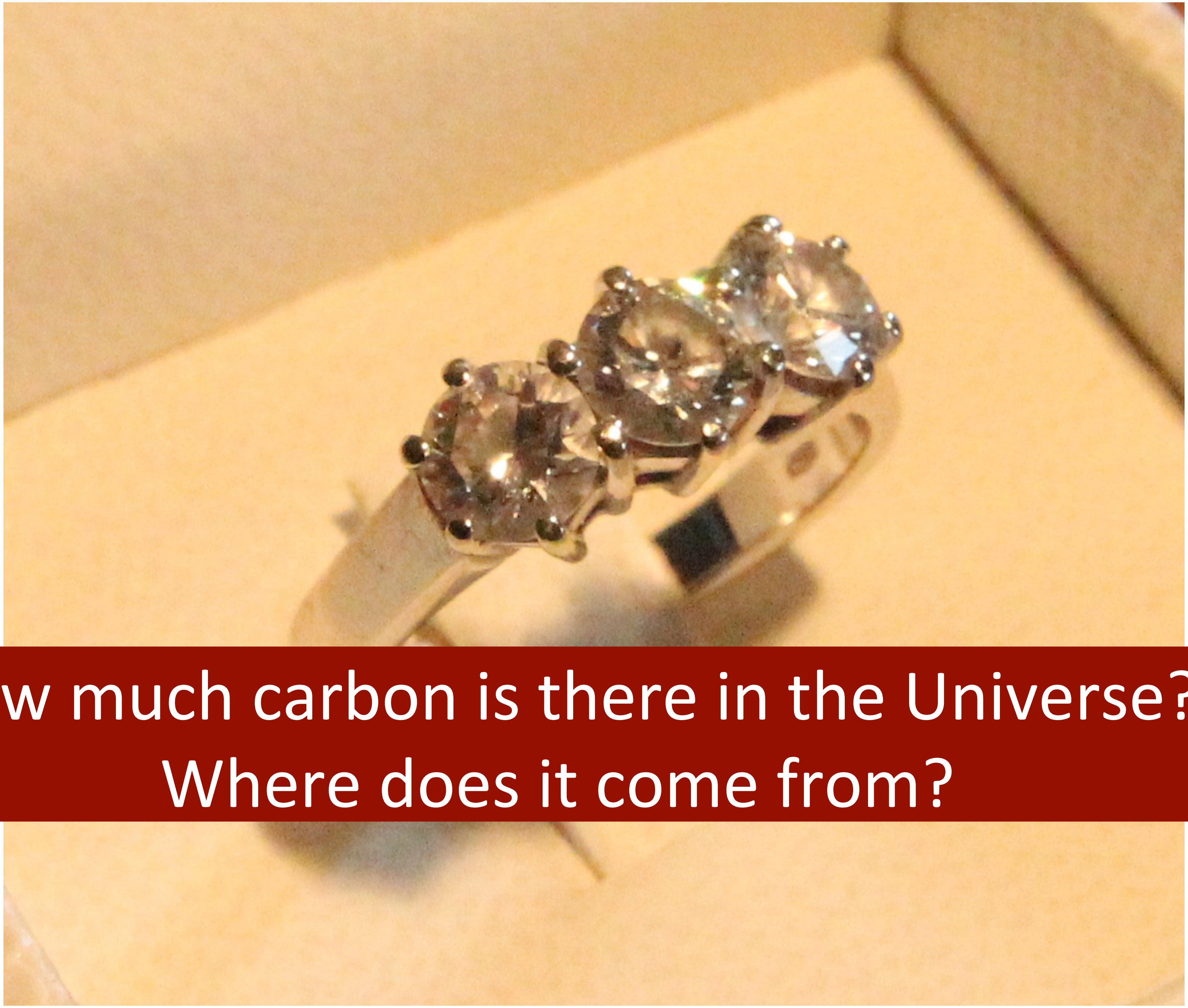
Nuclear Astrophysics

Marialuisa Aliotta
School of Physics and Astronomy - University of Edinburgh, UK
Scottish Universities Physics Alliance

79 ICFA Seminar – 6-9 November 2017, Ottawa, Canada

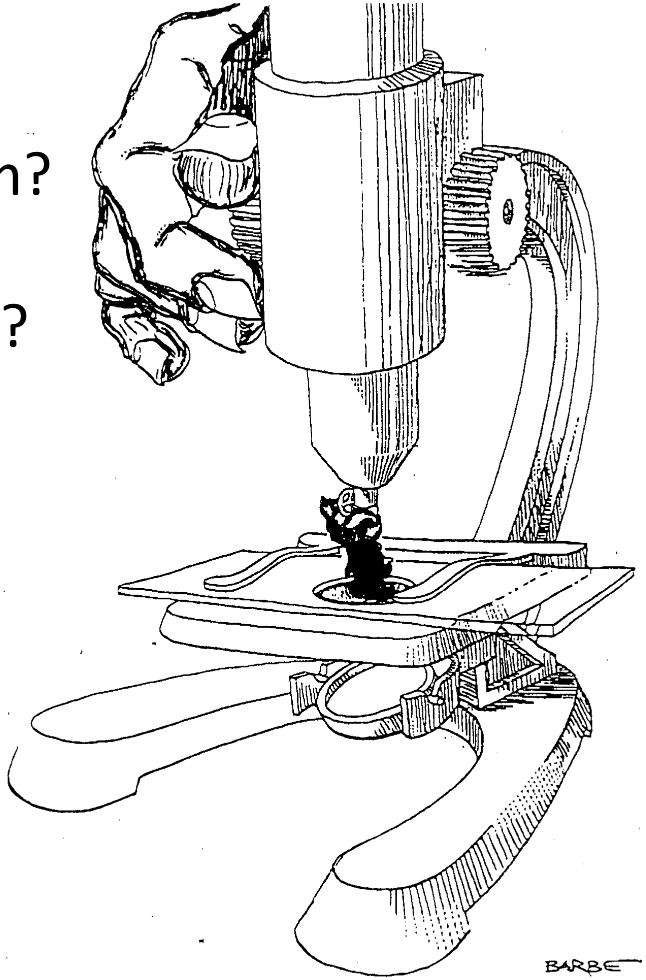
A Diamond is Forever



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

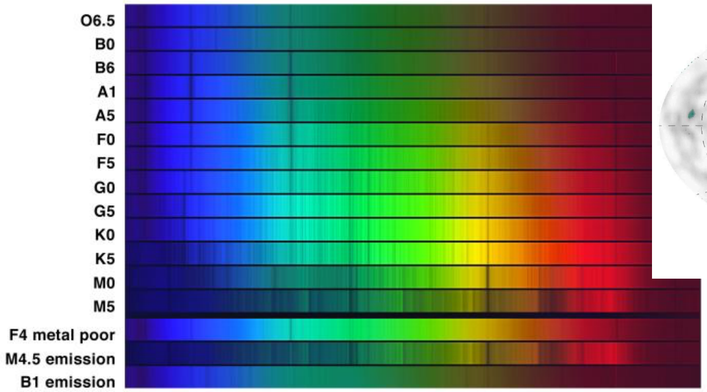
MICRO COSMOS

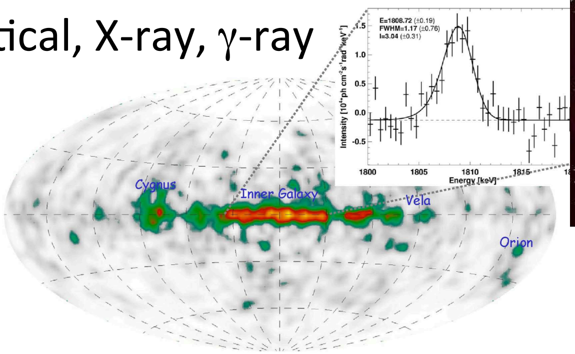
and

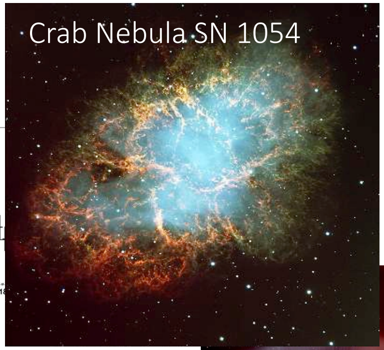
MACRO COSMOS

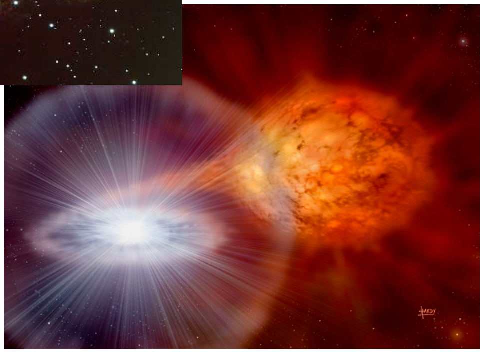
electromagnetic emissions

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









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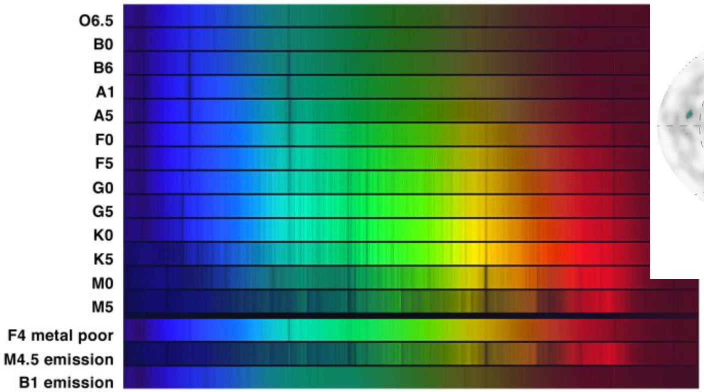
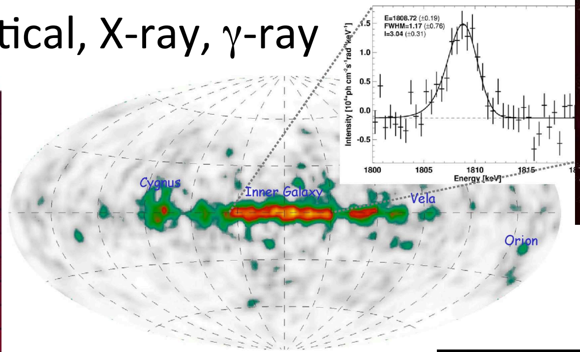
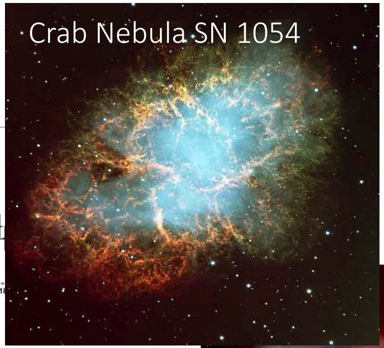
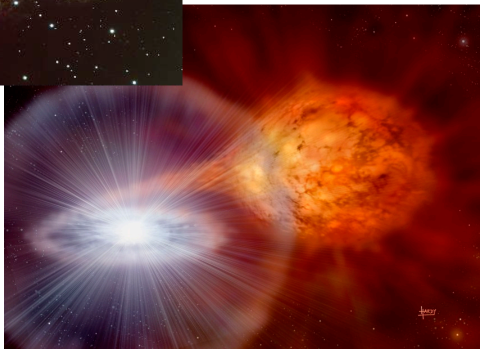


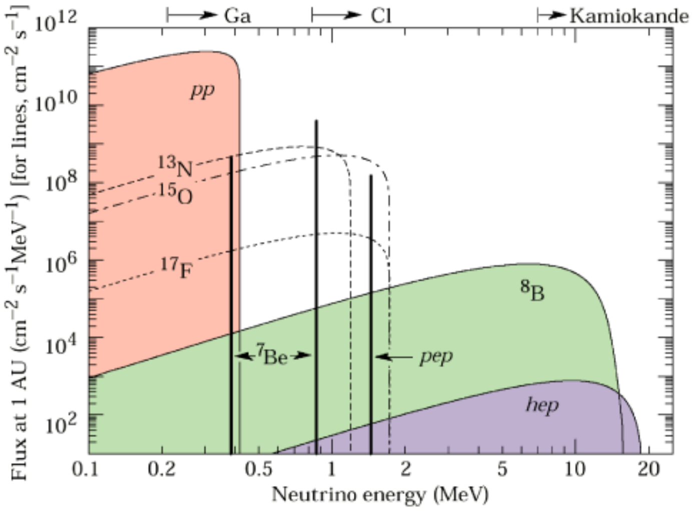


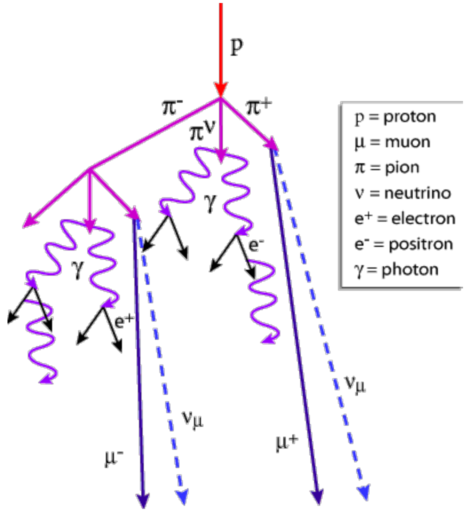




direct messengers

neutrinos, cosmic rays, meteorites, lunar samples, …





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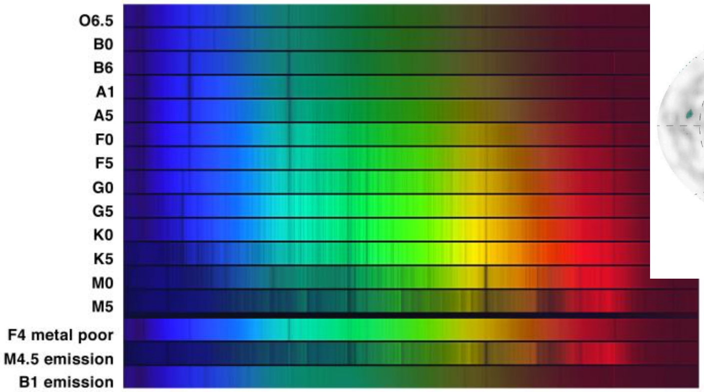

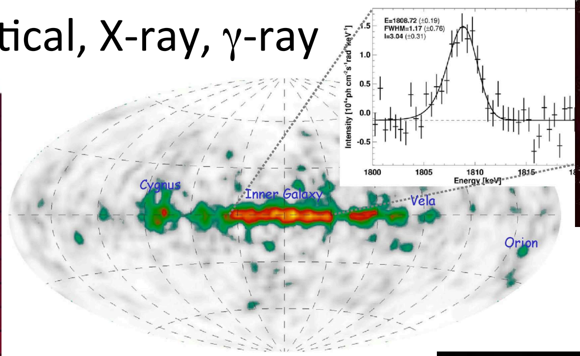

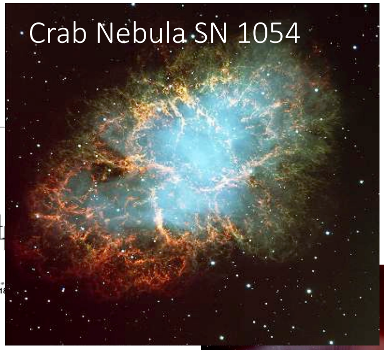

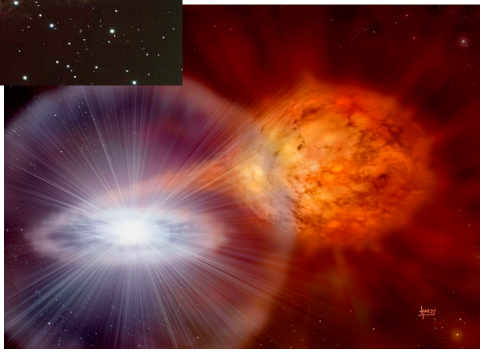

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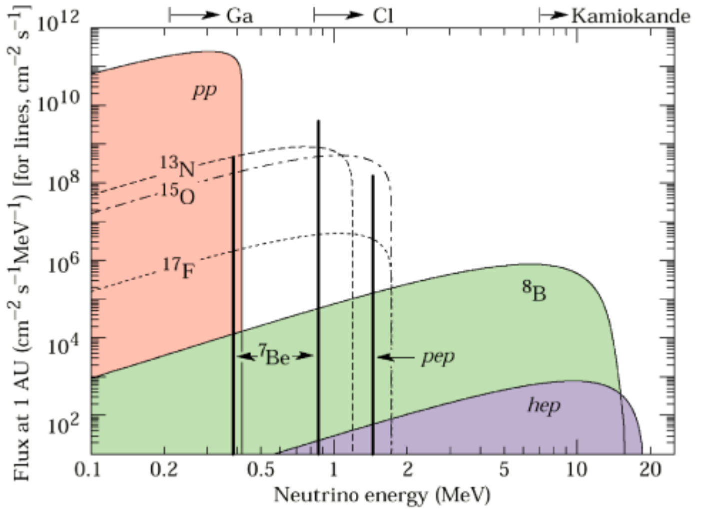
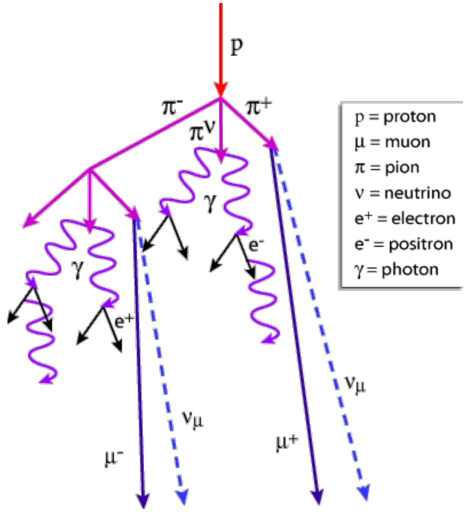
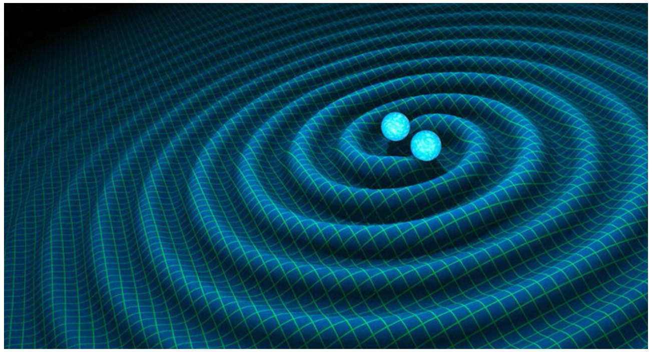




gravitational waves



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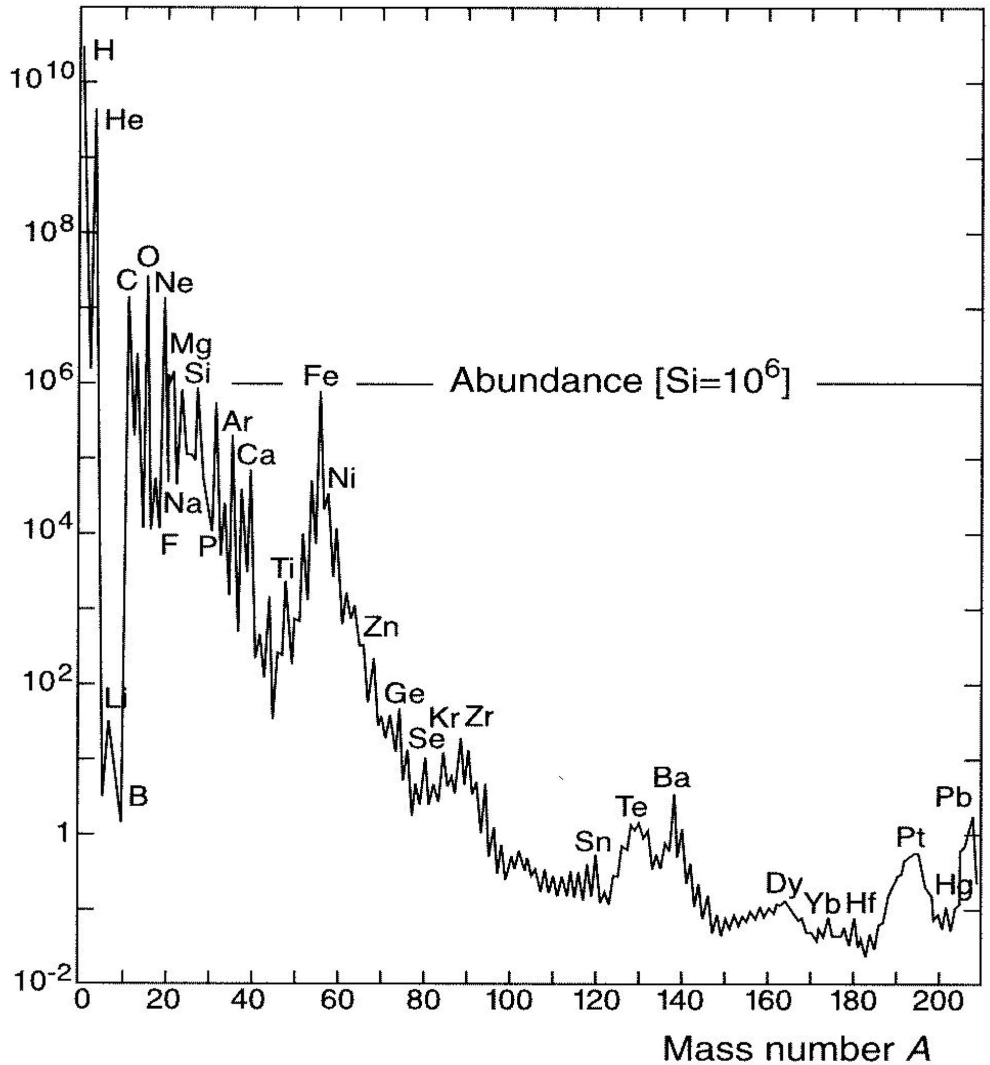
(Solar) Abundance Distribution



Data sources:

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

Features:

- distribution everywhere similar
- 12 orders-of-magnitude span

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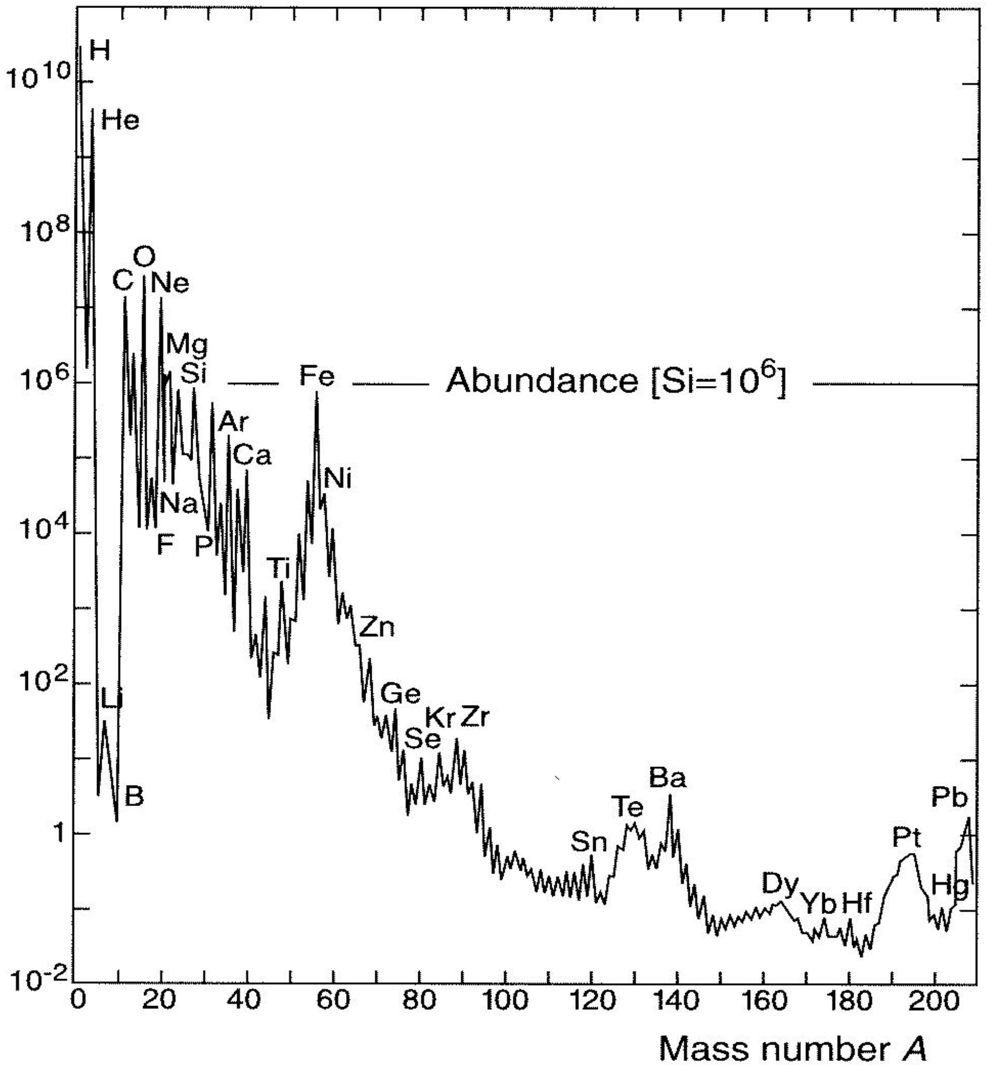

