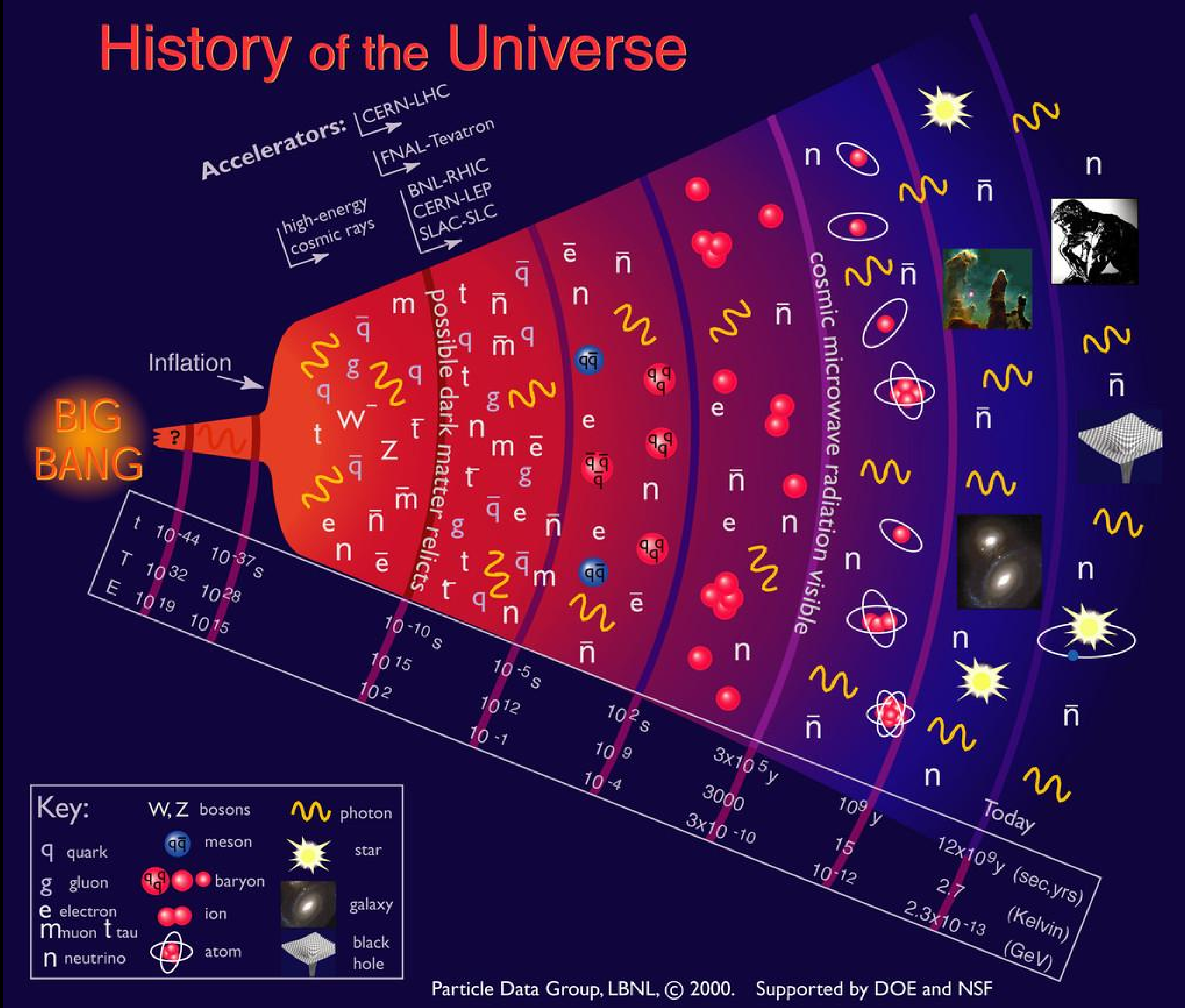
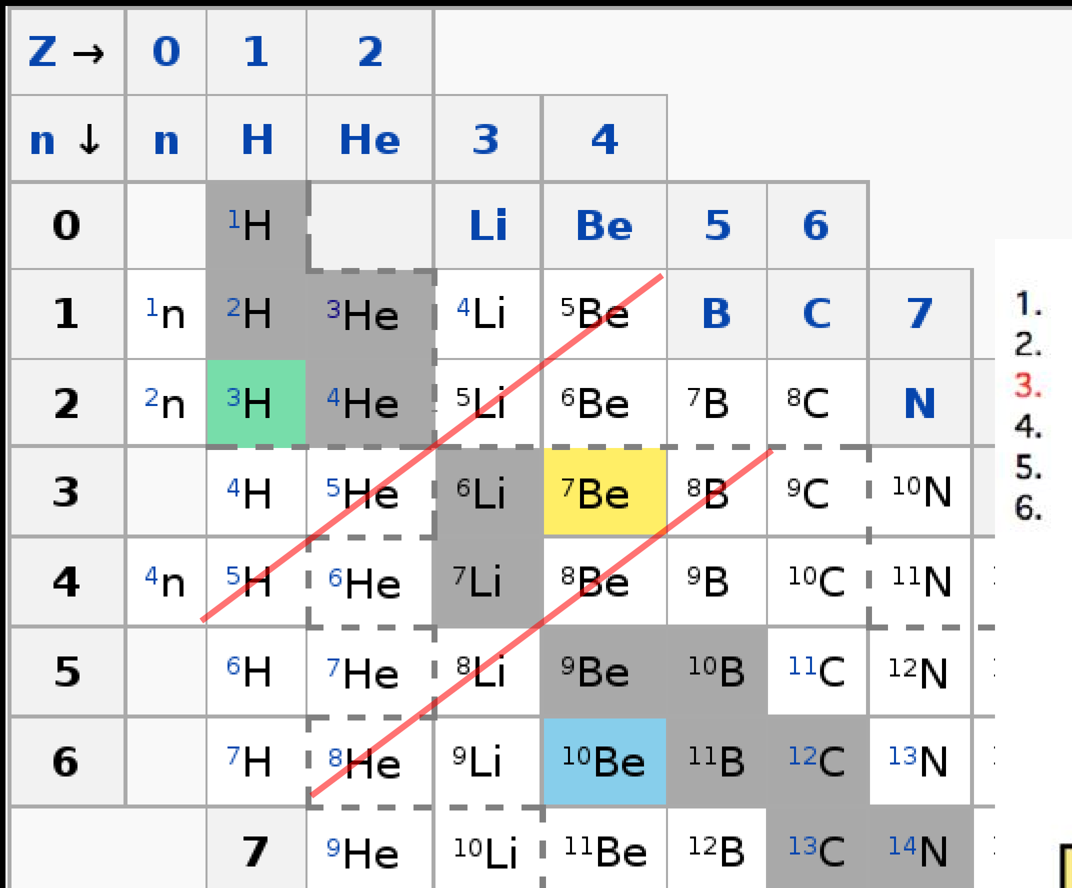
Where do we come from?
What are we made off?
Where do we go to?
...

