

- Carbon-rich (diamond, graphite, silicon carbide)

- Oxygen-rich (silicates, Al-rich oxides, ...)

  Group I (about 75%): show excess in ^{17}O compared to solar values;
  origin well-understood: red giants (1-3 $M_{\odot}$)

  Group II (about 10%): excess in ^{17}O, but depleted in ^{18}O (up to 2 o.o.m. less than in solar system)
  origin highly debated!

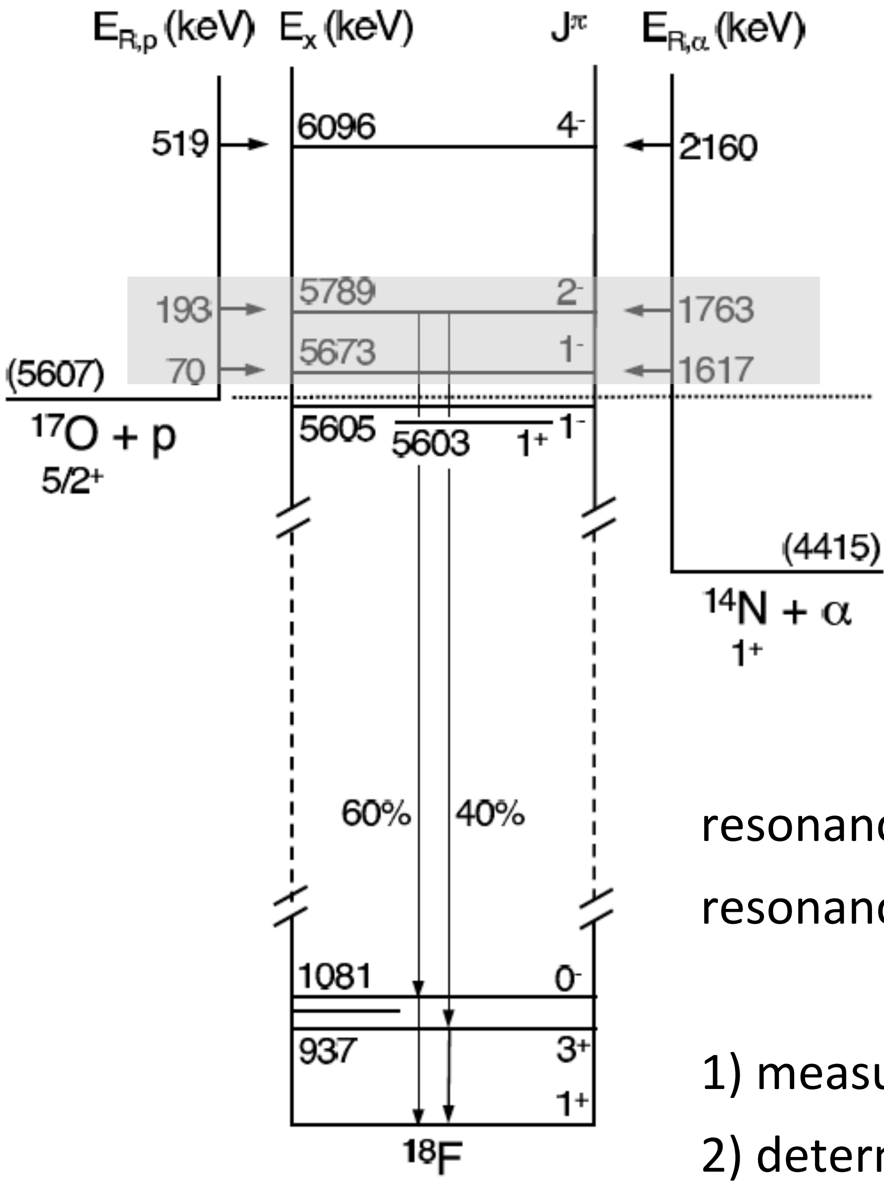


$^{17}O(p,\alpha)^{14}N$ reaction

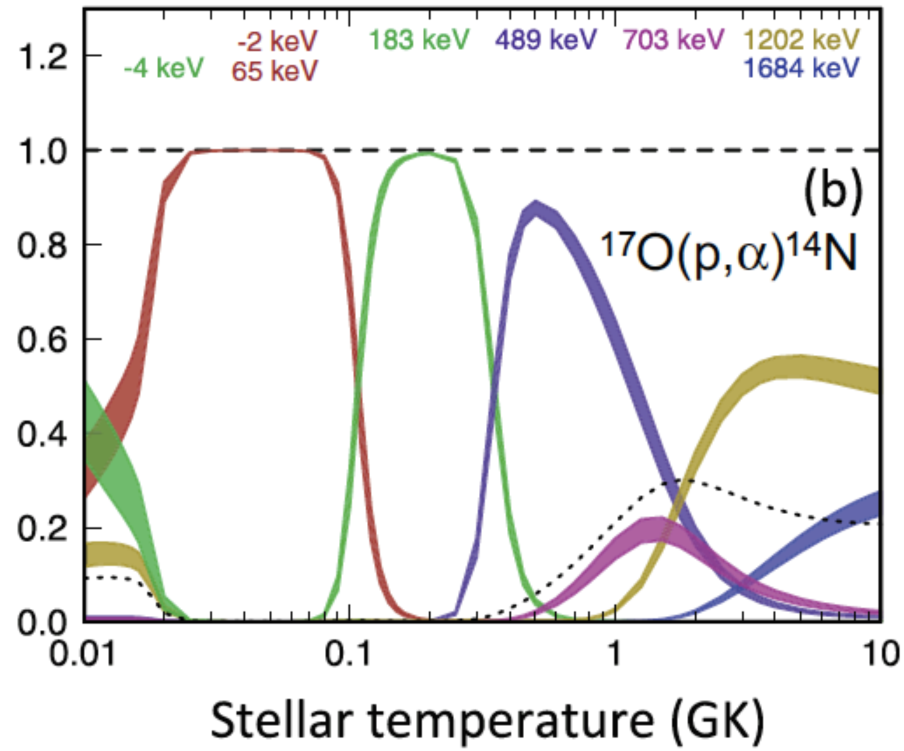
hydrogen burning in various stars + composition of pre-solar grains

PhD project
Carlo Bruno

The $^{17}O(p,\alpha)^{14}N$ reaction



Buckner et al, PRC 91 (2015) 015812



resonance strength of 193keV state well known

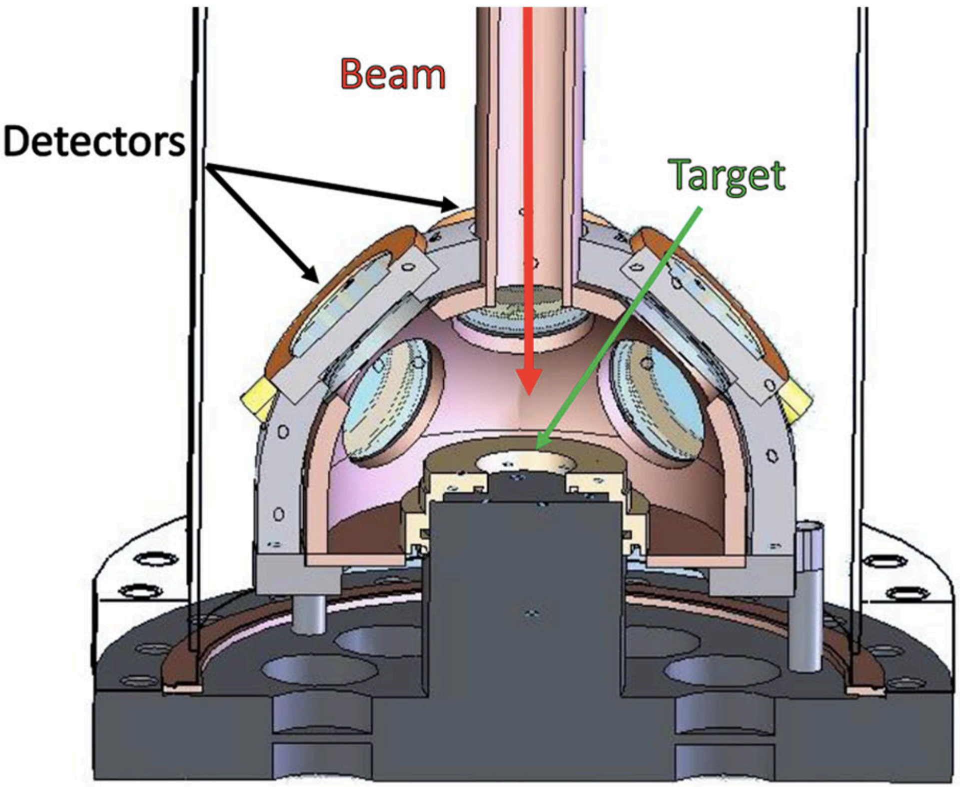
resonance strength of 70keV state largely uncertain

AIMS:

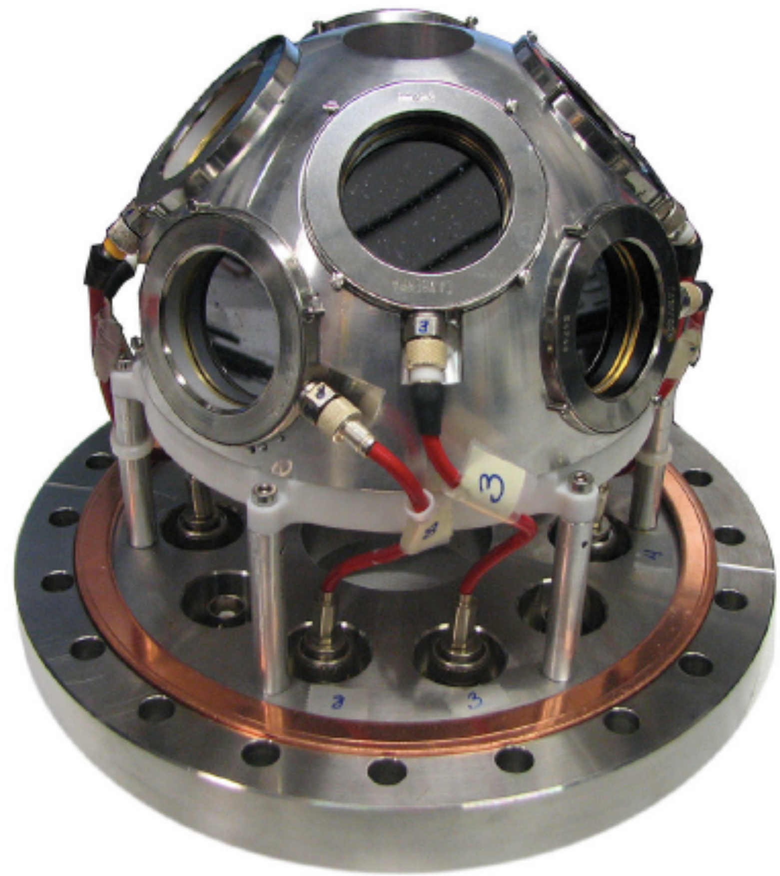
1) measure resonance strength of 70keV state

2) determine new reaction rate

Purpose-built scattering chamber to host array of 8 silicon detectors



Bruno et al EJPA 51 (2015) 94

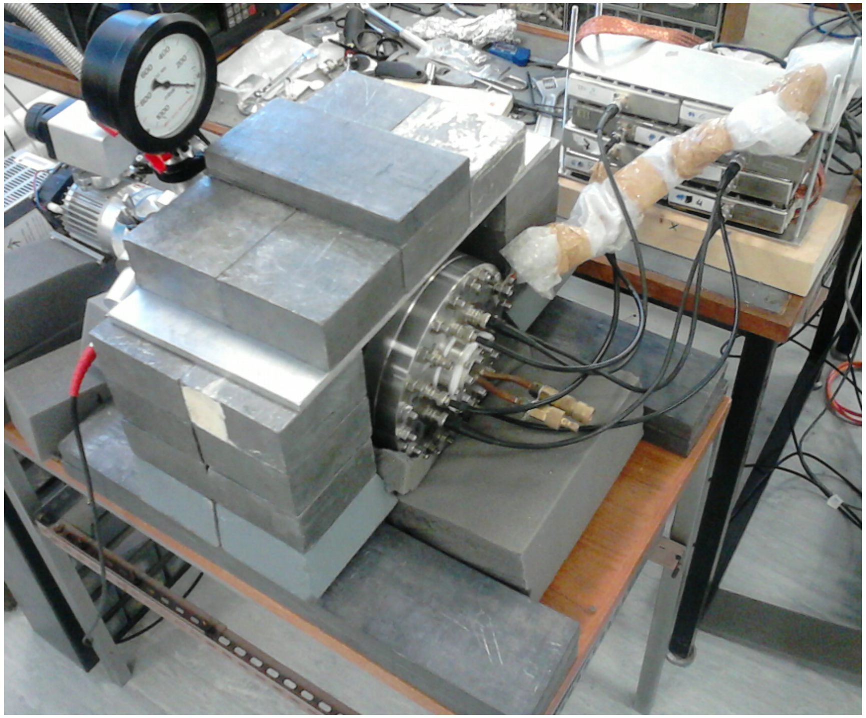


- protective aluminized Mylar foils (2.4 μm) before each detector
- expected alpha particle energy E ~ 200 keV (from 70 keV resonance in $^{17}O(p,\alpha)^{14}N$)

Commissioning Phase

- background measurements above- and under-ground; with and w/o shielding
- detector calibration + foils thickness measurement
- detection efficiency (simulations + measurements)
- re-determination of 193keV resonance strength

Edinburgh



Gran Sasso

Setup Commissioning and Background Comparison

Eur. Phys. J. A (2015) 51: 94
DOI 10.1140/epja/i2015-15094-y

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article – Experimental Physics