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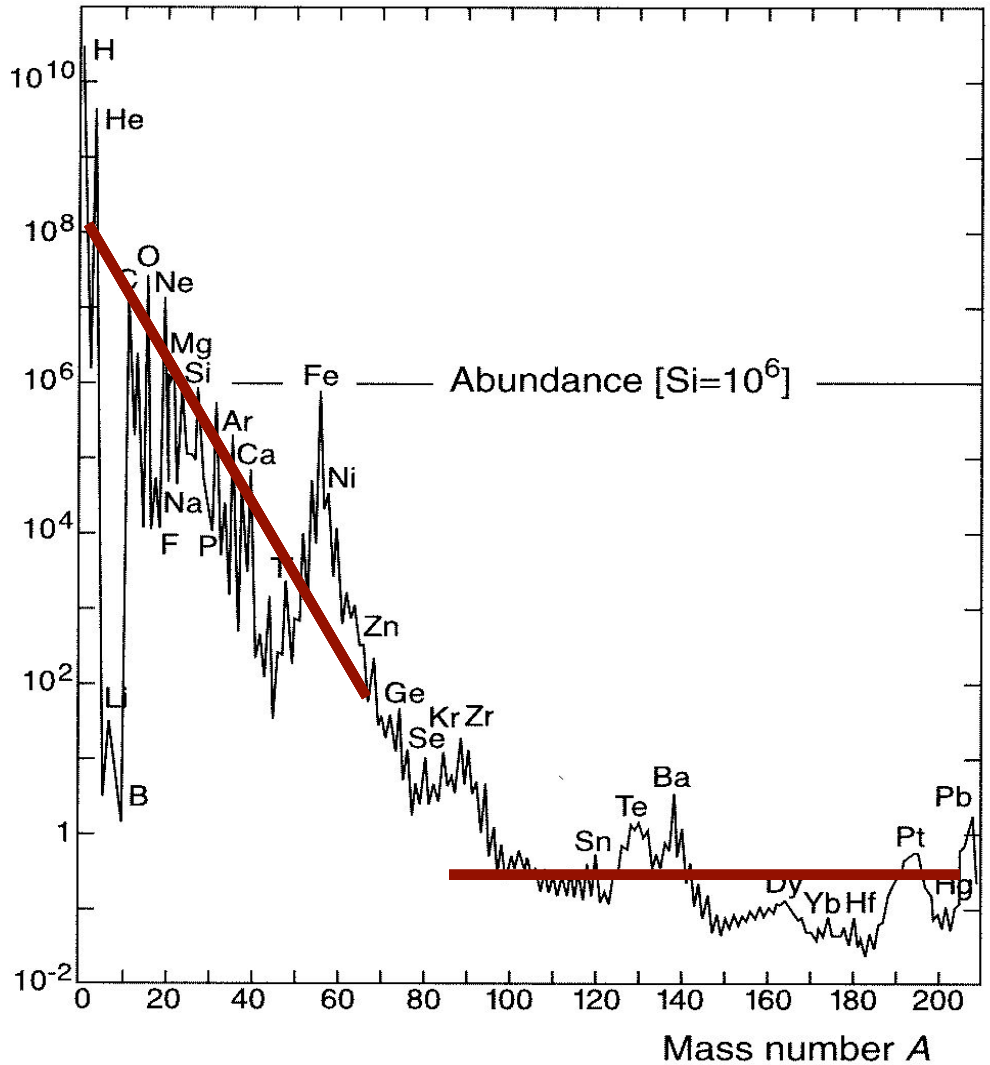

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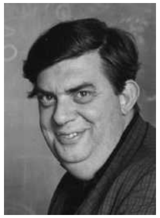
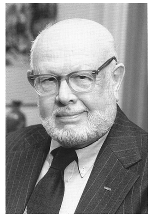
- H ~ 75%, He ~ 23%
- C → U ~ 2% ("metals")
- D, Li, Be, B under-abundant
- exponential decrease up to Fe
- nearly flat distribution beyond Fe

Burbidge, Burbidge, Fowler & Hoyle (B^2FH):

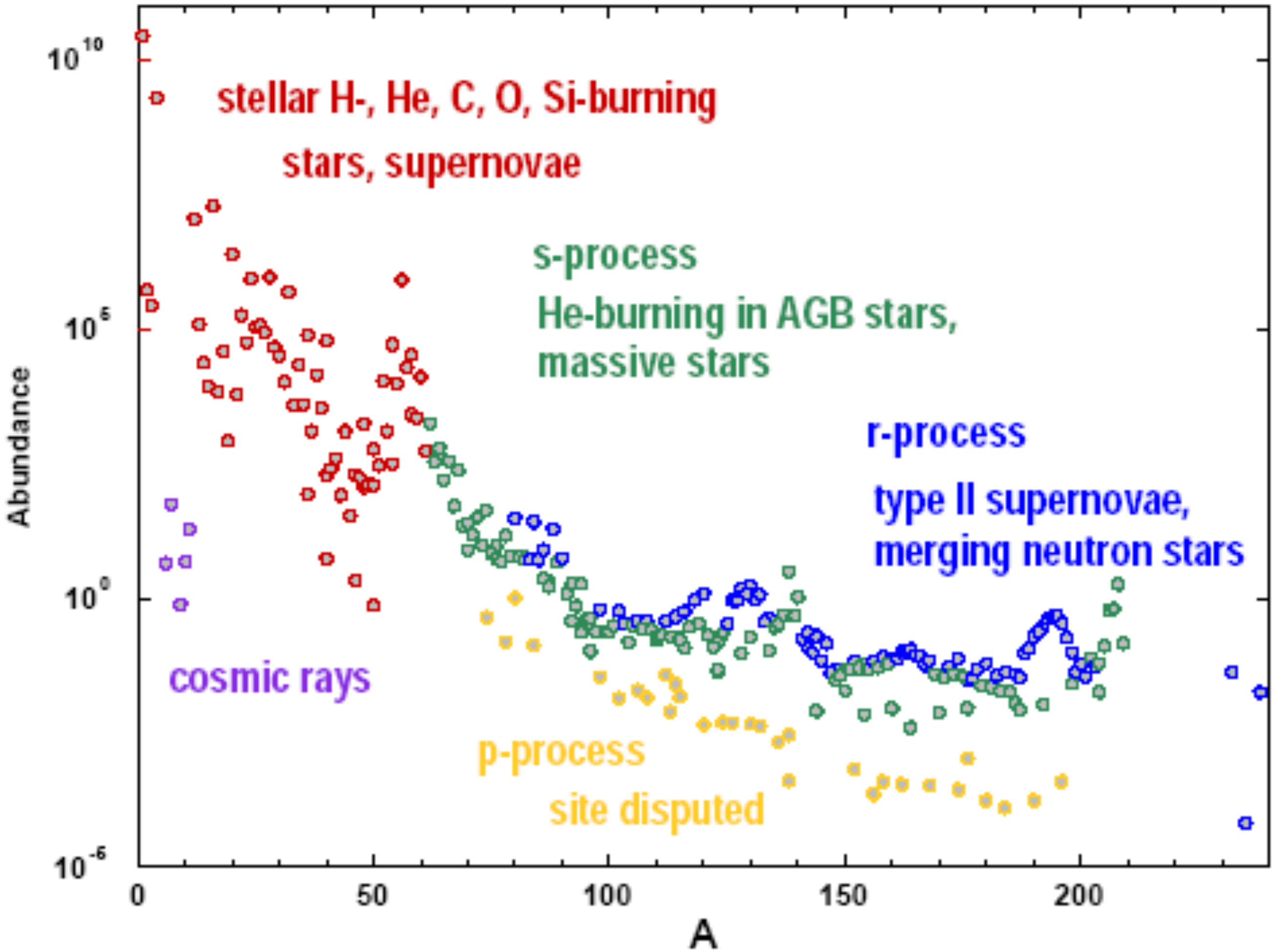
Rev. Mod. Phys. 29 (1957) 547


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



M. Wiescher, JINA lectures on Nuclear Astrophysics

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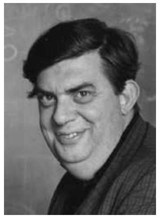
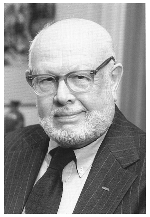


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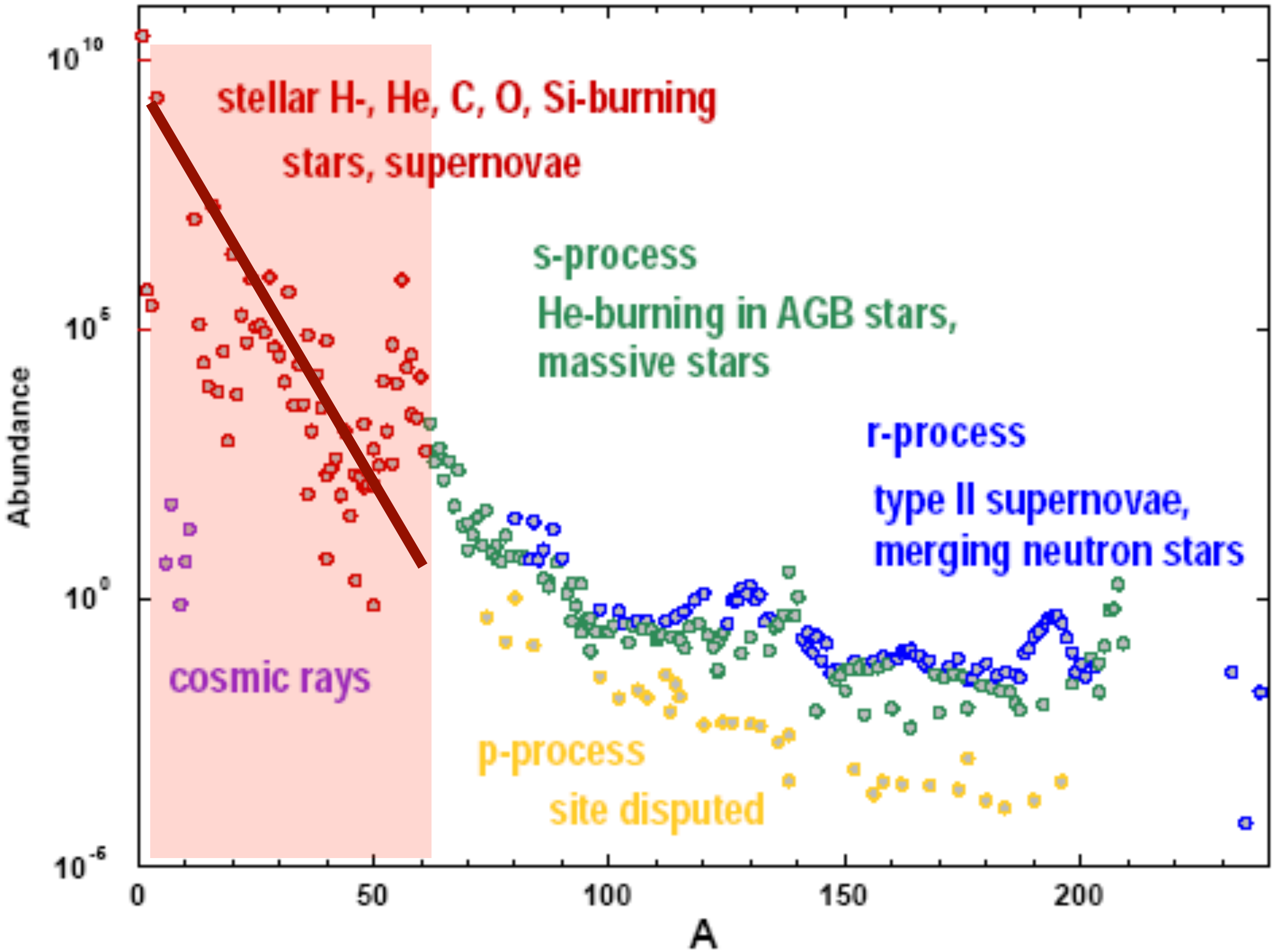
fusion of charged particles

mainly **stable nuclei**



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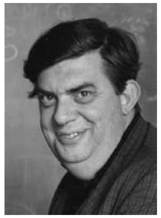
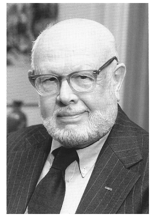
The Origin of the Elements

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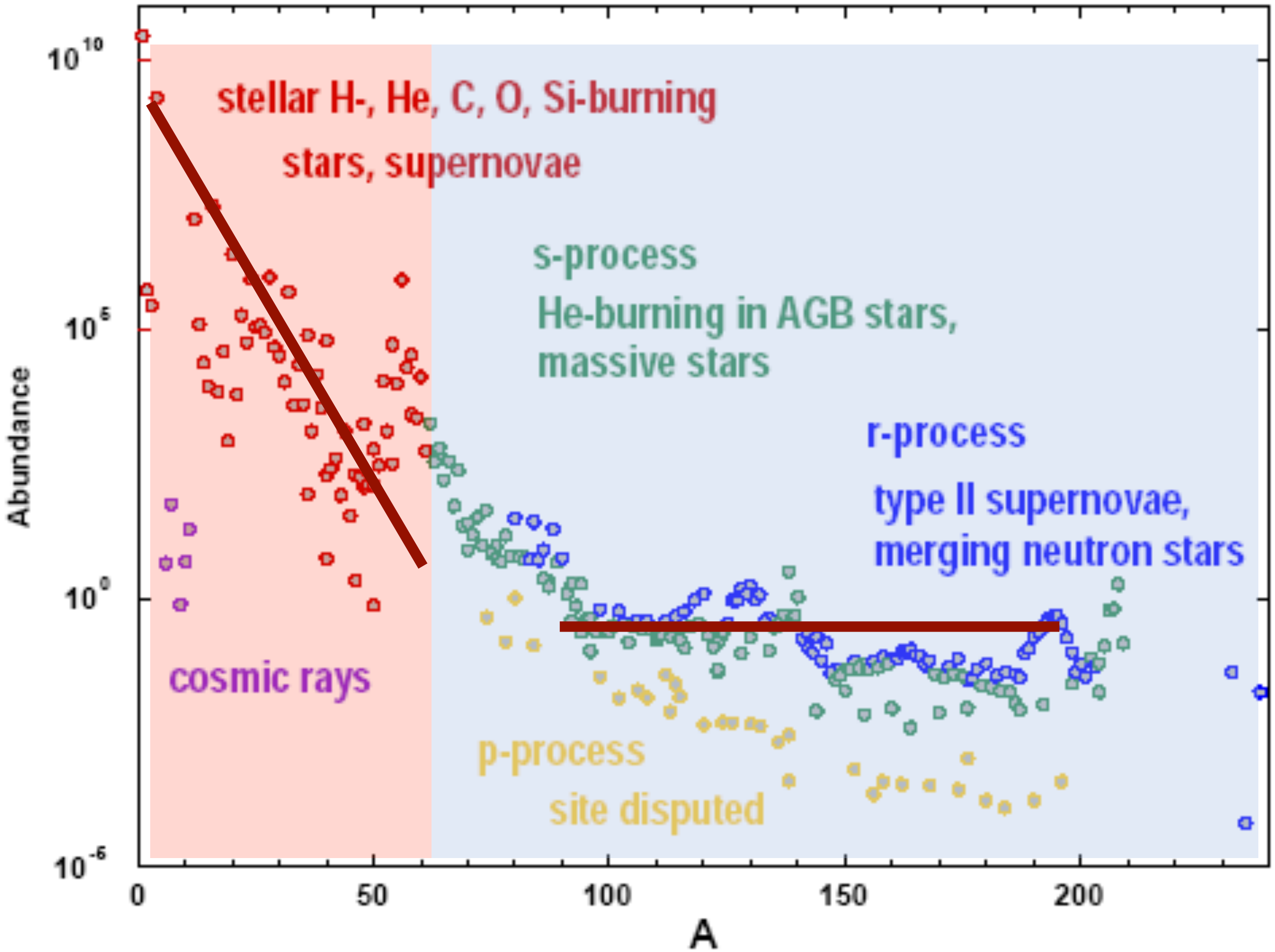


M. Wiescher, JINA lectures on Nuclear Astrophysics

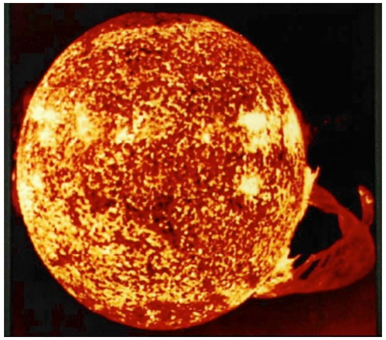
neutron-capture reactions

mainly **unstable nuclei**

Interstellar medium

BIRTH

gravitational contraction



Stars

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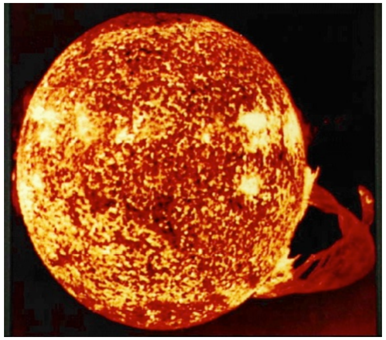


- energy production
- stability against collapse
- synthesis of "metals"

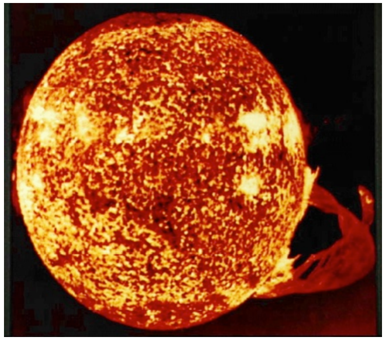
The Bigger Picture

Interstellar medium

BIRTH

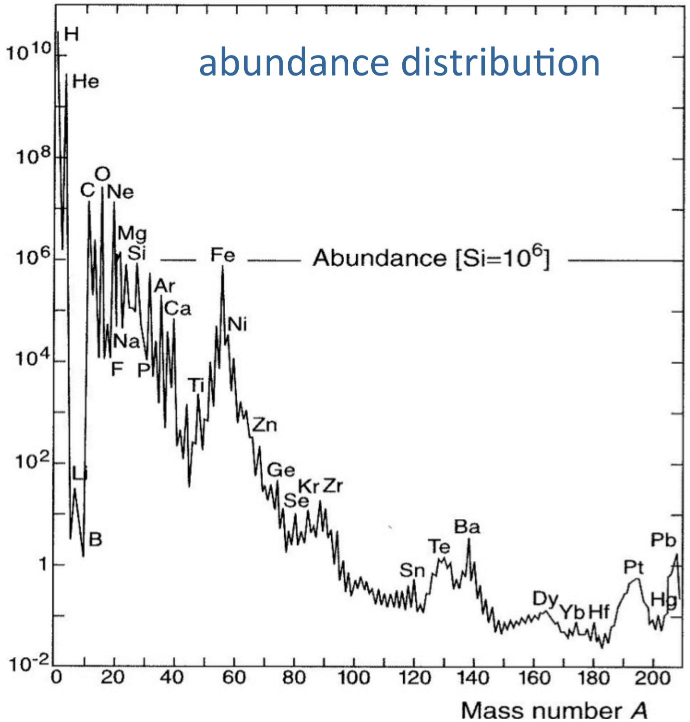
gravitational contraction

Stars



explosion ejection

DEATH



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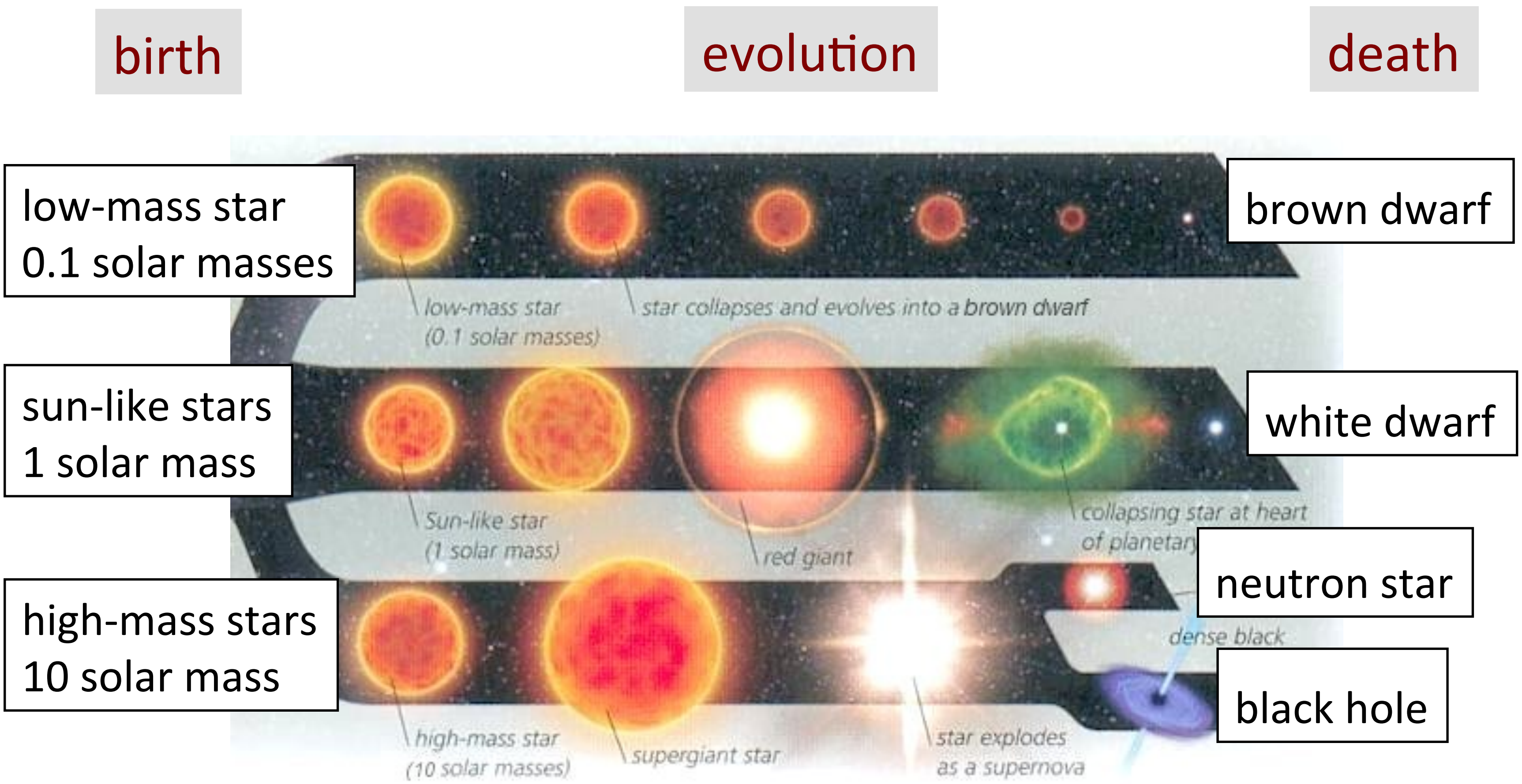


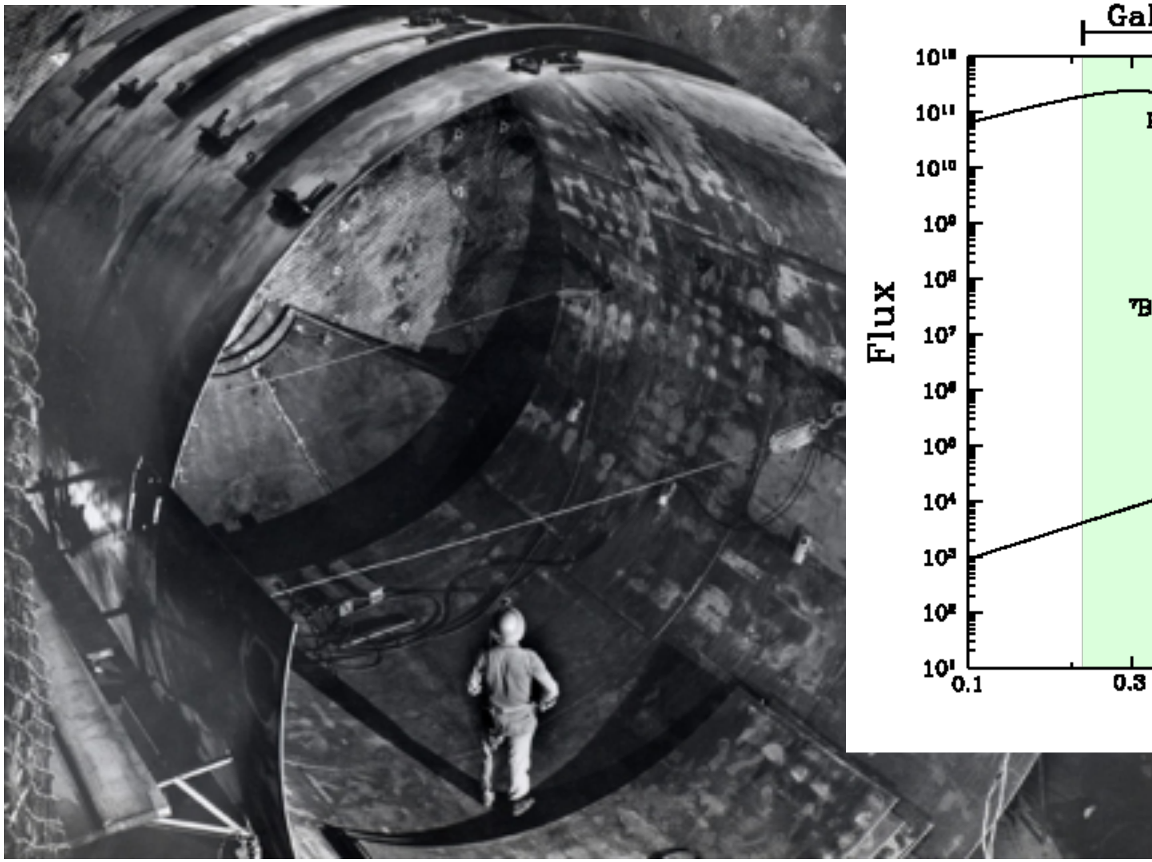
massive stars contribute to **chemical evolution** of the Universe

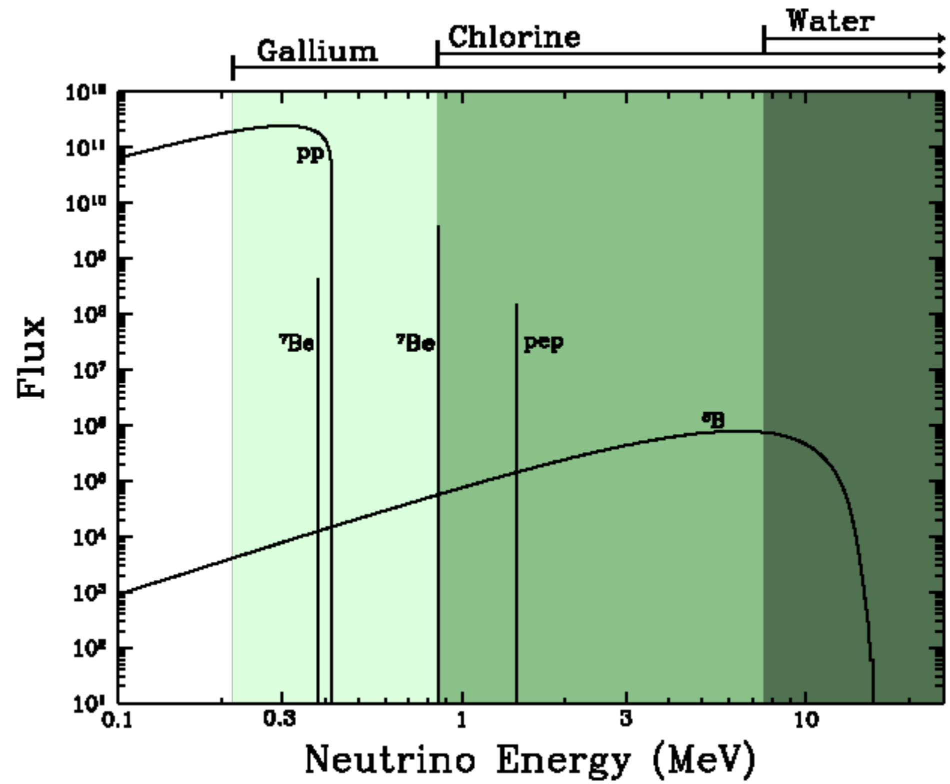
later generation stars form out of enriched material: **more metal rich**

Direct evidence for nuclear reactions in stars?