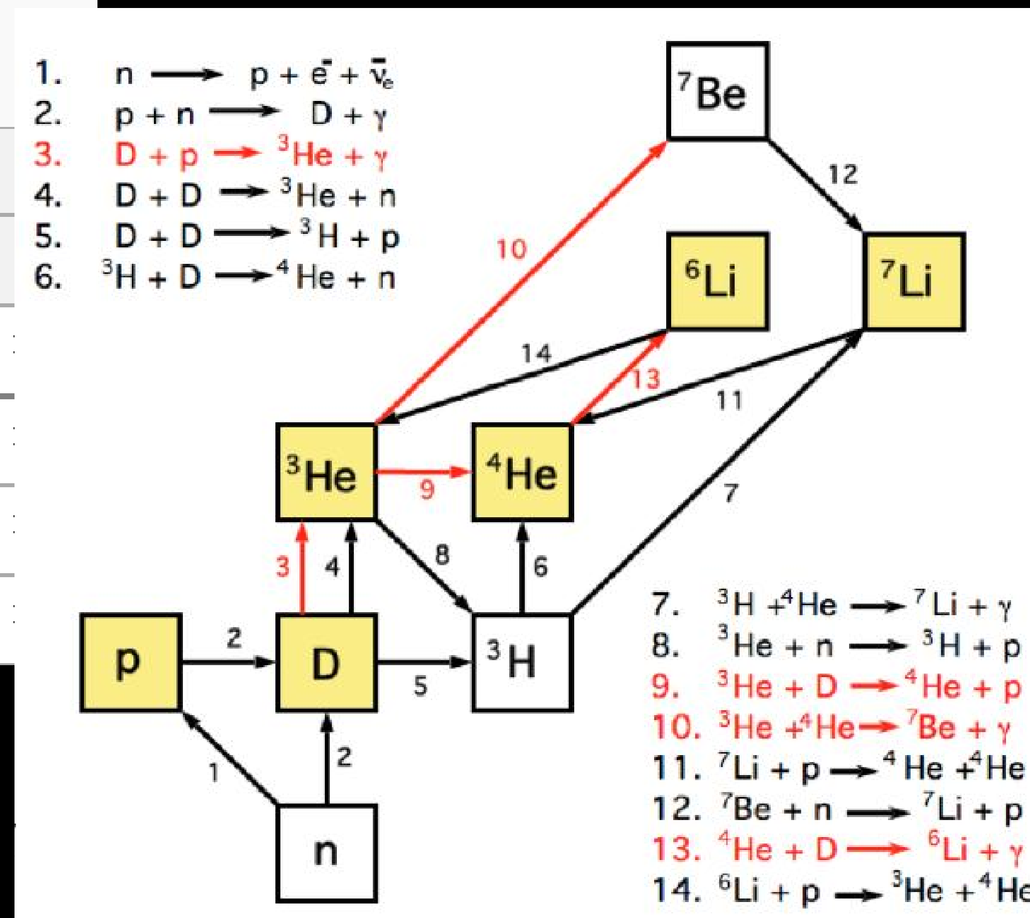
Science contributes to explore these questions

