Nuclear physics for Astrophysics - experiment

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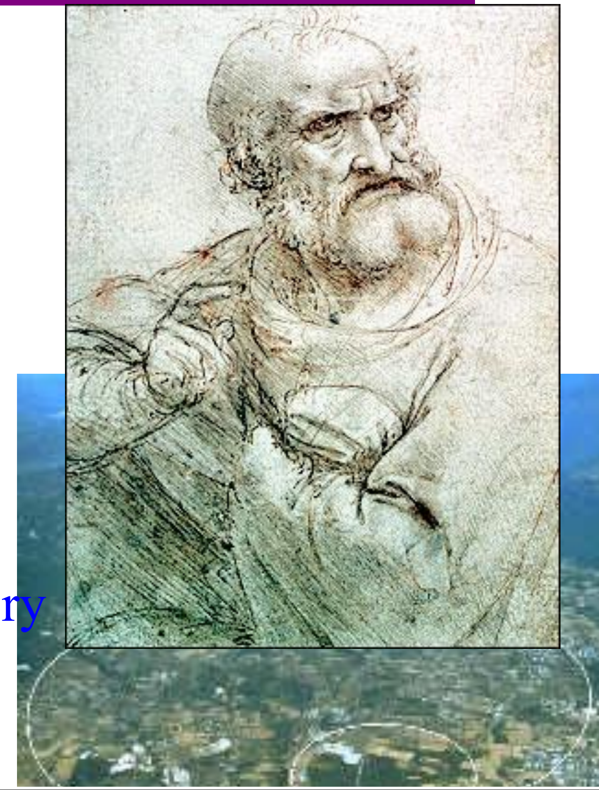
Questions

"The effort to understand the universe is one of the very few things that lifts human life a little above the level of farce, and gives it some of the grace of tragedy."
(S. Weinberg, "The first three minutes")

What is this?! Seen it?!

Questions

Tools to seek answers



“The effort to understand the universe is one of the very few things that lifts human life a little above the level of farce, and gives it some of the grace of tragedy.”
(S. Weinberg, “The first three minutes”)

The field

"Nuclei: the core of the mater, the fuel of stars"

motto of the Division of Nuclear Physics of the American Physical Society at the beginning of IIIrd millennium

Star physics! What is it?! Many things ...

Nuclear astrophysics:

- Nuclear Physics for Astrophysics (NPA)
- Star dynamics
- Nucleosynthesis modelling
- Specific observations (space X- & gamma-rays telescopes, cosmochemistry of meteorites, ...)
- *"multimessenger astronomy"* ...

1. Origin of Chemical Elements

Big questions

We knew for long time that our energy on Earth comes from the Sun!

1. **But what produces it in the Sun?**

Gravity (which governs planets' motion)?! No!

Chemical reactions like on Earth (fuel burning, explosions...)?! No

In the 1920s (A. Edington & J. Perrin) we got the answer: **nuclear reactions!** Namely fusion!

What about the other stars?!

2. **How were/are the chemical elements created? Where?**

(nucleosynthesis) The answer is same: **nuclear reactions!**

But which reactions?! How they proceed?!

3. **Did nucleosynthesis stop, or continues today?**

Alchemy of the Universe

The Nucleosynthesis of Chemical Elements

Supernova 1987A HUBBLESITE.org

- From Aristotle to Mendeleyev

In search of the building blocks of the universe…

Greek philosophers,
Asian philosophy

4 building blocks

water

air

fire

earth

18th-19th century Lavoisier, Dalton, …

distinction between compounds and pure elements

atomic theory revived

92 building blocks
(chemical elements)

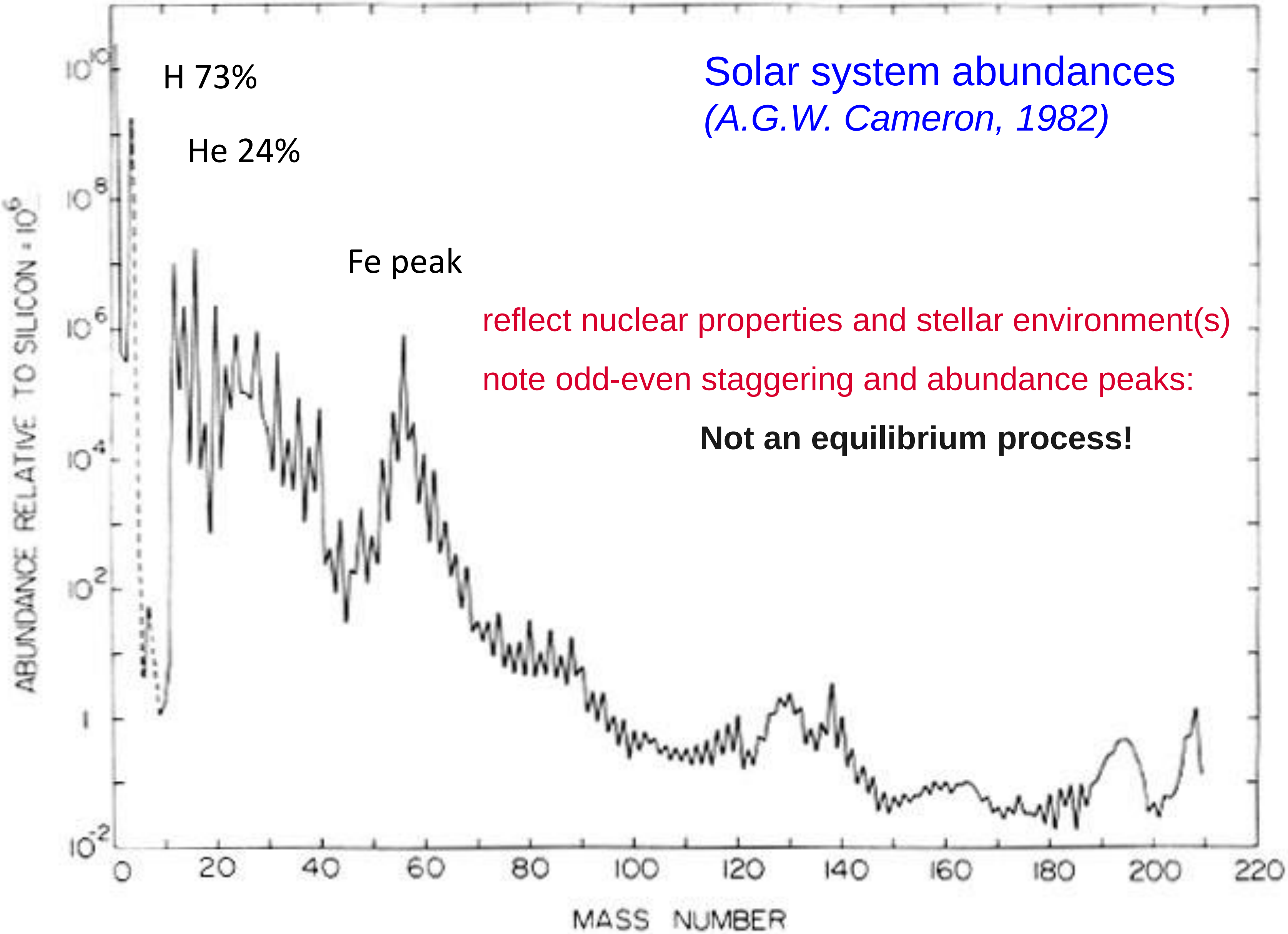
1896 Mendeleyev

Periodic Table of Elements

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun								

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Fingerprints we use:



We also work with:

- Stellar spectra (spectrometry)
- Pre-solar grains =>

Orgueil, France

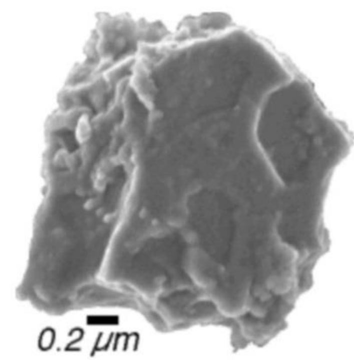
~20 stony meteorites fell on May 14, 1864, a few minutes after 8pm local

19

Orgueil Meteorite

CI Chondrite

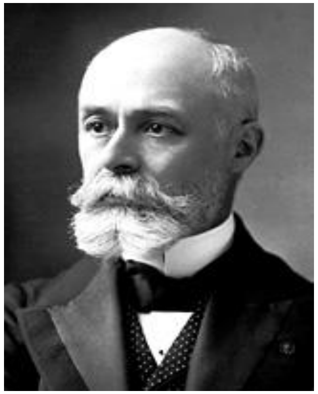
20



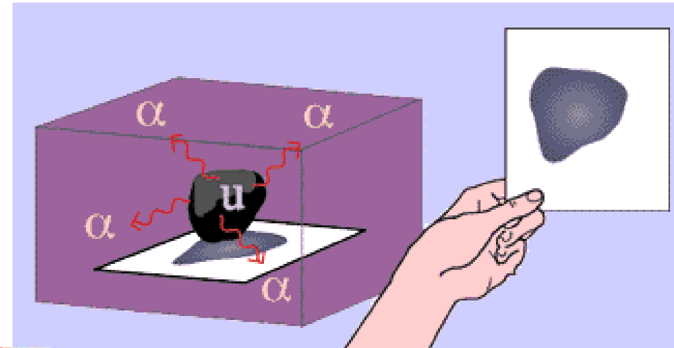
cosmochemistry

• Modern “Alchemy”: **radioactivity**

1896 Becquerel discovers *radioactivity*







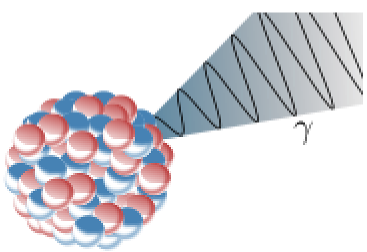
The Nobel Prize in Physics 1903

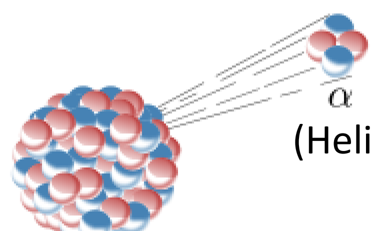
A. H. Becquerel   Pierre Curie   Marie Curie

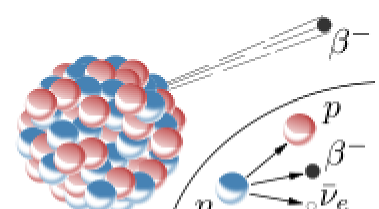
⇒ emission of radiation from atoms

⇒ 3 types observed: α, β and γ

“transmutation”







- Nucleosynthesis: the synthesis of *Elements* through *Nuclear Reactions*

Two original proposals:

(full) Big-Bang nucleosynthesis

all elements formed from protons and neutrons
sequence of n-captures and β decays
soon after the Big Bang

Alpher, Bethe & Gamow ("α β γ")
Phys. Rev. 73 (1948) 803

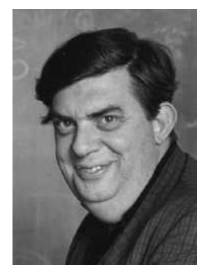
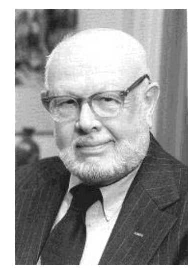


The Nobel Prize in Physics 1967

Stellar nucleosynthesis

After Big Bang
elements synthesised inside the stars
nuclear processes
well defined stages of stellar evolution