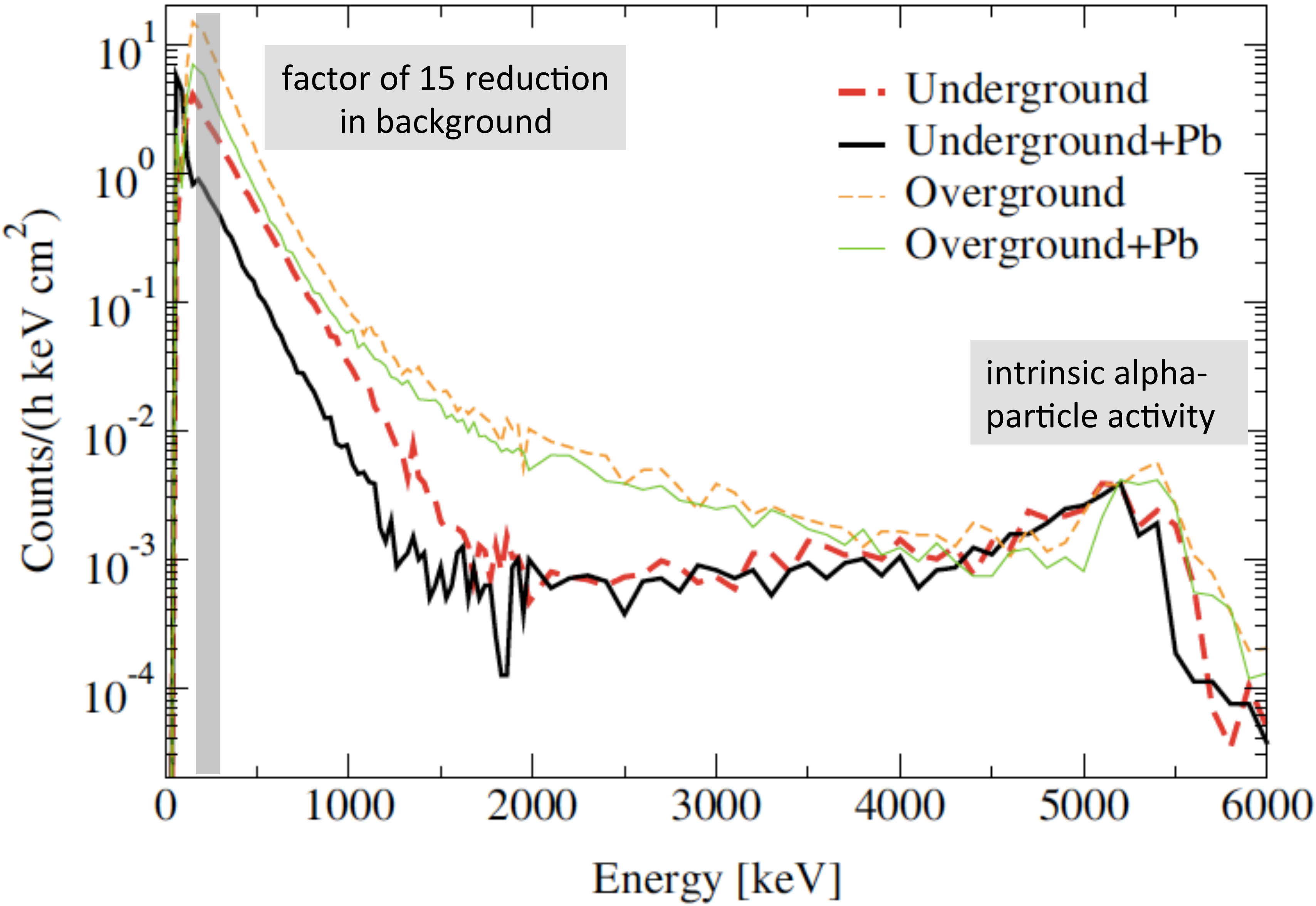
Resonance strengths in the $^{17,18}O(p,\alpha)^{14,15}N$ reactions and background suppression underground

Commissioning of a new setup for charged-particle detection at LUNA

LUNA Collaboration

C.G. Bruno[1], D.A. Scott[1], A. Formicola[2], M. Aliotta[1,a], T. Davinson[1], M. Anders[3], A. Best[2], D. Bemmerer[3], C. Broggini[4], A. Caciolli[4,5], F. Cavanna[6], P. Corvisiero[6], R. Depalo[4,5], A. Di Leva[7], Z. Elekes[8], Zs. Fülöp[8], G. Gervino[9], C.J. Griffin[1], A. Guglielmetti[10], C. Gustavino[11], Gy. Gyürky[8], G. Imbriani[7], M. Junker[2], R. Menegazzo[4], E. Napolitani[5], P. Prati[6], E. Somorjai[8], O. Straniero[2,12], F. Strieder[13], T. Szücs[3], and D. Trezzi[10]

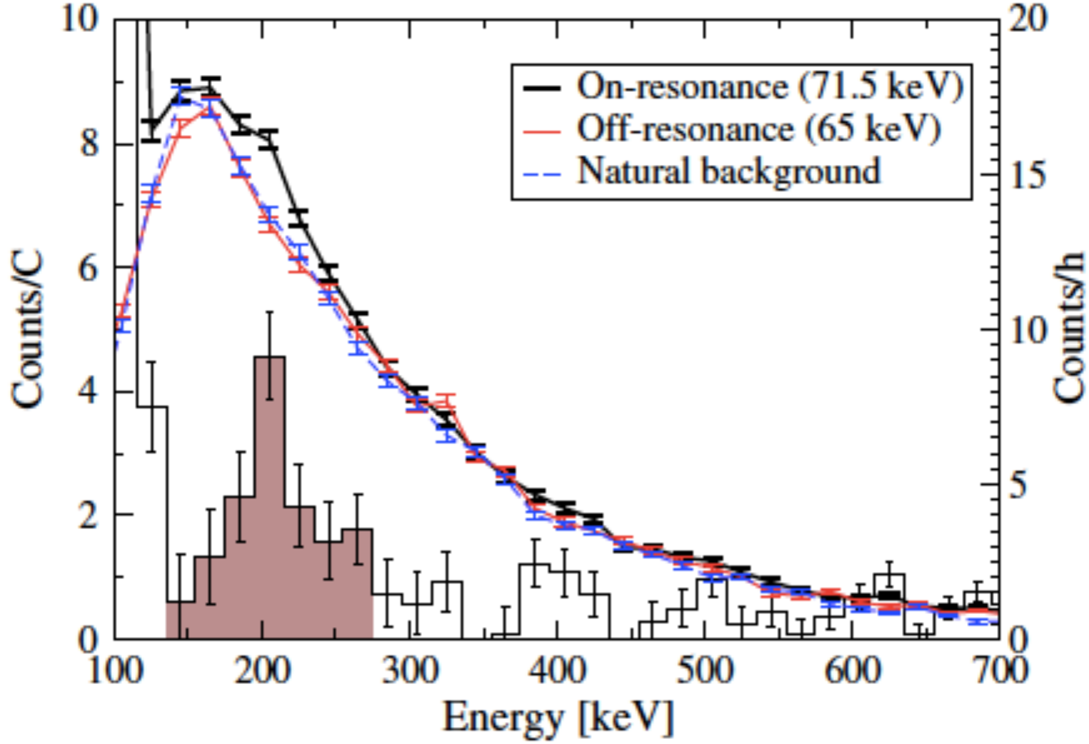
Background Suppression

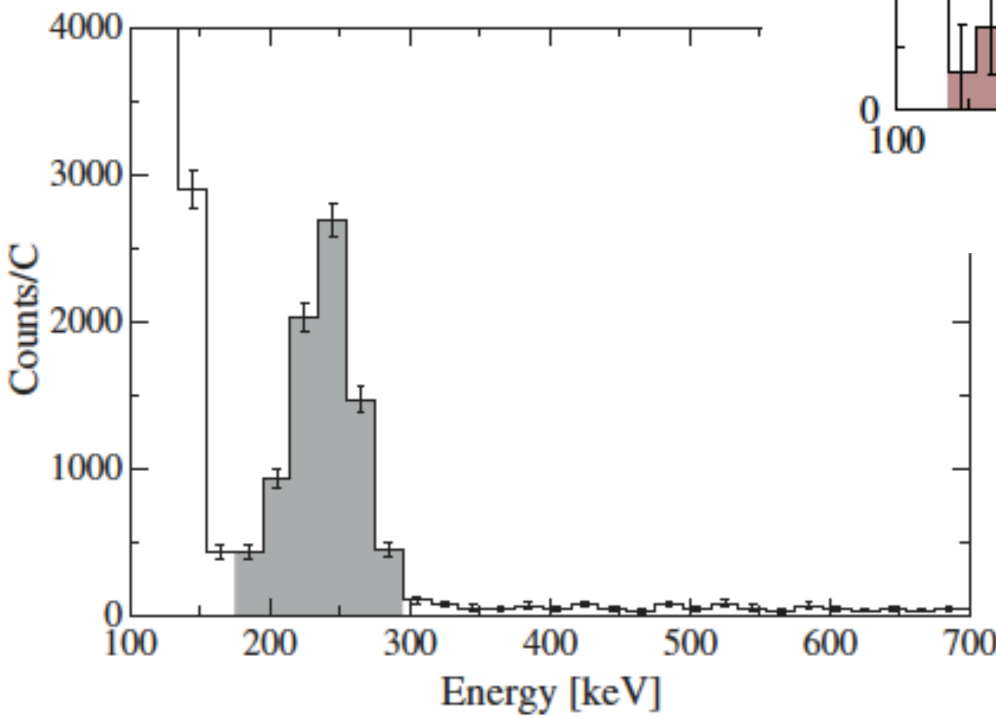


Results
$^{17}O(p,\alpha)^{14}N$ reaction

$^{17}O(p,\alpha)^{14}N$ Results

use stronger 193keV resonance to identify ROI for expected alpha particles from 70keV state





$\omega\gamma$ = 10.0 ± 1.4 (stat) ± 0.7 (sys) neV

most accurate result to date

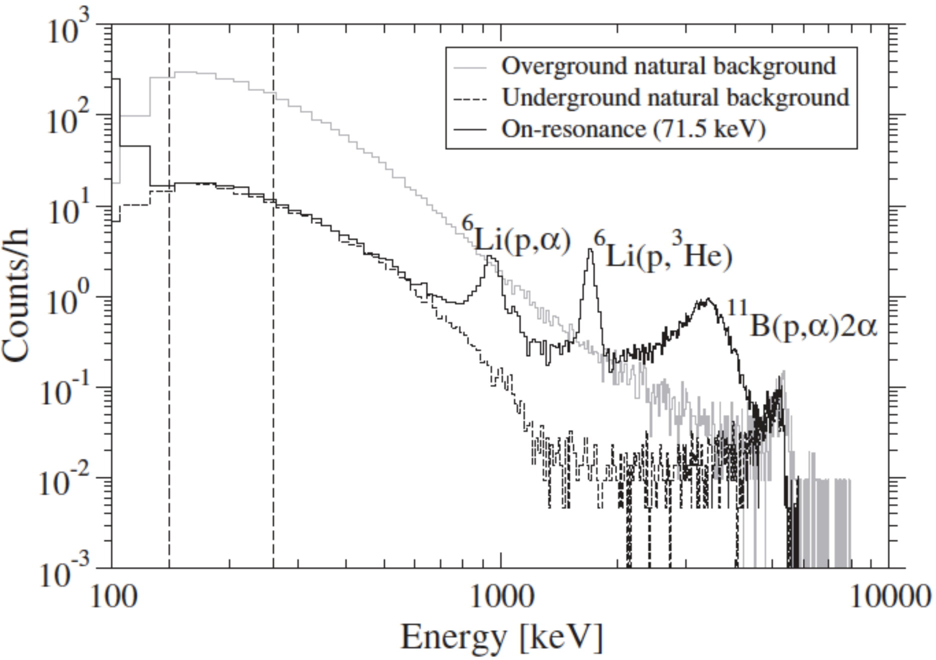
$^{17}O(p,\alpha)^{14}N$ Results

PRL 117, 142502 (2016) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2016

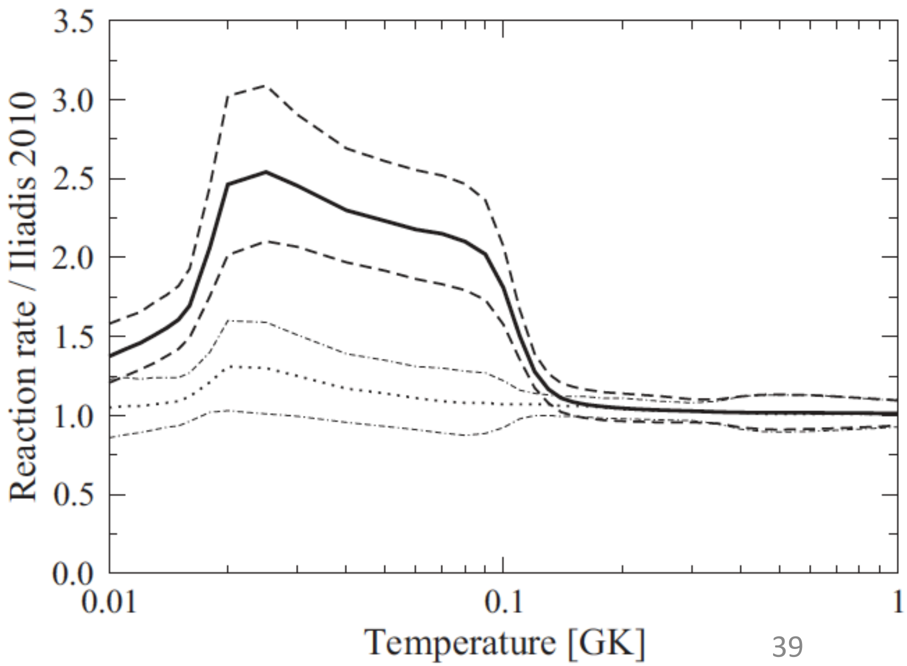
Improved Direct Measurement of the 64.5 keV Resonance Strength in the $^{17}O(p,\alpha)^{14}N$ Reaction at LUNA

C. G. Bruno,[1,*] D. A. Scott,[1] M. Aliotta,[1,†] A. Formicola,[2] A. Best,[3] A. Boeltzig,[4] D. Bemmerer,[5] C. Broggini,[6] A. Caciolli,[7] F. Cavanna,[8] G. F. Ciani,[4] P. Corvisiero,[8] T. Davinson,[1] R. Depalo,[7] A. Di Leva,[3] Z. Elekes,[9] F. Ferraro,[8] Zs. Fülöp,[9] G. Gervino,[10] A. Guglielmetti,[11] C. Gustavino,[12] Gy. Gyürky,[9] G. Imbriani,[3] M. Junker,[2] R. Menegazzo,[6] V. Mossa,[13] F. R. Pantaleo,[13] D. Piatti,[7] P. Prati,[8] E. Somorjai,[9] O. Straniero,[14] F. Strieder,[15] T. Szücs,[5] M. P. Takács,[5] and D. Trezzi[11]