Here: The contribution of “Nuclear Astrophysics”


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Big Bang Nucleosynthesis





The air we breath is O_2,N_2, CO_2, …

The water we drink is H_2O ….

The smart phone we use is Si, Ti, Ta, Ag, etc

Sir Arthur Eddington (1882-1944)

equations of the stellar structure → ““And what is possible in the Cavendish Laboratory may not be too difficult in the sun.” (1920)

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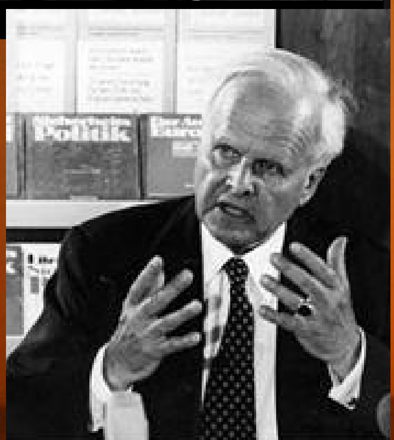

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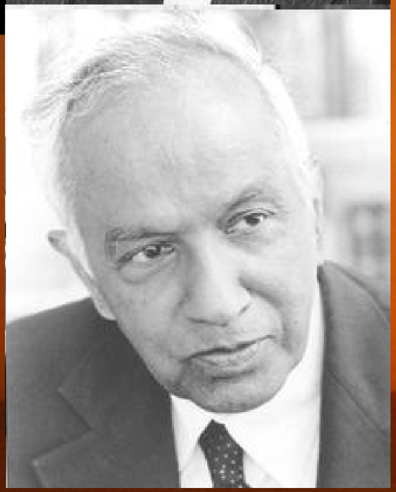