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


The Nobel Prize in Physics 1983

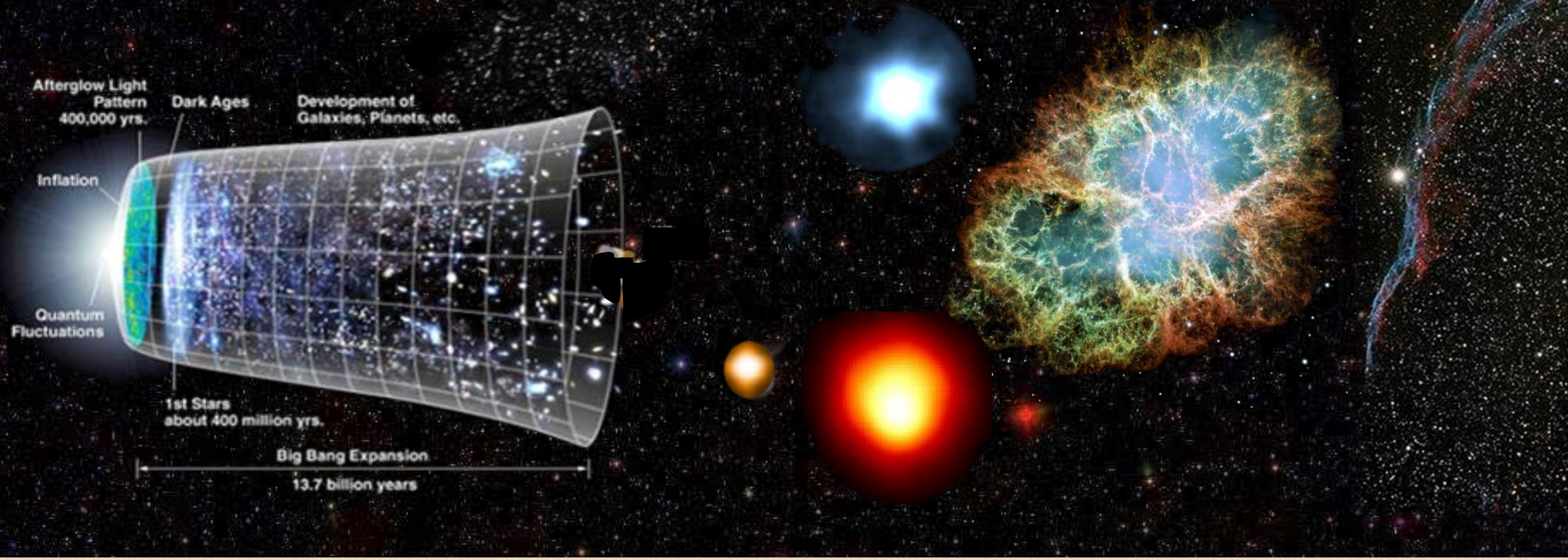
Which one is correct?

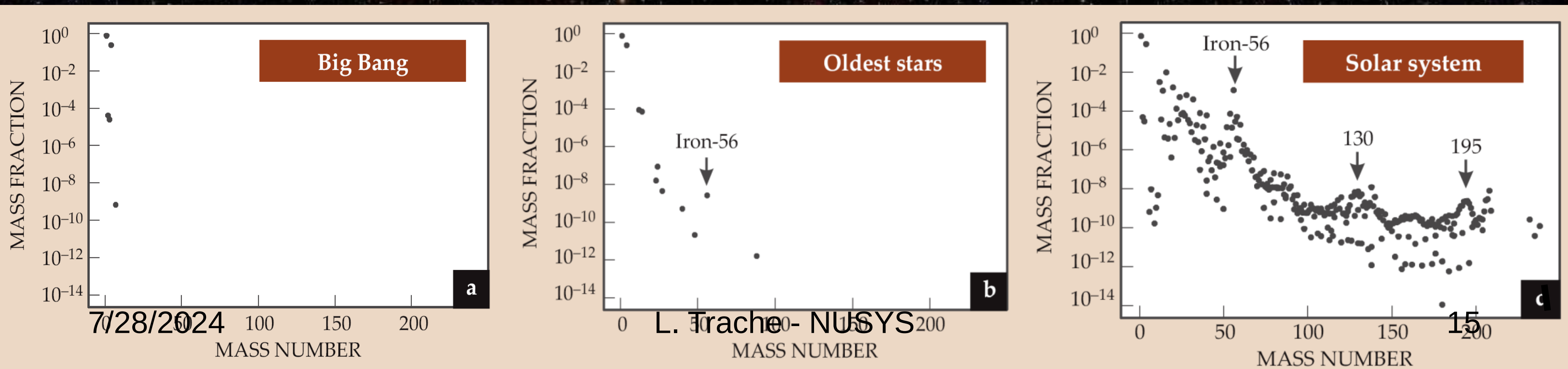
Nuclei and Nuclear Astrophysi… in XX c.

$E=mc^2$ and mass measurements

- A Edington & J. Perrin ~ 1920 – “en… origin of stars’ energy
- Astronomy becomes astro… discovery of galaxies
- 1930s – Bethe – CN… pp chain; the neutron is discovered
- 1948 – αβ… …uctor (Apr 1, 1948: Alpher, Bethe and Gamow in Phy… amazing legacy of a wrong paper” (M. Turner) is the … precision cosmology
- …57: B^2FH paper (Burbidge, Burbidge, Fowler and Hoyle) and Cameron (Chalk River): BBN and stellar nucleosynthesis
- 60s-70s: solar neutrinos detected and solar neutrino puzzle (Pontecorvo, Alvarez… R. Davis Jr., started 1948, Nobel prize 2002)
- Standard Model and “The first three minutes”; Big Bang Nucleosynthesis
- Neutrino oscillations confirmed (1997-2001 …)
- Cosmic Microwave Background …
- Neutron star mergers and multi-messenger astronomy (2017 -)
- We, the epigones!
  - Models
  - Hydrodynamics
  - **Nuclear data**

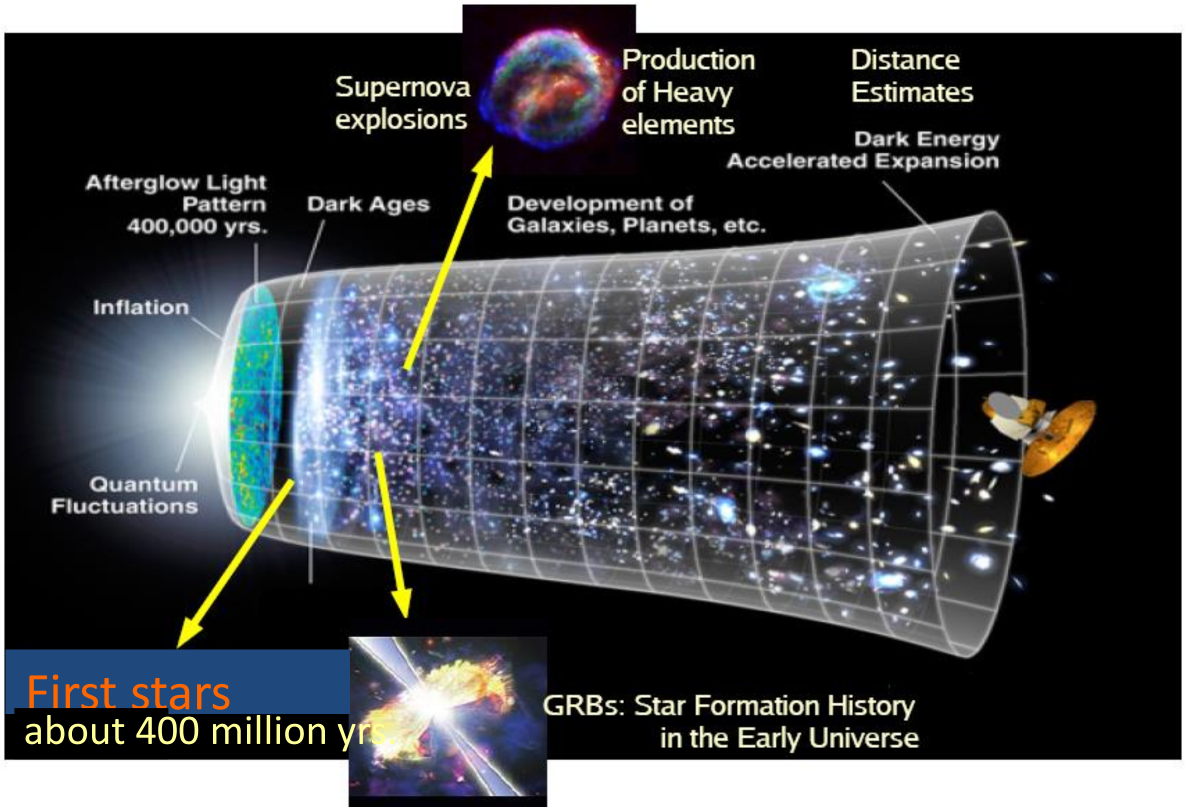
Galactic Chemical Evolution

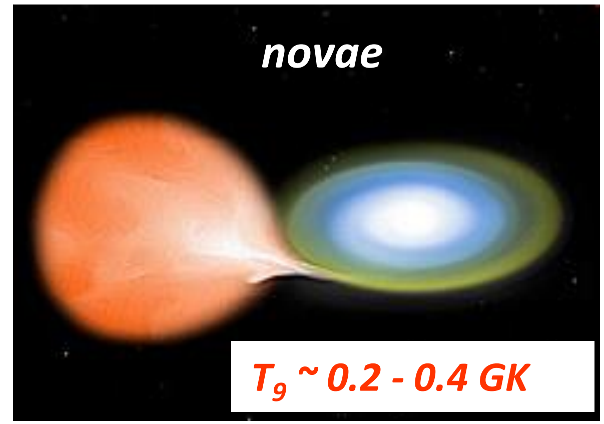


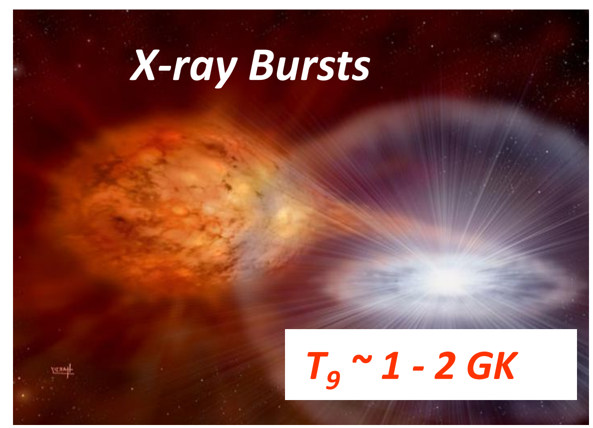


Astrophysical motivations for nuclear physics studies

The first sources of light: Population III stars







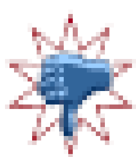
ANC - transfer

ANC – nuclear breakup

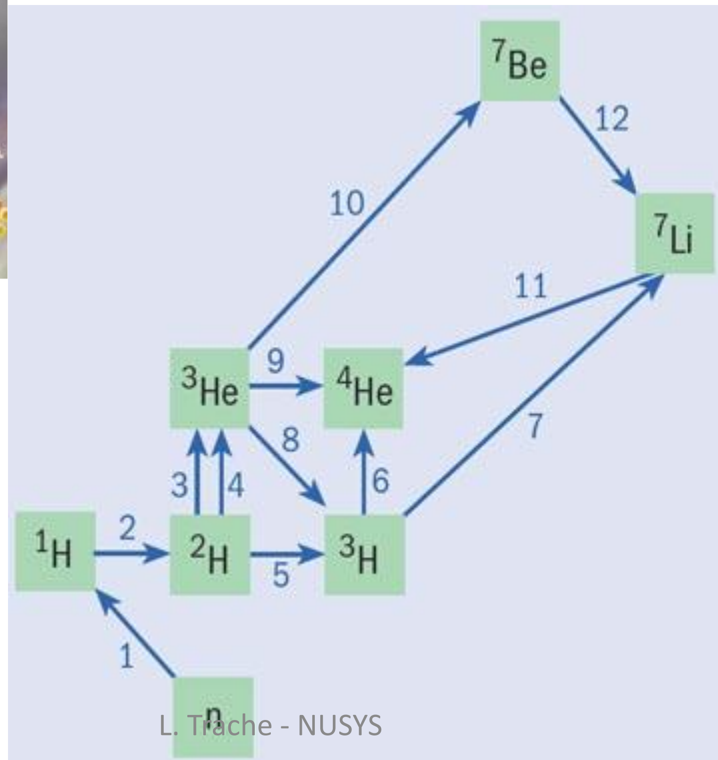
• Big Bang Nucleosynthesis

- occurred within the first 10-20 minutes of the Universe after the primordial quark-gluon plasma froze out to form neutrons and protons
- BBN stopped by further expansion and cooling (temperature and density fell below those required for nuclear fusion)
- BBN explains correctly the observed mass abundances of ^{1}H (75%), ^{4}He (24%), ^{2}H (0.003%), ^{3}He (0.004%), trace amounts (10^{-10}%) of Li and Be, and <u>no other heavy elements</u>