15x background reduction in ROI
+ improved experimental conditions



reaction rate ~ 2-2.5x higher
than previously assumed



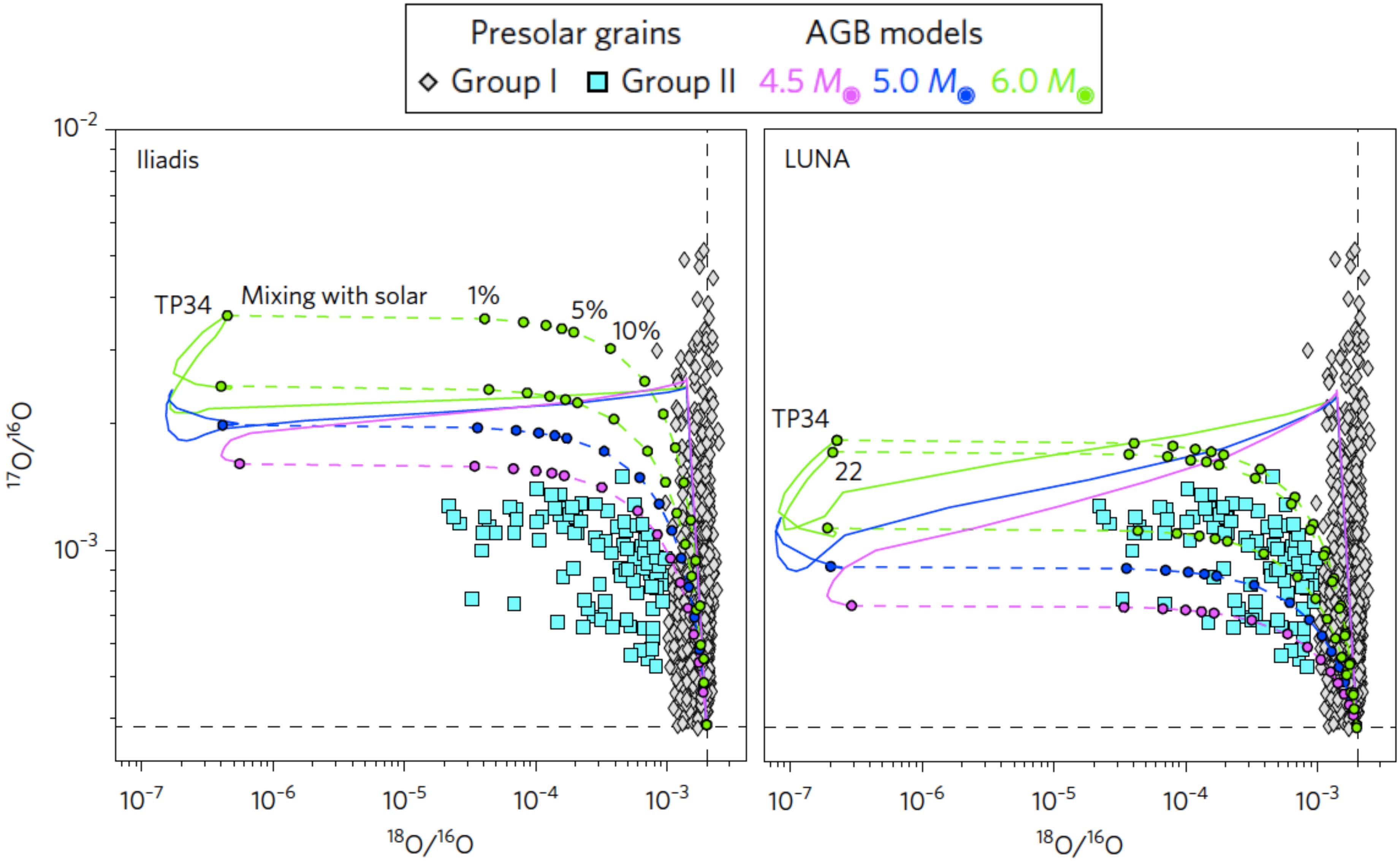
$^{17}O/^{16}O$ composition and origin of pre-solar grains revisited

nature astronomy
LETTERS
PUBLISHED: 30 JANUARY 2017 | VOLUME: 1 | ARTICLE NUMBER: 0027

Origin of meteoritic stardust unveiled by a revised proton-capture rate of ^{17}O

M. Lugaro[1,2*], A. I. Karakas[2-4], C. G. Bruno[5], M. Aliotta[5], L. R. Nittler[6], D. Bemmerer[7], A. Best[8], A. Boeltzig[9], C. Broggini[10], A. Caciolli[11], F. Cavanna[12], G. F. Ciani[9], P. Corvisiero[12], T. Davinson[5], R. Depalo[11], A. Di Leva[8], Z. Elekes[13], F. Ferraro[12], A. Formicola[14], Zs. Fülöp[13], G. Gervino[15], A. Guglielmetti[16], C. Gustavino[17], Gy. Gyürky[13], G. Imbriani[8], M. Junker[14], R. Menegazzo[10], V. Mossa[18], F. R. Pantaleo[18], D. Piatti[11], P. Prati[12], D. A. Scott[5,†], O. Straniero[14,19], F. Strieder[20], T. Szücs[13], M. P. Takács[7] and D. Trezzi[16]

On the origin of Group II grains



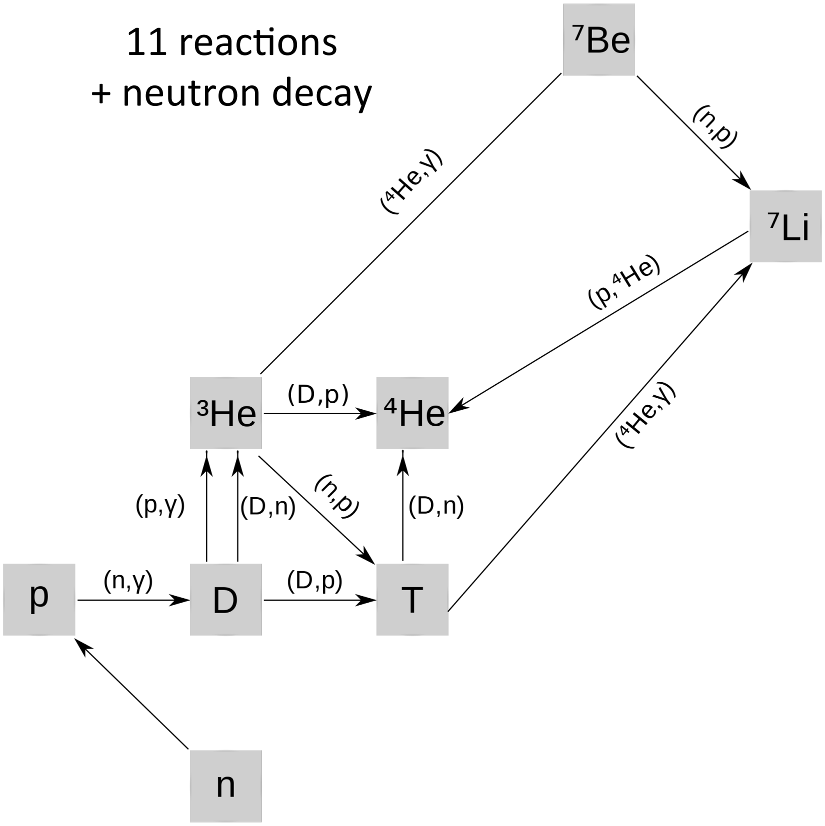
M Lugaro et al., Nature Astronomy 1 (2017) 0027

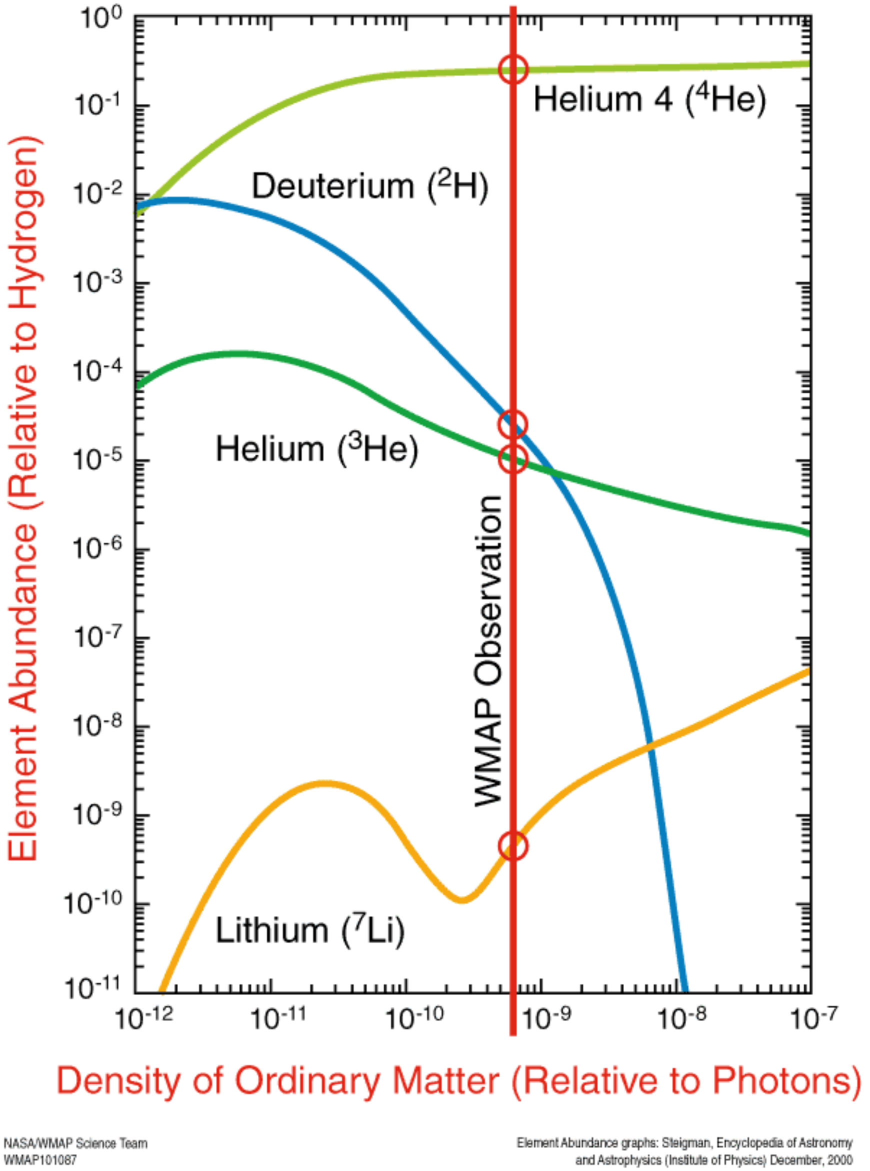
Big Bang Nucleosynthesis

BBN is only handle to probe state of universe during epoch of radiation domination

Primordial Nucleosynthesis (BBN): 3 minutes after Big Bang

11 reactions
+ neutron decay





observations of D, ^{3}He, ^{4}He, and ^{7}Li in very old (**metal poor**) stars provide stringent tests of Big Bang theory

Primordial Deuterium Abundance:
The d(p,γ)^{3}He Reaction

Observed abundance:

$[D/H] = (2.53 \pm 0.04) \times 10^{-5}$

Cooke et al, APJ 781 (2014) 31

about 5% lower than

Predicted abundance:

$[D/H] = (2.65 \pm 0.07) \times 10^{-5}$

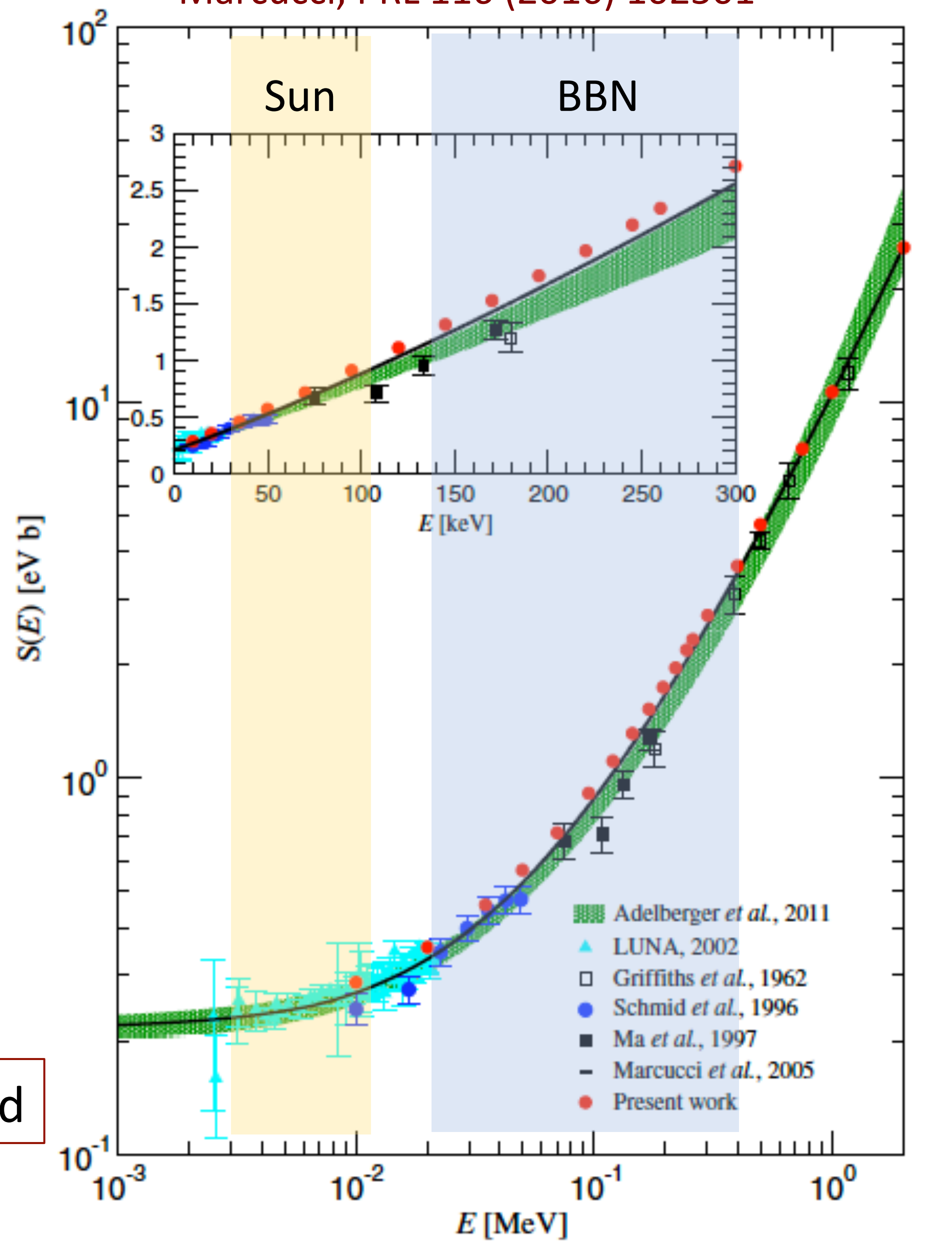
Di Valentino et al, PRD 90 (2014) 023543

main uncertainty in BBN prediction

due to $d(p,\gamma)^3He$ cross section

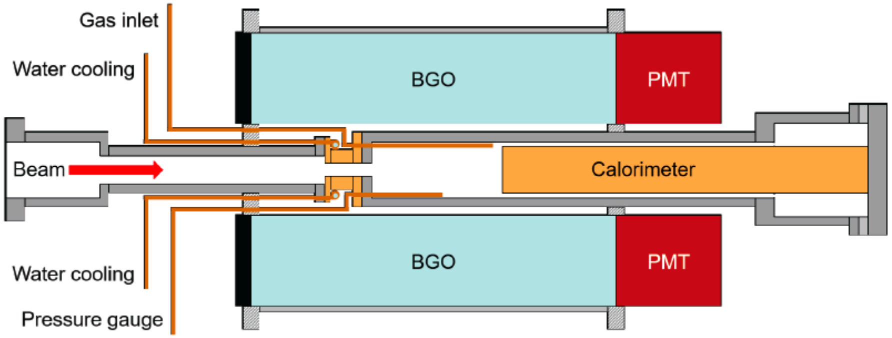
high precision data at BBN energies required