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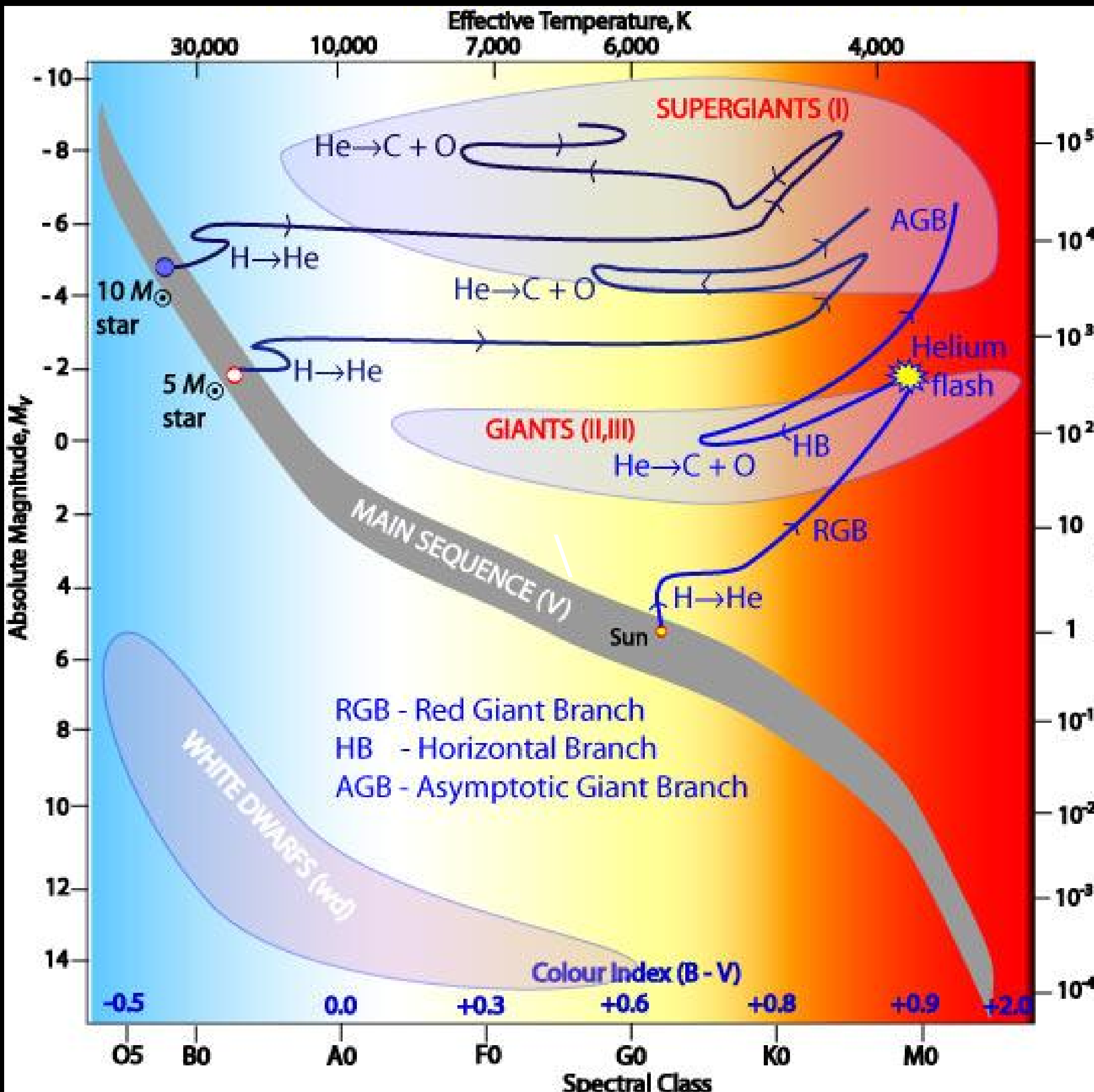
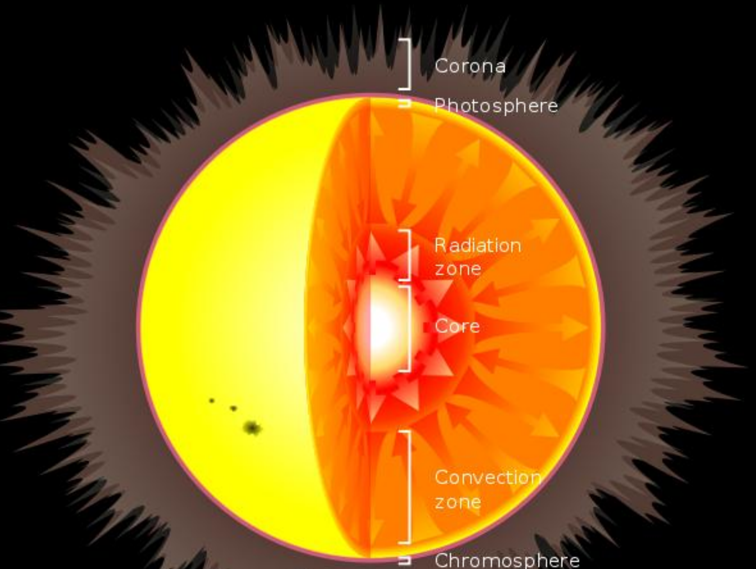
William Alfred Fowler (1911–1995)
Nobel Prize 1983 "for his theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the universe"