Solar Neutrino Detection at Homestake in 1960s

http://sanfordlab.org/article/270





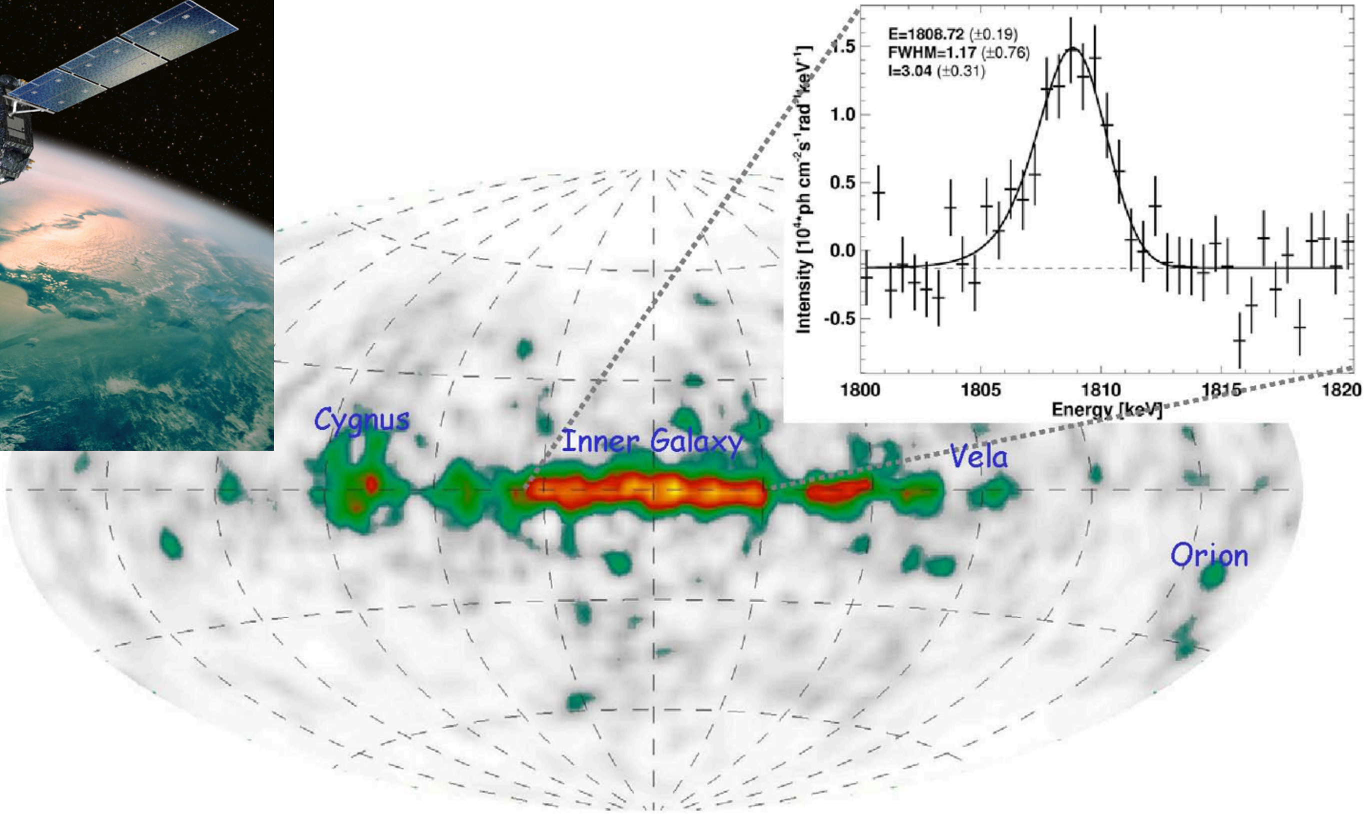
1965: Ray Davis inside chlorine tank that used as for solar neutrino detection
Credit: Anna Davis

Direct evidence of nucleosynthesis in stars

1982: discovery of 1.8 MeV γ-rays associated with ^{26}Al decay (t ½ = 7x10^5 y)

direct proof of ongoing nucleosynthesis in our Galaxy

observed with COMPTEL and INTEGRAL



Diehl et al., Nature 439 (2006) 45

Puzzling Facts and Open Questions

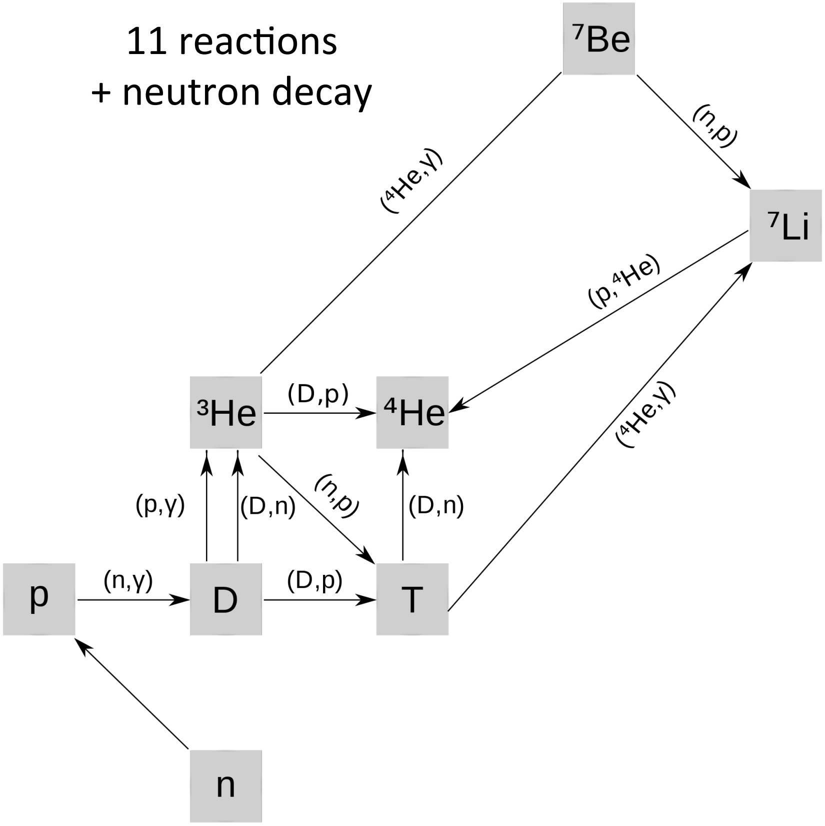
- Big Bang Nucleosynthesis: Li problem(s) and the D abundance
- Core metallicity of the Sun
- Fate of massive stars
- Explosive scenarios: X-ray bursts, novae, SN type Ia
- Pre-solar grains composition
- Origin of Heavy Elements
- Astrophysical site(s) for the r-process
- …

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



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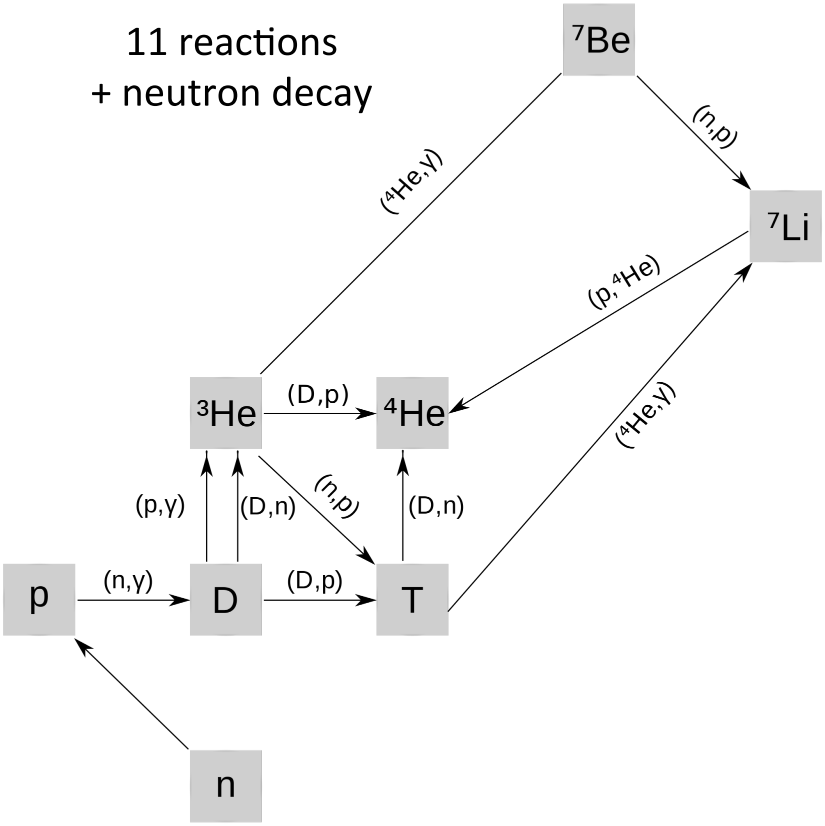

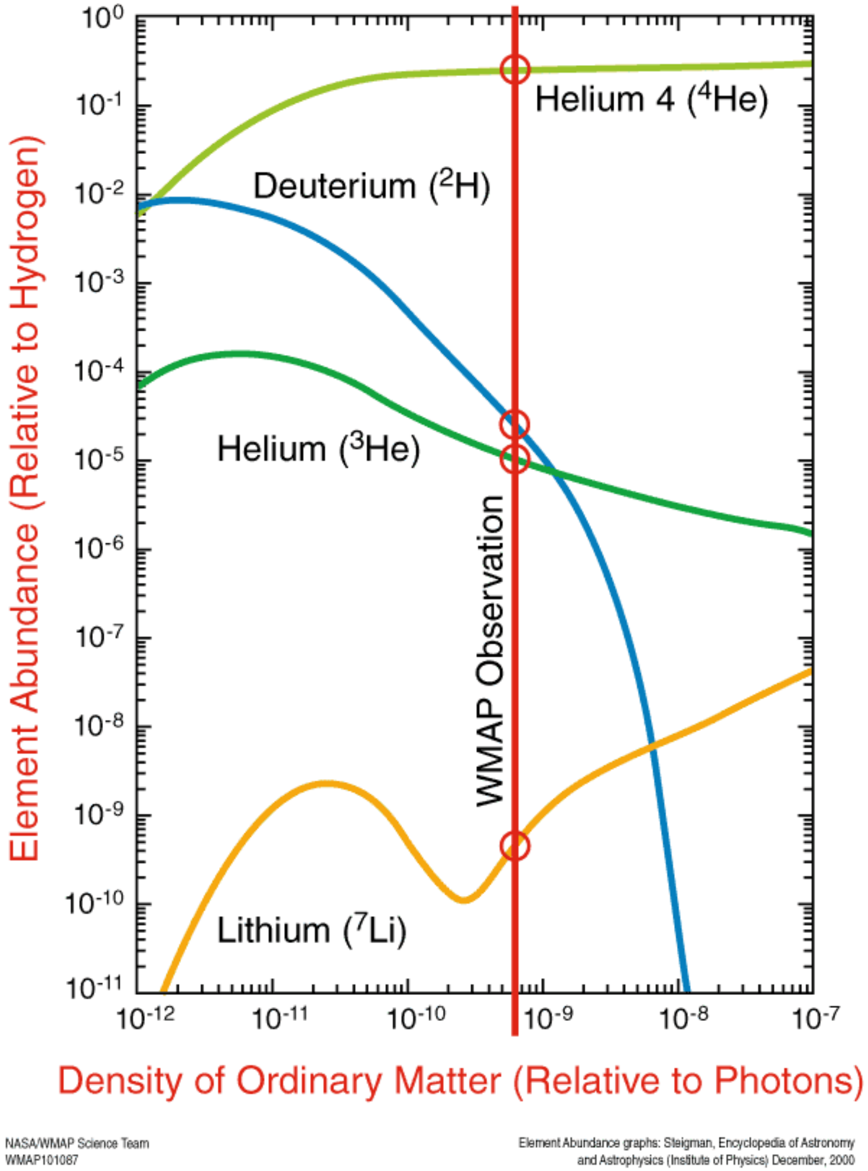

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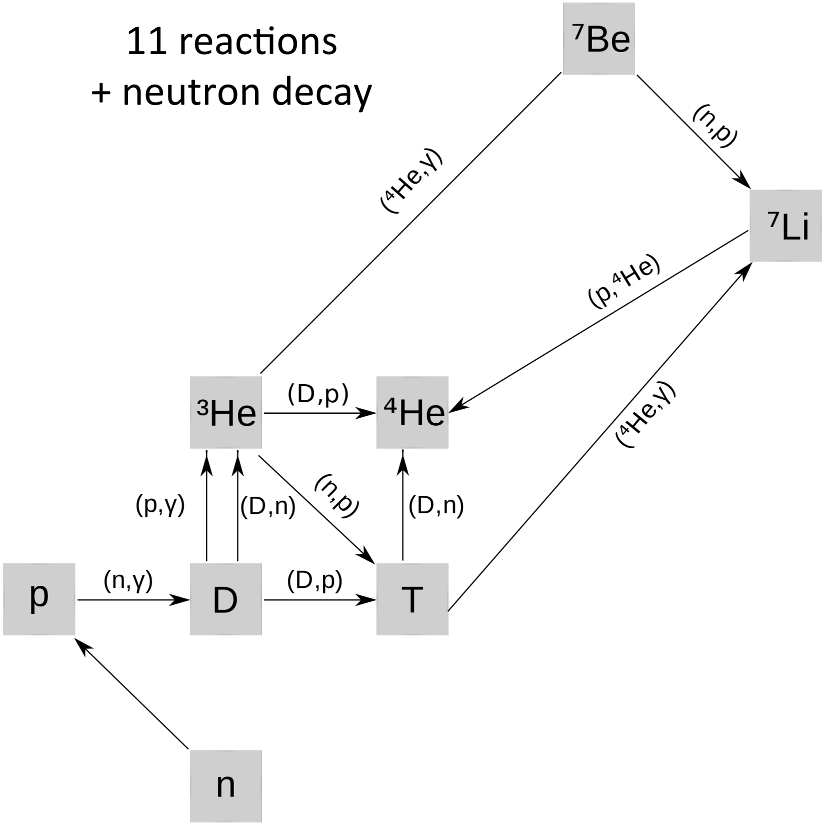
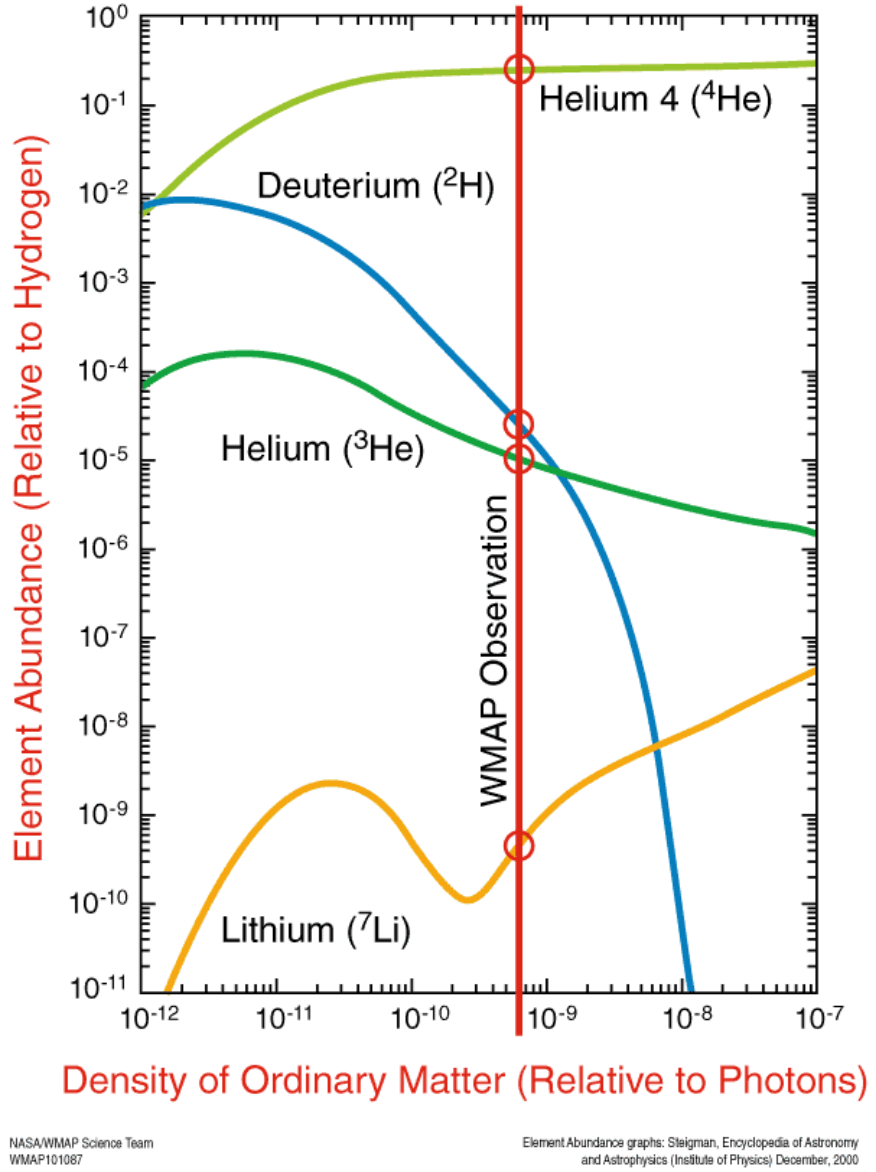


observations of D, ^{3}He, ^{4}He, and ^{7}Li in very old (**metal poor**) stars provide stringent tests of Big Bang theory



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?

first Lithium Problem

observed ^{7}Li

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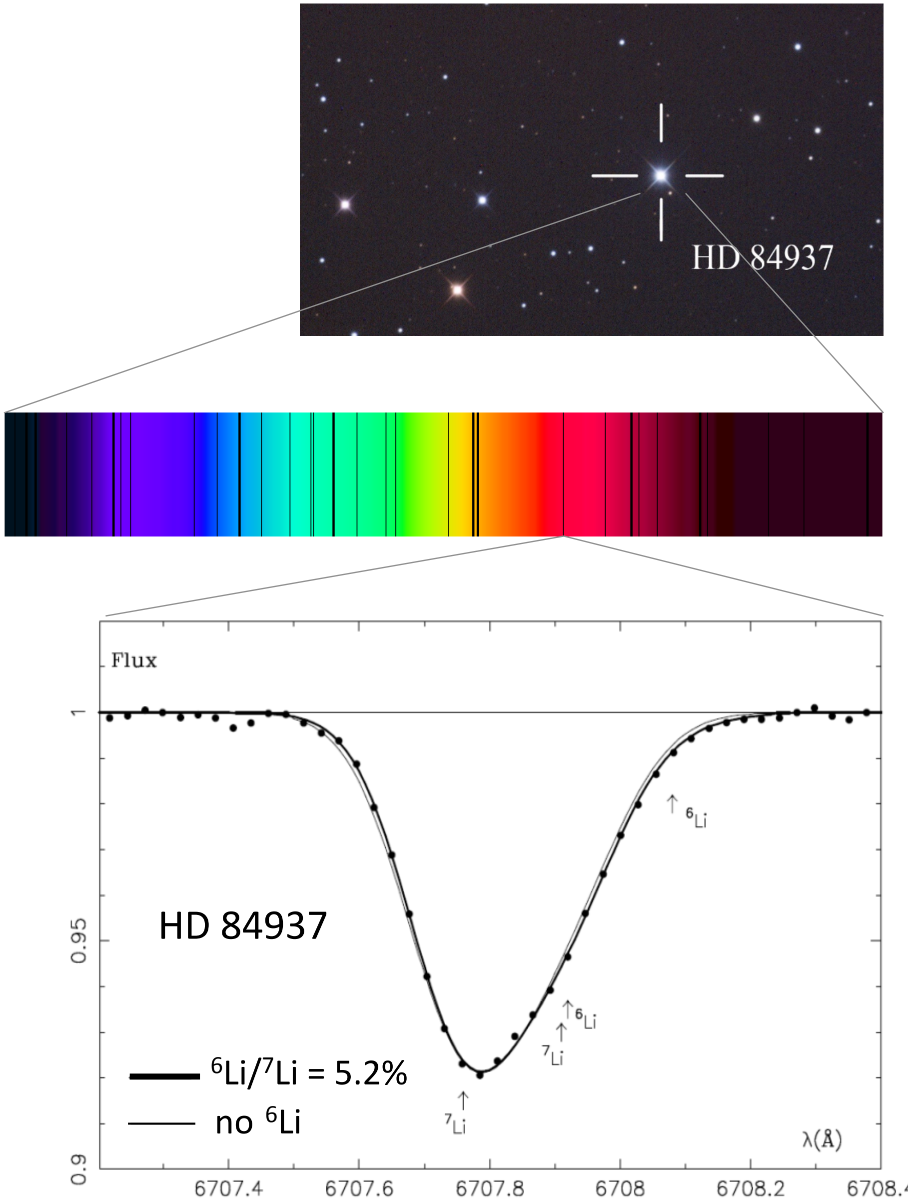
second Lithium Problem