Marcucci, PRL 116 (2016) 102501



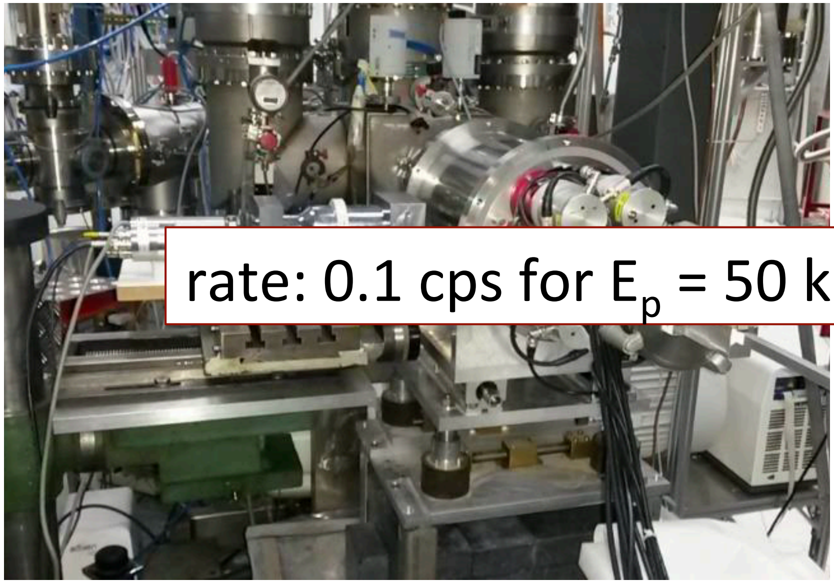
Measurements at LUNA

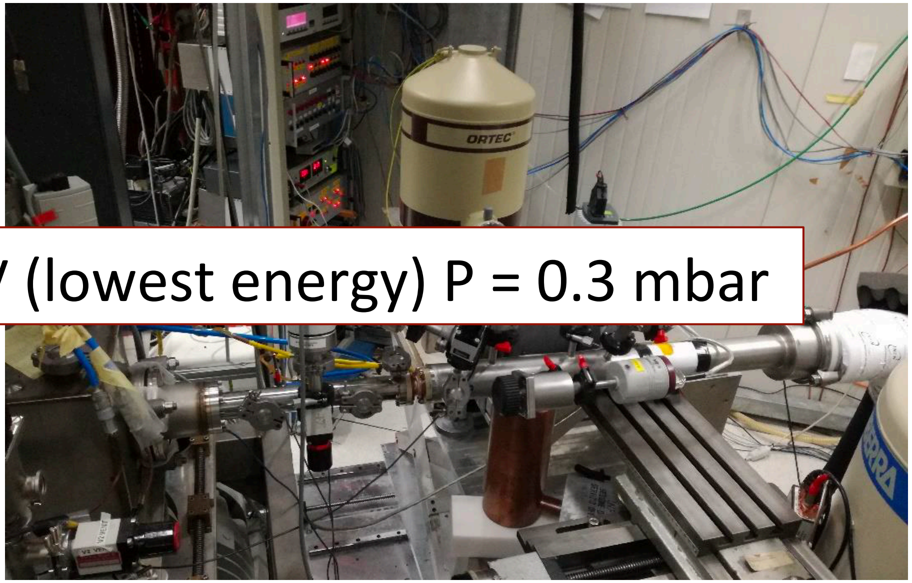
E_{beam} = 50 – 300 keV (full BBN range)



BGO Phase: high efficiency

HPGe Phase: high precision





rate: 0.1 cps for E_p = 50 keV (lowest energy) P = 0.3 mbar

Courtesy: V Mossa

Lithium Problem(s)

a success story:

discrepancy revealed thanks to close interplay among

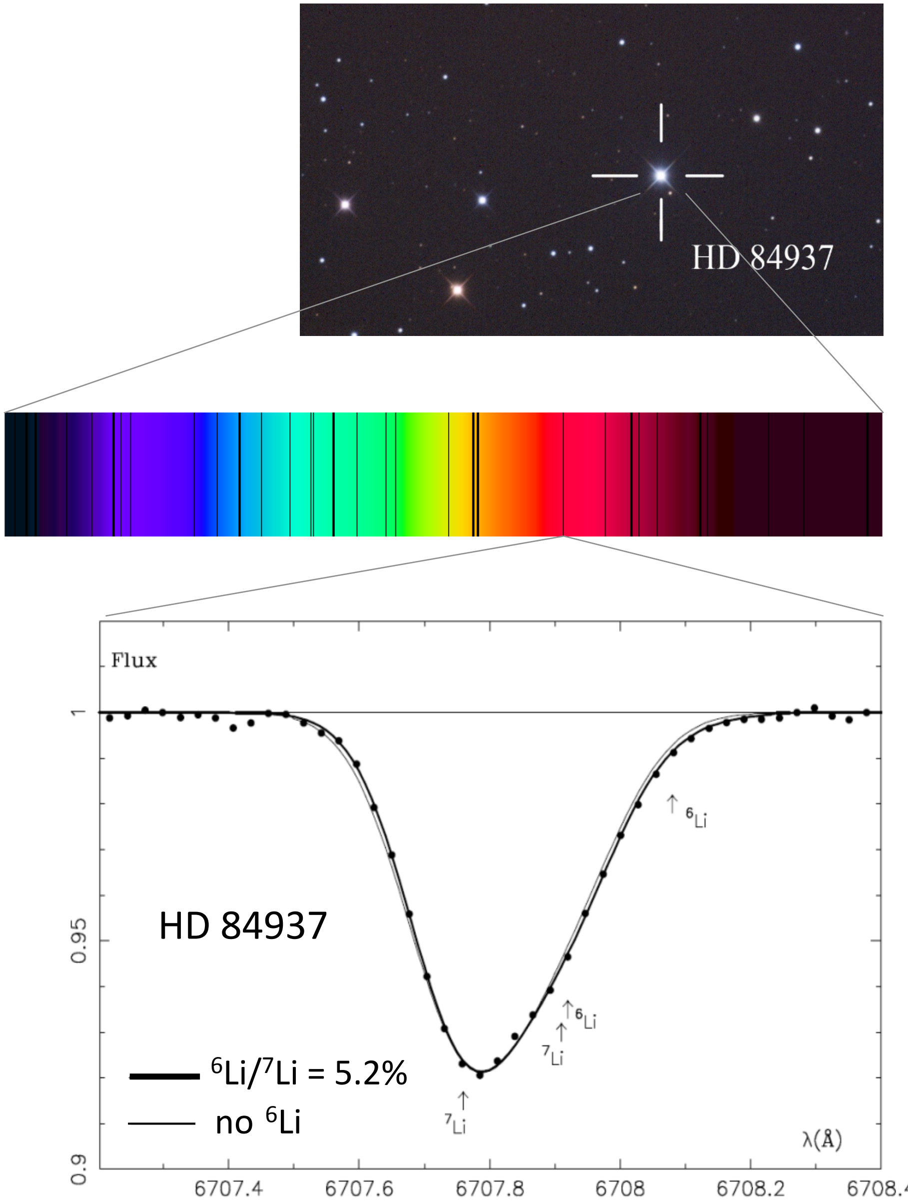
theory, observation, and experiment

first Lithium Problem

observed ^{7}Li

~ 3x lower than predicted

- no nuclear solution
- new (astro)physics?
- physics beyond Standard Model?



second Lithium Problem

observed ^{6}Li

~ 10^2 – 10^3 higher than predicted

poor nuclear physics inputs
or
challenges with observation?

The Second Lithium Problem

Production and destruction processes affecting ^6Li abundance

LUNA

^{6}Li production:
The $d(\alpha,\gamma)^{6}$Li Reaction

First direct measurement of d(α,γ)^{6}Li cross section at BBN energies

LUNA

Astroparticle Physics 89 (2017) 57–65

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropartphys

ELSEVIER

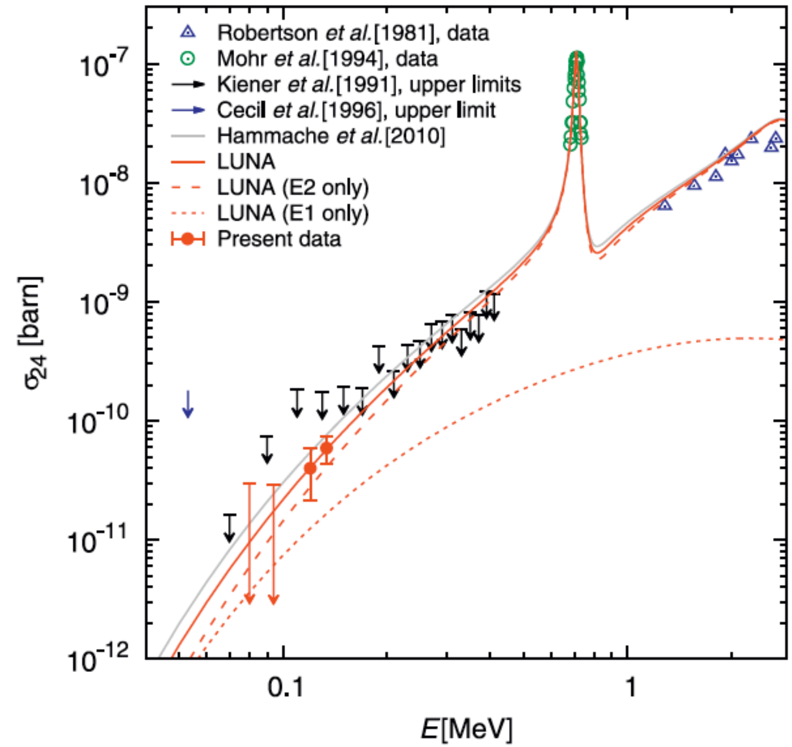
Big Bang ^{6}Li nucleosynthesis studied deep underground (LUNA collaboration)

D. Trezzi[a], M. Anders[b,c,1], M. Aliotta[d], A. Bellini[e], D. Bemmerer[b], A. Boeltzig[f,g], C. Broggini[h], C.G. Bruno[d], A. Caciolli[h,i], F. Cavanna[e], P. Corvisiero[e], H. Costantini[e,2], T. Davinson[d], R. Depalo[h,i], Z. Elekes[b], M. Erhard[h], F. Ferraro[e], A. Formicola[f], Zs. Fülop[j], G. Gervino[k], A. Guglielmetti[a], C. Gustavino[l,*], Gy. Gyürky[j], M. Junker[f], A. Lemut[e,3], M. Marta[b,4], C. Mazzocchi[a,5], R. Menegazzo[h], V. Mossa[m], F. Pantaleo[m], P. Prati[e], C. Rossi Alvarez[h], D.A. Scott[d], E. Somorjai[j], O. Straniero[n,o], T. Szücs[j], M. Takacs[b]

PRL 113, 042501 (2014) PHYSICAL REVIEW LETTERS week ending 25 JULY 2014

First Direct Measurement of the $^{2}H(\alpha,\gamma)^{6}Li$ Cross Section at Big Bang Energies and the Primordial Lithium Problem

M. Anders,[1,2,†] D. Trezzi,[3] R. Menegazzo,[4] M. Aliotta,[5] A. Bellini,[6] D. Bemmerer,[1] C. Broggini,[4] A. Caciolli,[4] P. Corvisiero,[6] H. Costantini,[6,‡] T. Davinson,[5] Z. Elekes,[1] M. Erhard,[4,§] A. Formicola,[7] Zs. Fülöp,[8] G. Gervino,[9] A. Guglielmetti,[3] C. Gustavino,[10,∥] Gy. Gyürky,[8] M. Junker,[7] A. Lemut,[6,*] M. Marta,[1,¶] C. Mazzocchi,[3,**] P. Prati,[6] C. Rossi Alvarez,[4] D. A. Scott,[5] E. Somorjai,[8] O. Straniero,[11,12] and T. Szücs[8]
(LUNA Collaboration)



^{6}Li/^{7}Li = (1.6 ± 0.3) x 10^{-5}

^{6}Li/H = (0.8 ± 0.18) x 10^{-14} (27% lower than previous BBN values)

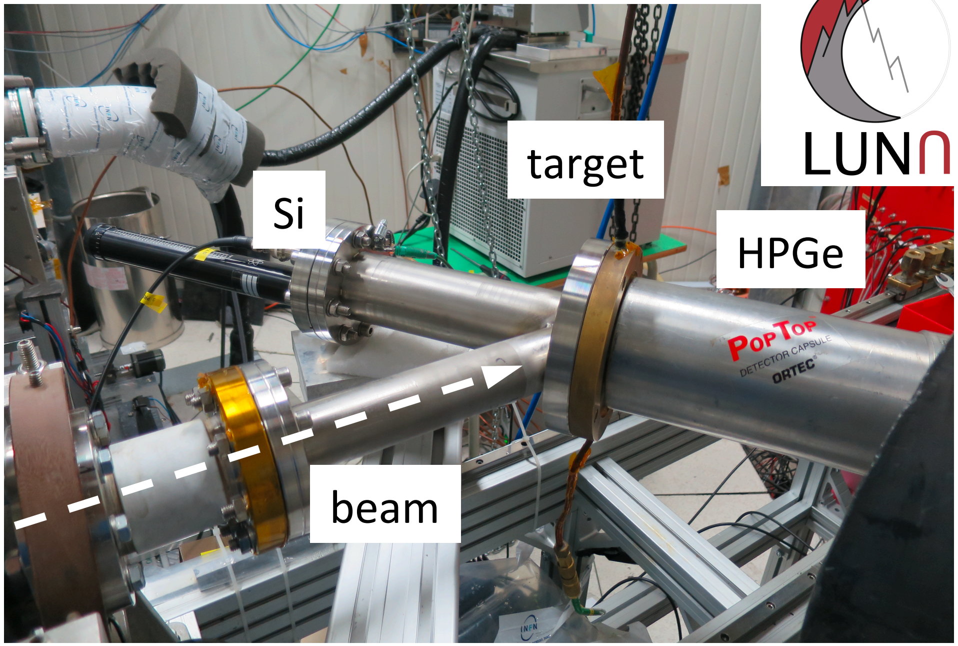
No nuclear physics solution to second Lithium problem