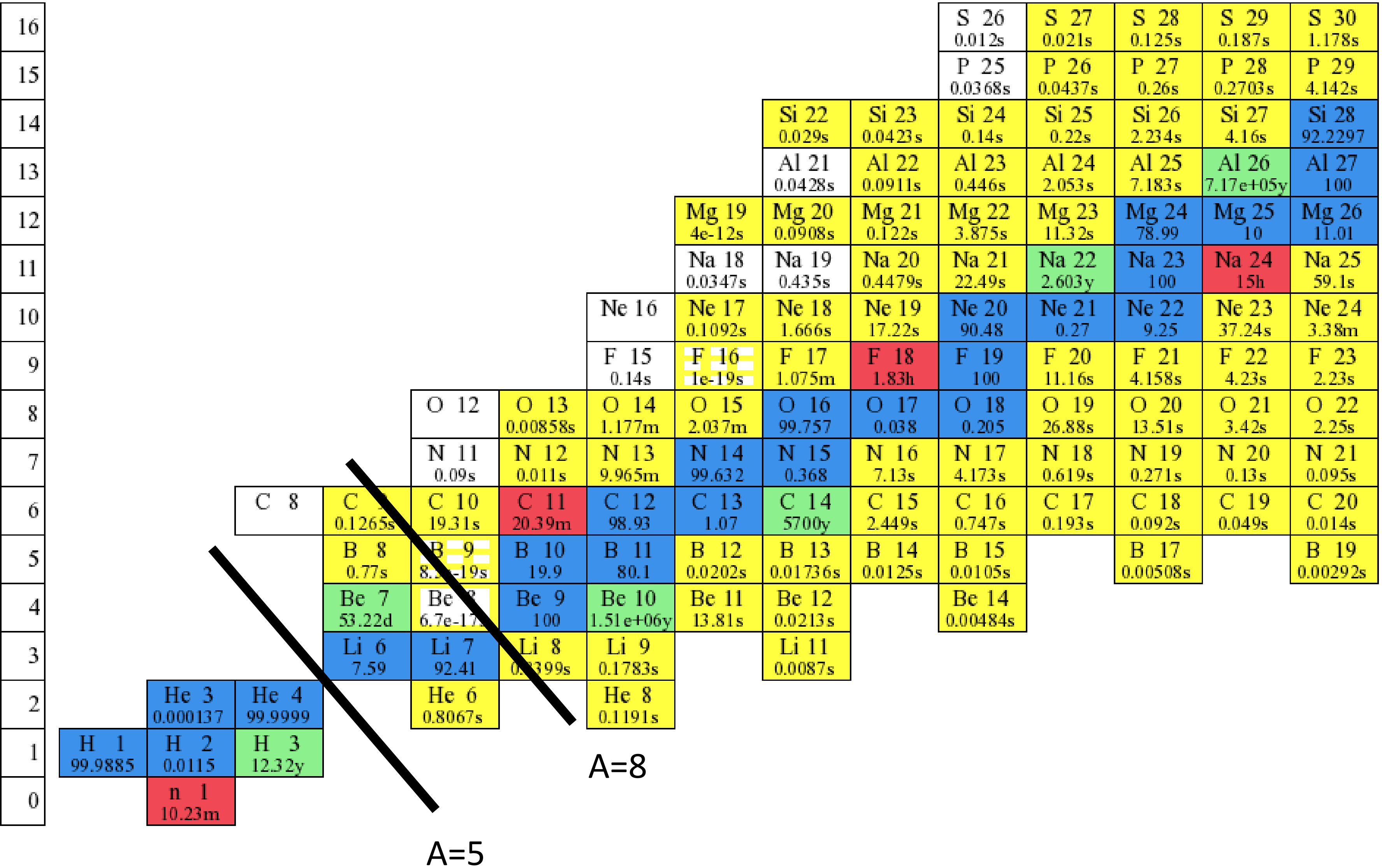
Mass stability gaps at **A=5** and **A=8** !!!

BBN 

No way to bridge the gap through sequence of neutron captures during BB …

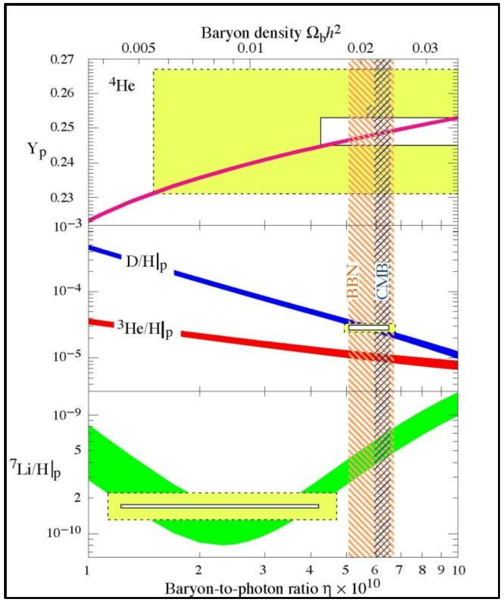


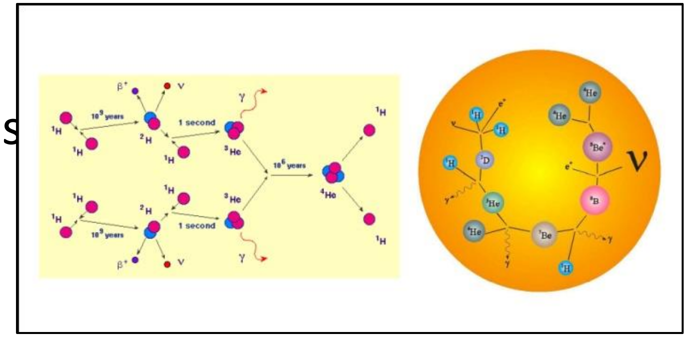
1. $n \longrightarrow {}^{1}H + e^{-} + \bar{\nu}$
2. ${}^{1}H + n \longrightarrow {}^{2}H + \gamma$
3. ${}^{2}H + {}^{1}H \longrightarrow {}^{3}He + \gamma$
4. ${}^{2}H + {}^{2}H \longrightarrow {}^{3}He + n$
5. ${}^{2}H + {}^{2}H \longrightarrow {}^{3}H + {}^{1}H$
6. ${}^{2}H + {}^{3}H \longrightarrow {}^{4}He + n$
7. ${}^{3}H + {}^{4}He \longrightarrow {}^{7}Li + \gamma$
8. ${}^{3}He + n \longrightarrow {}^{3}H + {}^{1}H$
9. ${}^{3}He + {}^{2}H \longrightarrow {}^{4}He + {}^{1}H$
10. ${}^{3}He + {}^{4}He \longrightarrow {}^{7}Be + \gamma$
11. ${}^{7}Li + {}^{1}H \longrightarrow {}^{4}He + {}^{4}He$
12. ${}^{7}Be + n \longrightarrow {}^{7}Li + {}^{1}H$


16
S 26 0.012s
S 27 0.021s
S 28 0.125s
S 29 0.187s
S 30 1.178s
15
P 25 0.0368s
P 26 0.0437s
P 27 0.26s
P 28 0.2703s
P 29 4.142s
14
Si 22 0.029s
Si 23 0.0423s
Si 24 0.14s
Si 25 0.22s
Si 26 2.234s
Si 27 4.16s
Si 28 92.2297
13
Al 21 0.0428s
Al 22 0.0911s
Al 23 0.446s
Al 24 2.053s
Al 25 7.183s
Al 26 7.17e+05y
Al 27 100
12
Mg 19 4e-12s
Mg 20 0.0908s
Mg 21 0.122s
Mg 22 3.875s
Mg 23 11.32s
Mg 24 78.99
Mg 25 10
Mg 26 11.01
11
Na 18 0.0347s
Na 19 0.435s
Na 20 0.4479s
Na 21 22.49s
Na 22 2.603y
Na 23 100
Na 24 15h
Na 25 59.1s
10
Ne 16
Ne 17 0.1092s
Ne 18 1.666s
Ne 19 17.22s
Ne 20 90.48
Ne 21 0.27
Ne 22 9.25
Ne 23 37.24s
Ne 24 3.38m
9
F 15 0.14s
F 16 1e-19s
F 17 1.075m
F 18 1.83h
F 19 100
F 20 11.16s
F 21 4.158s
F 22 4.23s
F 23 2.23s
8
O 12
O 13 0.00858s
O 14 1.177m
O 15 2.037m
O 16 99.757
O 17 0.038
O 18 0.205
O 19 26.88s
O 20 13.51s
O 21 3.42s
O 22 2.25s
7
N 11 0.09s
N 12 0.011s
N 13 9.965m
N 14 99.632
N 15 0.368
N 16 7.13s
N 17 4.173s
N 18 0.619s
N 19 0.271s
N 20 0.13s
N 21 0.095s
6
C 8
C 0.1265s
C 10 19.31s
C 11 20.39m
C 12 98.93
C 13 1.07
C 14 5700y
C 15 2.449s
C 16 0.747s
C 17 0.193s
C 18 0.092s
C 19 0.049s
C 20 0.014s
5
B 8 0.77s
B 9
B 10 19.9
B 11 80.1
B 12 0.0202s
B 13 0.01736s
B 14 0.0125s
B 15 0.0105s
B 17 0.00508s
B 19 0.00292s
4
Be 7 53.22d
Be
Be 9 100
Be 10 1.51e+06y
Be 11 13.81s
Be 12 0.0213s
Be 14 0.00484s
3
Li 6 7.59
Li 7 92.41
Li 8
Li 9 0.1783s
Li 11 0.0087s
2
He 3 0.000137
He 4 99.9999
He 6 0.8067s
He 8 0.1191s
1
H 1 99.9885
H 2 0.0115
H 3 12.32y
0
n 1 10.23m
A=8
A=5

Nuclear astrophysics

- **Nuclear astrophysics** – increasingly motivation for NP research:
  - Nuclei are the fuel of the stars
  - Origin of chemical elements: nucleosynthesis = a large series of nuclear reactions
  - & elemental/isotopic abundances are indelible fingerprints of cosmic processes
- Big successes of NA:
  - **BBN** – quantitative, parameter free (& no of neutrinos=3)
  - Heavier elements created **in stars**
  - **Solar reactions** understood (pp-chains, CNO, solar neutrinos…)
  - Nucleosynthesis is **on-going** process!
  - (quasi-) understand novae, XRB, neutron stars …, but not super-novae …





Work for NPA

- The cosmic Li puzzle: why we see only 1/3 of predicted ^{6,7}Li ! Why?!
- Precision …

After BBN, very little happened in nucleosynthesis for a long time (~400M yr).

temperature and density too small !!!

It required galaxy and star formation via gravitation to advance the synthesis of heavier elements.

matter coalesces to higher temperature and density…

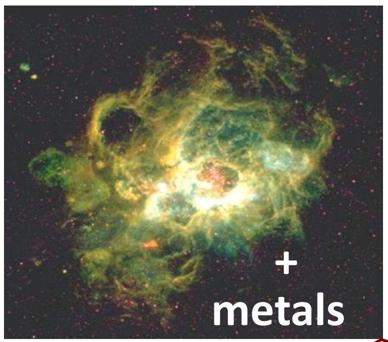
Because in stars the reactions involve mainly charged particles, stellar nucleosynthesis is a slow process.