observed ^{6}Li

~ $10^2 - 10^3$ higher than predicted



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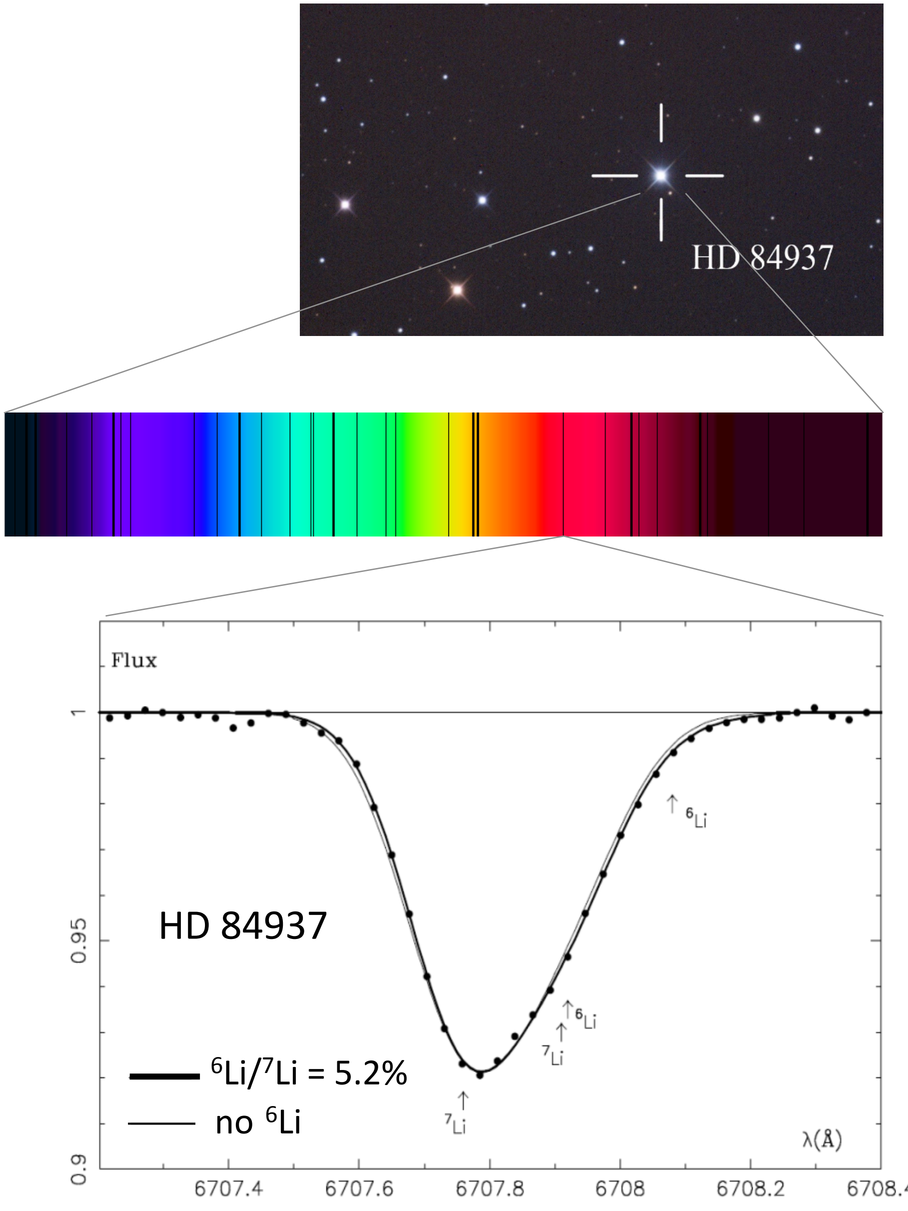


second Lithium Problem

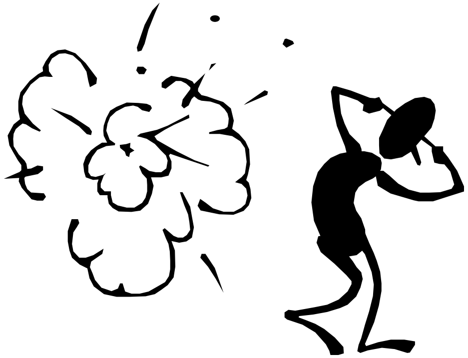
observed ^{6}Li

~ $10^2 - 10^3$ higher than predicted

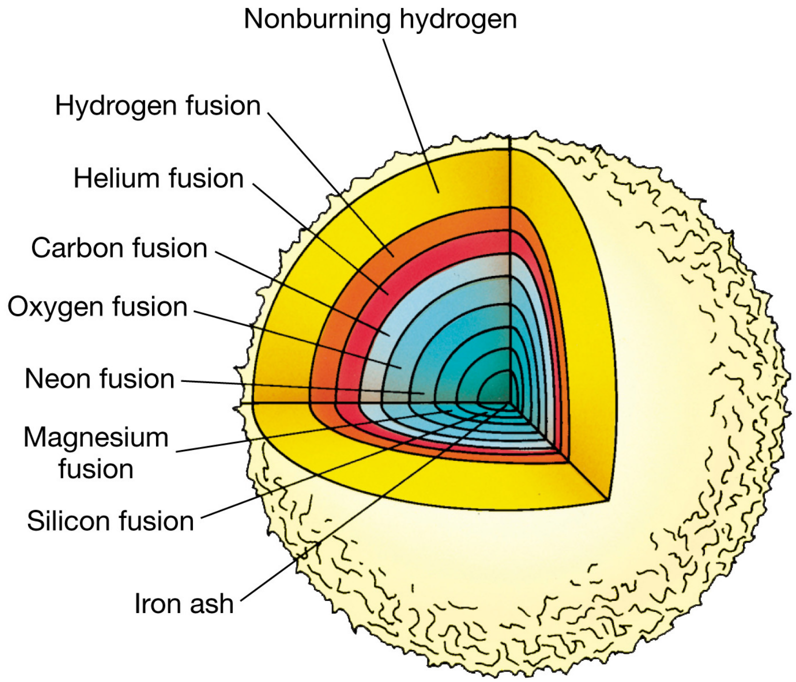
poor nuclear physics inputs
or
challenges with observation?

Fate of Massive Stars

Supernovae or White Dwarfs?



Late Evolution of Massive Stars



fusion reactions become endothermic

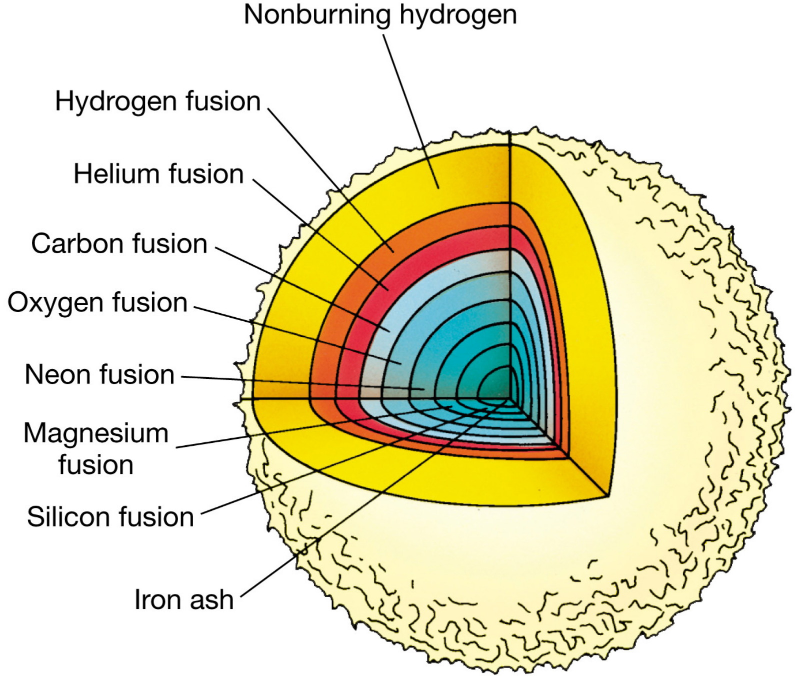
↓

gravitational collapse

↓

catastrophic supernova explosion

Late Evolution of Massive Stars



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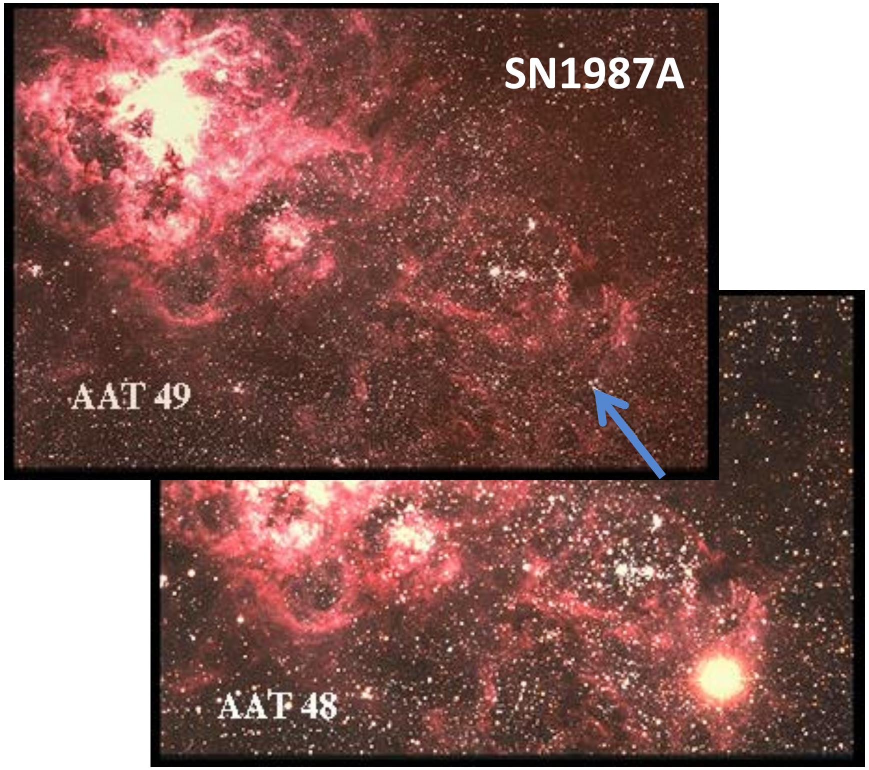

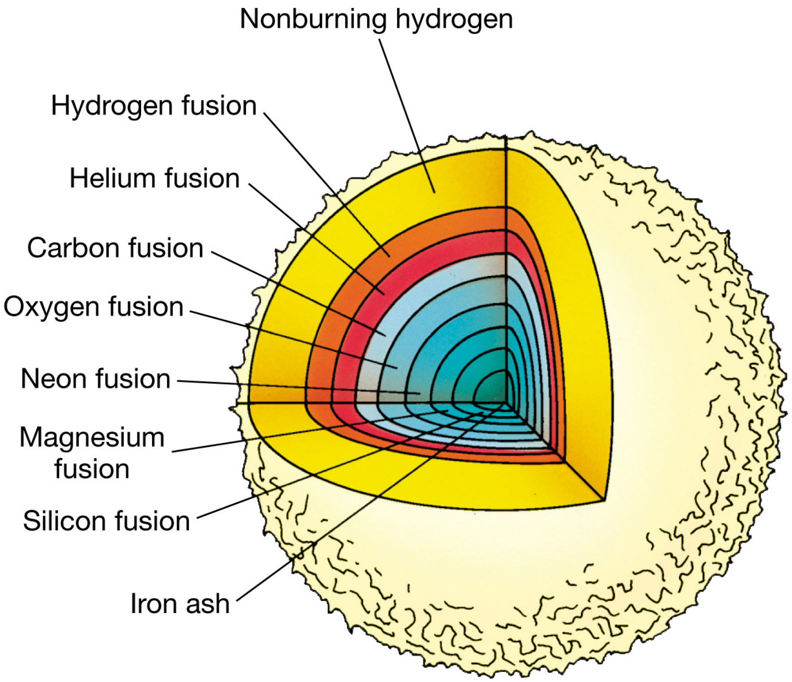

fusion reactions become endothermic

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gravitational collapse

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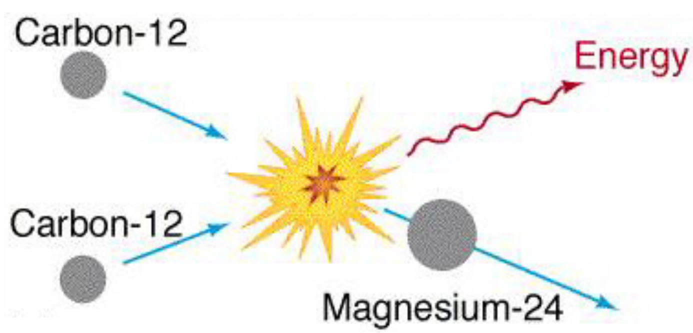
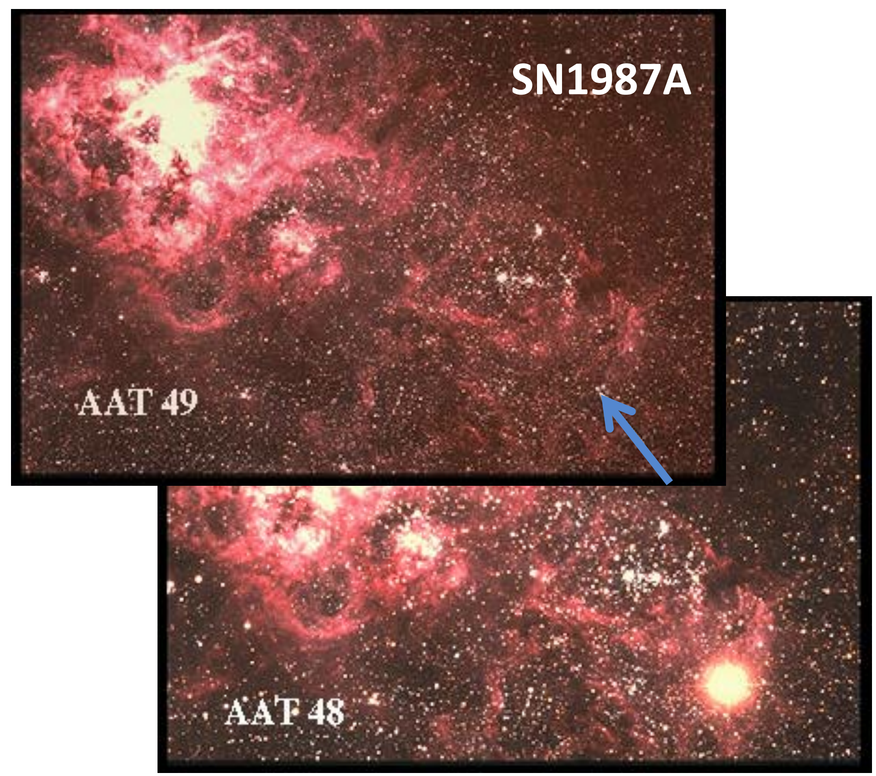
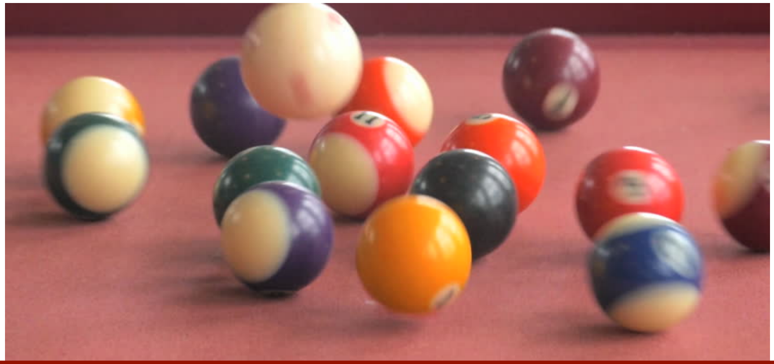
catastrophic supernova explosion

limiting mass determined by



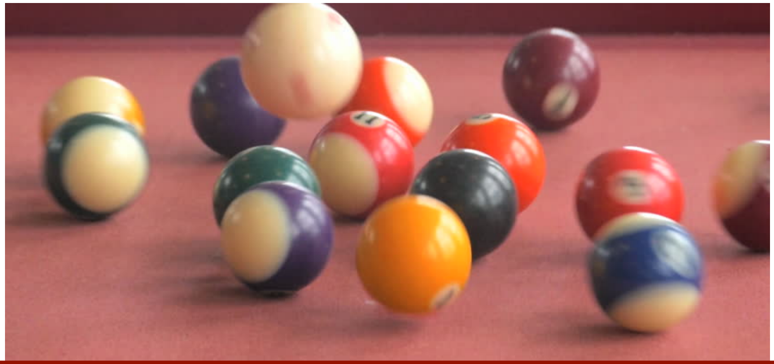
still highly uncertain





Experimental Challenges of Direct Measurements

- nuclear reactions in stars are very rare processes
  - **p+p fusion takes 10^9 y** (in the Sun)



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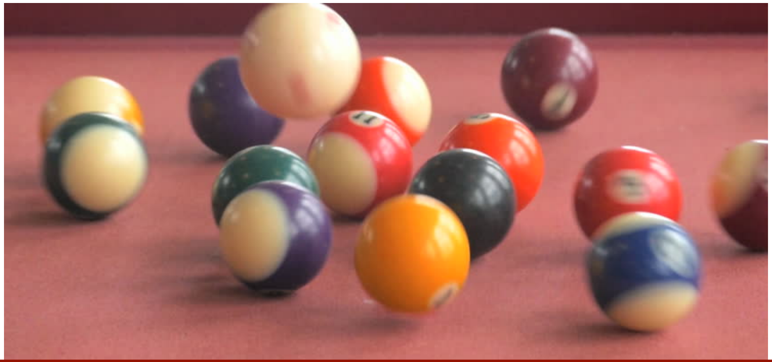
  - **1-200 events/PhD**



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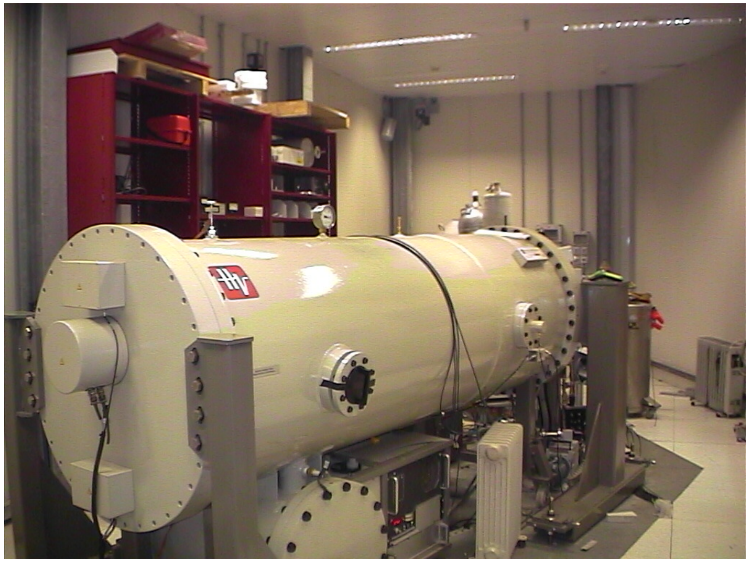
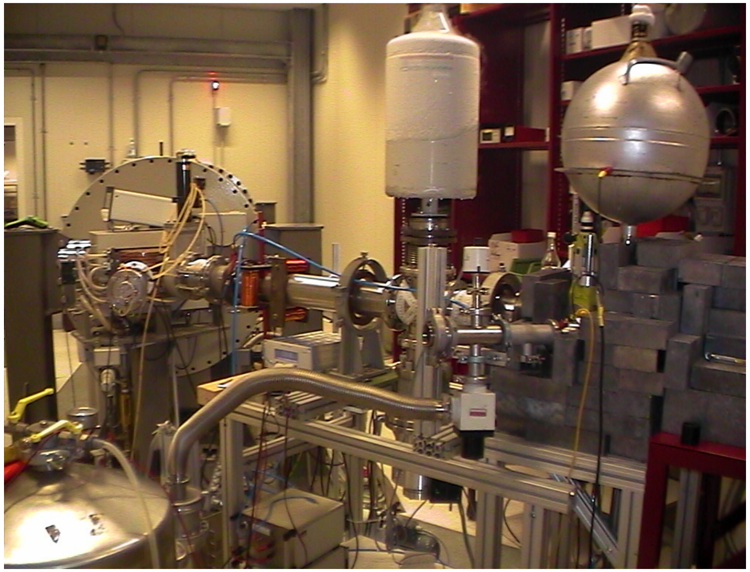
    - **1-200 events/PhD**
- need for ultra low background
    - ideally **underground**

LUNA: Laboratory for Underground Nuclear Astrophysics





only underground accelerator in the world

but new ones coming up in the US and China

LUNA

VOLUME 82, NUMBER 26 PHYSICAL REVIEW LETTERS 28 JUNE 1999

First Measurement of the $^3He(^3He, 2p)^4He$ Cross Section down to the Lower Edge of the Solar Gamow Peak

R. Bonetti,[1] C. Broggini,[2,*] L. Campajola,[3] P. Corvisiero,[4] A. D'Alessandro,[5] M. Dessalvi,[4] A. D'Onofrio,[6] A. Fubini,[7] G. Gervino,[8] L. Gialanella,[9] U. Greife,[9] A. Guglielmetti,[1] C. Gustavino,[5] G. Imbriani,[3] M. Junker,[5] P. Prati,[4] V. Roca,[3] C. Rolfs,[9] M. Romano,[3] F. Schuemann,[9] F. Strieder,[9] F. Terrasi,[3] H.P. Trautvetter,[9] and S. Zavatarelli[4]
(LUNA Collaboration)

excluded a "nuclear solution" to the missing neutrino problem

LUNA

VOLUME 82, NUMBER 26 PHYSICAL REVIEW ... 28 JUNE 1999

First Measurement of the $^{3}He(^{3}$... ...dge

R. Bonetti,[1] C. Broggini,[2,*] ... Fubini,[7]
G. Gervino,[8] L. Gial... ... Roca,[3]
C. Rol...

Available online at www.sciencedirect.com
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Physics Letters B 634 (2006) 483–487
PHYSICS LETTERS B
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ELSEVIER

First measurement of the $^{14}N(p,\gamma)^{15}O$ cross section down to 70 keV

LUNA Collaboration

A. Lemut[a], D. Bemmerer[b], F. Confortola[a], R. Bonetti[c], C. Broggini[b,*], P. Corvisiero[a], H. Costantini[a], J. Cruz[d], A. Formicola[e], Zs. Fülöp[f], G. Gervino[g], A. Guglielmetti[c], C. Gustavino[e], Gy. Gyürky[f], G. Imbriani[h], A.P. Jesus[d], M. Junker[e], B. Limata[h], R. Menegazzo[b], P. Prati[a], V. Roca[h], D. Rogalla[i], C. Rolfs[j], M. Romano[h], C. Rossi Alvarez[b], F. Schümann[j], E. Somorjai[f], O. Straniero[k], F. Strieder[j], F. Terrasi[i], H.P. Trautvetter[j]

...blem

slowest reaction in CNO cycle in the Sun

LUNA

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

Fir ... Edge

... keV

R. Bonet ... . Fubini,[7]
G. Gerv ... . Roca,[3]

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

www.elsevier.com/locate/physletb

Astronomy & Astrophysics

The bottleneck of CNO burning and the age of Globular Clusters

G. Imbriani[1,2,3], H. Costantini[4], A. Formicola[5,6], D. Bemmerer[7], R. Bonetti[8], C. Broggini[9], P. Corvisiero[4], J. Cruz[10], Z. Fülöp[11], G. Gervino[12], A. Guglielmetti[8], C. Gustavino[6], G. Gyürky[11], A. P. Jesus[10], M. Junker[6], A. Lemut[4], R. Menegazzo[9], P. Prati[4], V. Roca[2,3], C. Rolfs[5], M. Romano[2,3], C. Rossi Alvarez[9], F. Schümann[5], E. Somorjai[11], O. Straniero[1,2], F. Strieder[5], F. Terrasi[2,13], H. P. Trautvetter[5], A. Vomiero[14], and S. Zavatarelli[4],

ELSEVIER

First measureme...

A. Lemut[a], D. Bemmerer[b], ... A. Formicola ... H. Costantini[a], J. Cruz[d], A.P. Jesu... Gy. Gyürky[f], G. Imbriani[h], ... M. Rom... V. Roca[h], D. Rogalla[i], C. Rolfs[j], ... O. Straniero ...

increased age of universe by 1 billion years

slowest reaction ...

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

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

Fir ... Edge

PHYSICS LETTERS B
www.elsevier.com/locate/physletb

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]

increased rate by factor 2.5 → faster ^{17}O destruction

A. Lemut[a], D. Bem... H. Costantini[a], J. Cruz[d], A. For... Gy. Gyürky[f], G. Imbriani[h], A.P. Je... V. Roca[h], D. Rogalla[i], C. Rolfs[j], M. Ro...