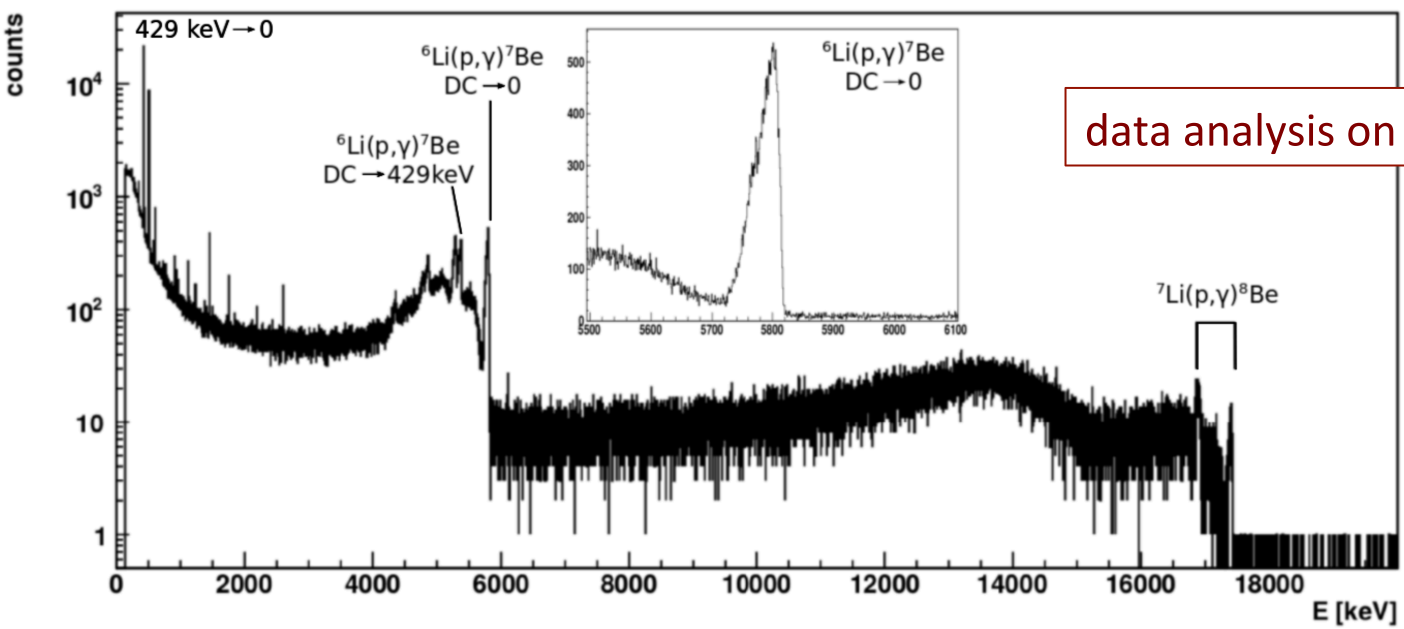
^{6}Li destruction: The $^{6}Li(p,\gamma)^{7}Be$ and $^{6}Li(p,\alpha)^{3}He$ Reactions

Thomas Chillery's
PhD project

The $^{6}Li(p,\gamma)^{7}Be$ and the $^{6}Li(p,\alpha)^{3}He$ reactions at LUNA

- E_{cm} = 30 – 340 keV
- evaporated ^{6}Li solid targets (95% enrichment)
- $^{6}Li_2O$, $^{6}Li_2WO_4$ and $^{6}LiCl$
- HPGe in close geometry
- silicon detector for $^{6}Li(p,\alpha)^{3}He$

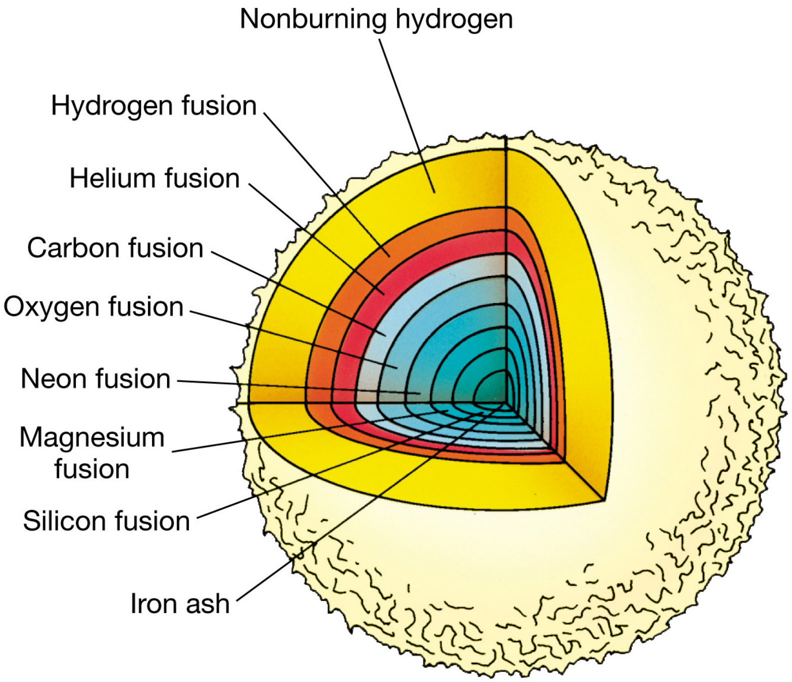




data analysis on going

Fate of Massive Stars

Supernovae or White Dwarfs?



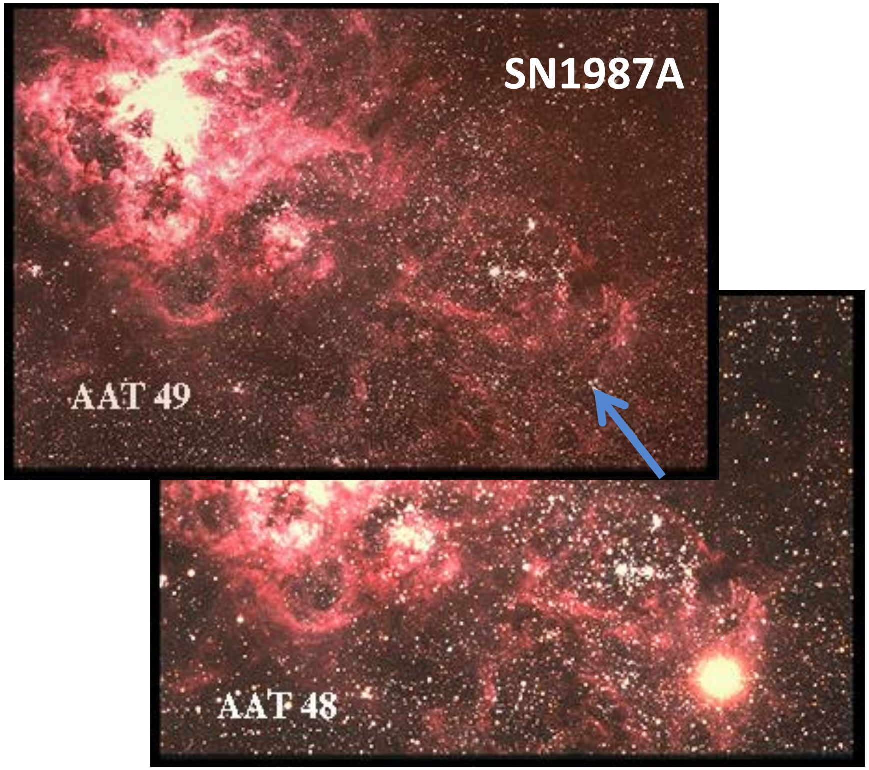
fusion reactions become endothermic

↓

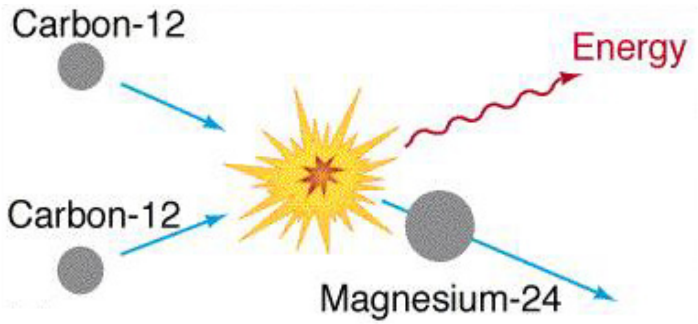
gravitational collapse

↓

catastrophic supernova explosion



limiting mass determined by



still highly uncertain

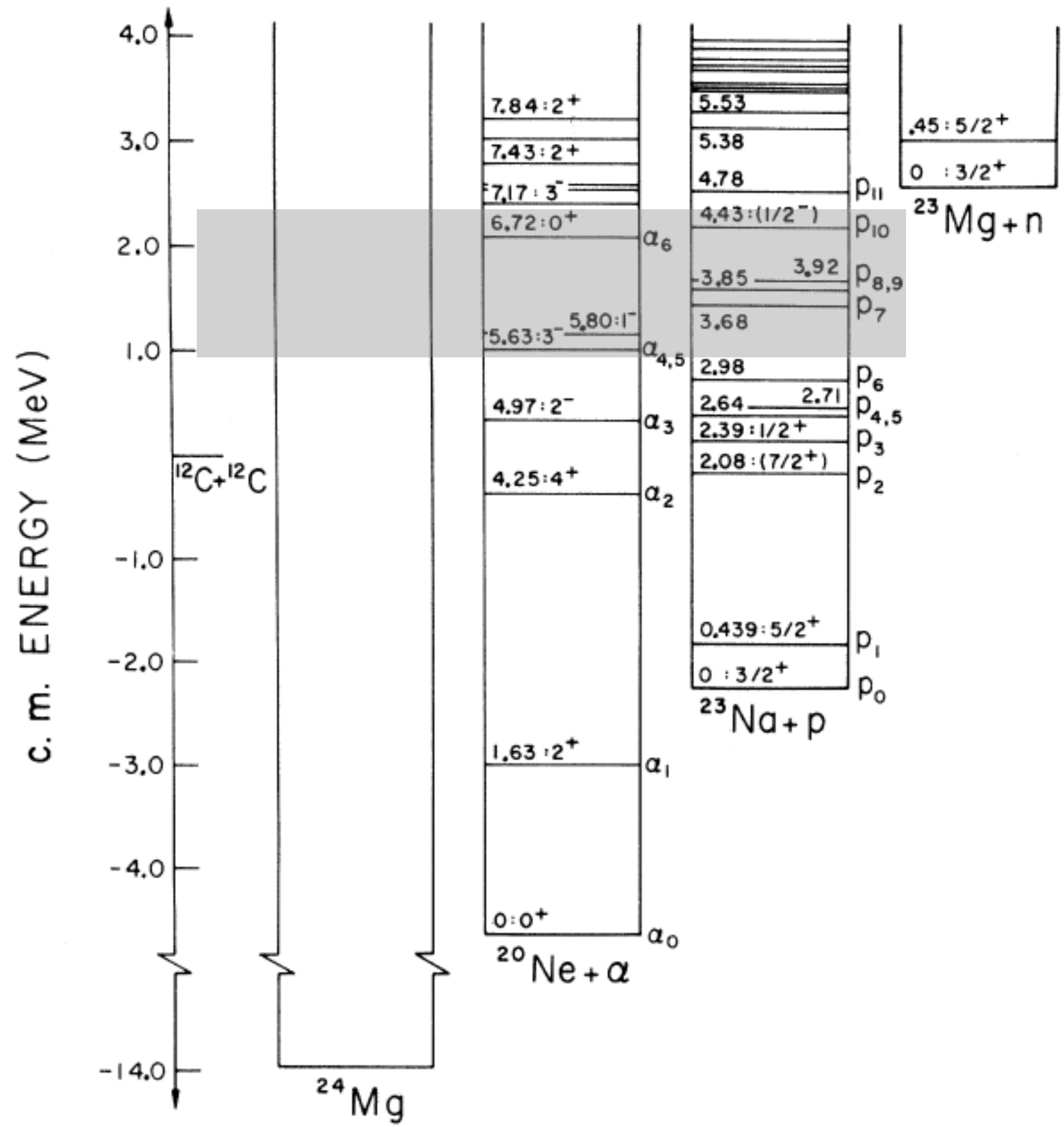
Carbon Burning

- Determines final evolution of massive stars (8-10 solar masses): CO WD or ccSN
- Dictates ignition conditions for thermonuclear explosions

$^{12}C + ^{12}C \rightarrow ^{24}Mg^*$

$\rightarrow ^{20}Ne + \alpha + 4.62$ MeV

$\rightarrow ^{23}Na + p + 2.24$ MeV



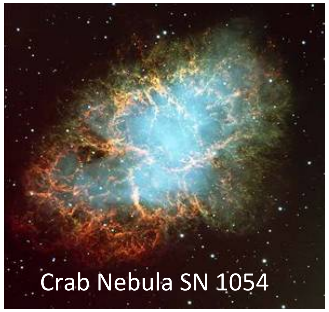
The 12C+12C reactions

$^{12}C+^{12}C$

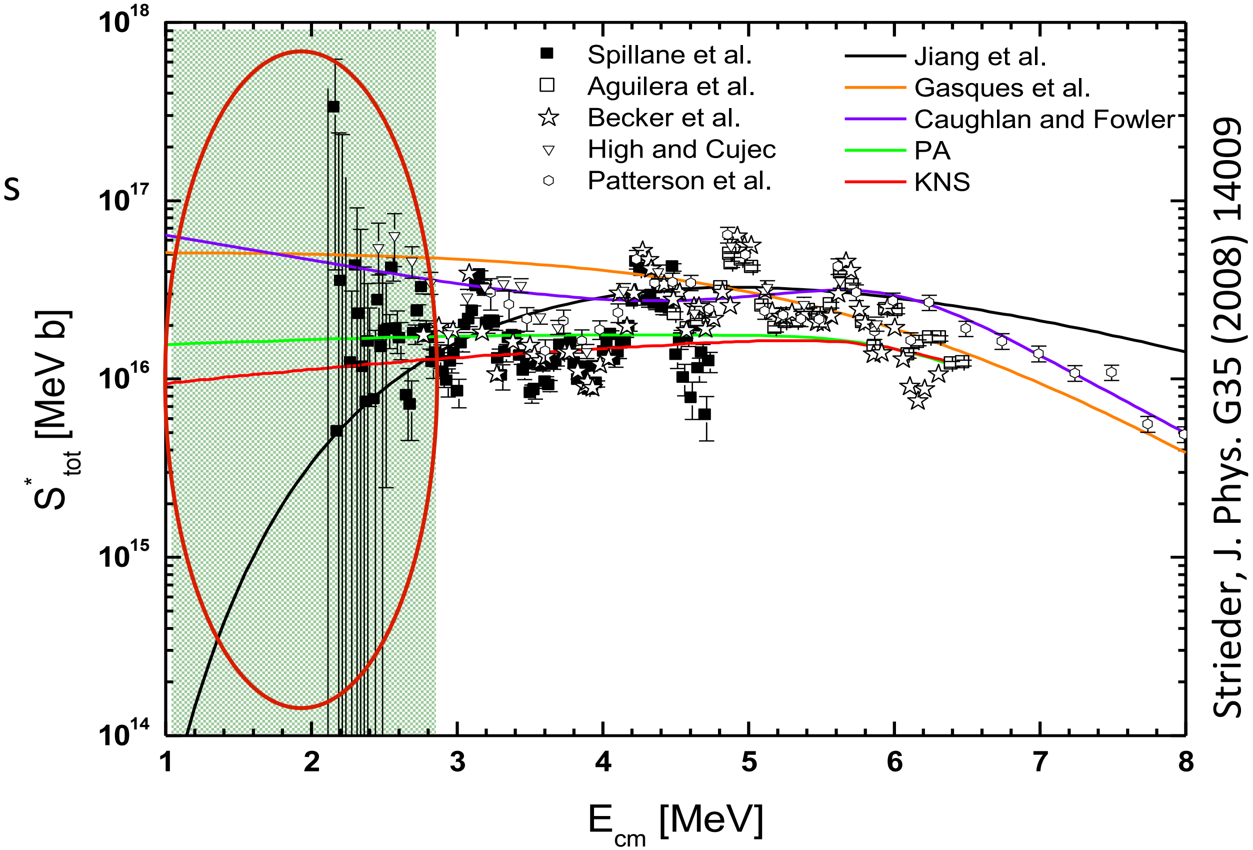
importance: evolution of massive stars

Gamow region: 1 – 3 MeV

min. measured E: 2.1 MeV (by γ-ray spectroscopy)



extrapolations differ by 3 orders of magnitude



main experimental challenges:

- complex and not well understood ‘resonance-like’ structures
- beam induced background at low energies (mostly on H and D contaminants)

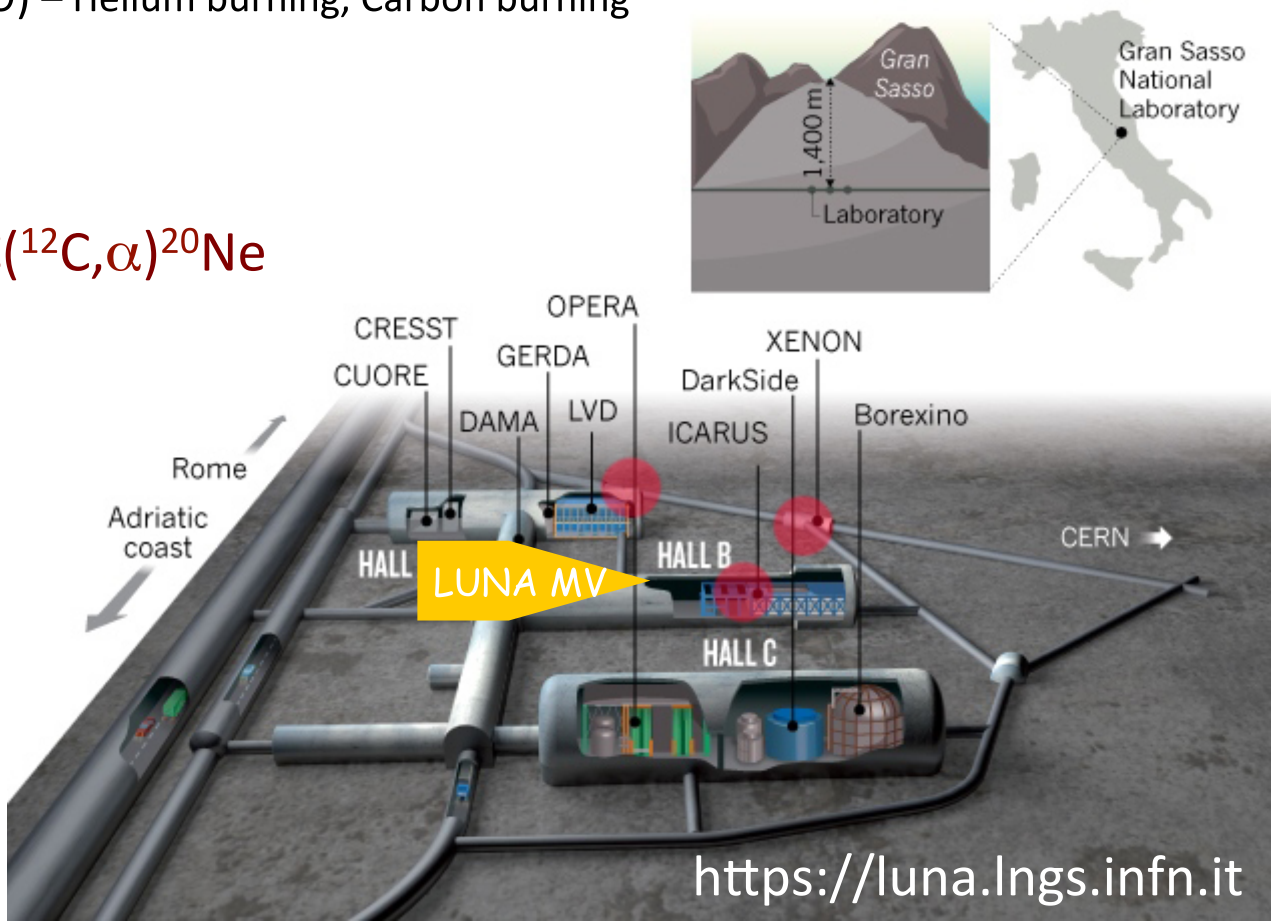
THE LUNA Collaboration

LUNA 50 kV (1992-2001) – Solar Phase

LUNA 400 kV (2000-2018) – CNO, Mg-Al and Ne-Na cycles, BBN

LUNA-MV (from 2019) – Helium burning, Carbon burning

- $^{12}C(^{12}C,p)^{23}Na$ and $^{12}C(^{12}C,\alpha)^{20}Ne$
- $^{13}C(\alpha,n)^{16}O$
- $^{22}Ne(\alpha,n)^{25}Mg$
- $^{12}C(\alpha,\gamma)^{16}O$

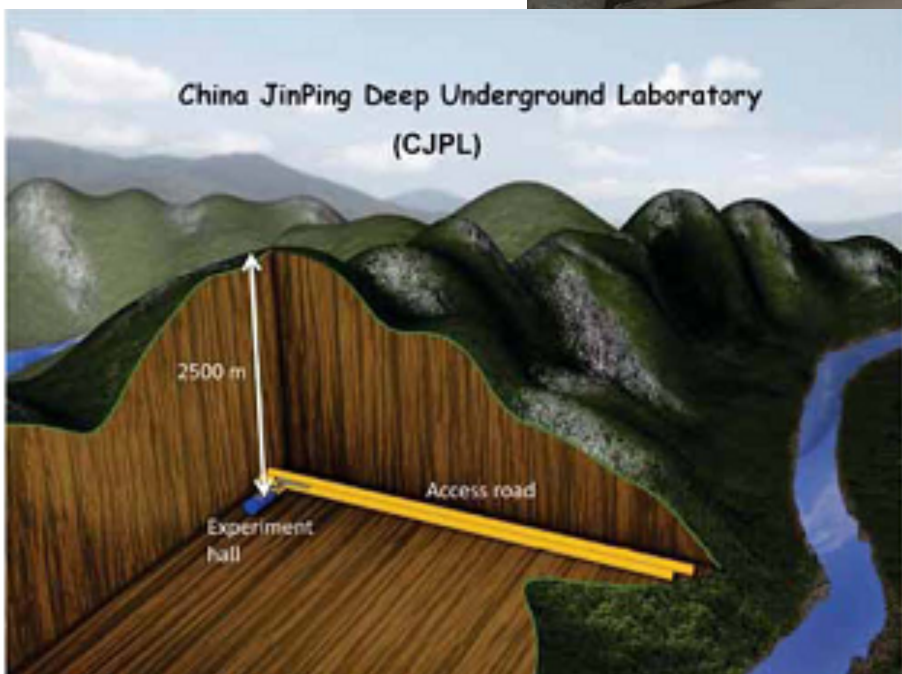


Future Underground Facilities for Nuclear Astrophysics

JUNA

Jinping Underground lab for Nuclear Astrophysics

锦屏深地核天体物理实验室



2,400 meters deep in a mountain in Sichuan Province

China Institute of Atomic Energy

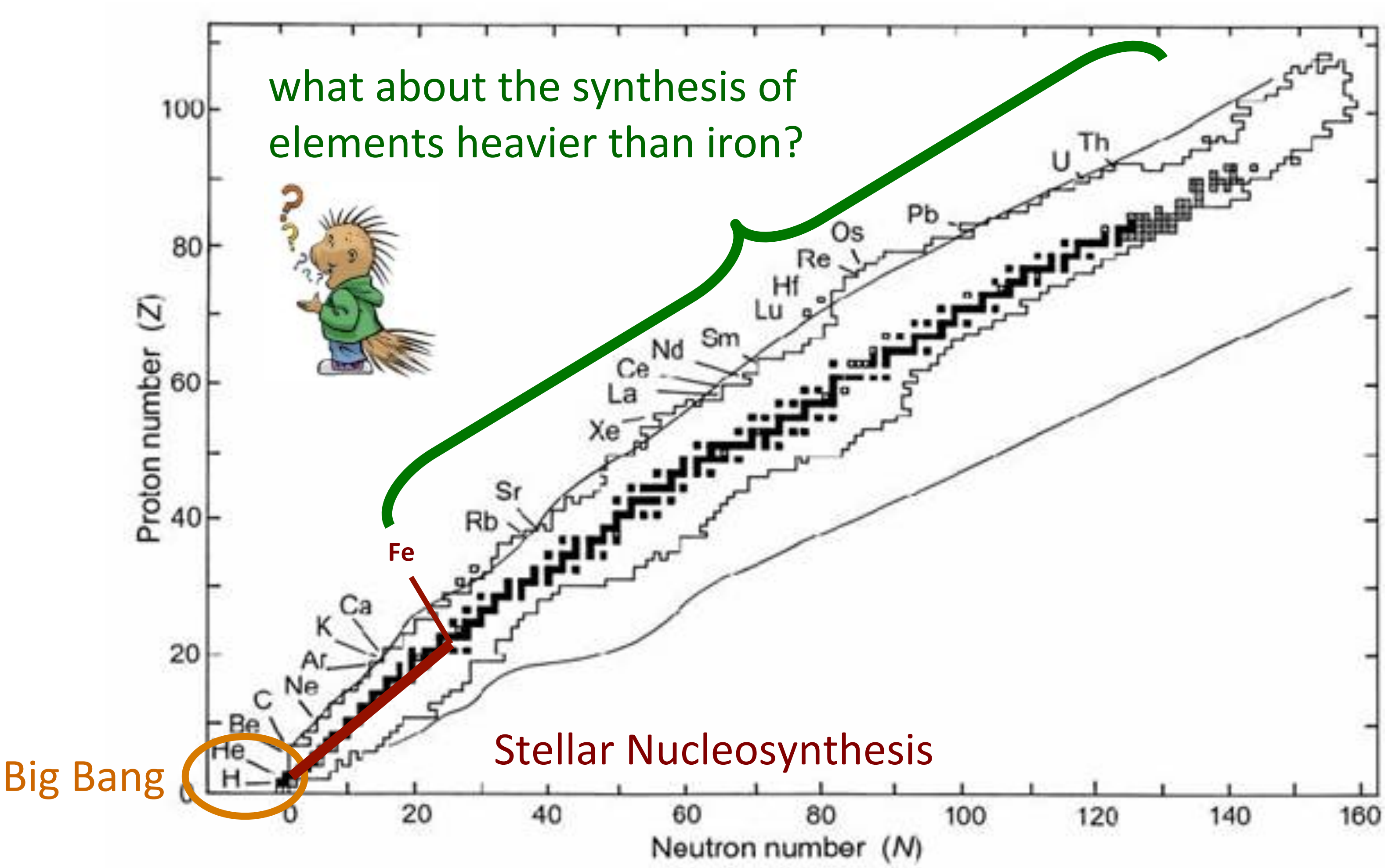
Compact Accelerator Systems for Performing Astrophysical Research

Collaboration between:

- University of Notre Dame
- Colorado School of Mines
- South Dakota School of Mines and Technology

SURF: Sanford Underground Laboratory at Homestake (4300 m.w.e.)

How were Elements from Iron to Uranium made?

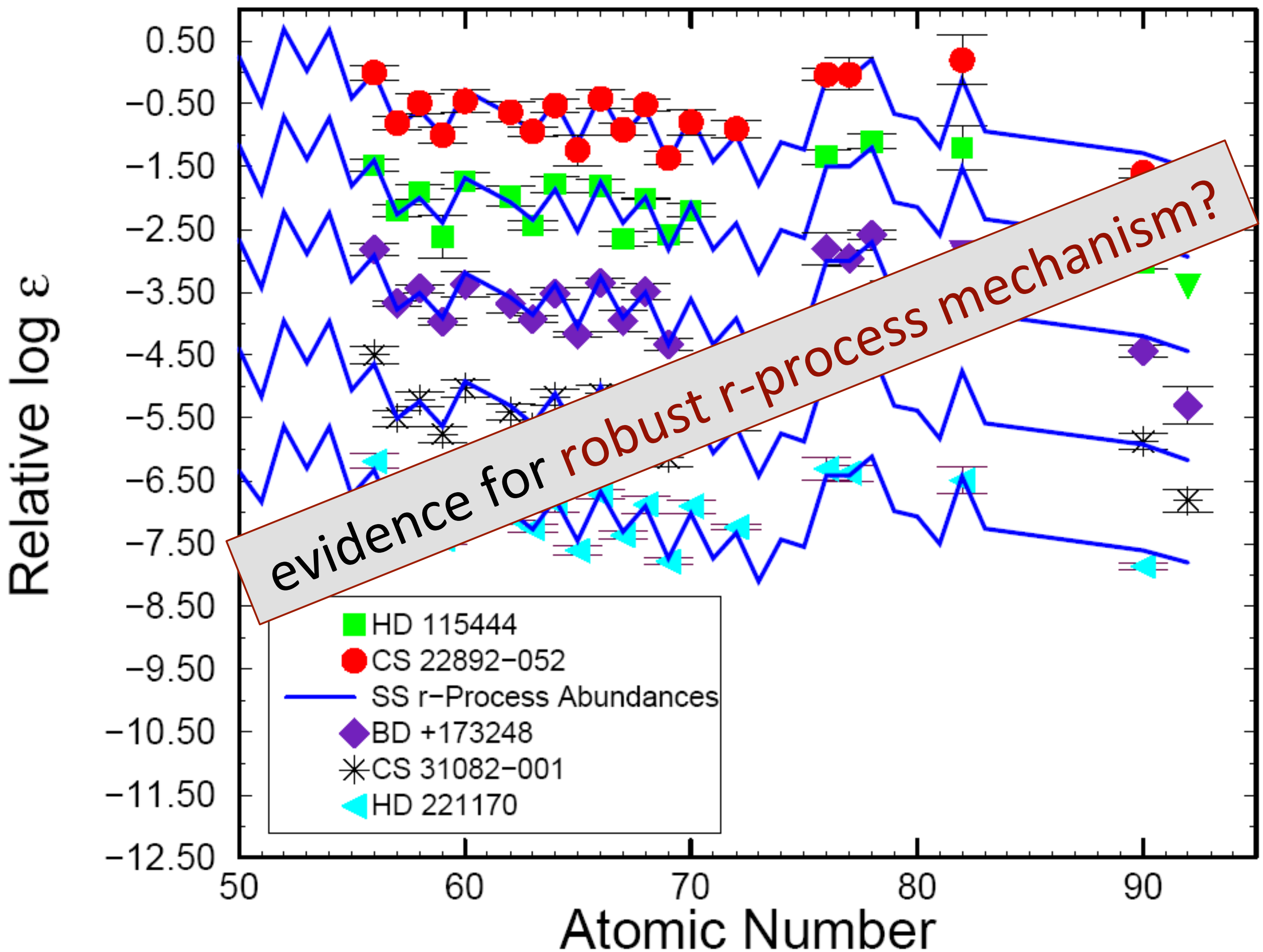


"The 11 Greatest Unanswered Questions of Physics"