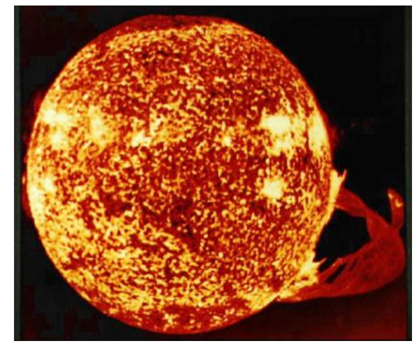
• Stellar life cycle

Interstellar gas

BIRTH
gravitational contraction

Stars





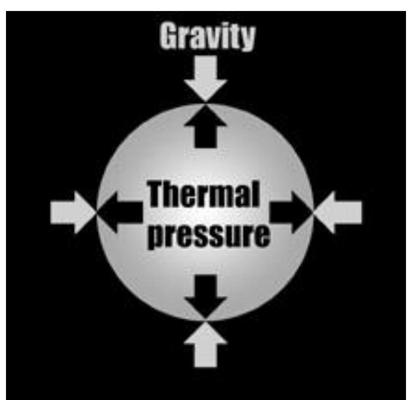
DEATH
explosion

element mixing

thermonuclear reactions

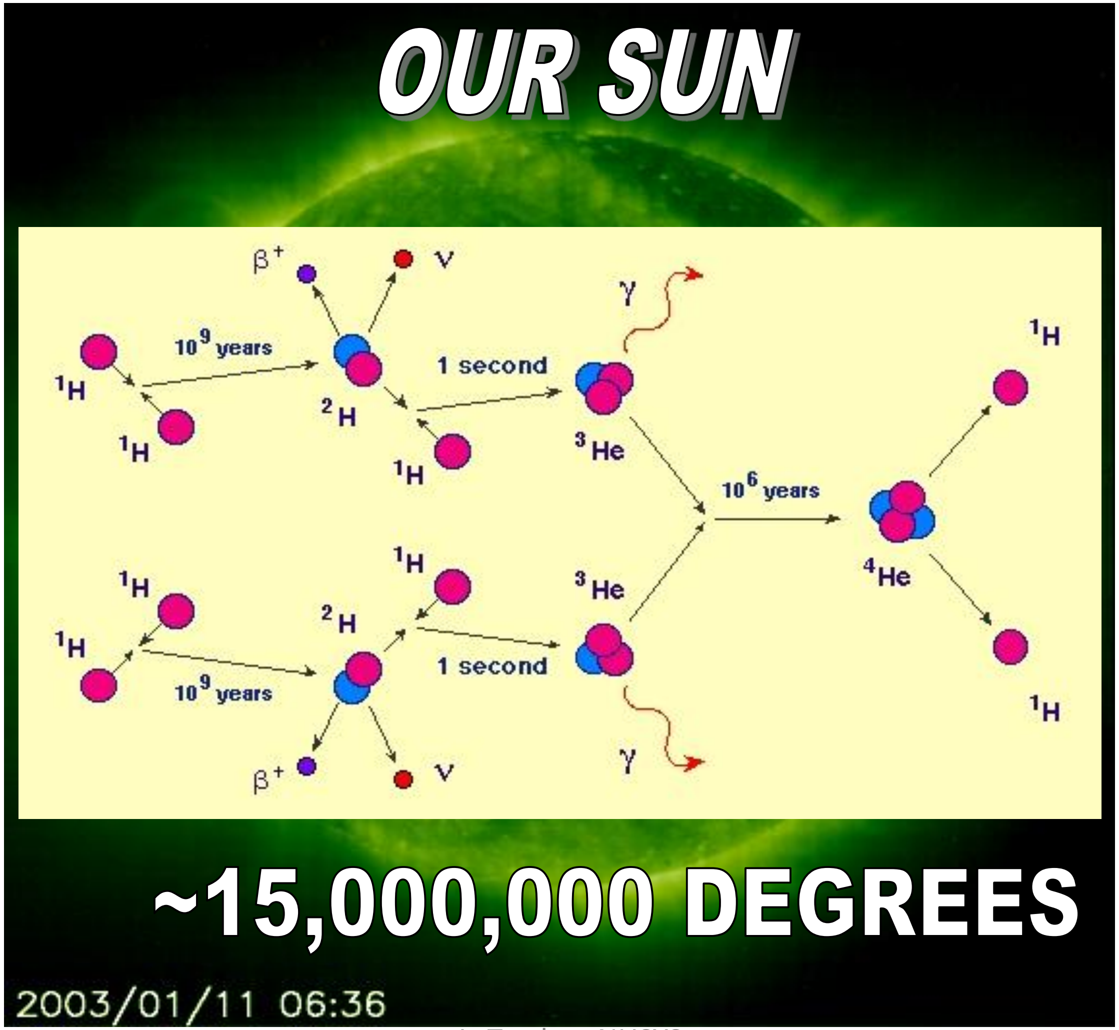
⇕

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



• Hydrogen Burning

- slow or fast (explosive) H-burning
- almost 95% of all stars spend their lives burning the H in their core (including our Sun). Our Sun is a slow nuclear reactor (a fusion reactor we could not make!)

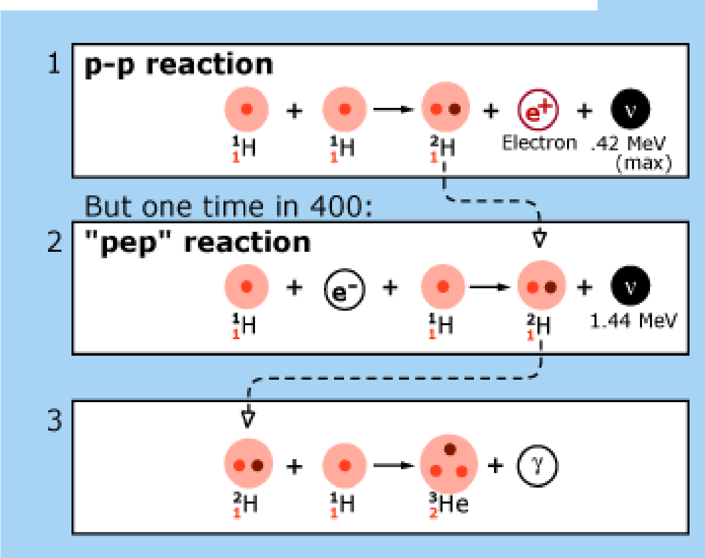


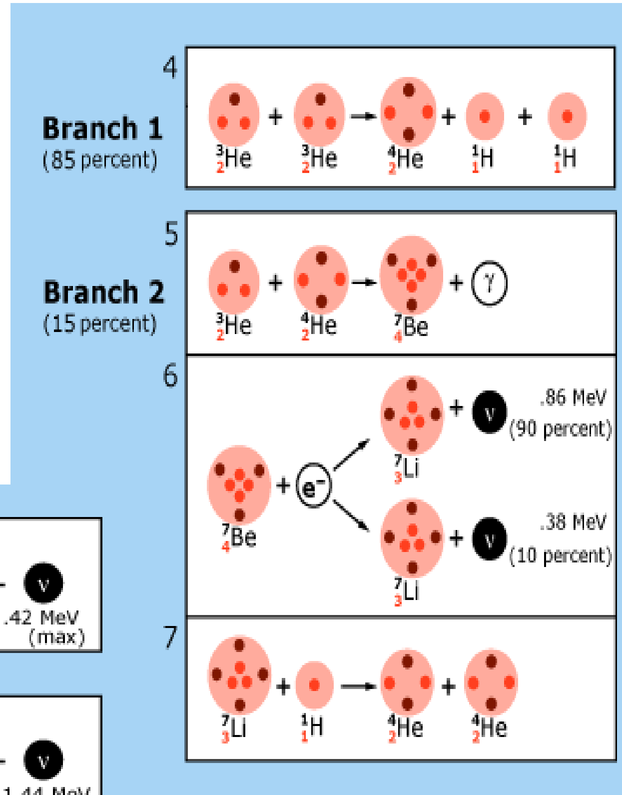
Detailed Sun workings: a reactor

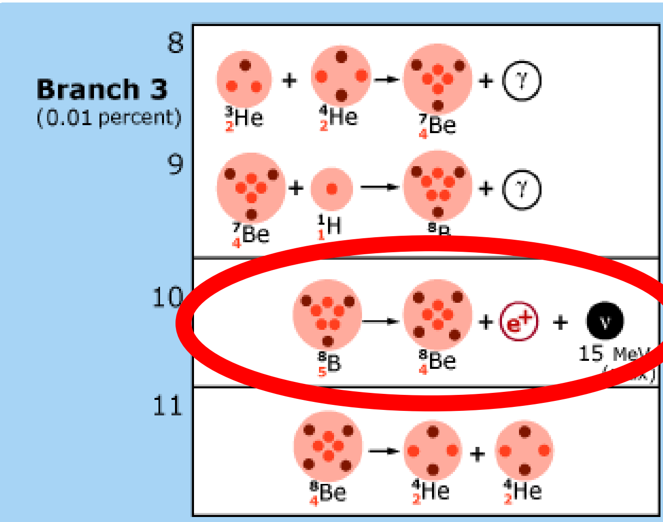
$^{7}Be(p,\gamma)^{8}B$ - solar neutrino problem – proof!

$$4\,{}^{1}H \rightarrow {}^{4}He + 2e^{+} + 2\nu$$

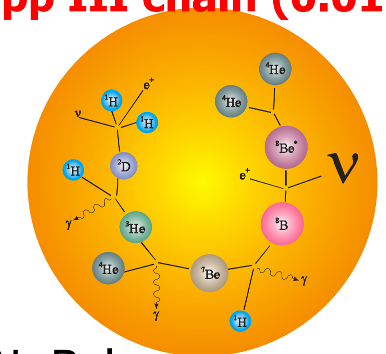
p-p chain reactions







pp III chain (0.01%)



The figures are adapted from J. N. Bahcall, *Neutrinos from the Sun*

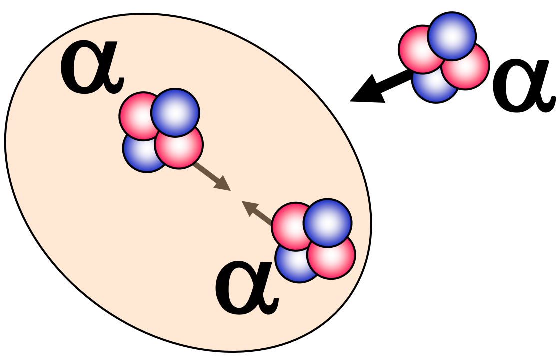
• Helium Burning: **Carbon formation**

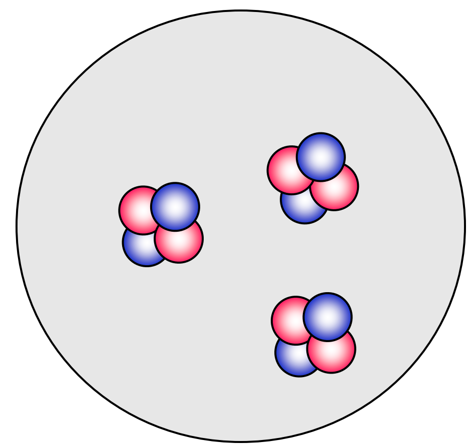
- *BBN produced <u>no elements heavier than Li</u> due to the absence of a stable nucleus with 8 nucleons*

- *in stars ^{12}C formation set the stage for the entire nucleosynthesis of heavy elements*

<u>How is Carbon synthesized in stars?</u>

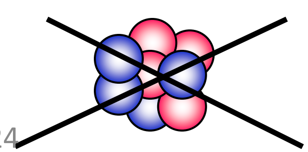
T ~ $6*10^8$ K and ρ ~ $2*10^5$ gcm^{-3}





$^4He + ^4He \leftrightarrow ^8Be$

$^8Be + ^4He \leftrightarrow ^{12}C\ (0^+_2)$
"Hoyle state"



^8Be unstable
($\tau \sim 10^{-16}$ s)

Work for NPA

Question here:

- Better (more precise) data for pp-chains: $^{3}He+^{4}He$, $^{7}Be(p,\gamma)$, …
- Are there alternatives to the 3α process?!