... S. Zavatarelli[4], E. Somorjai[11], ... Lemut[4]

slowest reaction

1 billion years


A&A 420, 625–629 (2004)
DOI: 10.1051/0004-6361:20040981
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VOLUME 82, N
28 JUNE 1999
PRL 117, 142502 (2016)
week ending
PTEMBER 2016
LETTERS
PUBLISHED: 30 JANUARY 2017 | VOLUME: 1 | ARTICLE NUMBER: 0027
nature astronomy
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]
solving puzzle on origin of some pre-solar grains

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)

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  $^{13}C(\alpha,n)^{16}O$ (to start soon)

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

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

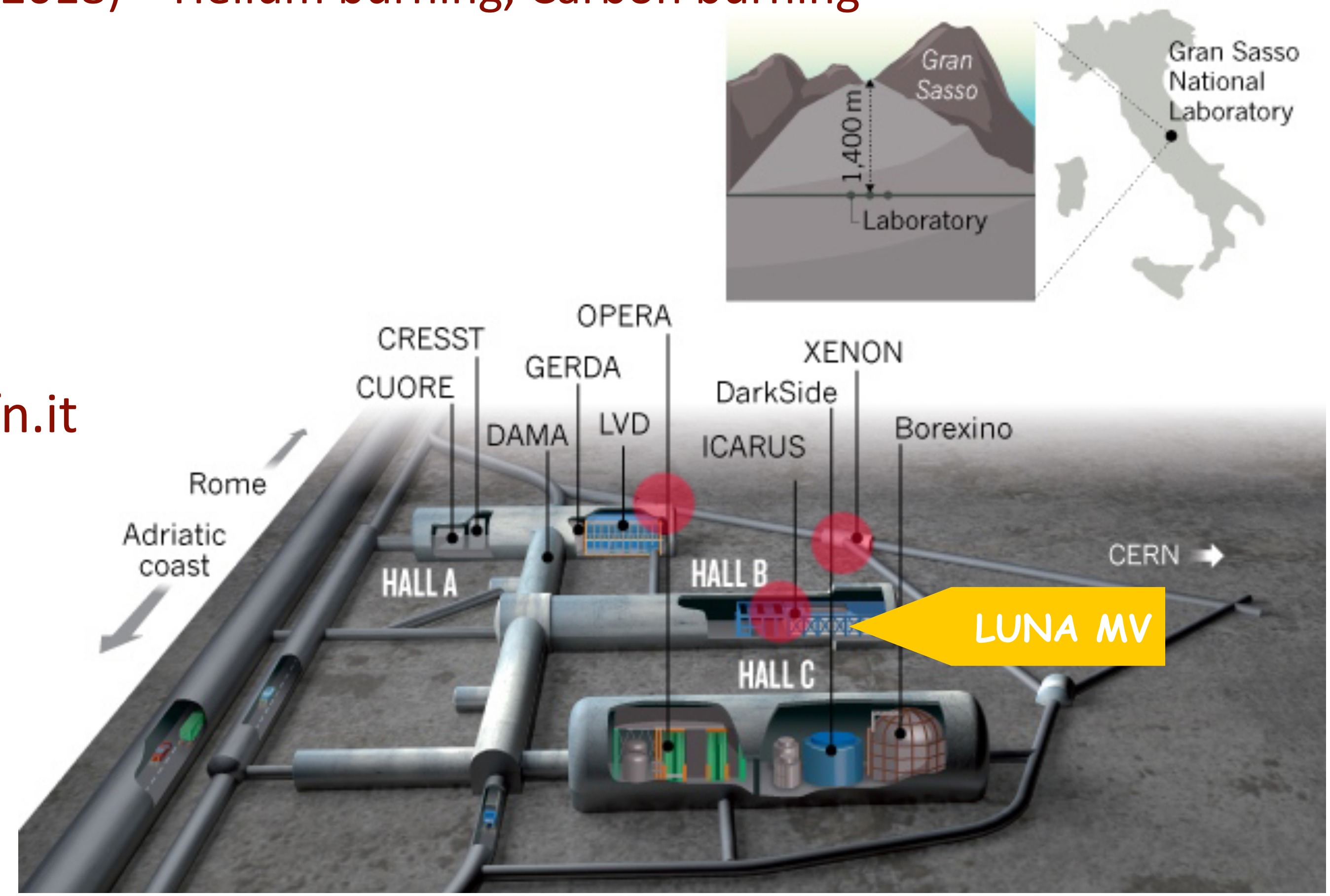
THE LUNA Collaboration

LUNA 50 kV (1992-2001) – Solar Phase

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

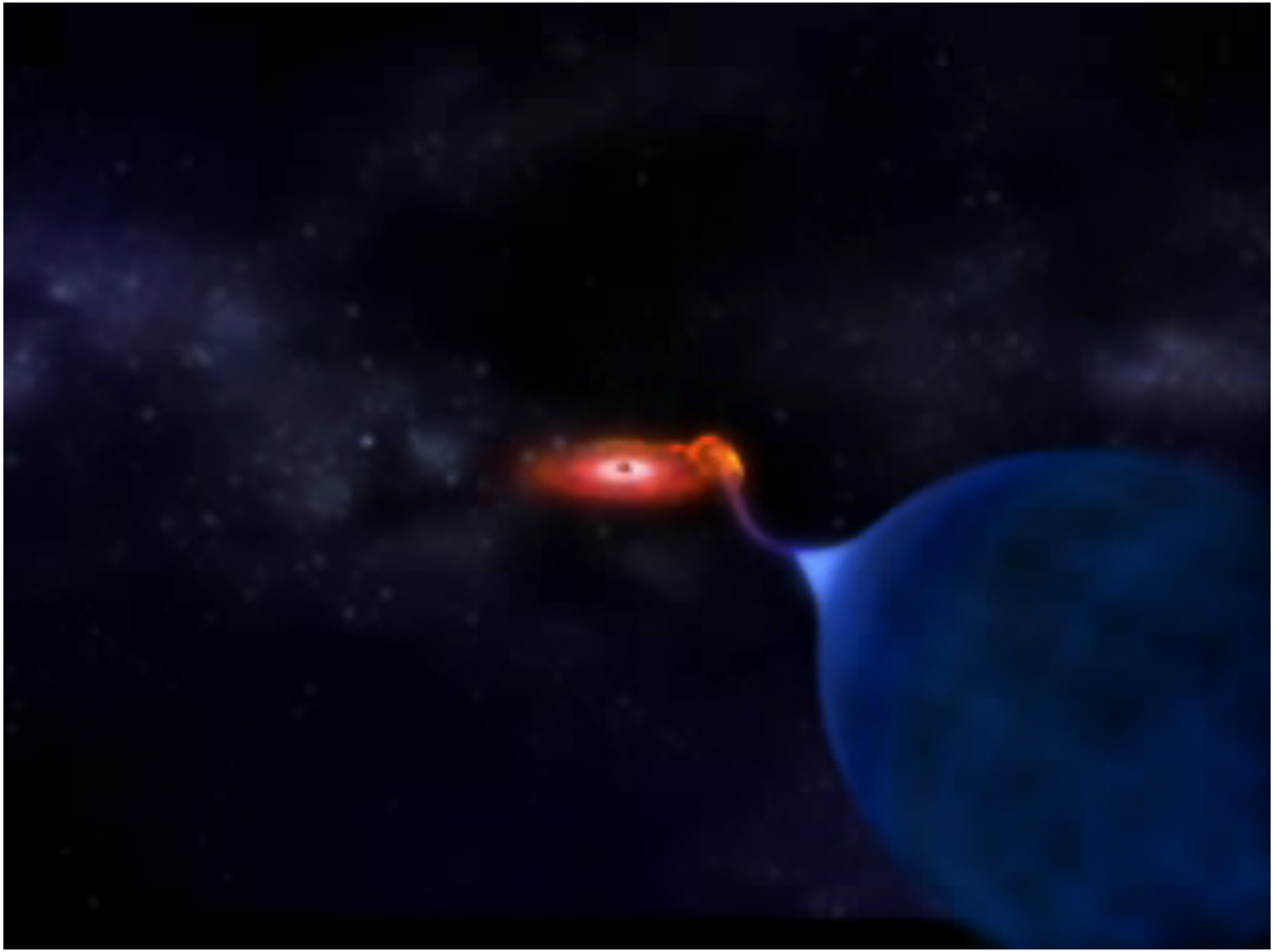
LUNA-MV (from 2018) – Helium burning, Carbon burning