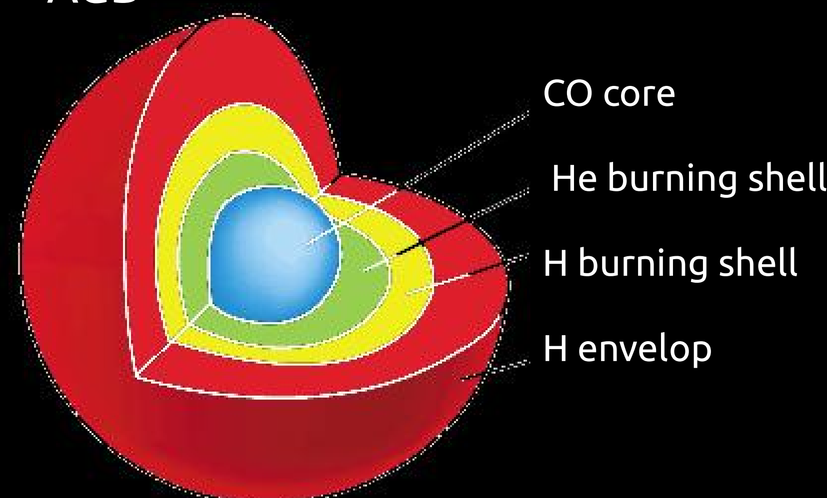
Subramanyan Chandrasekhar (1910 - 1995)
Nobel Prize 1983 "for his theoretical studies of the physical processes of importance to the structure and evolution of the stars"