Helium Burning, **Oxygen formation**

- *Oxygen production, carbon consumption:*

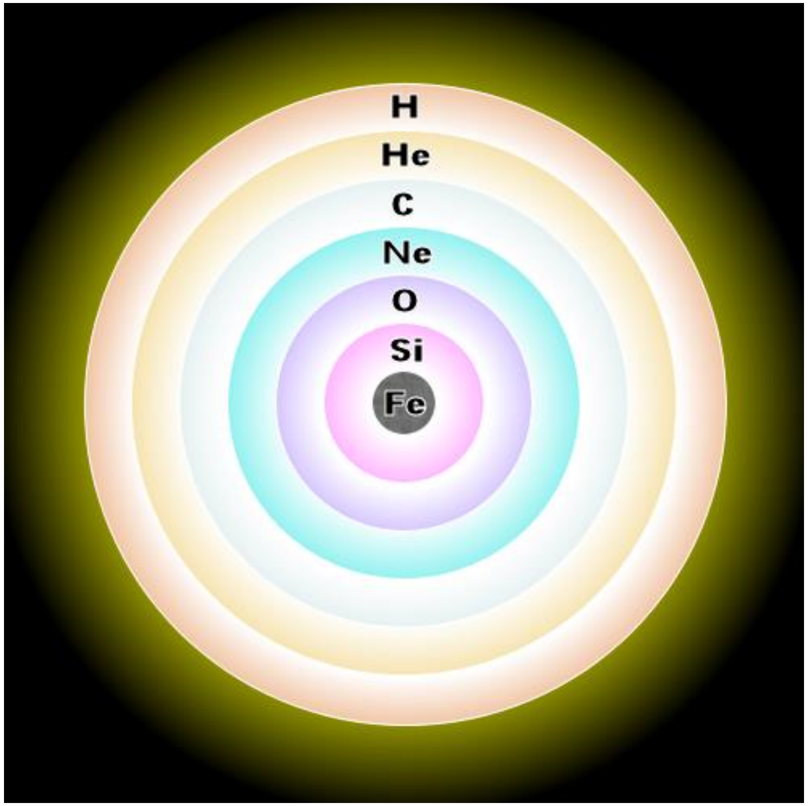
$$^{12}C + ^{4}He \rightarrow ^{16}O + \gamma$$

Still a big puzzle for experimentalists reaction $^{12}C(\alpha,\gamma)^{16}O$. Need c.s. at ~300 keV, could measure down to ~1 MeV only. Estimated c.s. at $10^{-15} – 10^{-17}$ b, excludes so far direct measurements!

Reaction rate is very small $\Rightarrow$ Oxygen production is possible,
But not all Carbon burns and Carbon-based life became possible…

• Nucleosynthesis up to Iron

A massive star near the end of its lifetime has "onion ring" structure



Carbon burning $\Rightarrow$ $T \sim 6{*}10^8$ K, $\rho \sim 2{*}10^5$ gcm^{-3}

$^{12}C + ^{12}C \rightarrow ^{20}Ne + ^4He + 4.6$ MeV

$\qquad\qquad\quad ^{23}Na + ^1H + 2.2$ MeV

Neon burning $\Rightarrow$ $T \sim 1.2{*}10^9$ K, $\rho \sim 4{*}10^6$ gcm^{-3}

$^{20}Ne + \gamma \rightarrow ^{16}O + ^4He$

$^{20}Ne + ^4He \rightarrow ^{24}Mg + \gamma$

Oxygen burning $\Rightarrow$ $T \sim 1.5{*}10^9$ K, $\rho \sim 10^7$ gcm^{-3}

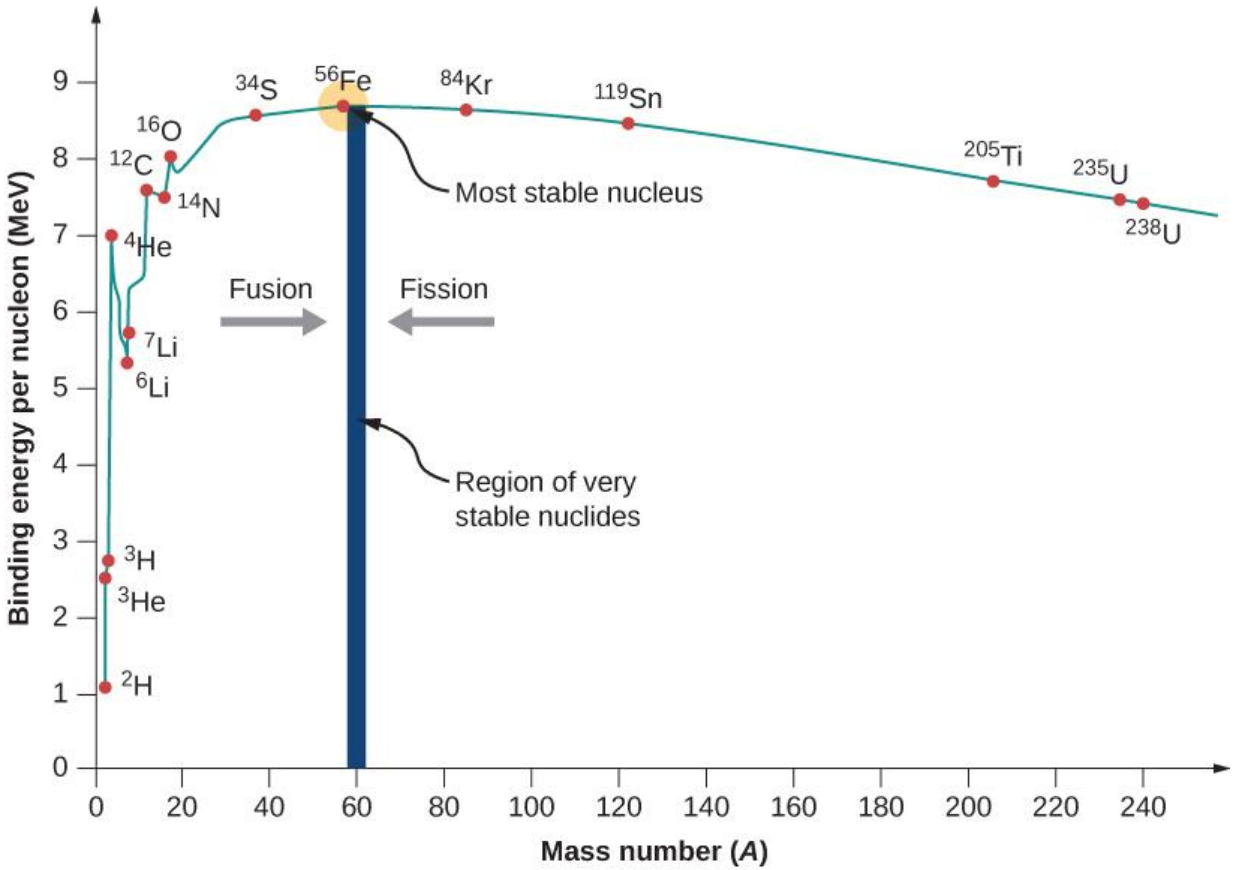
$^{16}O + ^{16}O \rightarrow ^{28}Si + ^4He + 10$ MeV

$\qquad\qquad\quad ^{31}P + ^1H + 7.7$ MeV

Silicon burning $\Rightarrow$ $T \sim 3{*}10^9$ K, $\rho \sim 10^8$ gcm^{-3}

major ash: Fe

stars can no longer convert mass into energy via nuclear fusion !


Binding energy per nucleon (MeV)
Mass number (A)
0
1
2
3
4
5
6
7
8
9
0
20
40
60
80
100
120
140
160
180
200
220
240
²H
³He
³H
⁶Li
⁷Li
⁴He
¹²C
¹⁴N
¹⁶O
³⁴S
⁵⁶Fe
⁸⁴Kr
¹¹⁹Sn
²⁰⁵Ti
²³⁵U
²³⁸U
Most stable nucleus
Fusion
Fission
Region of very
stable nuclides

Questions for NPA

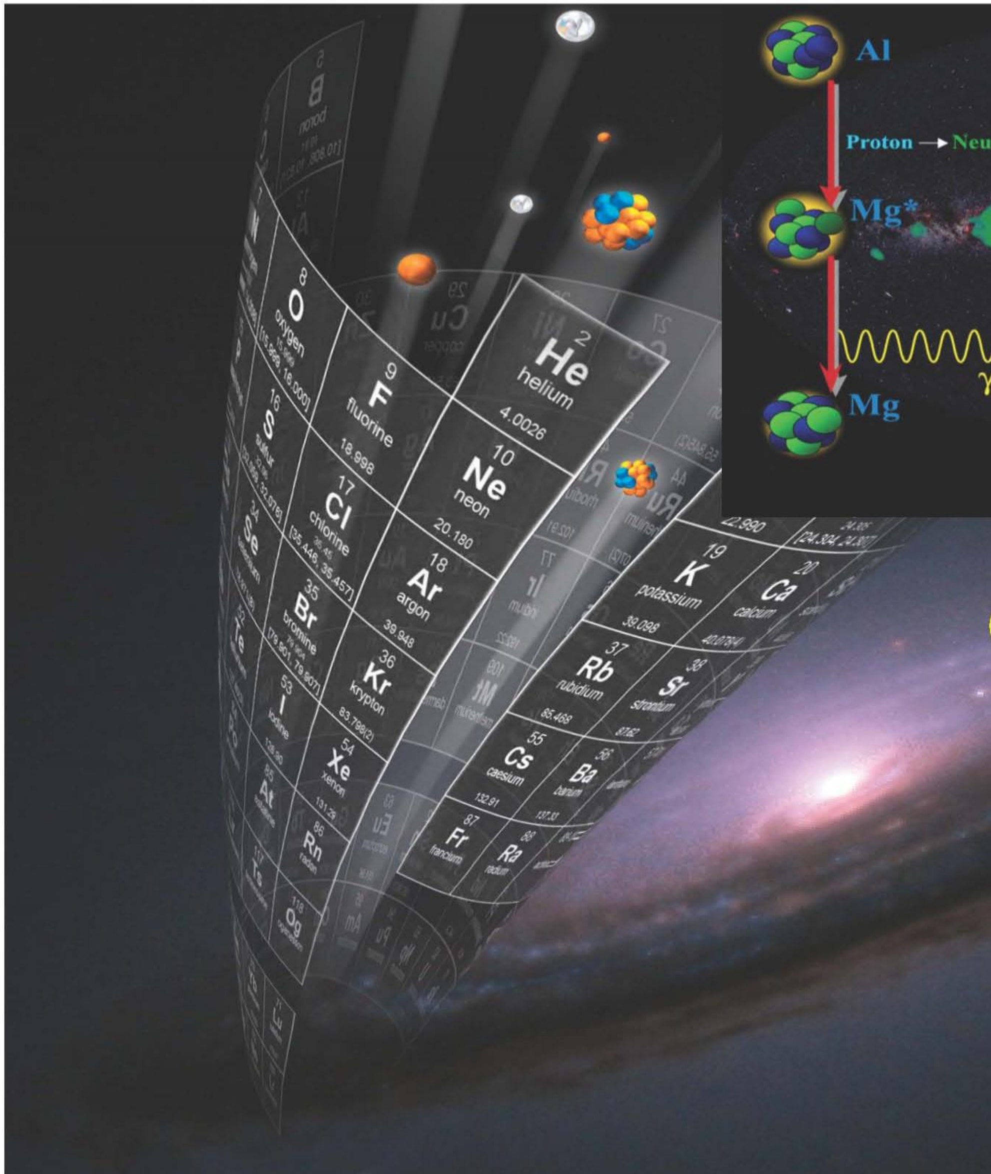
- Important ion-ion fusion reactions
  - $^{12}C + ^{12}C$
  - $^{12}C + ^{16}O$
  - $^{16}O + ^{16}O$