https://luna.lngs.infn.it

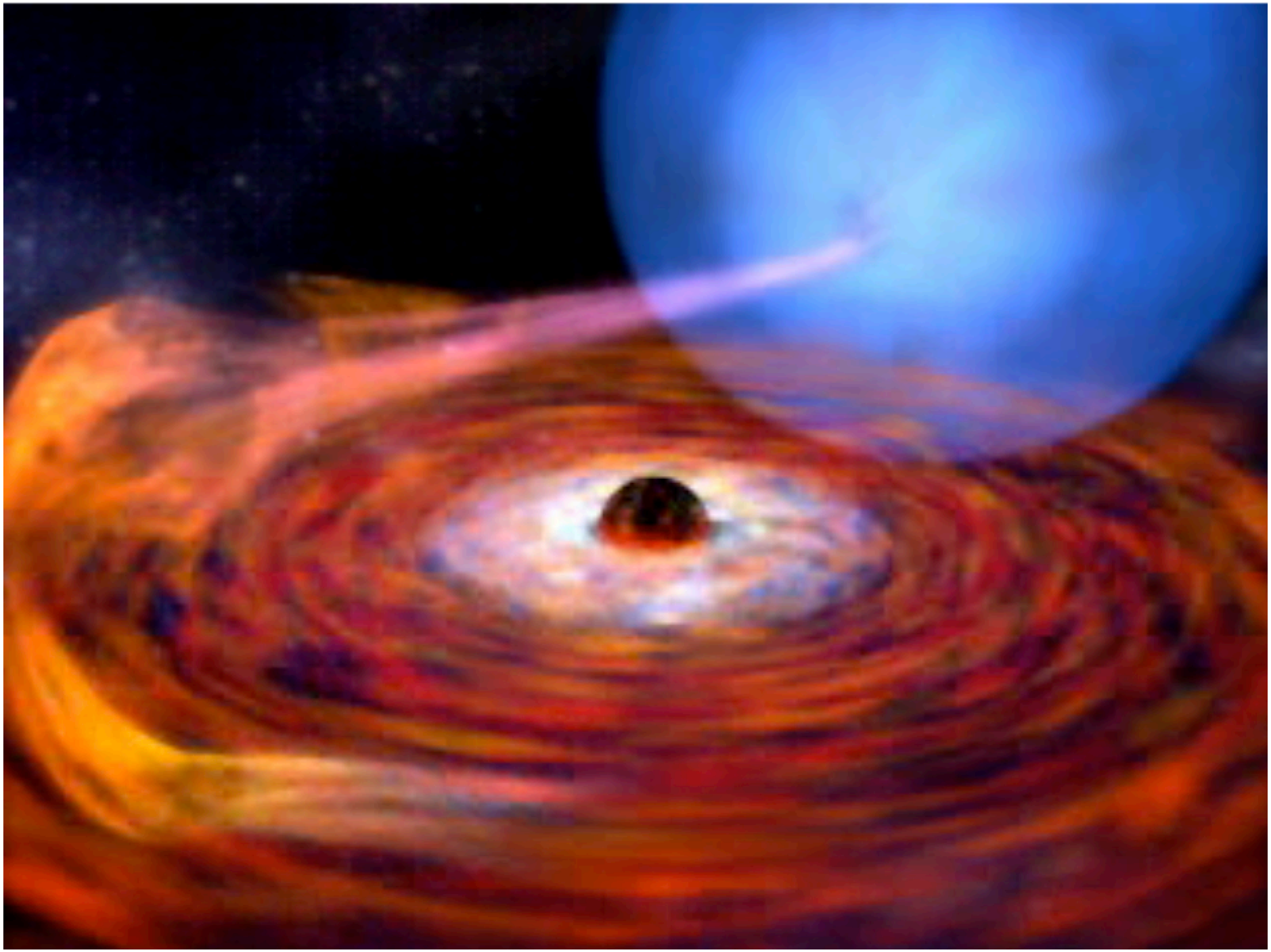


X-ray Bursts and Other Explosions

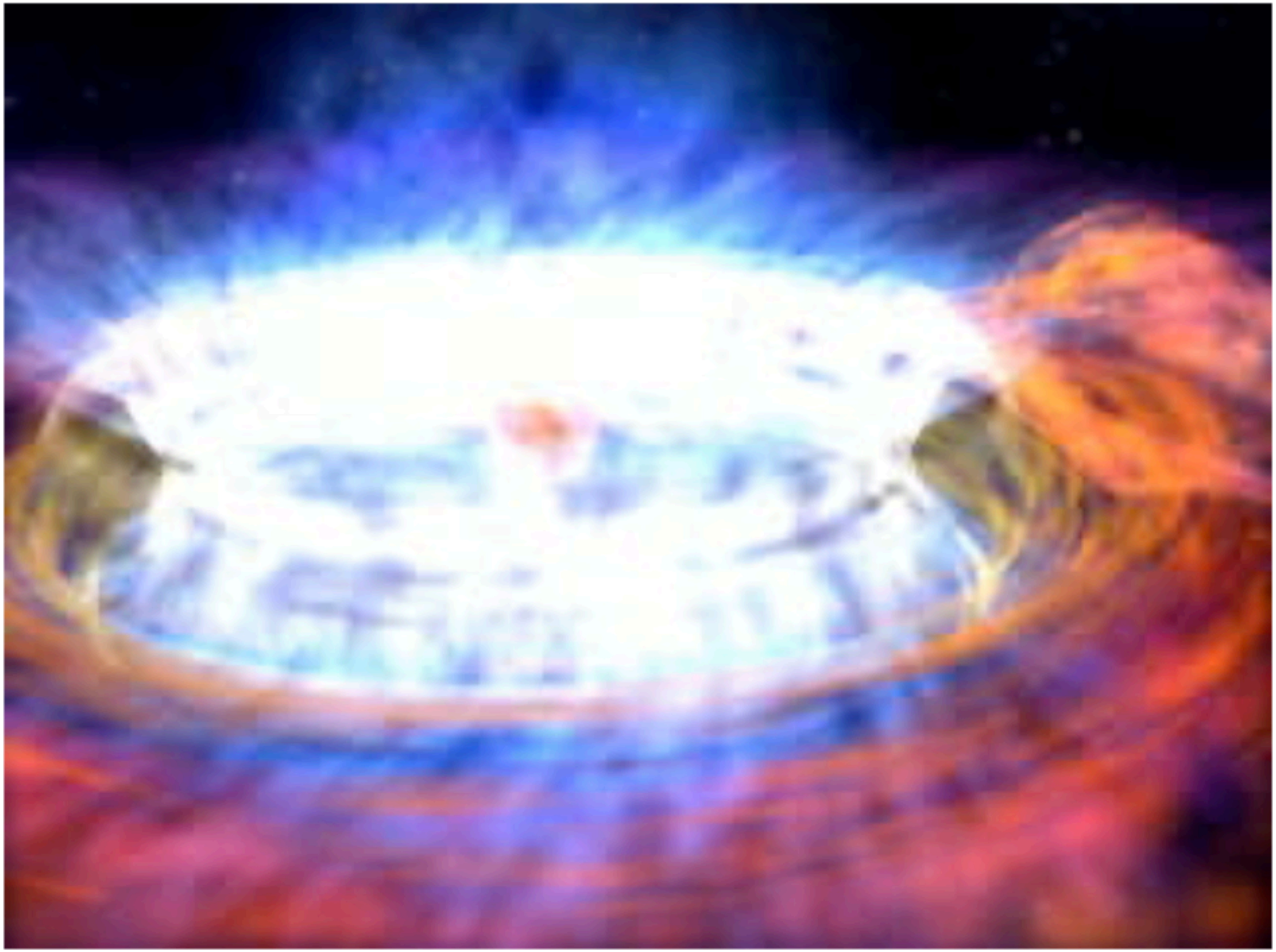
50% of stars found in binary systems



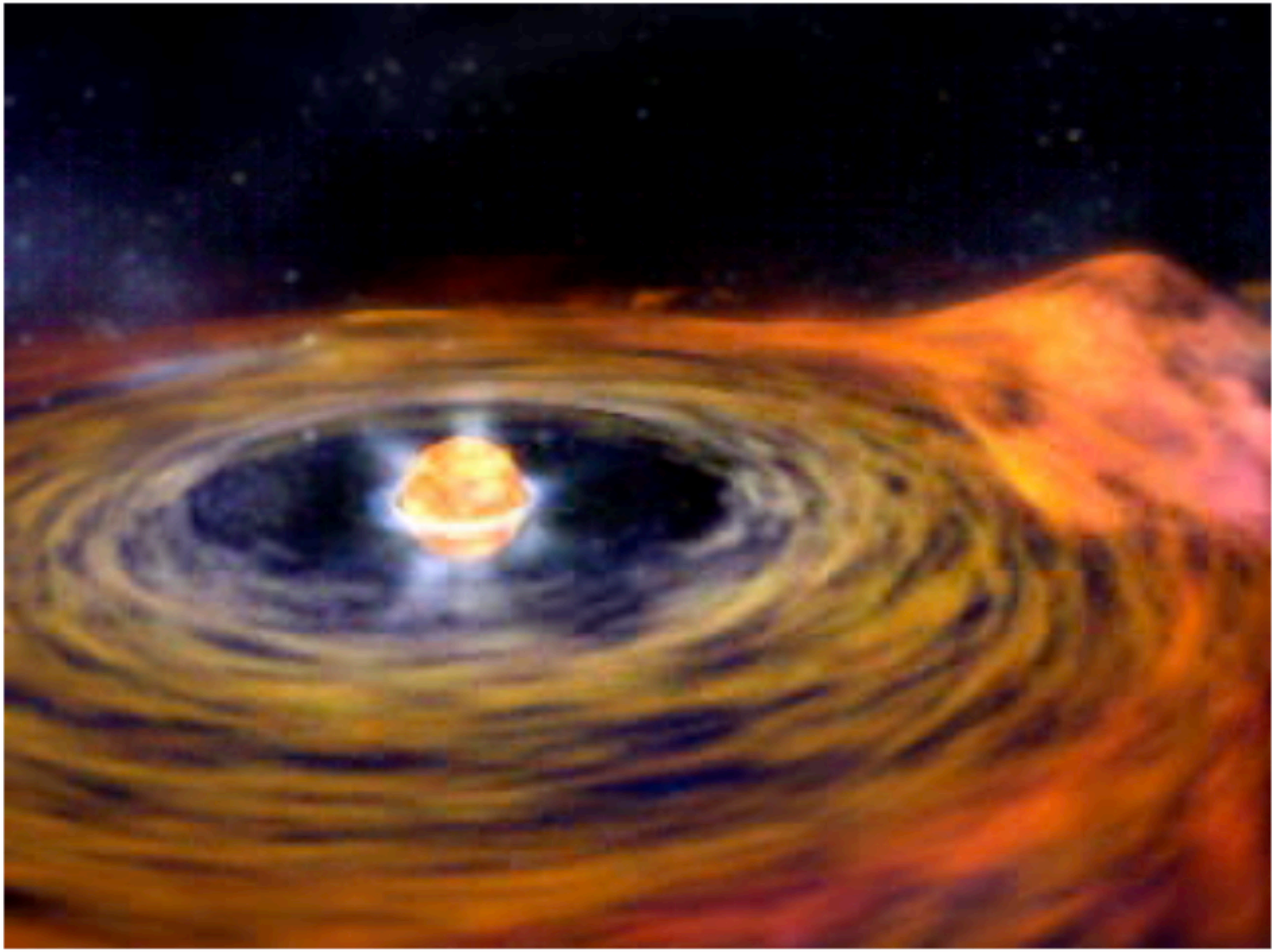
50% of stars found in binary systems



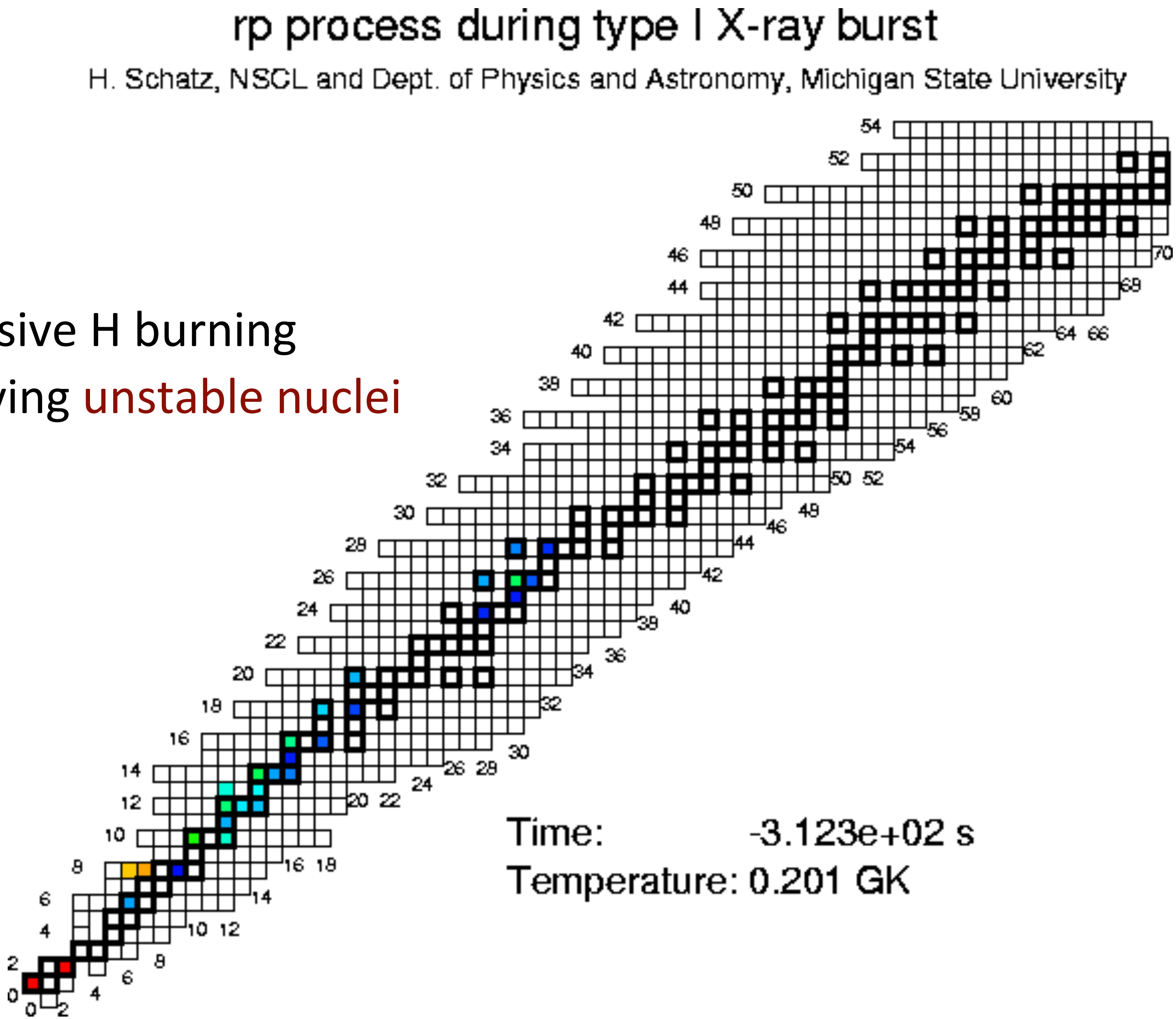
50% of stars found in binary systems



50% of stars found in binary systems

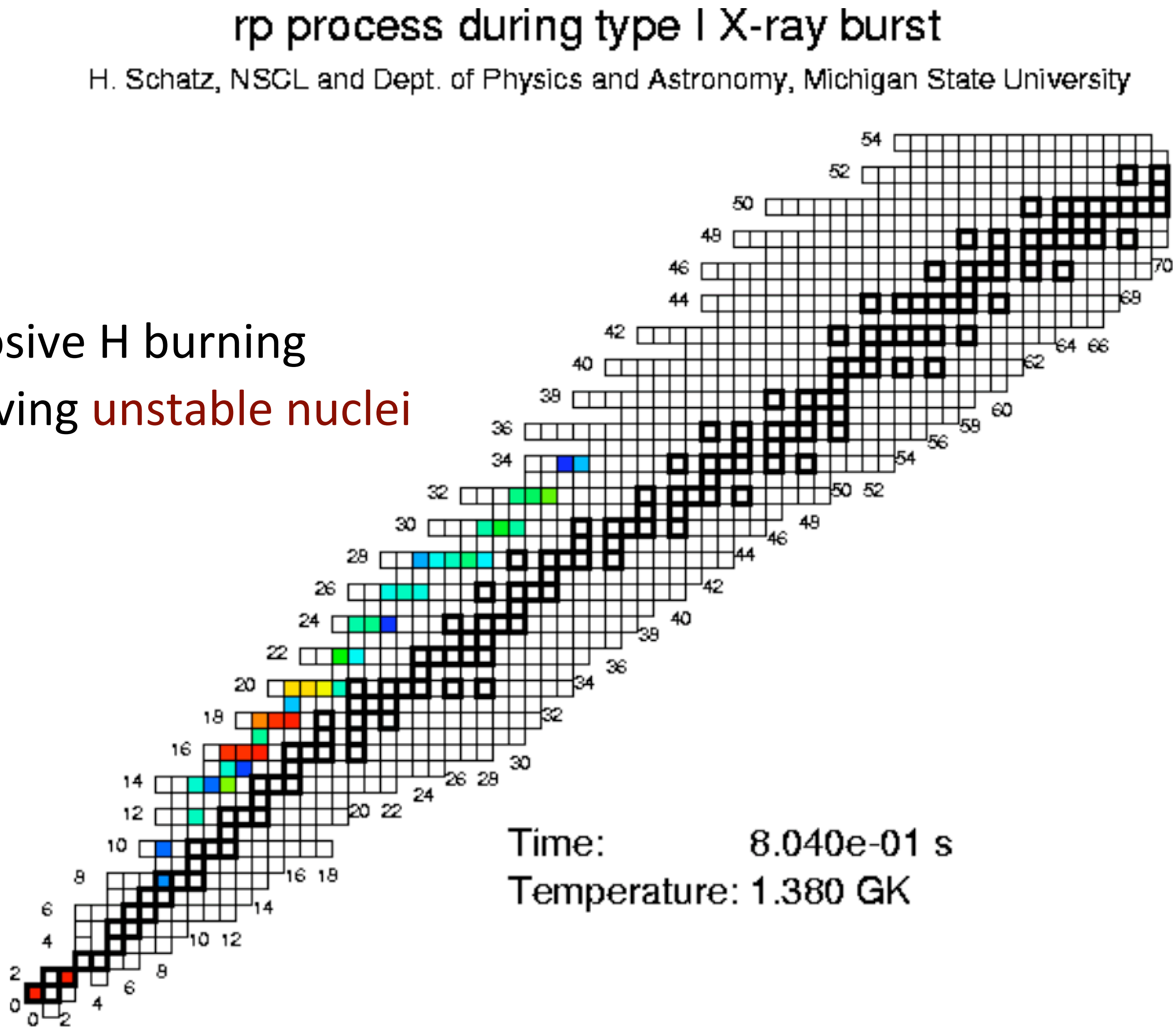


explosive H burning
involving unstable nuclei



Nucleosynthesis Path in X-ray Bursts

explosive H burning
involving unstable nuclei



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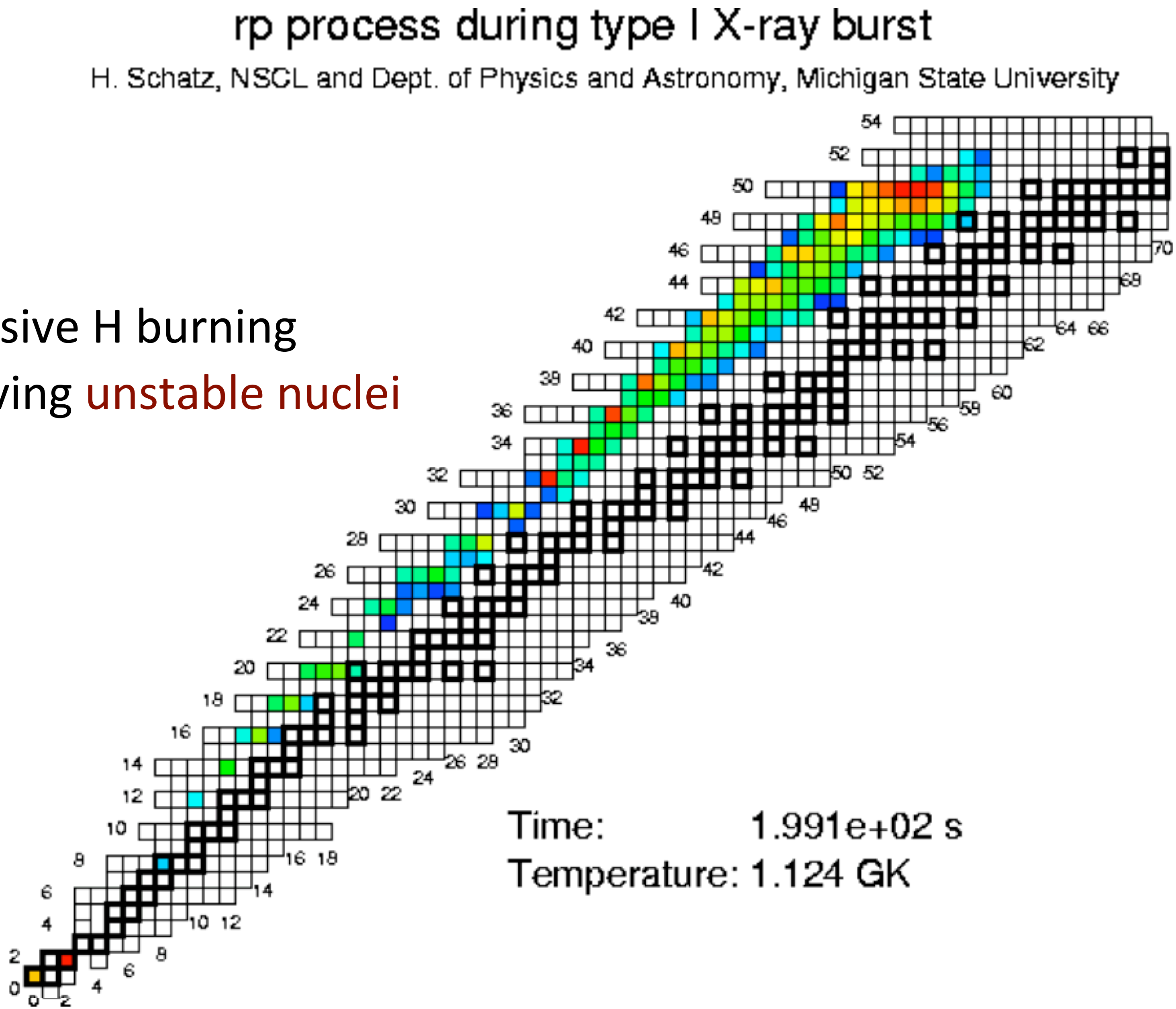

Nucleosynthesis Path in X-ray Bursts

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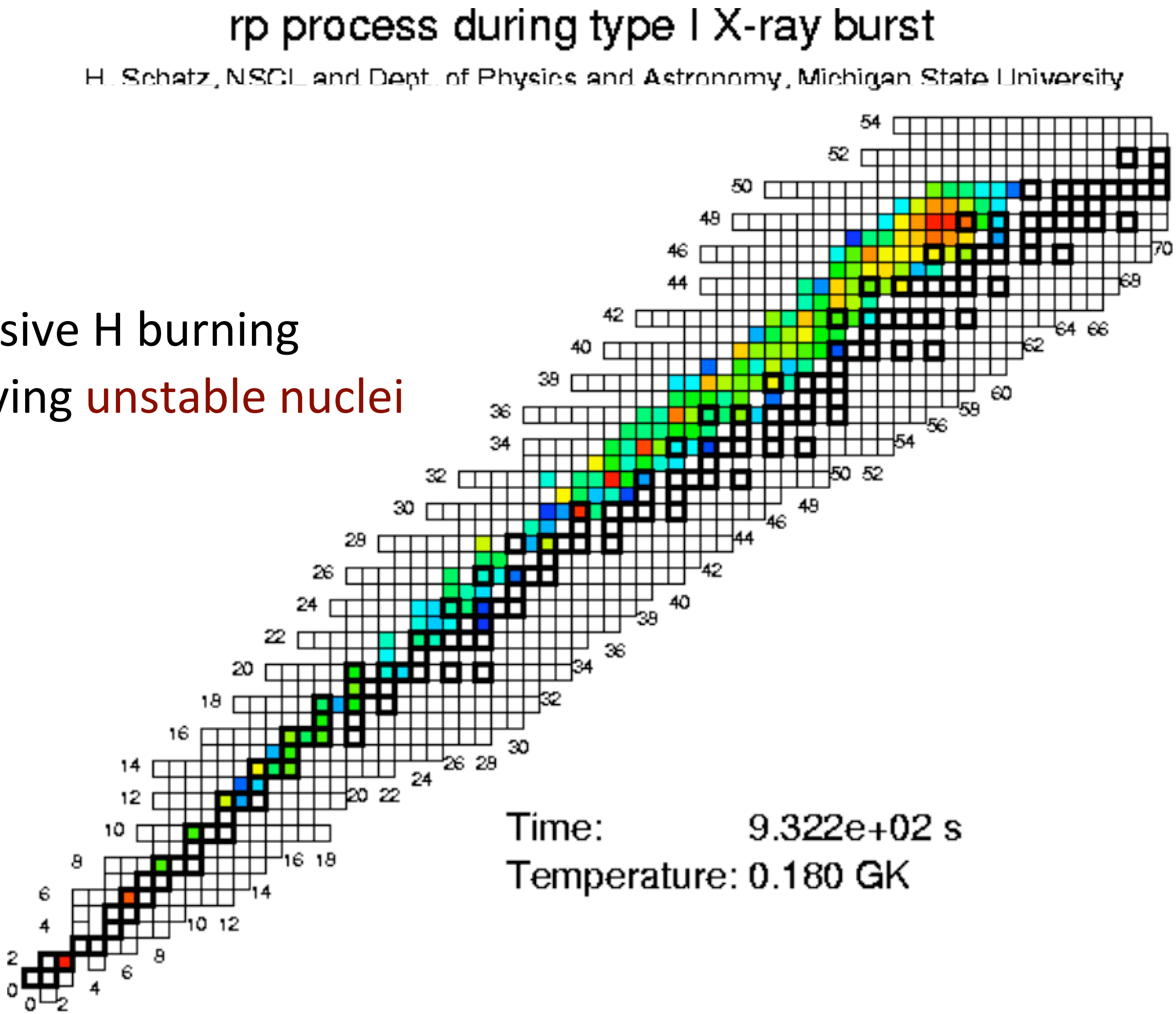
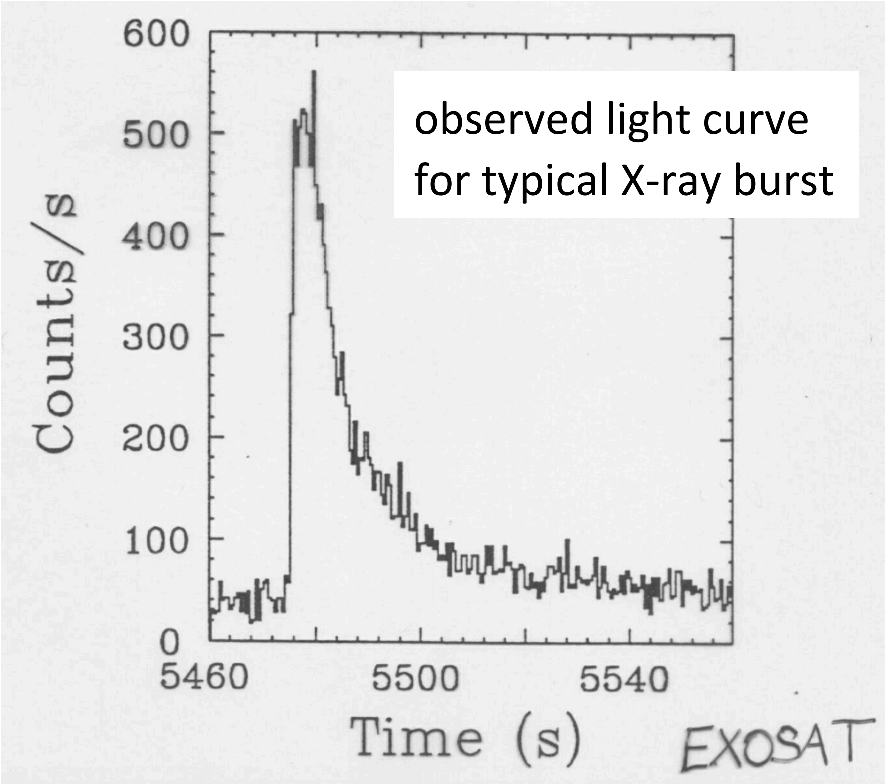