from: National Academy of Science Report, 2002

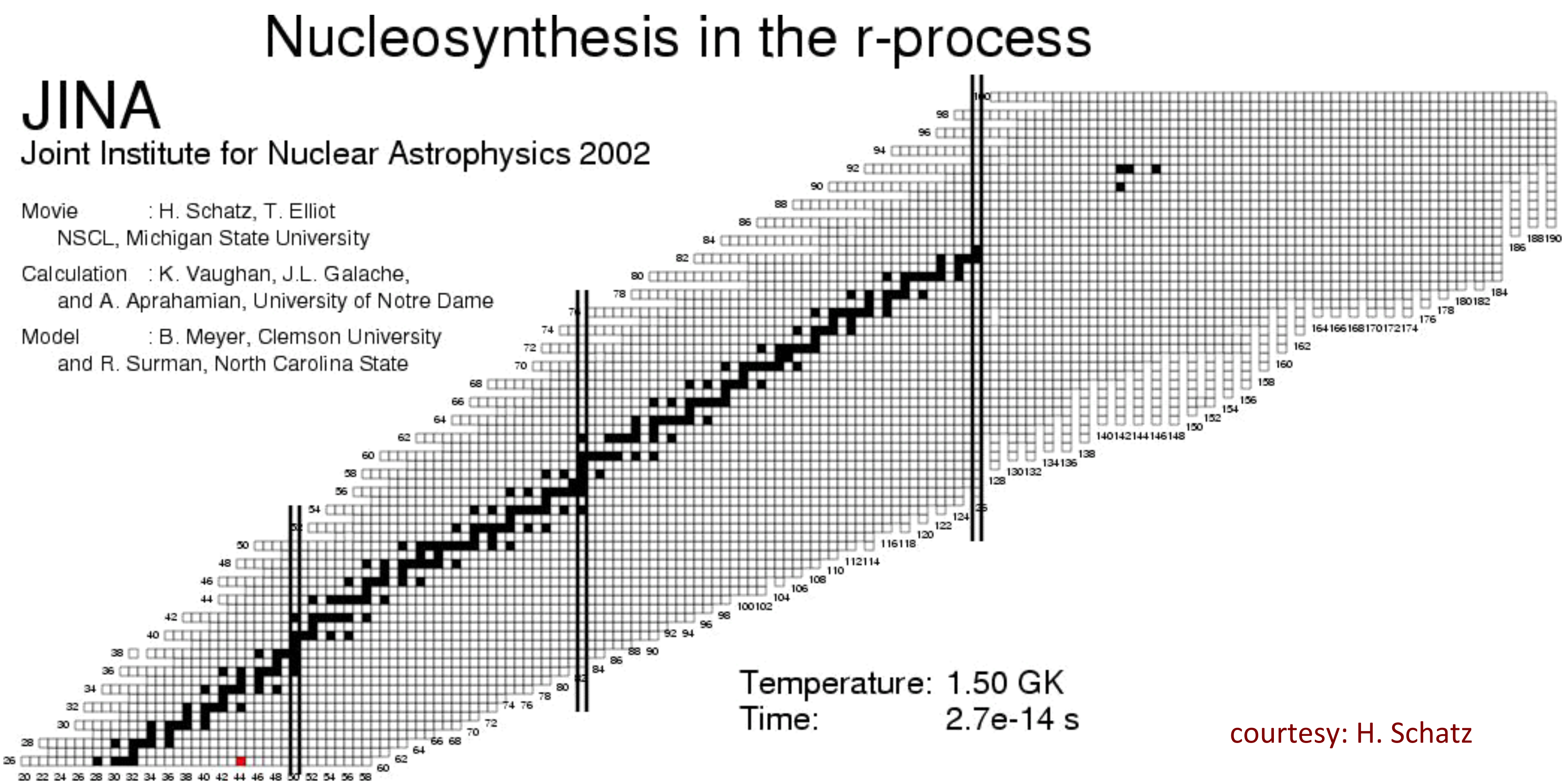
the Origin of Heavy Elements

heavy element abundances in metal poor stars show remarkable similarities and excellent agreement with solar values (not a metal poor star!)



evidence for robust r-process mechanism?

Kratz et al.: APJ 662 (2007) 39

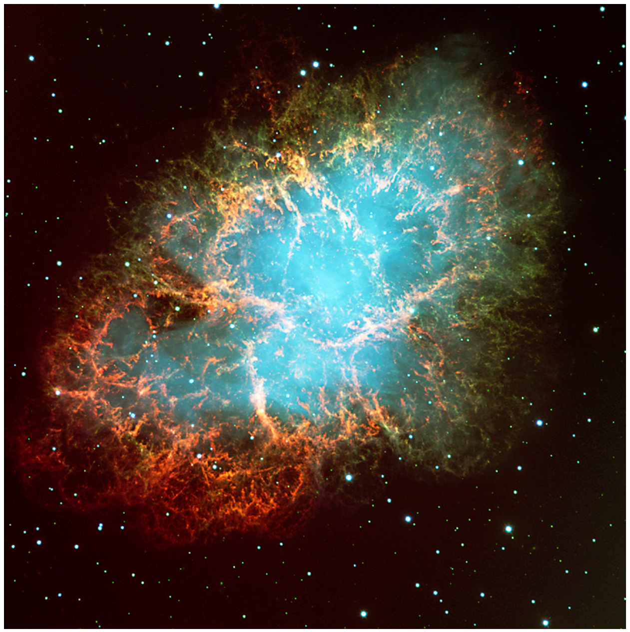


courtesy: H. Schatz

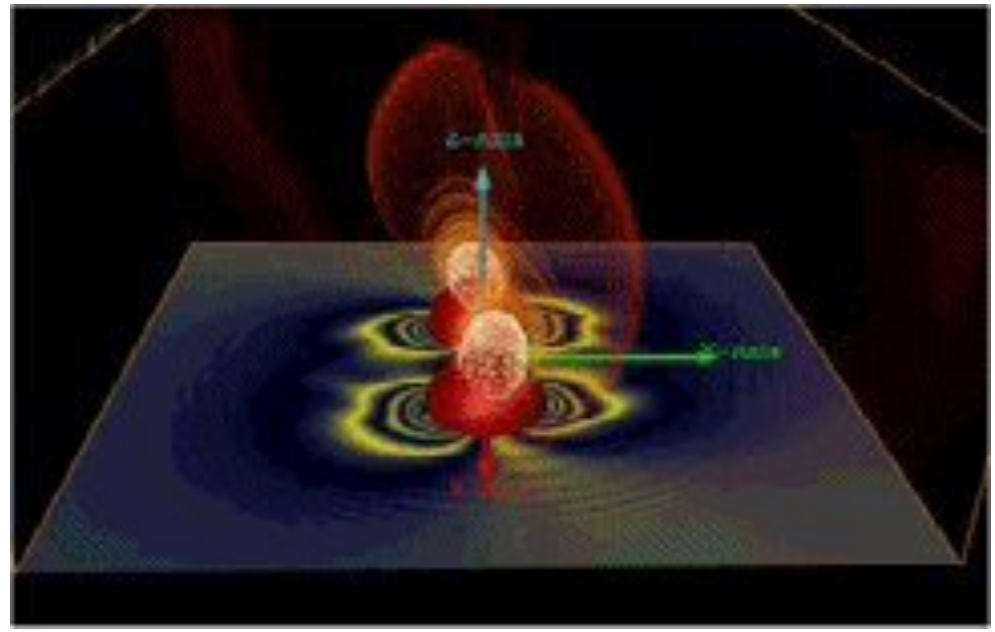
large neutron fluxes required! (~10^{28} n/cm^3)

what astrophysical sites for r-process:

core collapse supernovae



merging neutron stars



- neutrino driven wind of proto-neutron star
- He shell of exploding massive star
- others?...

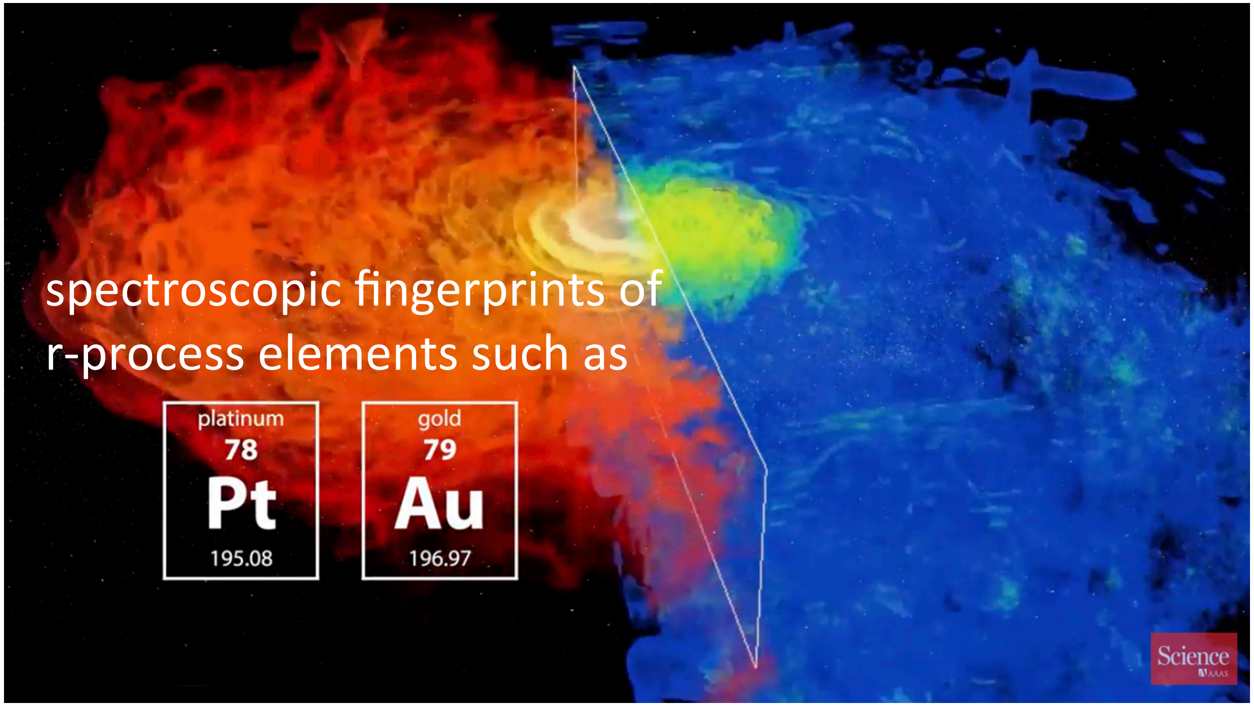
17 August 2017

130 million light years from Earth

LIGO and VIRGO: first observation of gravitational waves from merging neutron stars

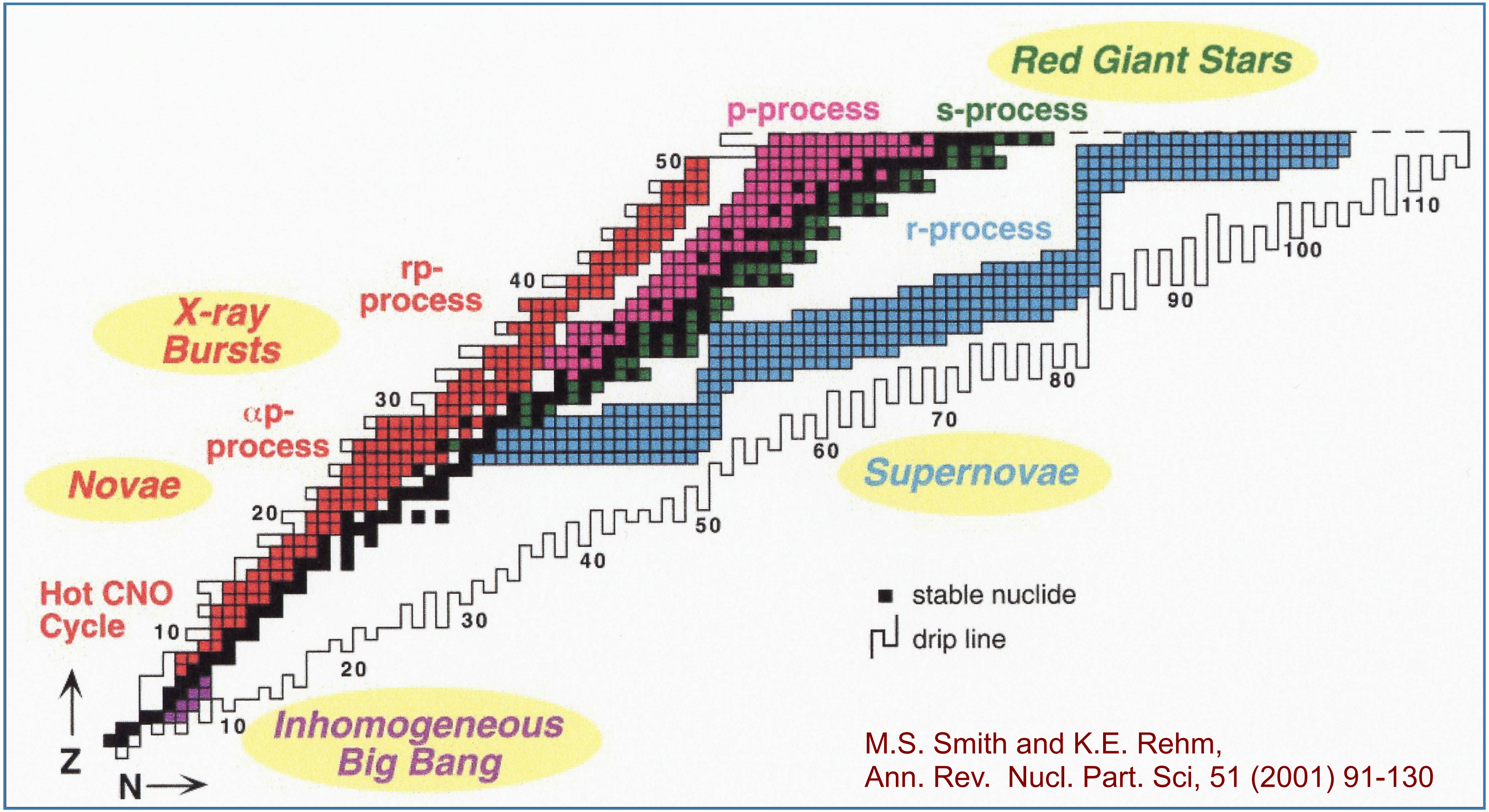
event observed by 70 ground- and space-based observatories