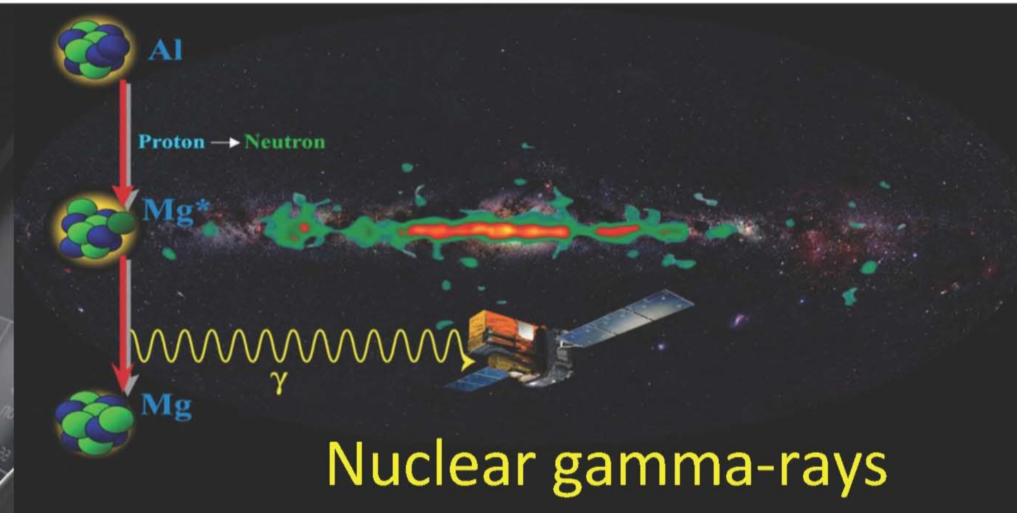
  Large Coulomb barriers, difficult to measure directly
- Reaction rates in stellar plasmas vs. rates in laboratory (screening effect?!)
- Masses, structure and decays of neutron-rich nuclei
- Fission of heavy and hot nuclei
- Supernovae, neutron stars, neutron stars mergers are sensitive to the **Equation of state (EoS) of nuclear matter**. Larger densities, larger charge asymmetries, new degrees of freedom …
- …

Nucleosynthesis is going on

Proofs:

- Sun is shining!
- Decay of ^{26}Al ($T_{1/2}$=0.7 M yr) detected by terrestrial and space gamma-ray telescopes
  - Example: Diehl, R. et al. Radioactive 26Al from massive stars in the Galaxy. Nature **439,** 45–47 (2006).
- Other galactic emitters observed… Tc
- Remnants in Earth sediments: ^{60}Fe, ^{244}Pu, …





Nuclear gamma-rays and Cosmic Nucleosynthesis

Roland Diehl
Technical University München and
MPE and Origins Cluster emeritus
Garching

Contents:

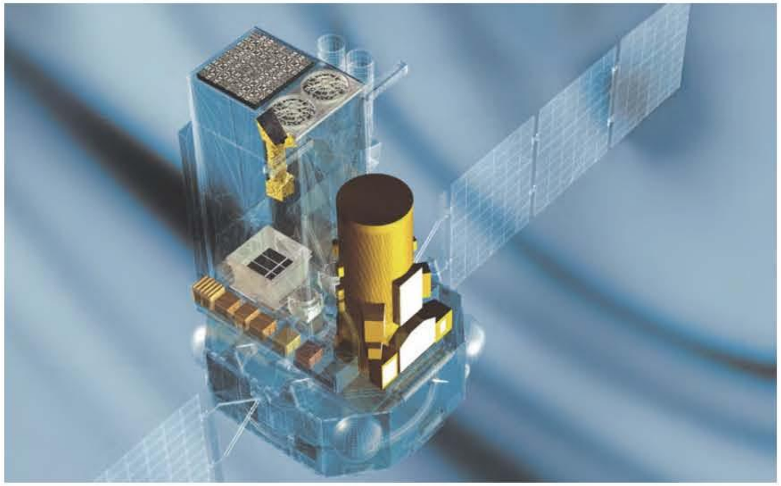
1. Science goals of γ-ray observations
2. Sources:
   Supernova explosions
3. Transport:
   Galactic-scale nucleosynthesis

with work from (a.o.)
Martin Krause, Karsten Kretschmer, Moritz Pleintinger,
Thomas Siegert, Rasmus Voss, Wei Wang, Christoph Weinberger

Figure: ChETEC 2021

Current Nuclear Gamma-Ray Line Telescopes:

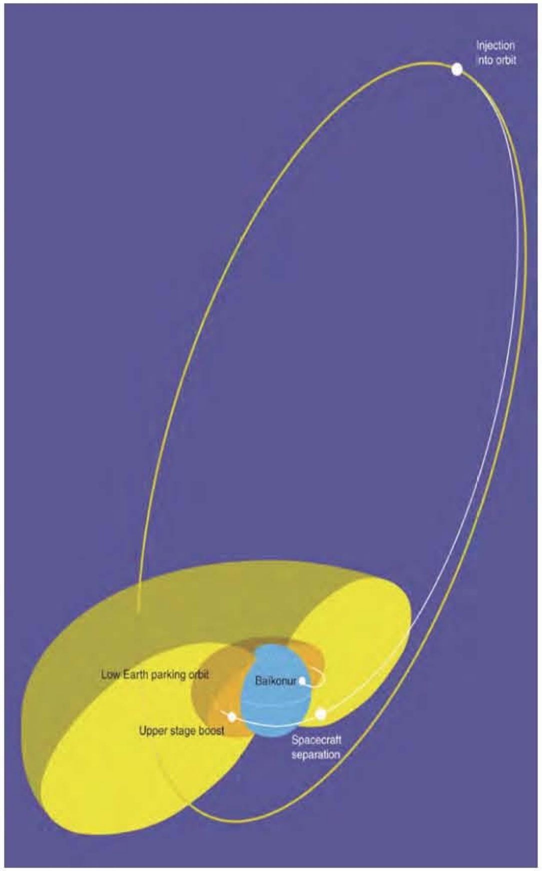
ESA's INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL)



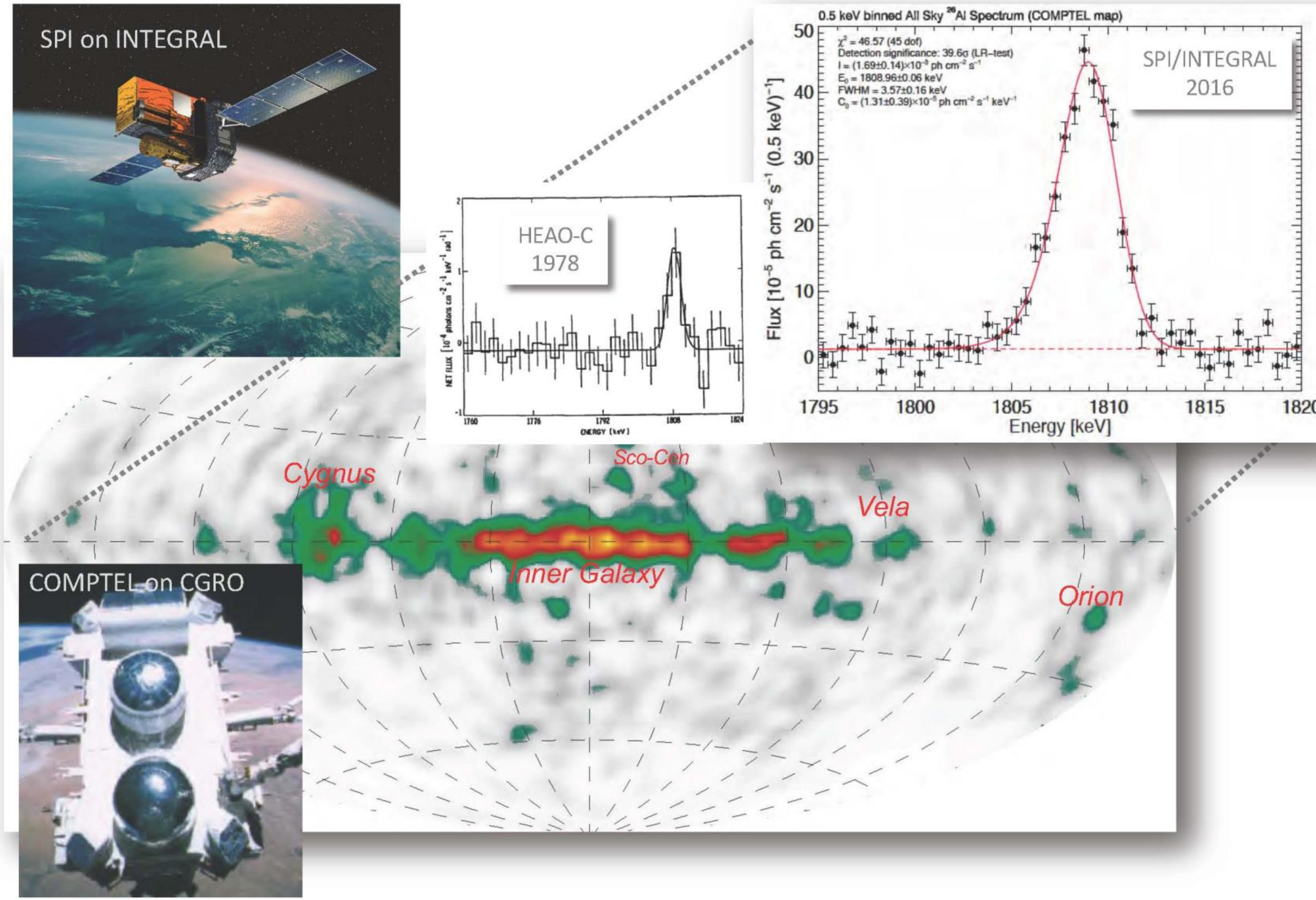
Mission: 2002-(2024+..2029)

Instruments: 2 main (imager, spectrometer), 2 aux

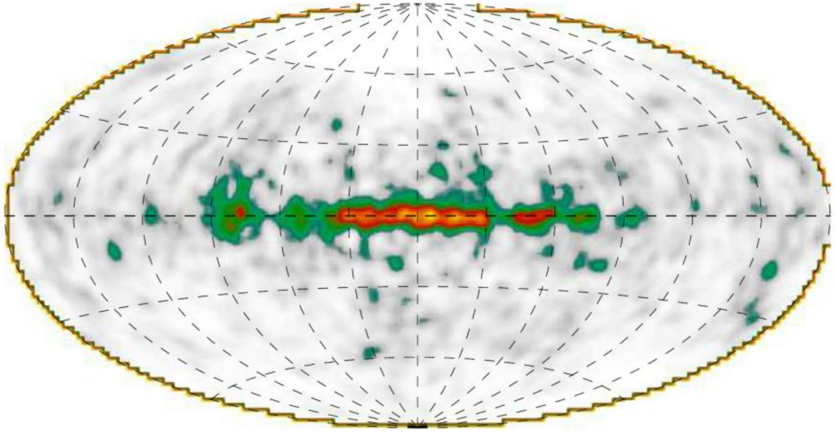
3-day orbit, excentric and outside radiation belts