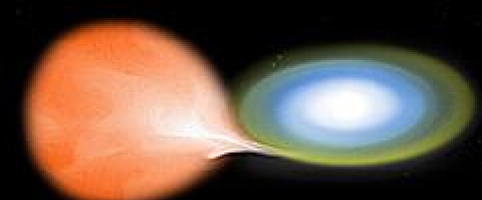


Main sequence star

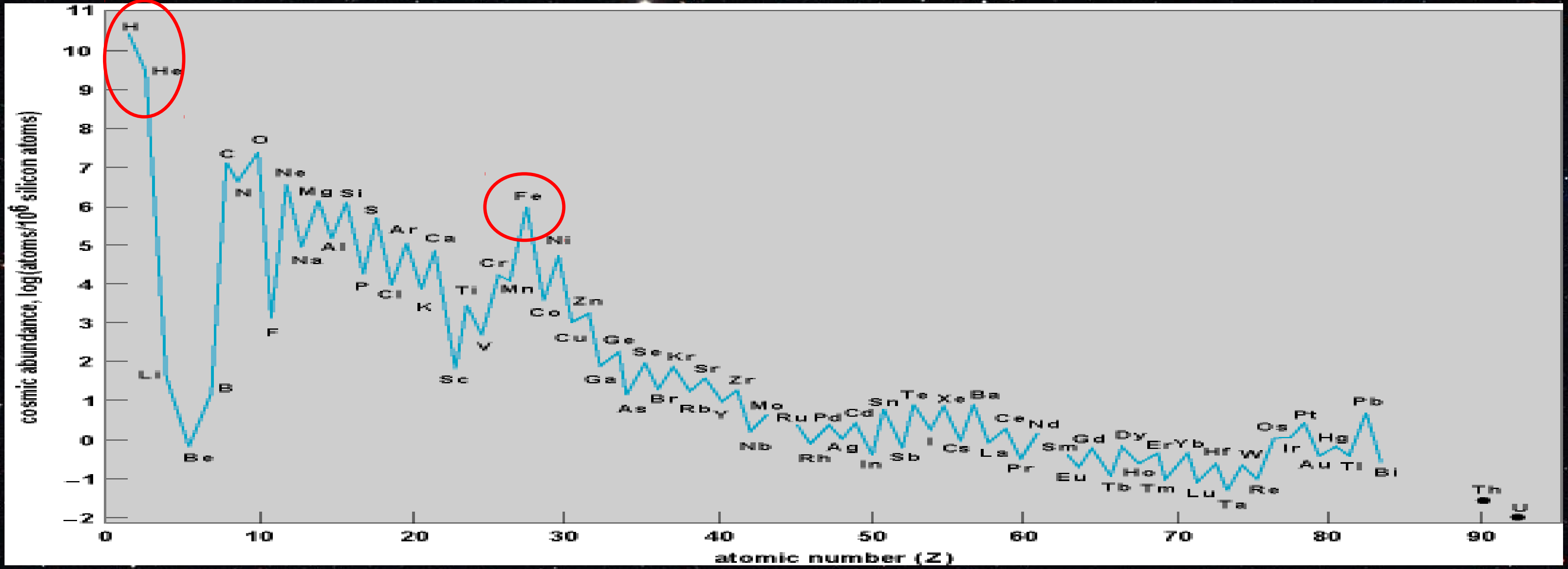
AGB