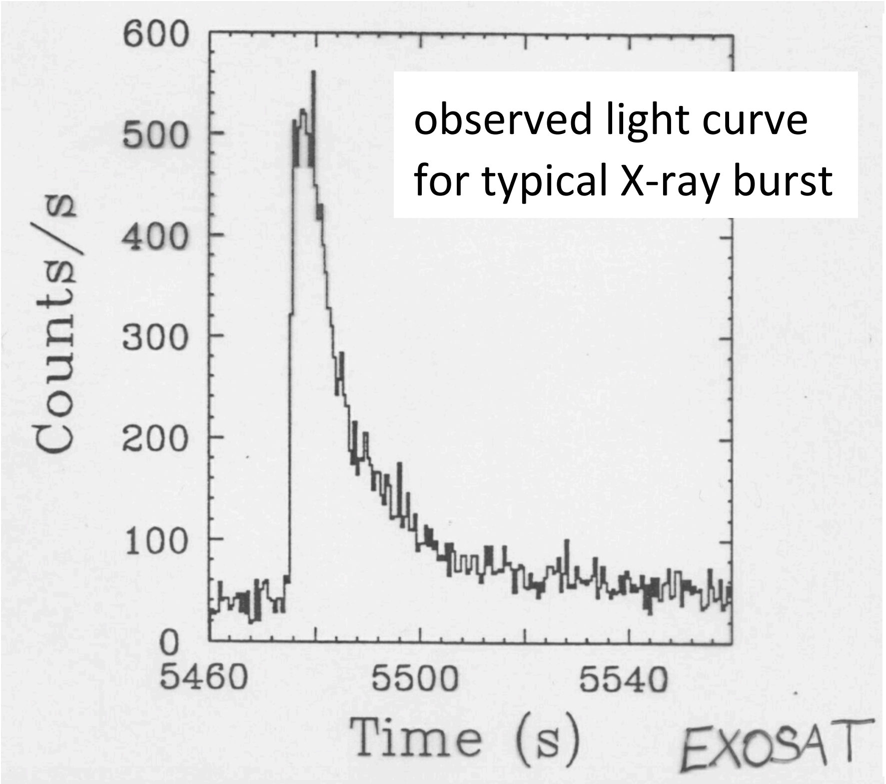
light curves measured to great accuracy

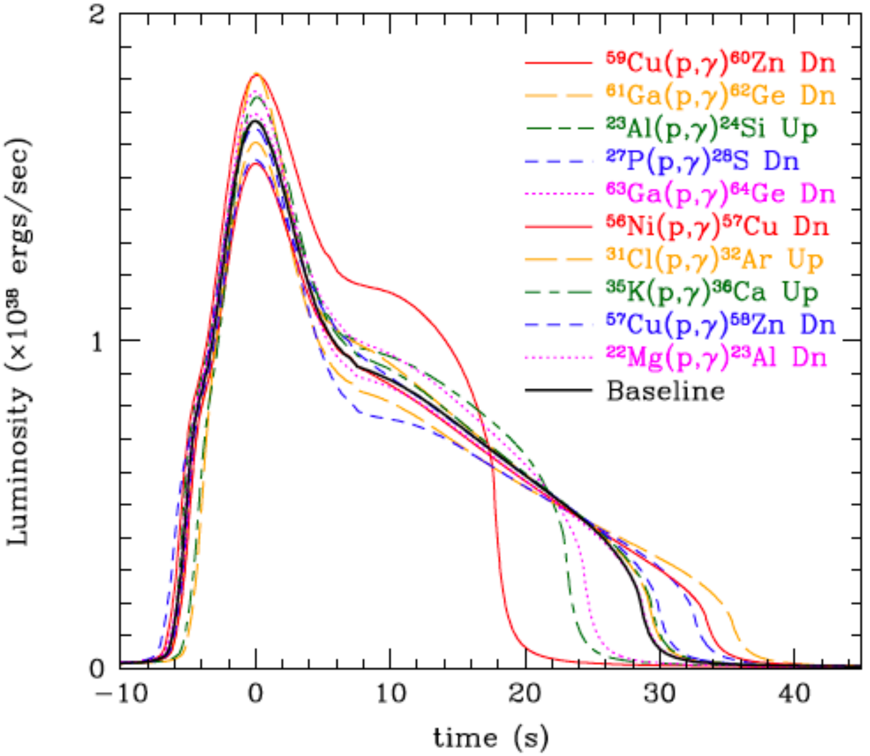


light curves measured to great accuracy

sensitivity studies to assess impact of reaction rate uncertainties

validate models against observations





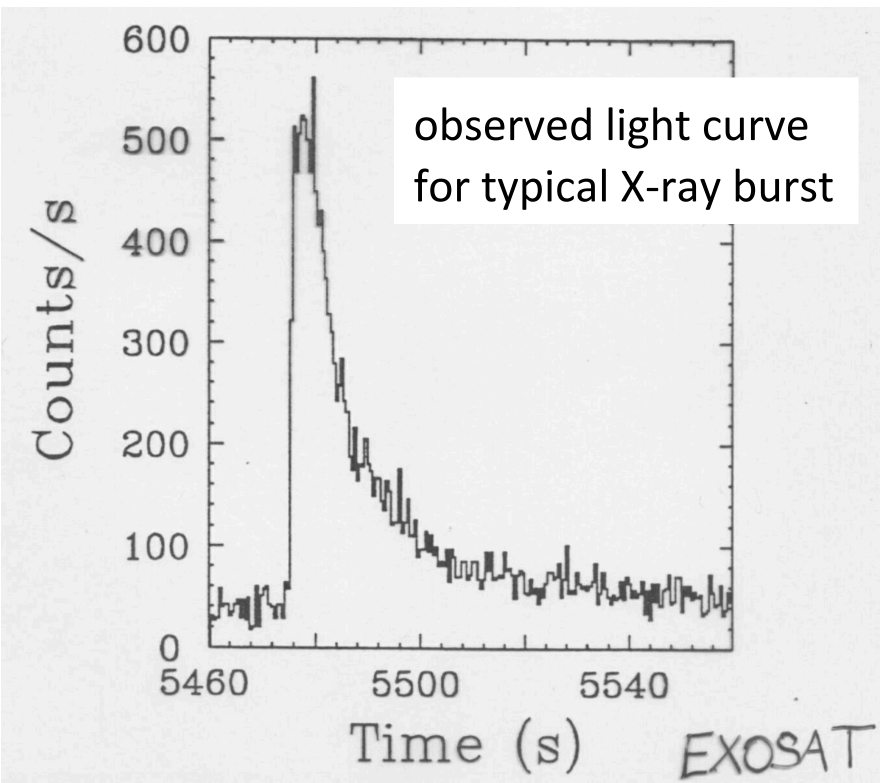
Cyburt *et al.* 2016

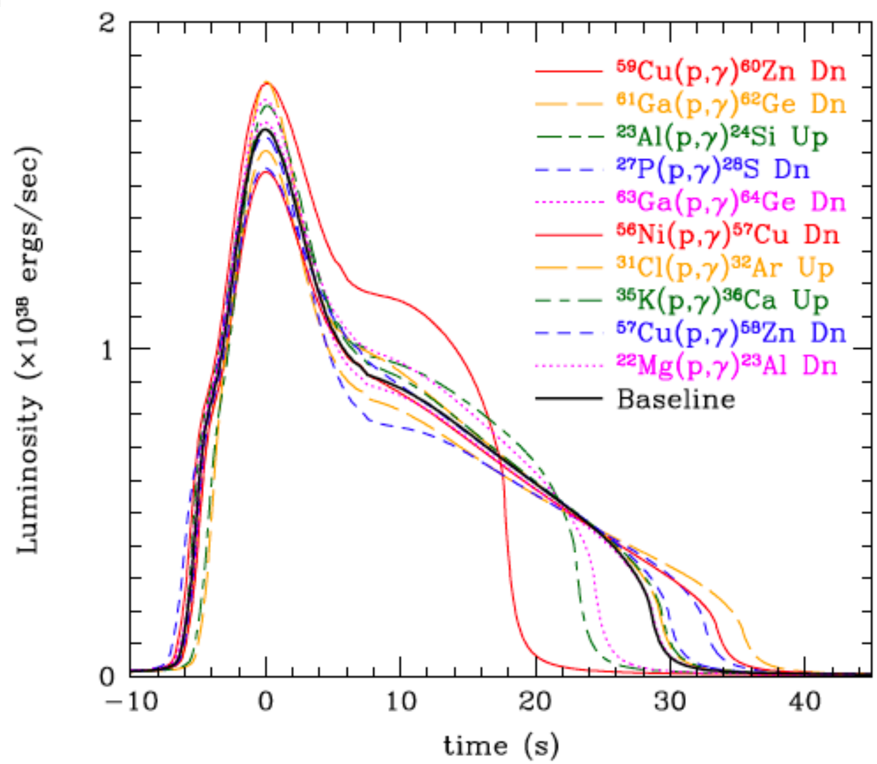
light curves measured to great accuracy

sensitivity studies to assess impact of reaction rate uncertainties

validate models against observations

yet most reactions beyond current capabilities



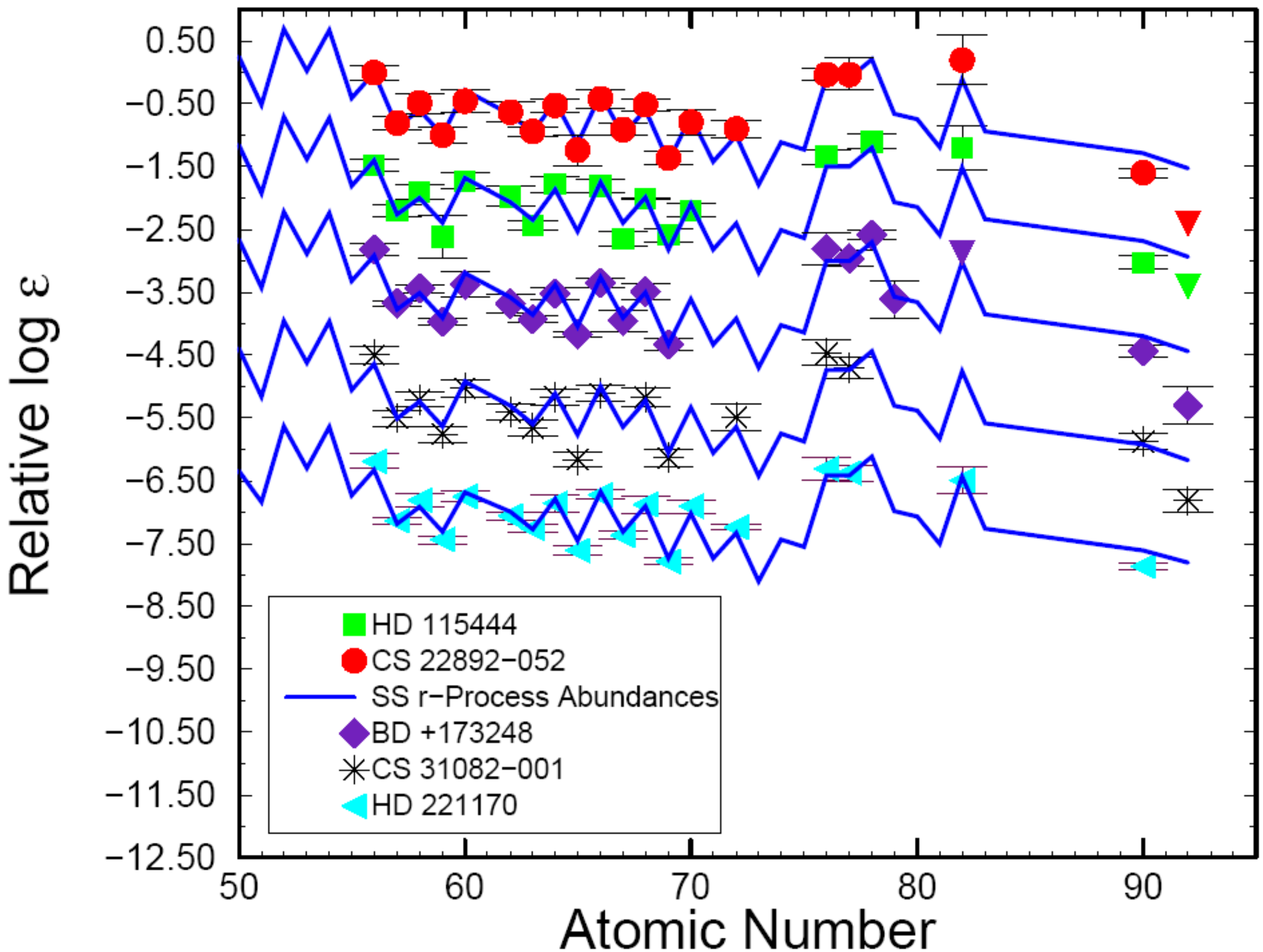


Cyburt *et al.* 2016

the Origin of Heavy Elements

r-process elements in metal-poor stars

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



Kratz et al.: APJ 662 (2007) 39

r-process elements in metal-poor stars

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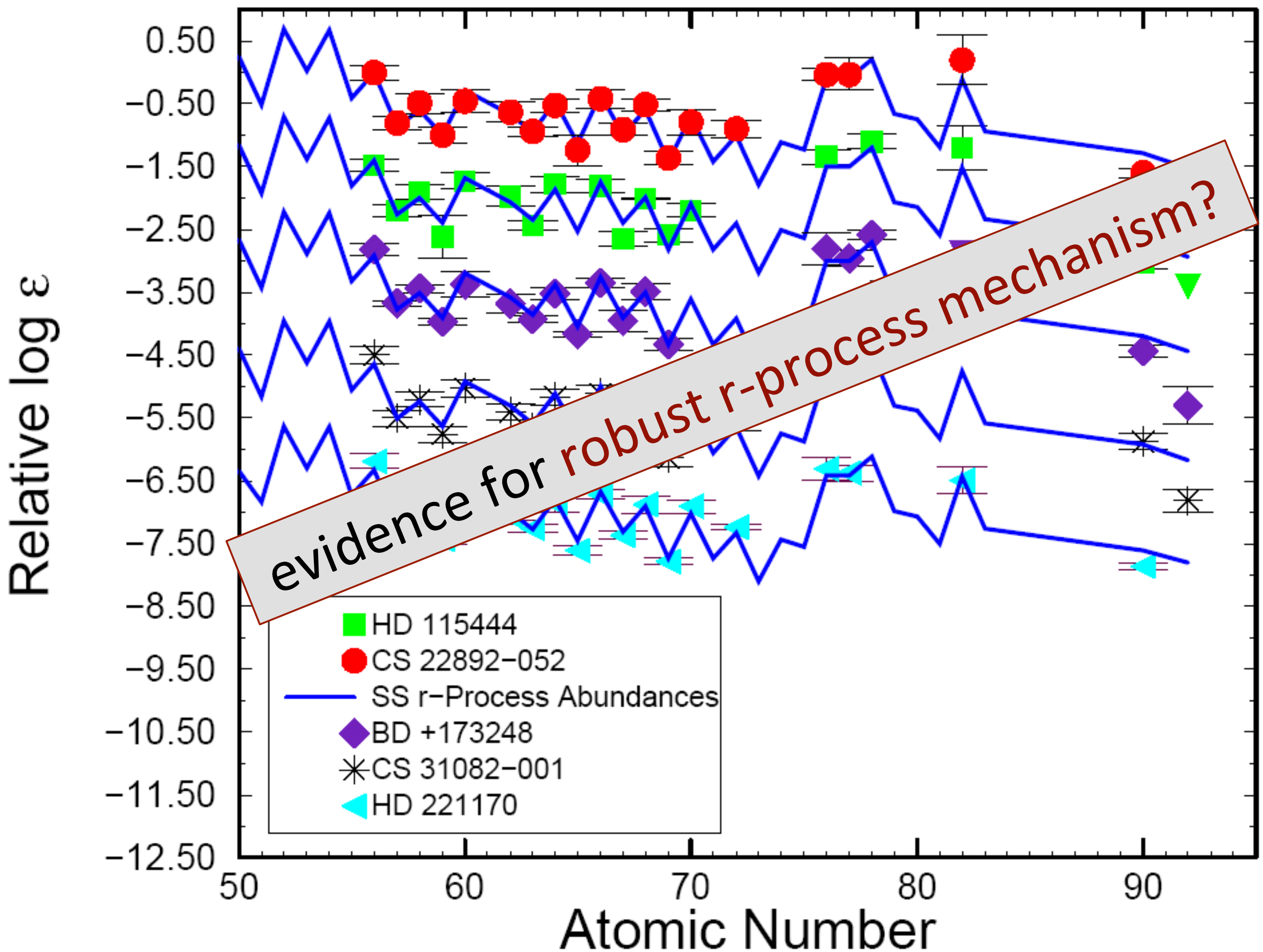
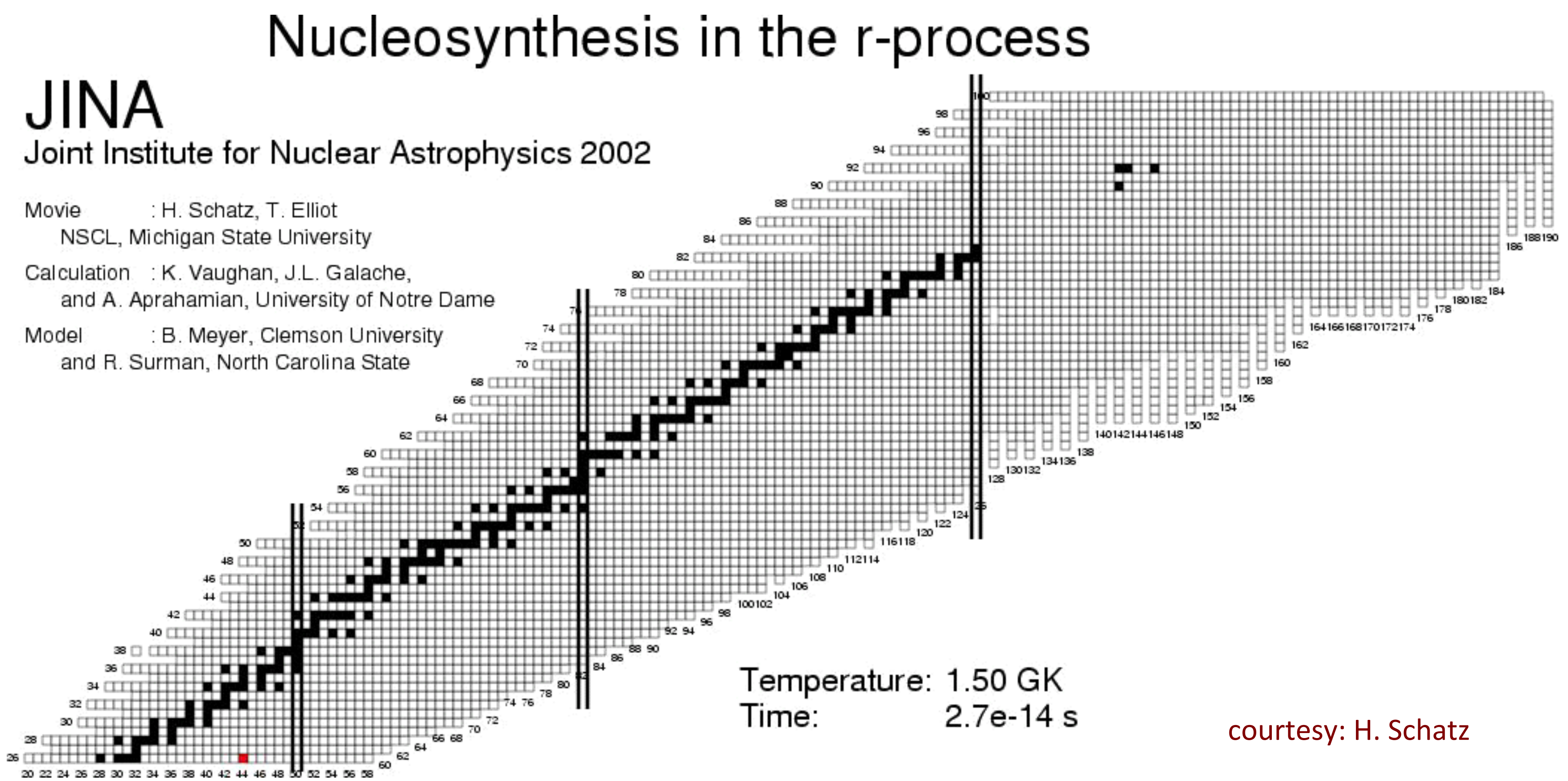


Kratz et al.: APJ 662 (2007) 39



courtesy: H. Schatz

Nucleosynthesis in the r-process

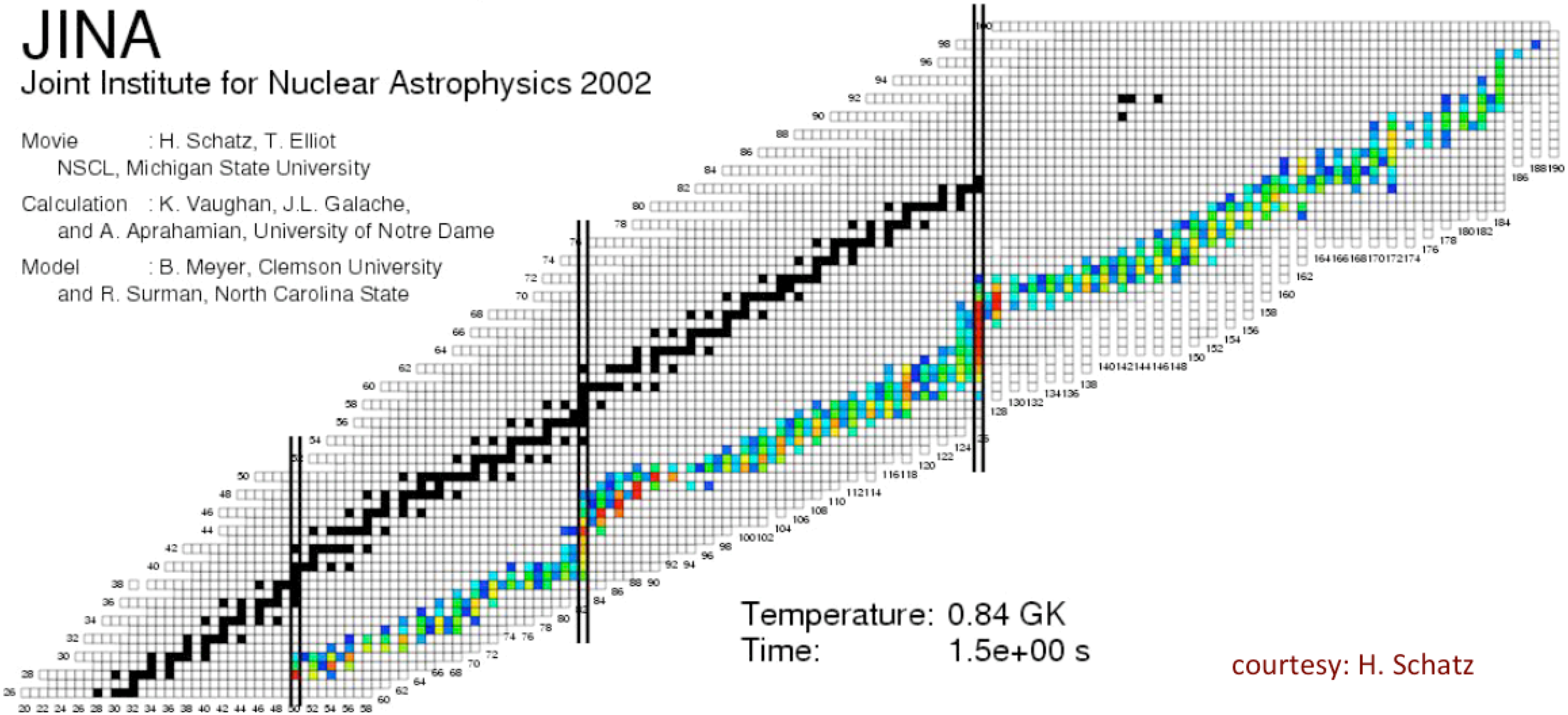
JINA

Joint Institute for Nuclear Astrophysics 2002

Movie : H. Schatz, T. Elliot
NSCL, Michigan State University

Calculation : K. Vaughan, J.L. Galache,
and A. Aprahamian, University of Notre Dame

Model : B. Meyer, Clemson University
and R. Surman, North Carolina State



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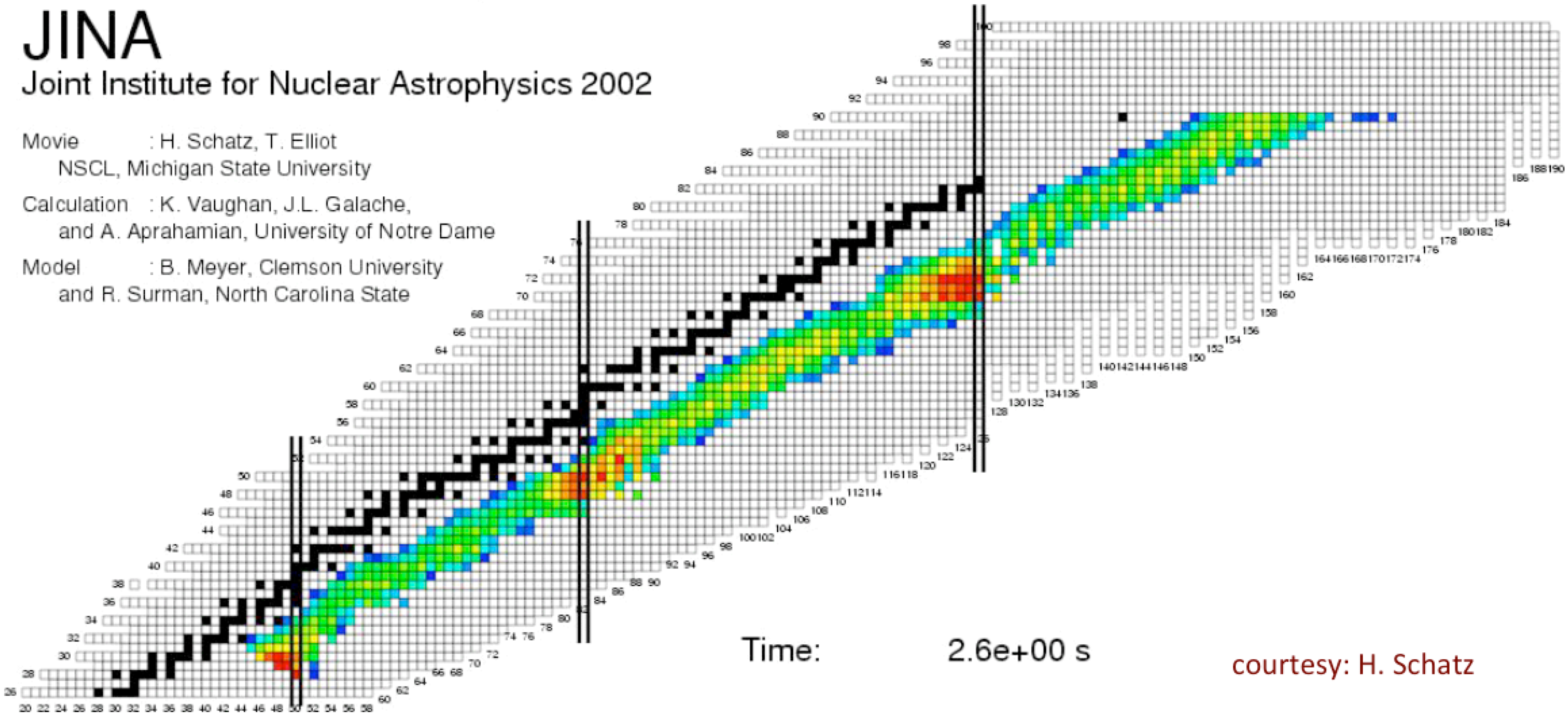
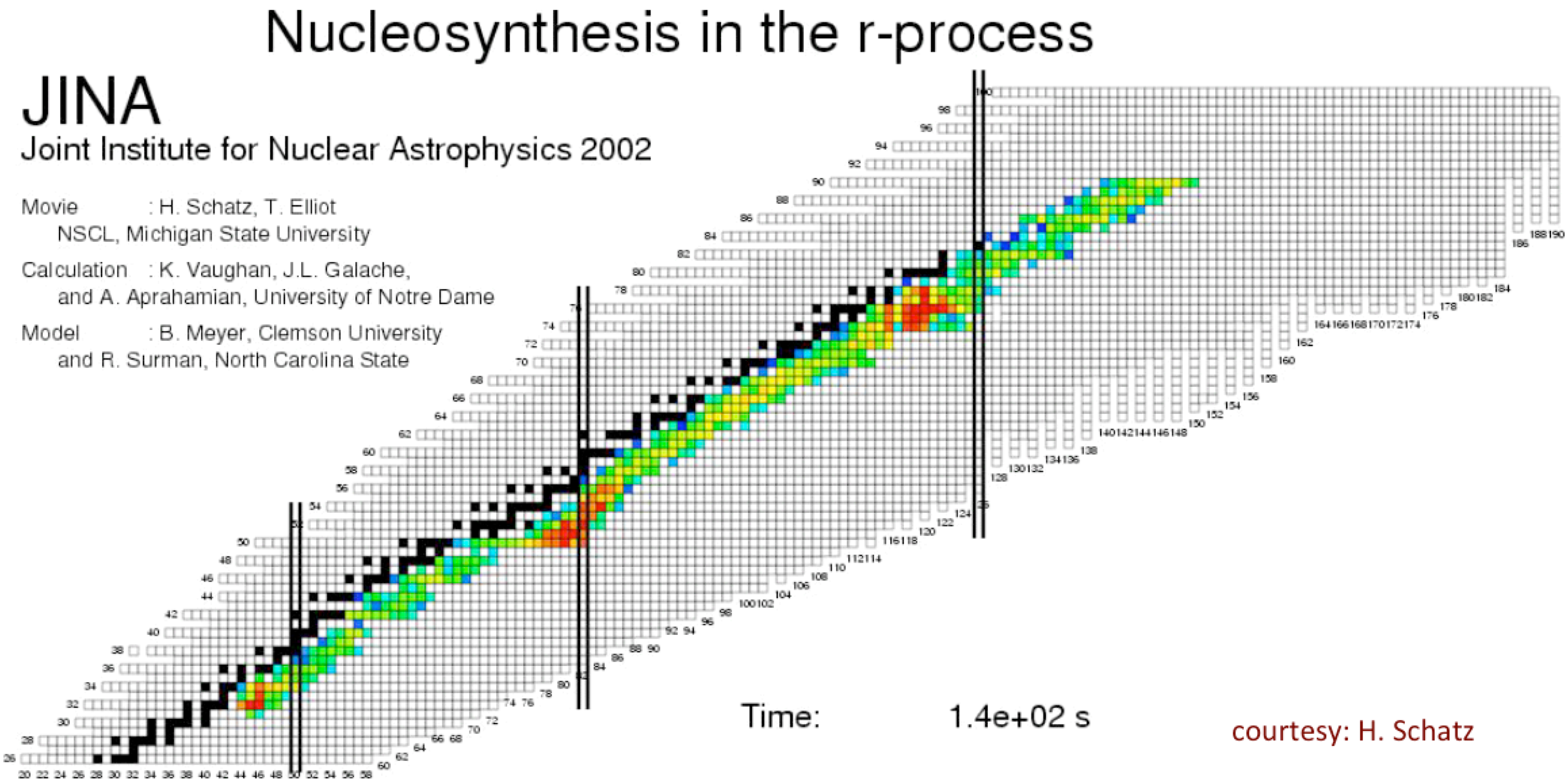


courtesy: H. Schatz

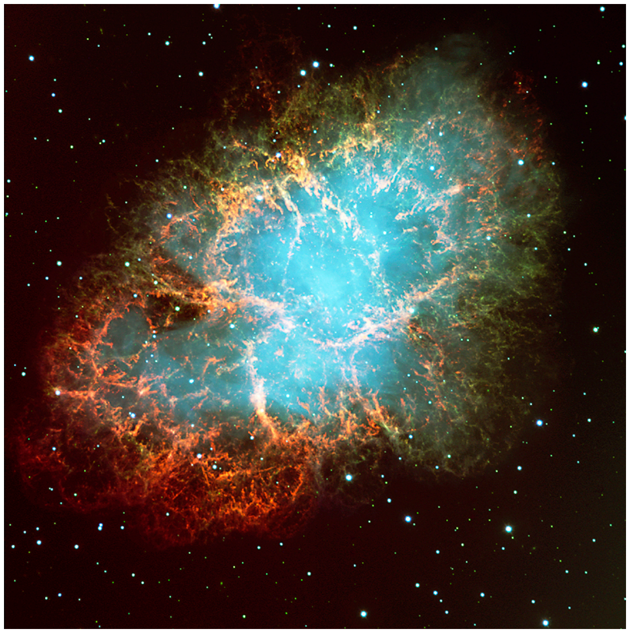


courtesy: H. Schatz

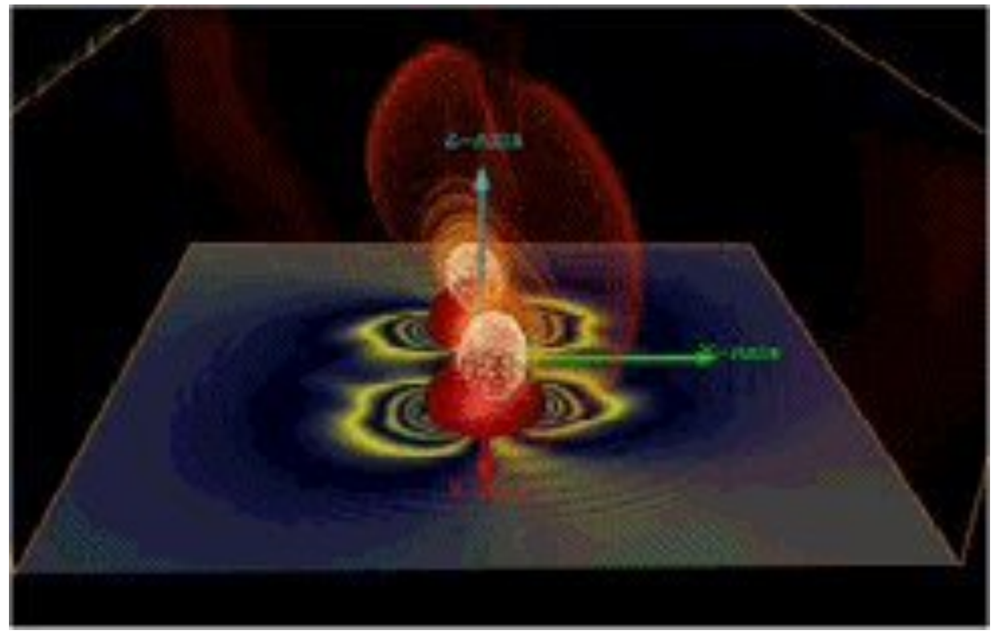
large neutron fluxes required! (~10^{28} n/cm^3)

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 merging neutron stars
- others?...