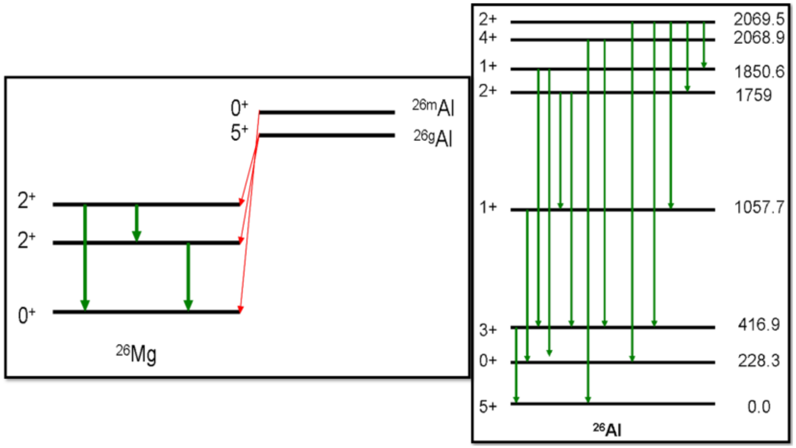


^{26}Al γ-rays from the Galaxy



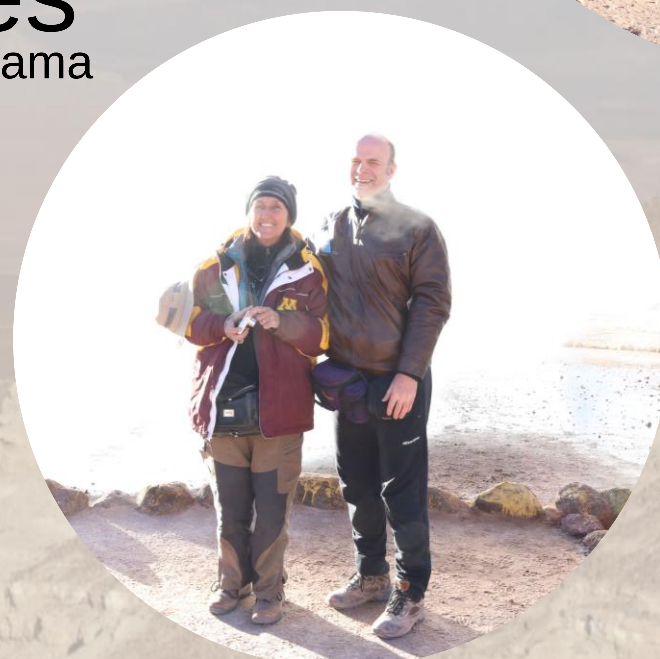
^{26}Al from space telescopes





Samples. Microbialites

- Chile, Atacama Desert, Vilama Formation



Samples. Stromatolite

- Kenya, Turkana Basin

Samples. Mass Concentration Enhancement

- Check for our Rare Earth Elements mass concentration enhancement to confirm the uptake hypothesis
- ICP-MS (Mass Spectrometry) REEs measurements on (determination of trace-elements concentration):

❑ our geological samples

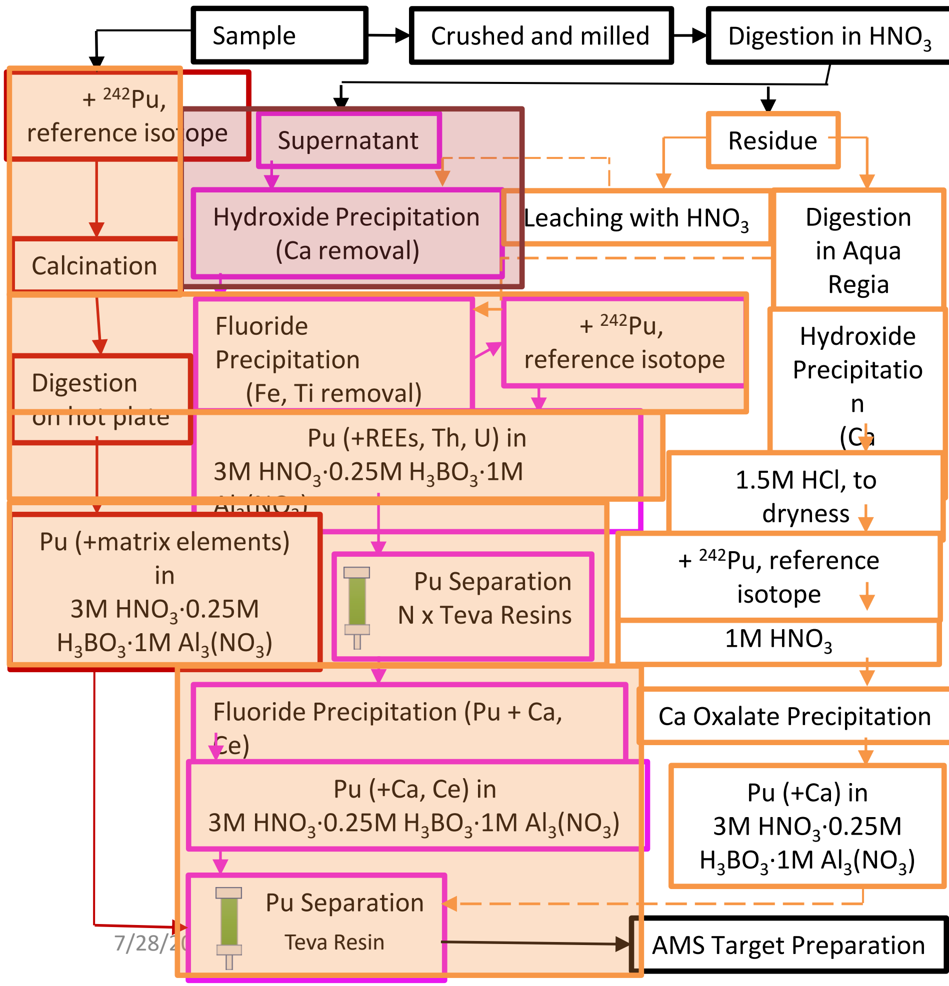
❑ proxy water samples from the same geological areas

Finally, our REEs ratio of carbonate/water indicates concentration enhancement factor

Atacama
Microbialite/Water
REEs – 10^4-10^7
Th, U – 10^3-10^4

Kenya
Sample/Water
REEs – 10^3-10^4
Th, U – 10^2-10^3

Chemical procedure – Plutonium extraction. Chemical yield



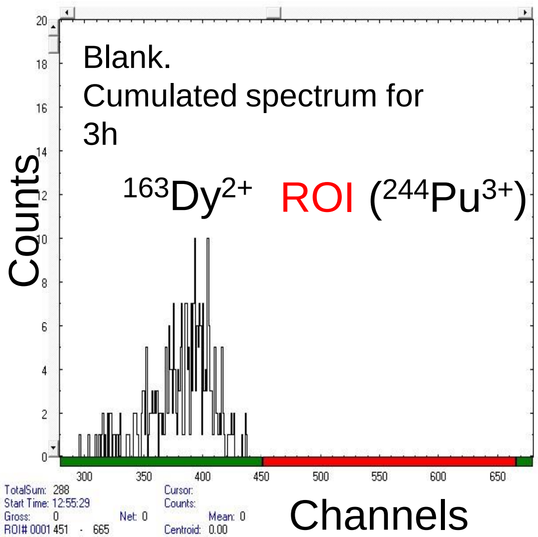
ICP-MS measurements of the supernatant (before and after) and the precipitate
Chemical recoveries for REEs, Th and U:
ranging from 70% to 99%

Alpha Spectrometry – Determination of Plutonium Chemical Recovery,
The analyte (20 mBq - ^{242}Pu – certified material NPL) uniformly distributed on a surface

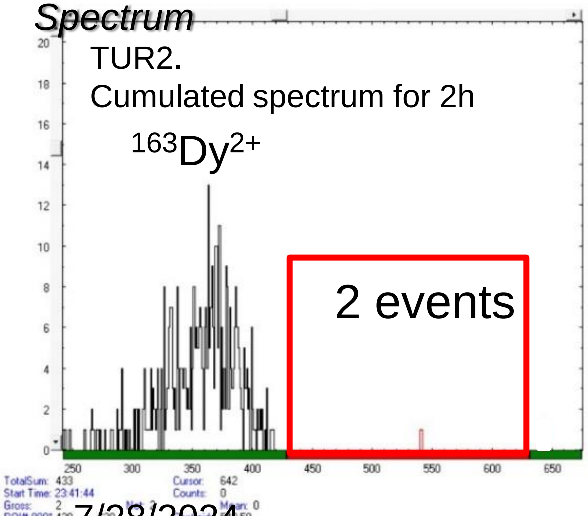
Sample	Chemical yield [%]	RSD [%]
AS11, **Atacama Sample**	**96.1**	17.2
AS19, **Atacama Sample**	**94.3**	16.6
AS15, **Turkana Sample**	**50.9**	15.7
AS18, **Turkana Sample**	**63.6**	18.4

AMS plutonium results. ^{244}Pu ISM flux

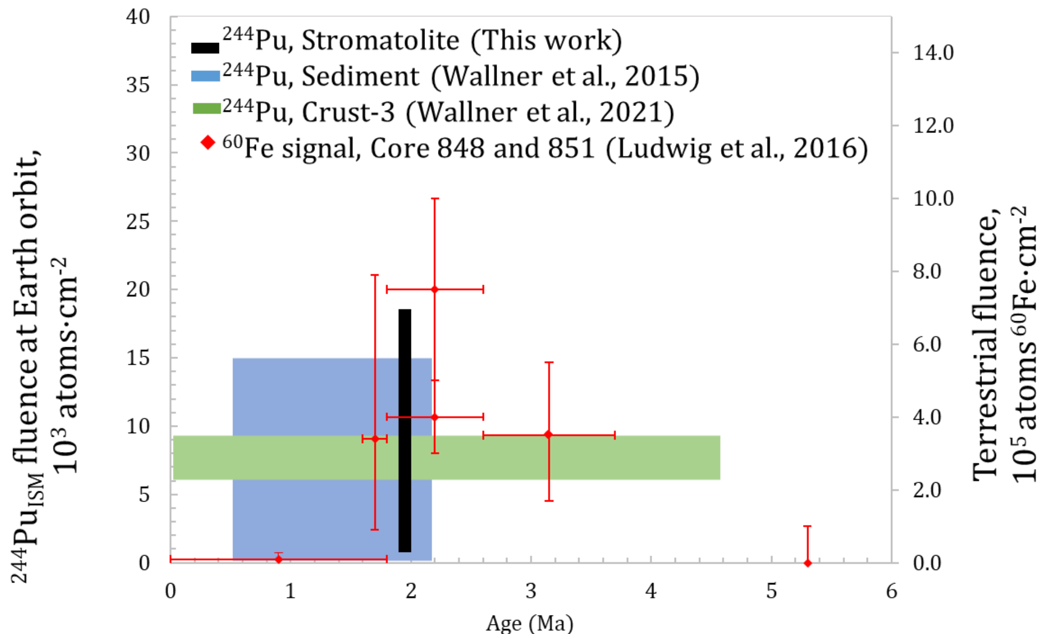
Blank Sample. AMS Spectrum



Turkana Stromatolite. AMS Spectrum



$$\Phi_{ISM\,^{244}Pu} = \frac{\frac{^{244}Pu_{excess}}{m\_stromatolite} \cdot Av \left(\frac{water_{Ac}}{stromatolite_{Ac}}\right)}{A/_V} \cdot 4 = [\,^{244}Pu\ atoms/_{cm^2}]$$



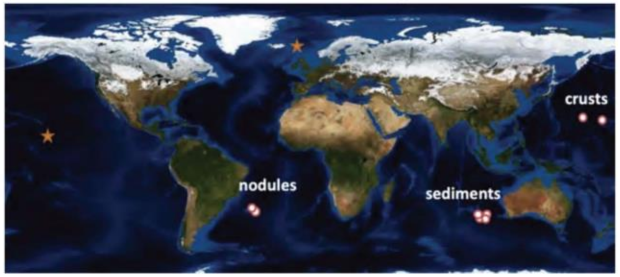
Our measurement indicates an extraterrestrial ^{244}Pu influx of interstellar material into the inner Solar System coincident in time with ^{60}Fe signal

Same source
Core-Collapse SNe

Iuliana Stanciu thesis, TUM Dec. 2022

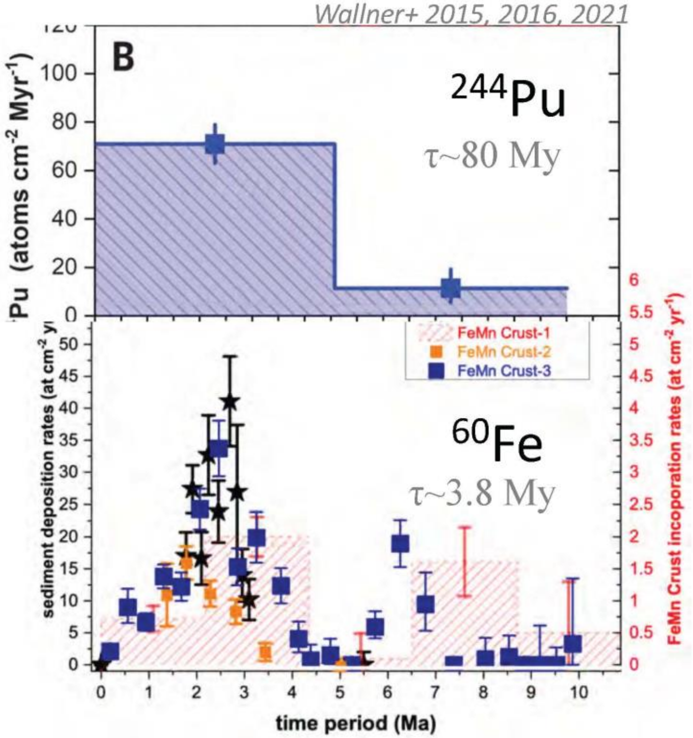
^{60}Fe and ^{244}Pu from nearby nucleosynthesis found on Earth

Knie+ 2004, Fimiani+ 2016, Ludwig+ 2016, Koll+ 2019, ...