including in visible light 11h after GW detection



neutron star mergers could well be the main source for r-process elements

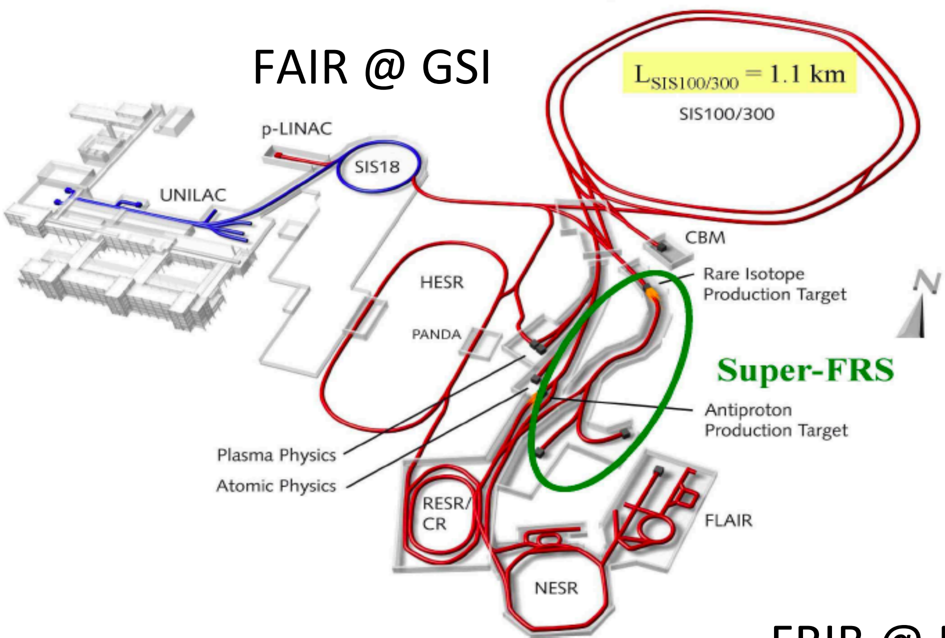
A new era in Astronomy has just begun…



many reactions involve UNSTABLE species, hence need for **Radioactive Ion Beams**

Upcoming Radioactive Beam Facilities

FAIR @ GSI

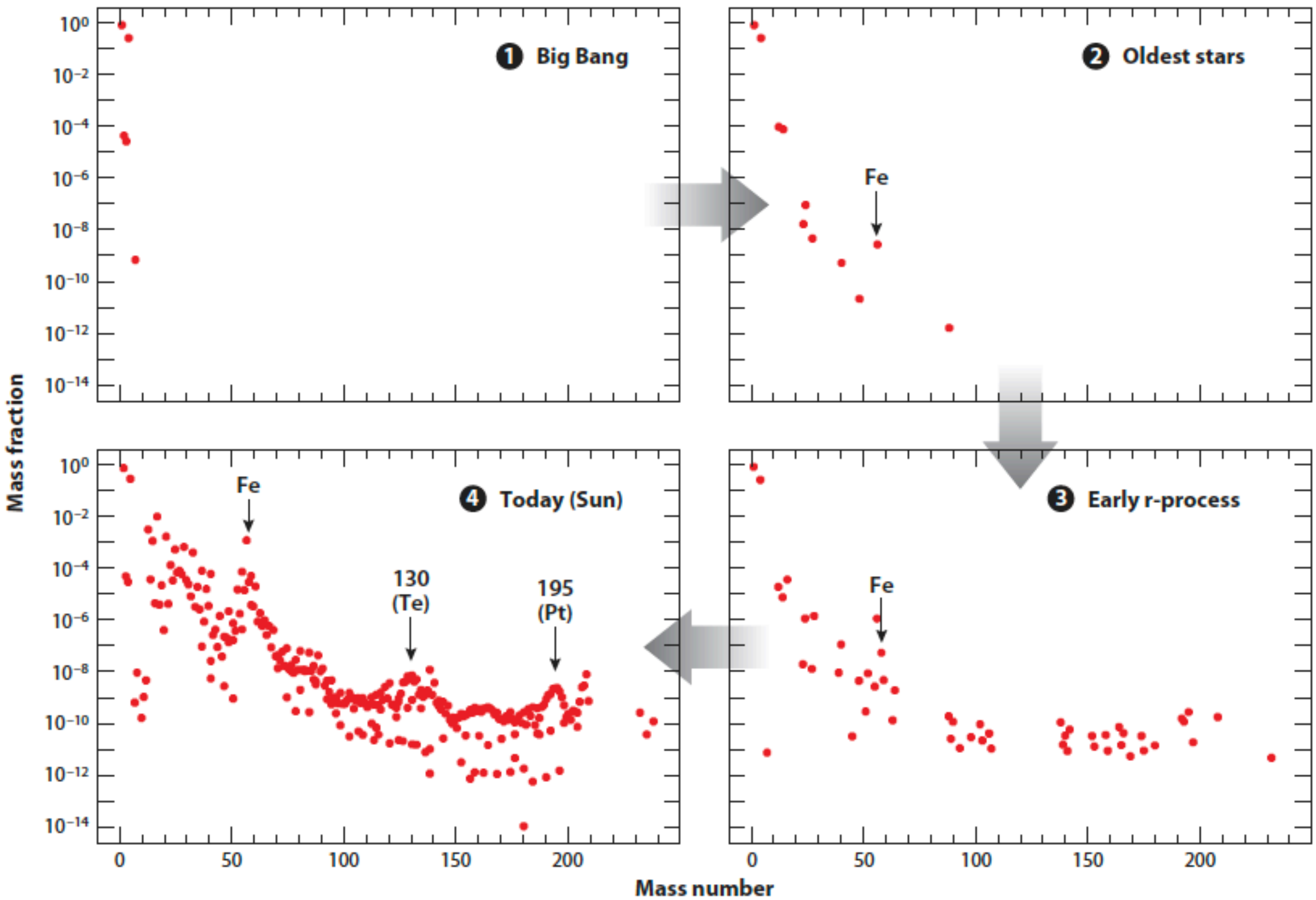


ARIEL @ TRIUMF

FRIB @ MSU

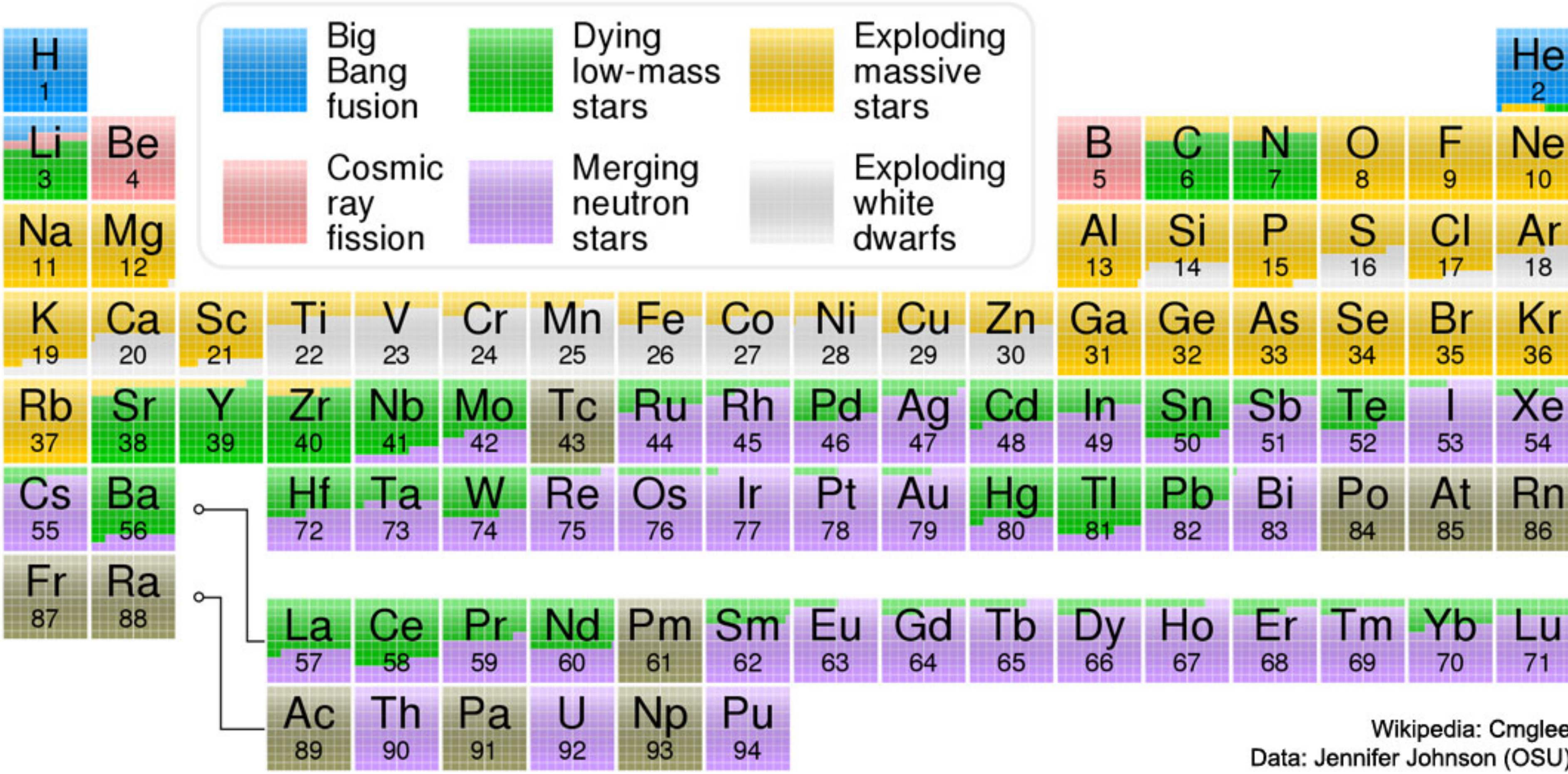
To Conclude…

a superposition of nucleosynthesis events that occurred in the past



Wiescher, Kaeppeler and Langanke, Annu. Rev. Astron. Astrophys. 50 (2012) 165-210

Nuclear Astrophysics 60 years on:



A truly remarkable achievement

Astrophysics

Stellar evolutionary codes
nucleosynthesis calculations
astronomical observations

Plasma Physics

degenerate matter
electron screening
equation of state

Nuclear Physics

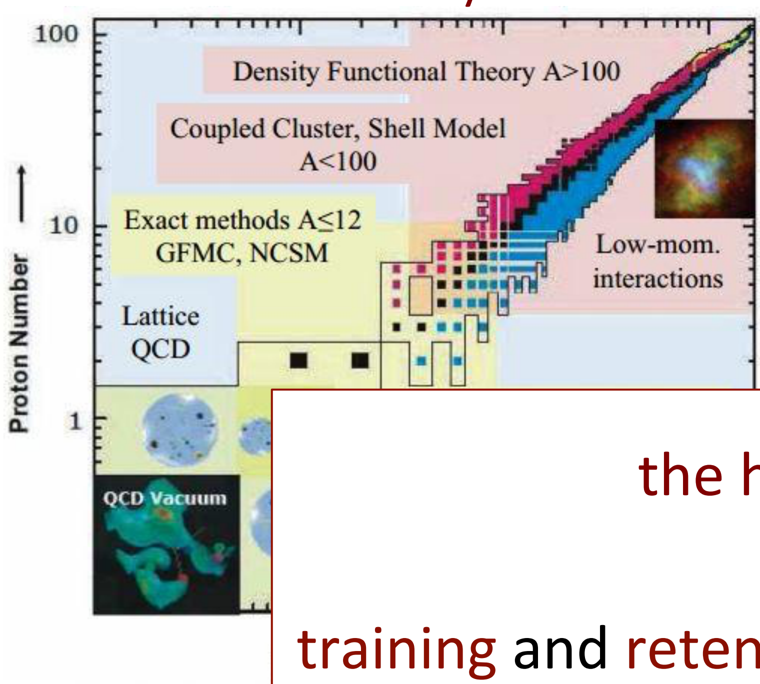
experimental and
theoretical Inputs
stable and exotic nuclei

Atomic Physics

radiation-matter interaction
energy losses, stopping powers
spectral lines
materials and detectors

Ingredients from Future Breakthroughs

theory

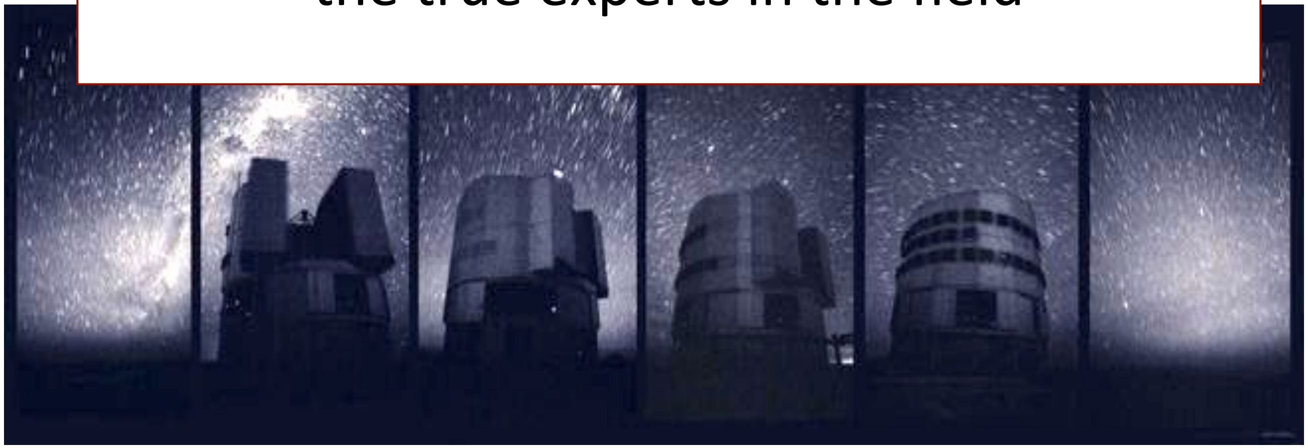


experiments

the human factor

training and retention of young researchers

the true experts in the field




THANK YOU