GW170817: A Major Discovery

17 August 2017

130 million light years from Earth

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

GW170817: A Major Discovery

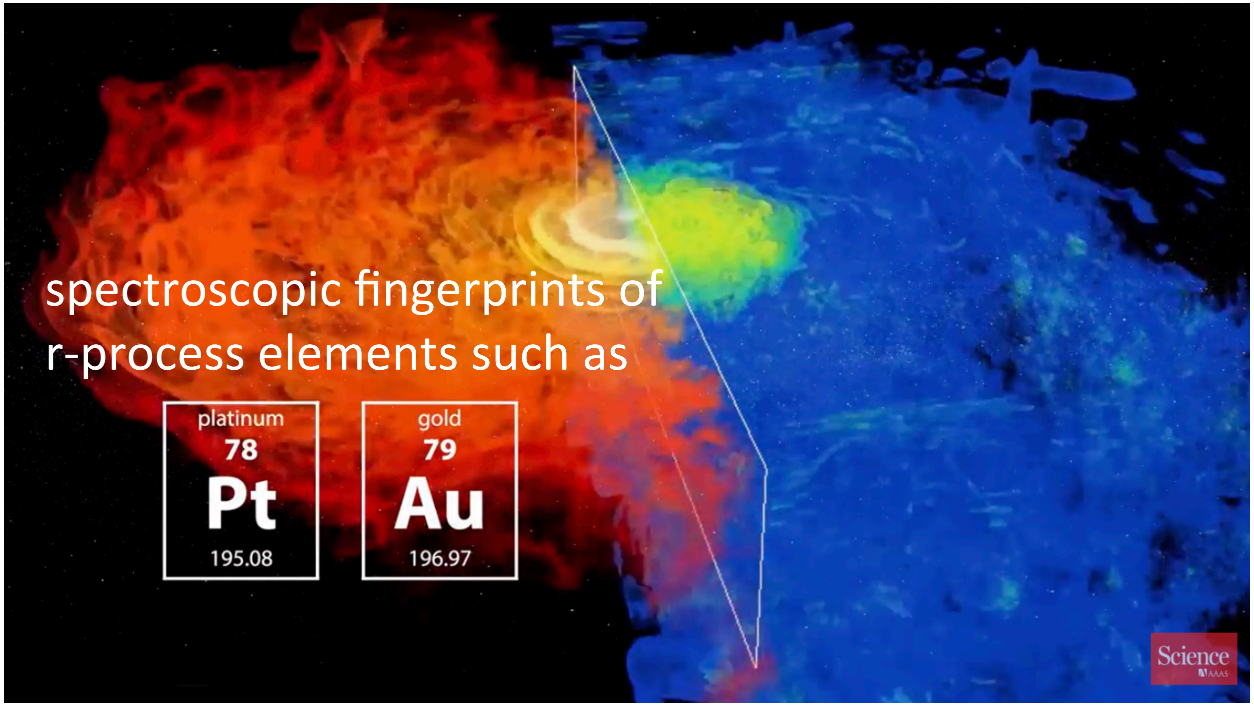
17 August 2017

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



GW170817: A Major Discovery

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

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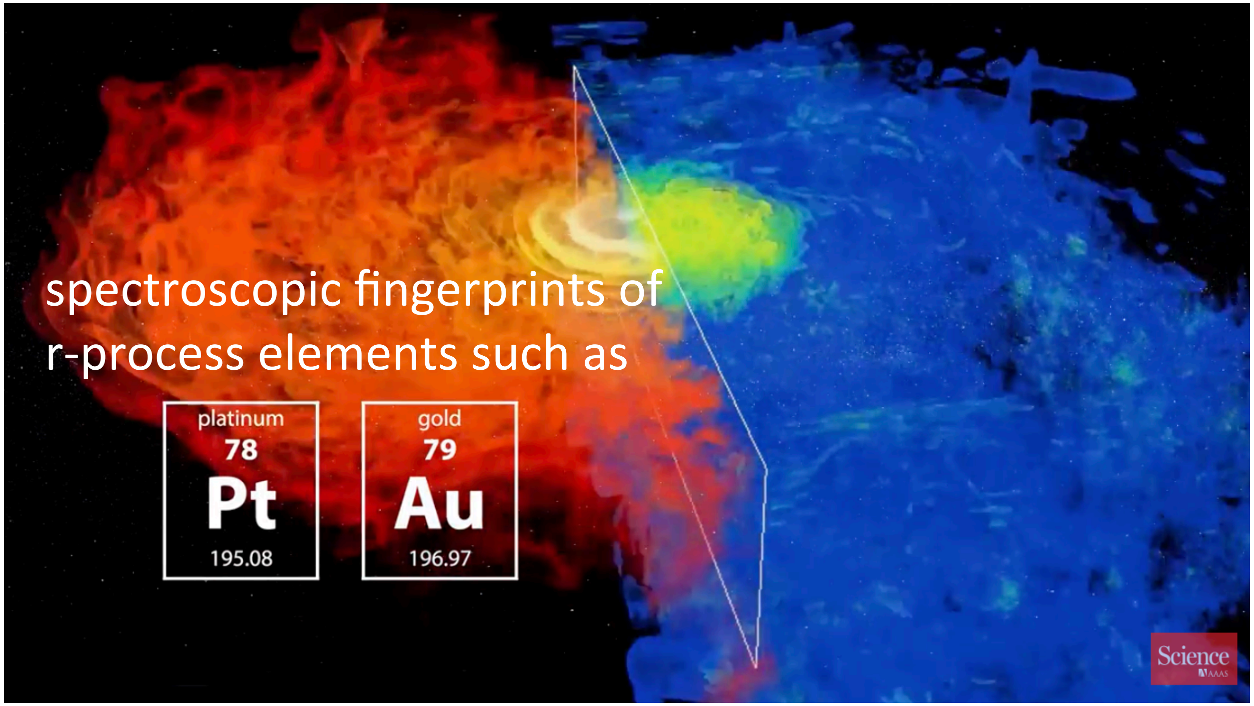
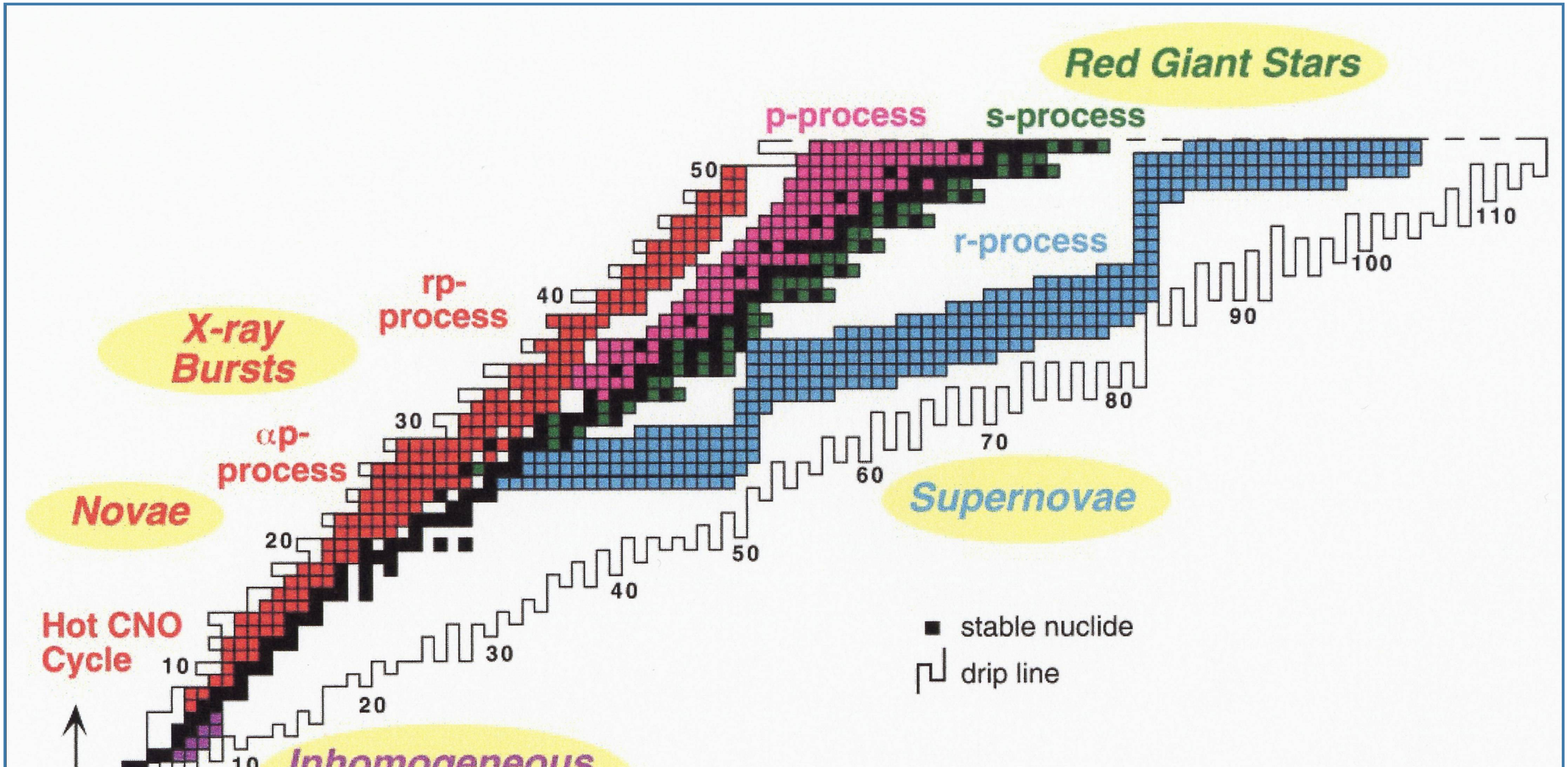


neutron star mergers could well be the main source for r-process elements

A new era in Astronomy has just begun…

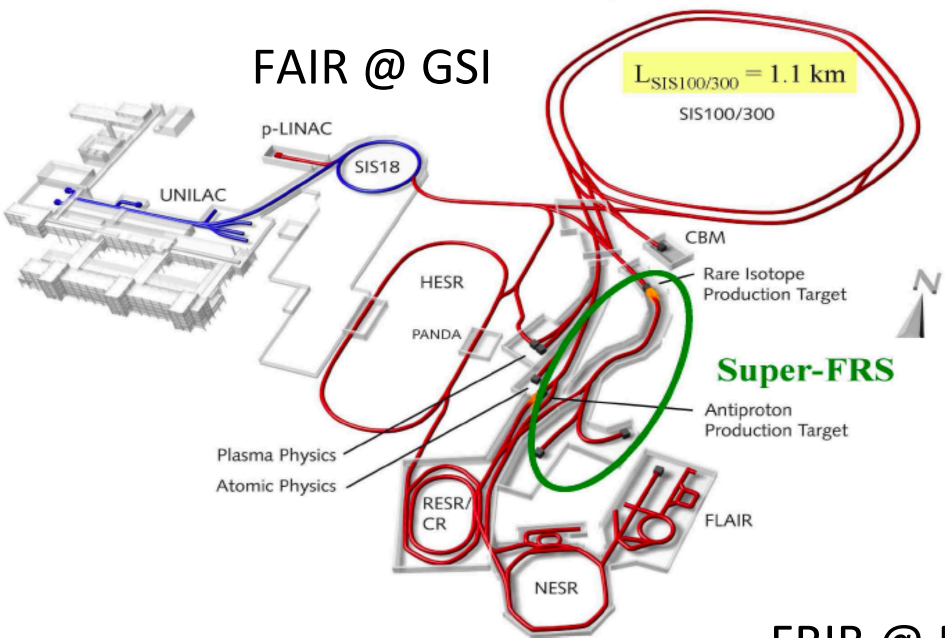


M.S. Smith and K.E. Rehm,
Ann. Rev. Nucl. Part. Sci, 51 (2001) 91-130

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

Upcoming Radioactive Beam Facilities

FAIR @ GSI

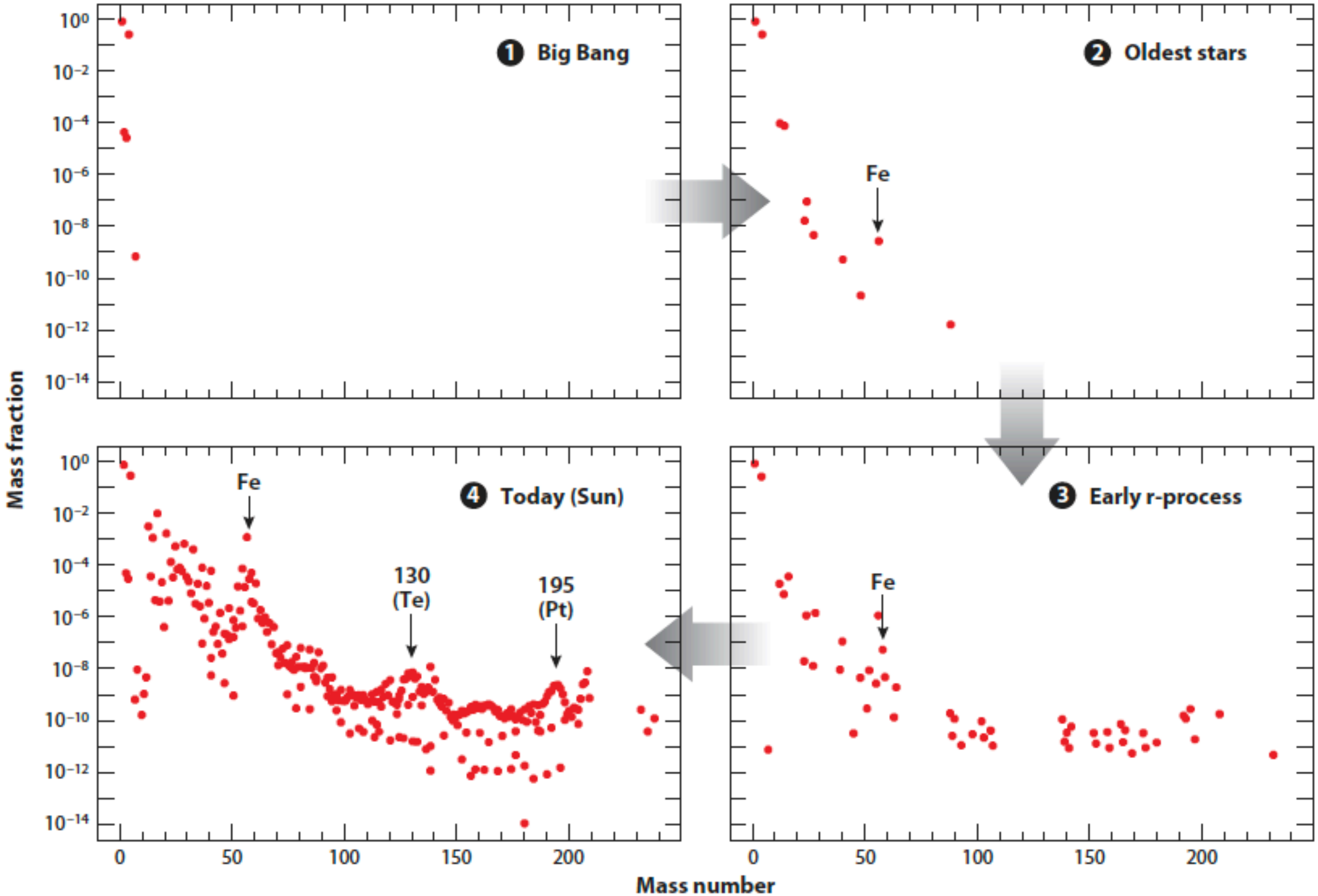


ARIEL @ TRIUMF

FRIB @ MSU

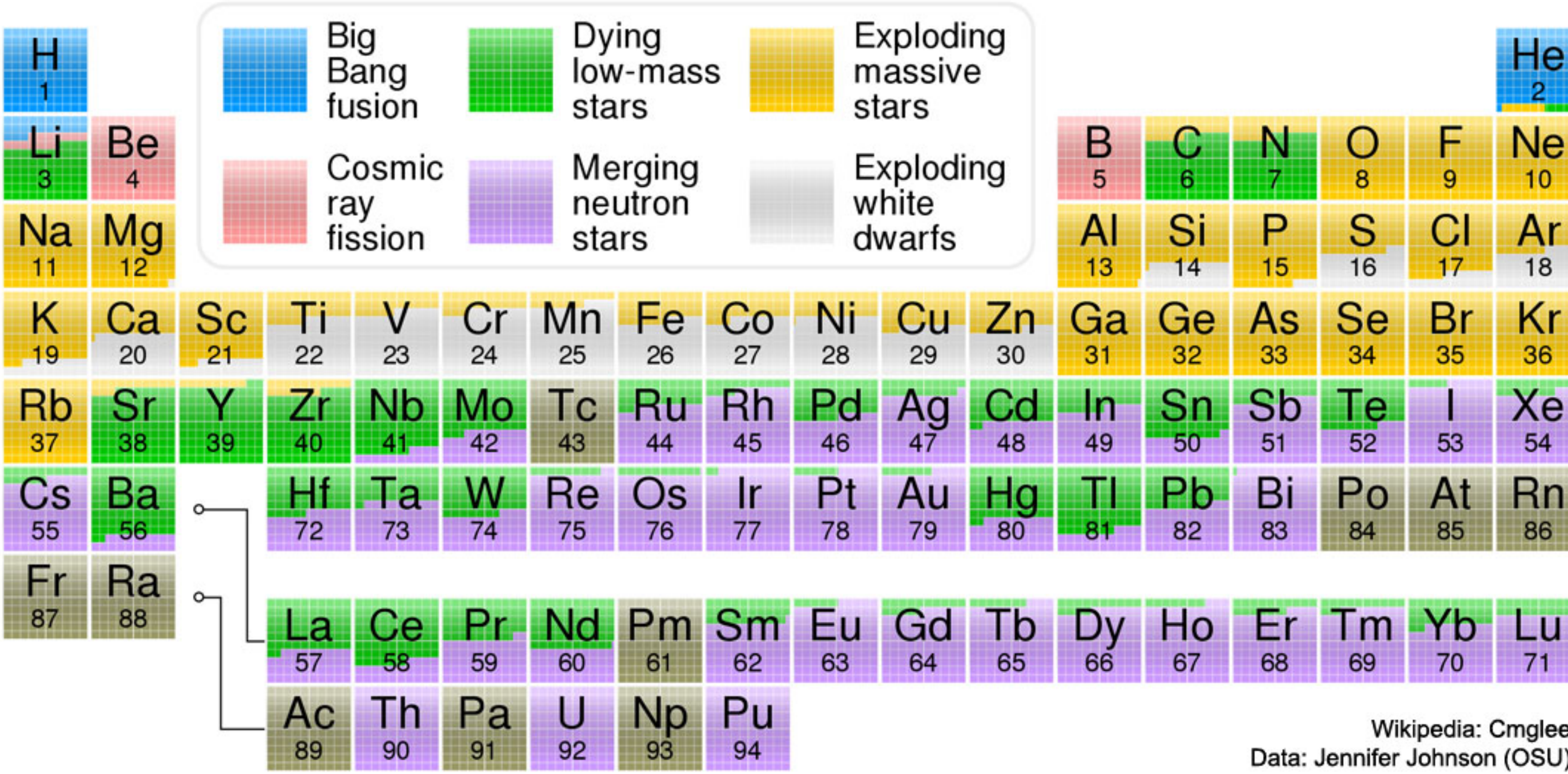
To Conclude…

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

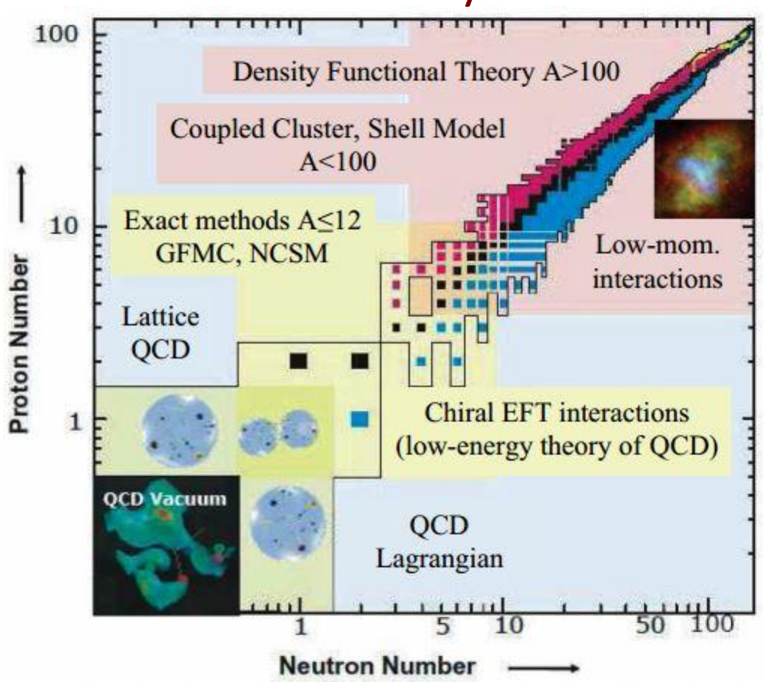
experimental and
theoretical Inputs
stable and exotic nuclei

Atomic Physics

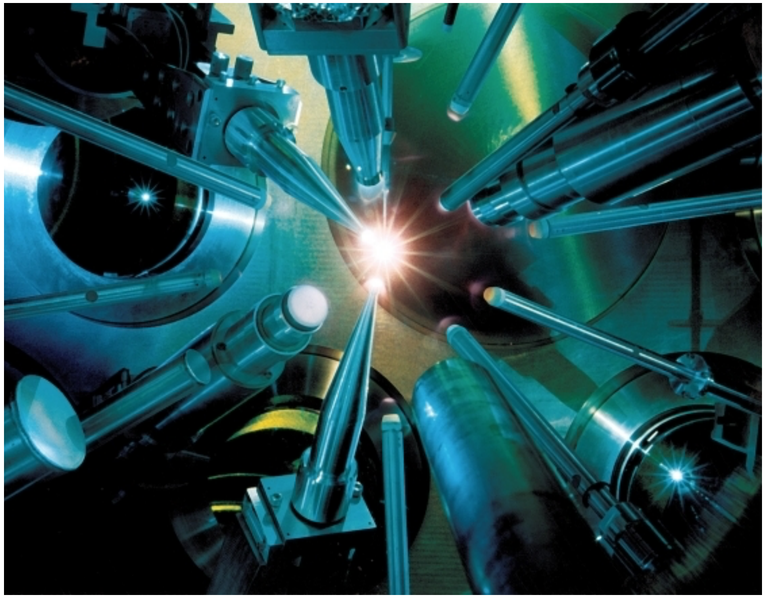
radiation-matter interaction
energy losses, stopping powers
spectral lines
materials and detectors

Ingredients from Future Breakthroughs

theory



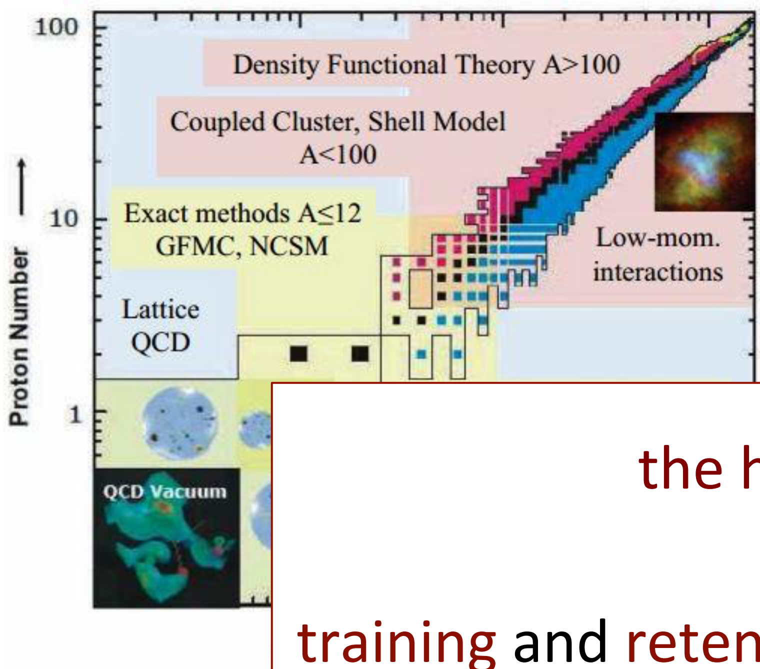
experiments



observations

Ingredients from Future Breakthroughs

theory

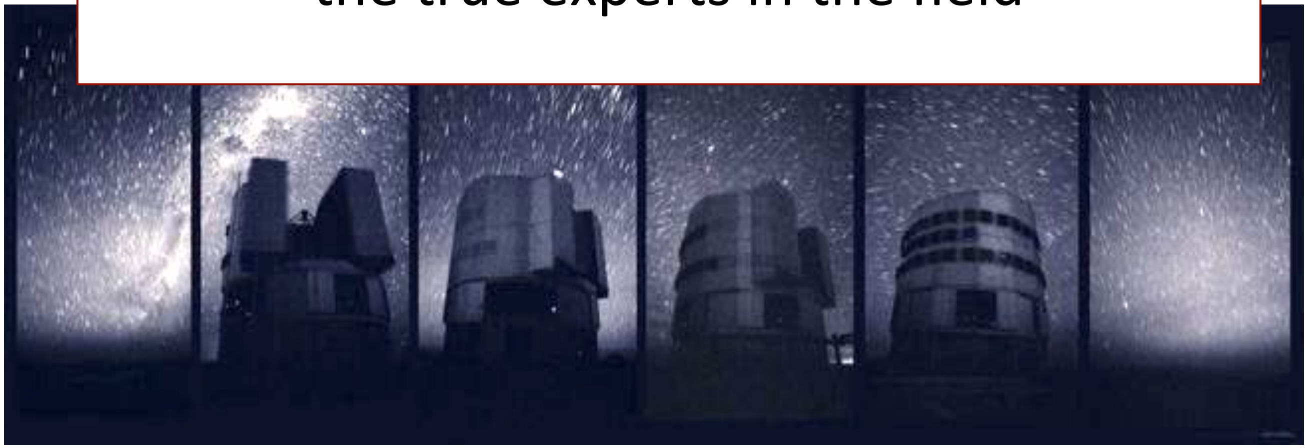


experiments

the human factor

training and retention of young researchers

the true experts in the field

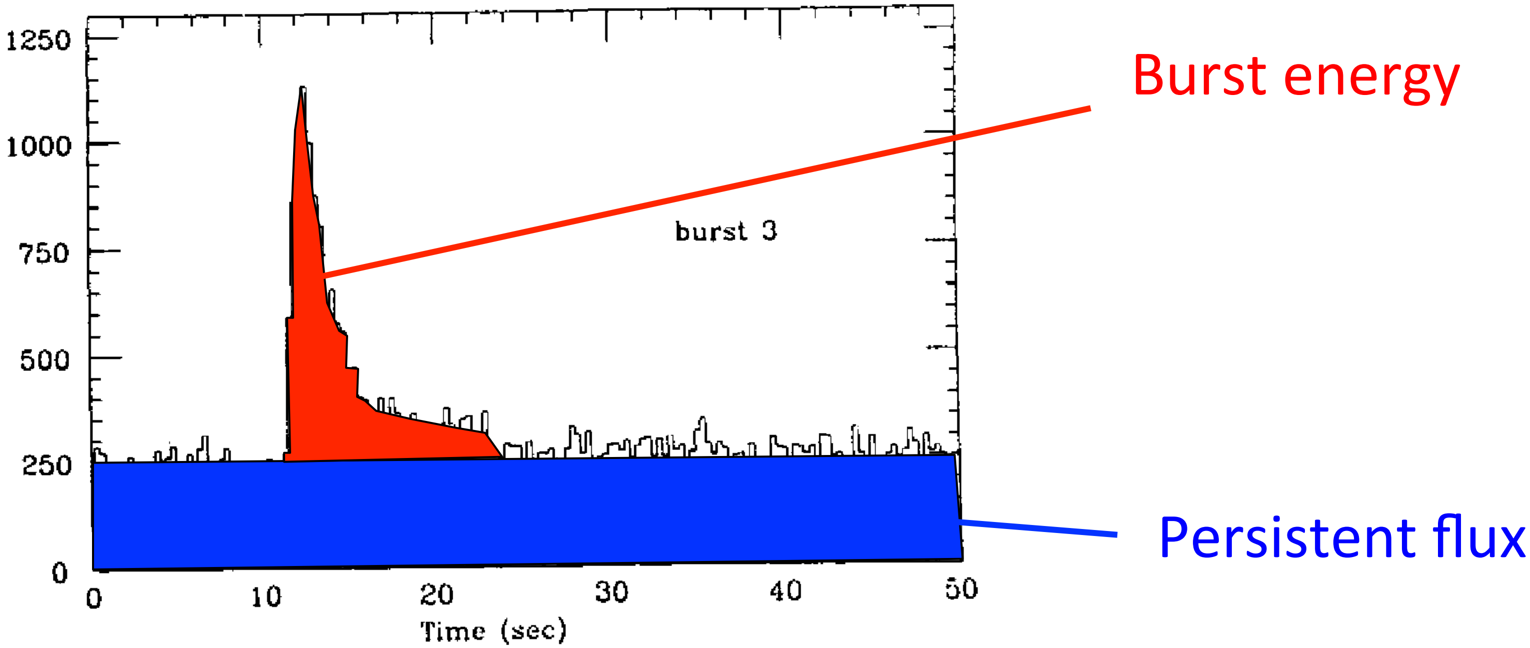



THANK YOU

X-ray Bursts Features

X-ray bursts: most common astrophysical explosions observed

total ~230 X-ray binaries known



Energy in persistent flux / Energy in bursts ~ 40

Gravitational energy / Thermonuclear ~ 200 [MeV/u] / 5 [MeV/u] ~ 40

X-ray bursts: thermonuclear origin