+ lunar material probes; + antarctic snow

Wallner+ 2015, 2016, 2021



peak of radioactivity influx
≈3 & 6-8 My ago!

What are its sources?

How did these traces of nucleosynthesis get here?

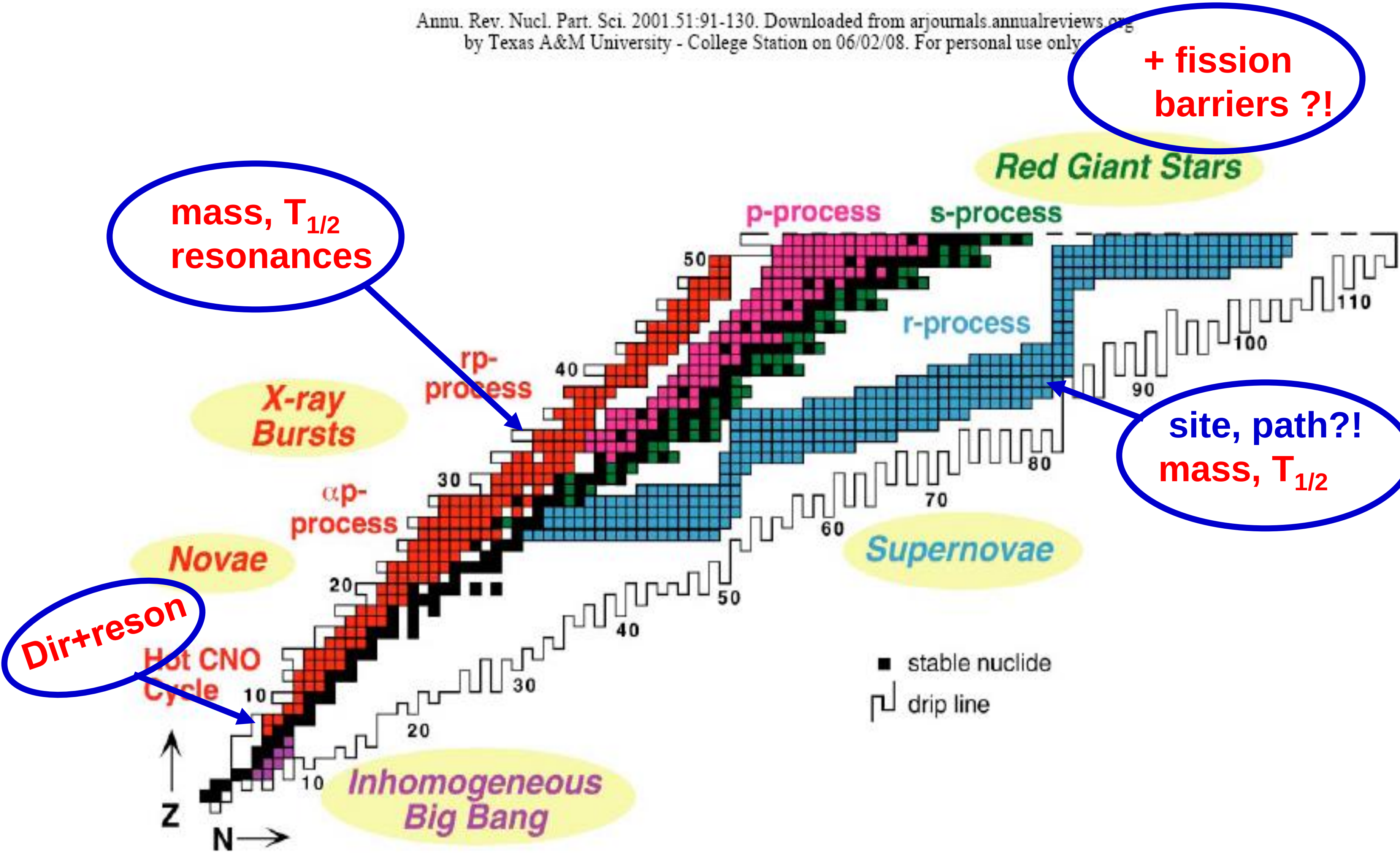
Nucleosynthesis summary

- Big Bang Nucleosynthesis (BBN)
  - H, d, 3He, 4He, 7Li
- Stellar nucleosynthesis
  - Fusion of light nuclei up to Fe
  - Capture processes beyond iron:
    - s-process slow neutron capture (AGB stars)
    - r-process rapid neutron capture; Q: where, which path(s) …?

      Supernovae or/and neutron star mergers ?!

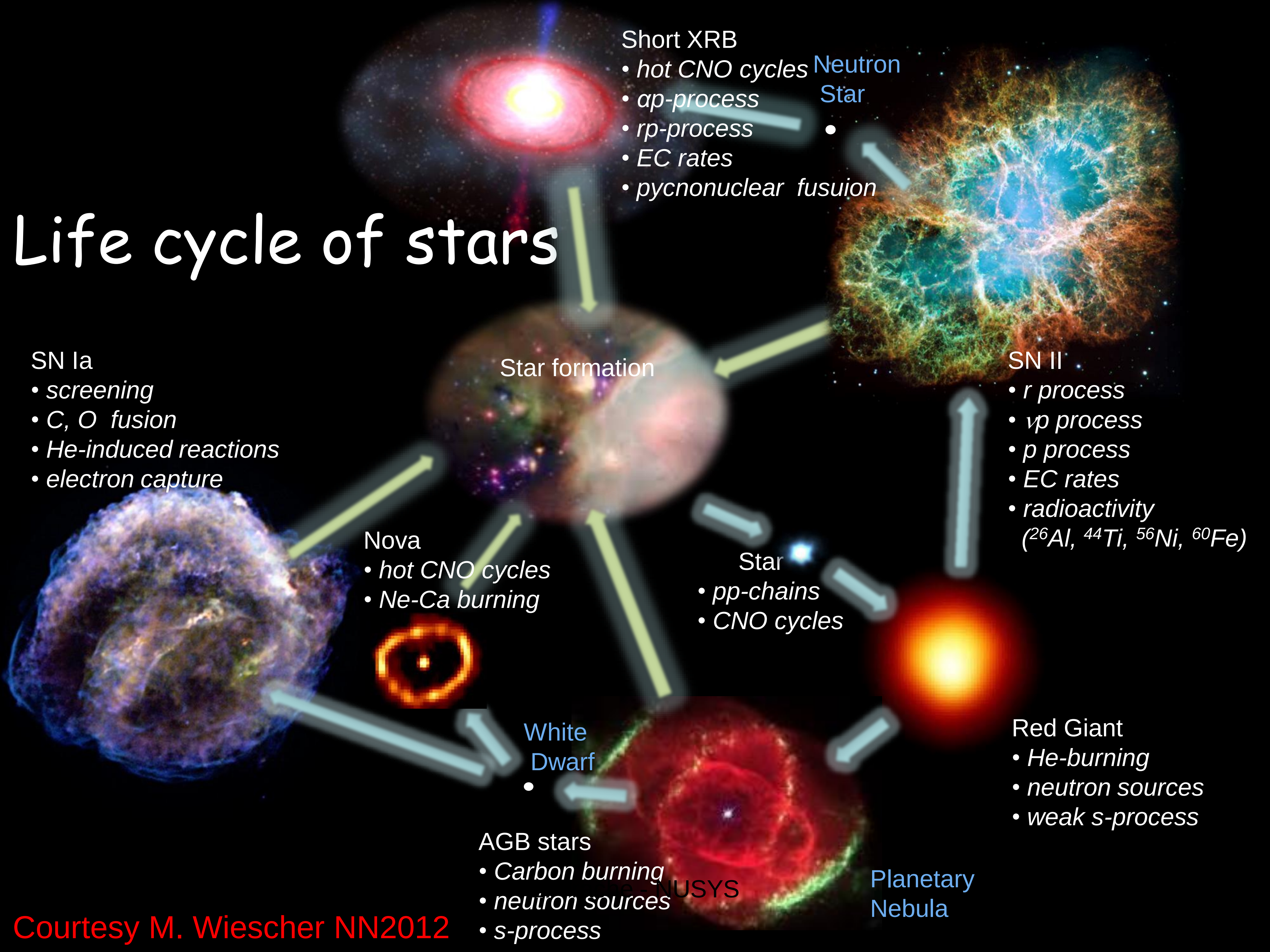
      BTW watch the words: “multi-messenger astronomy”
    - Intermediate … i-process
    - p-process
    - rp-process
- A: no unique processes, diversity of observations means diversity of phenomena; quiescent burning and explosive …

M. Smith & E. Rehm



Two big problems:

1. - very small energies and very small cross sections ⇒indirect methods
2. - reactions in stars involve(d) radioactive nuclei ⇒ use RNB


Life cycle of stars
Short XRB
• hot CNO cycles
• αp-process
• rp-process
• EC rates
• pycnonuclear fusuion
Neutron
Star
Star formation
SN Ia
• screening
• C, O fusion
• He-induced reactions
• electron capture
SN II
• r process
• νp process
• p process
• EC rates
• radioactivity
(^{26}Al, ^{44}Ti, ^{56}Ni, ^{60}Fe)
Nova
• hot CNO cycles
• Ne-Ca burning
Star
• pp-chains
• CNO cycles
White
Dwarf
Red Giant
• He-burning
• neutron sources
• weak s-process
AGB stars
• Carbon burning
• neutron sources
• s-process
NUSYS
Planetary
Nebula
Courtesy M. Wiescher NN2012

• Messages to take away…

Nuclear reactions play a crucial role in the Universe:

1. **they provide the energy in stars including that of the Sun.**
2. **they produced all the elements we depend on.**
3. **nucleosynthesis is on-going process in our galaxy**

There are ~270 stable nuclei in the Universe. By studying reactions between them we have produced ~3000 more (unstable) nuclei.

There are ~4000 more (unstable) nuclei which we know nothing about, and which will hold many surprises and applications. Present techniques are unable to produce them in sufficient quantities, but you are getting there!

It will be the next generation of accelerators and the next generation of scientists (*why not some of you?!)* which will ~~complete~~ do the work of this exciting research field.

Acknowledgements

- I acknowledge the use of several slides and/or knowledge, information, pictures, figures … from colleagues with or without specific consent
- Thanks to M. Wiescher, R. Diehl, A. Banu, I. Stanciu and many others; to websites APS, HSTI …