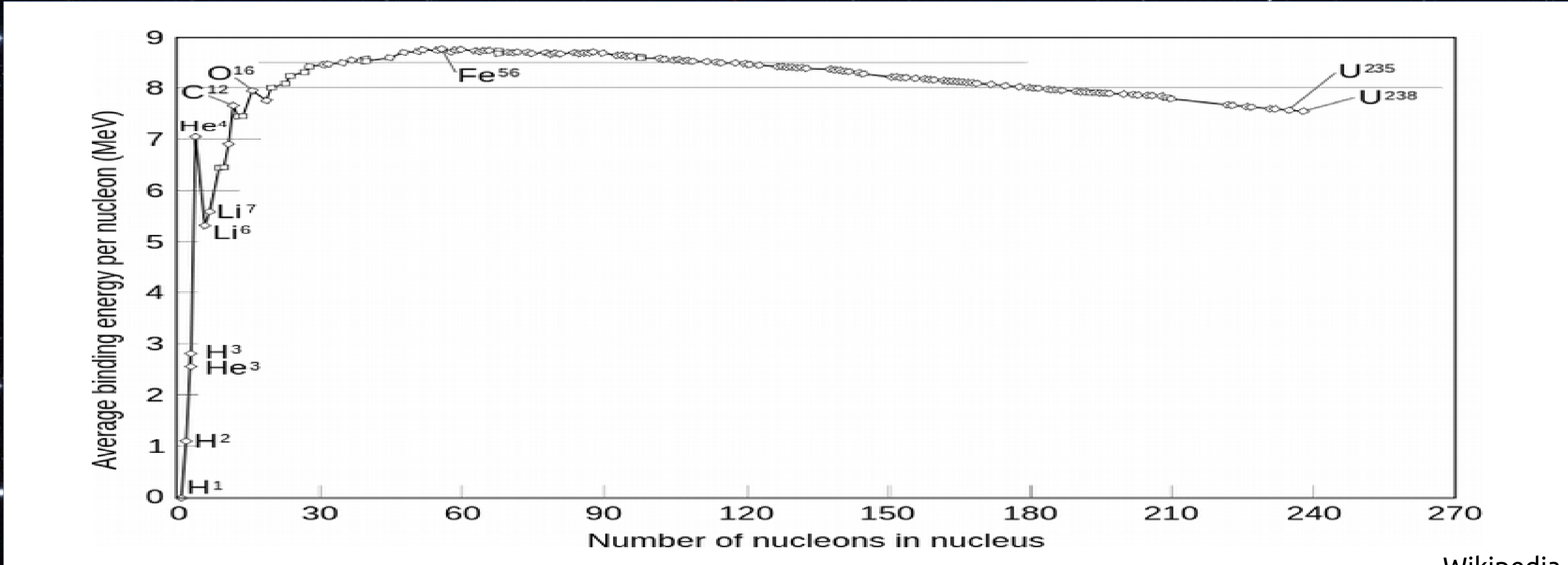


Novae



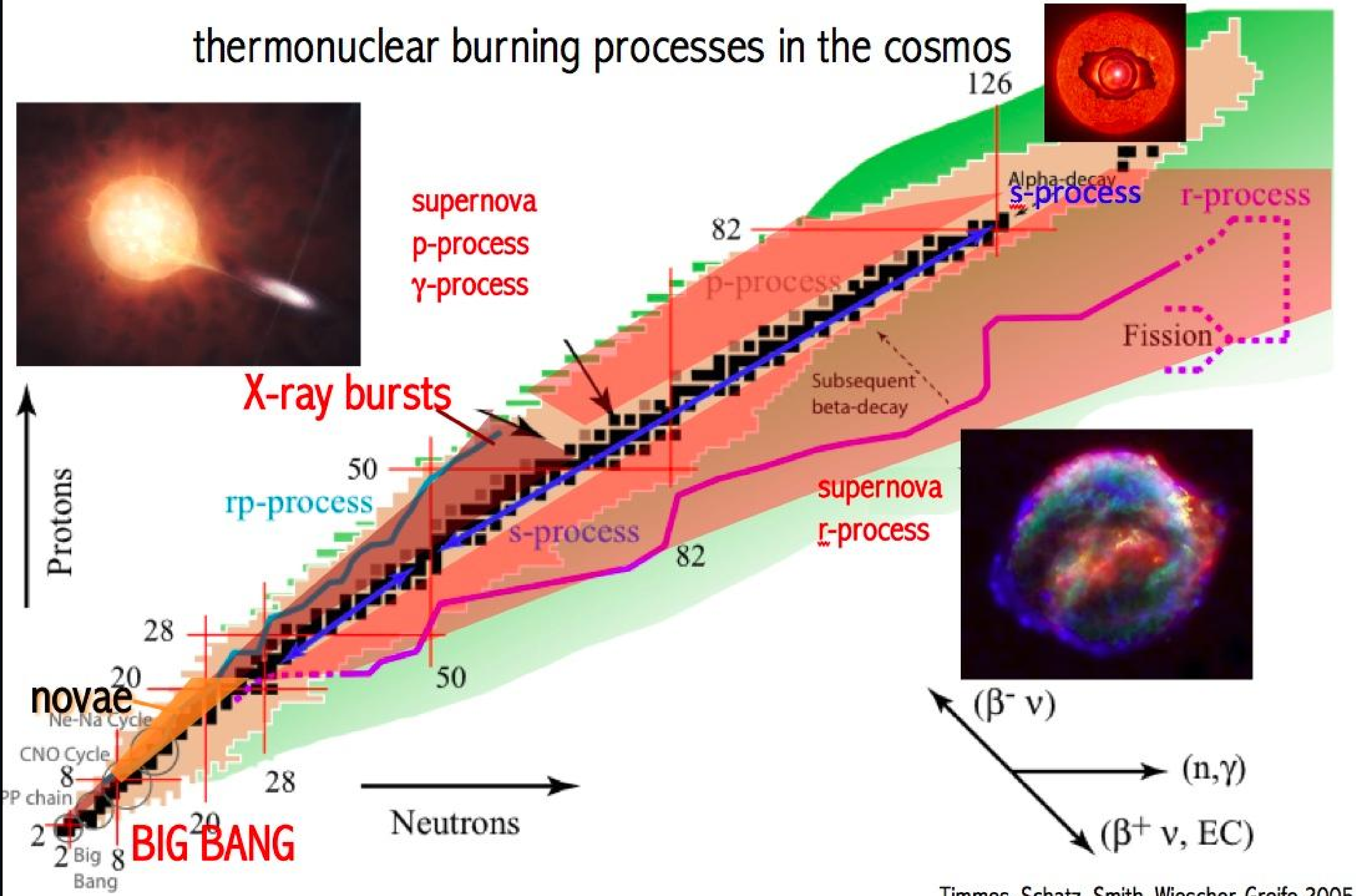
The cosmic abundance of the chemical elements





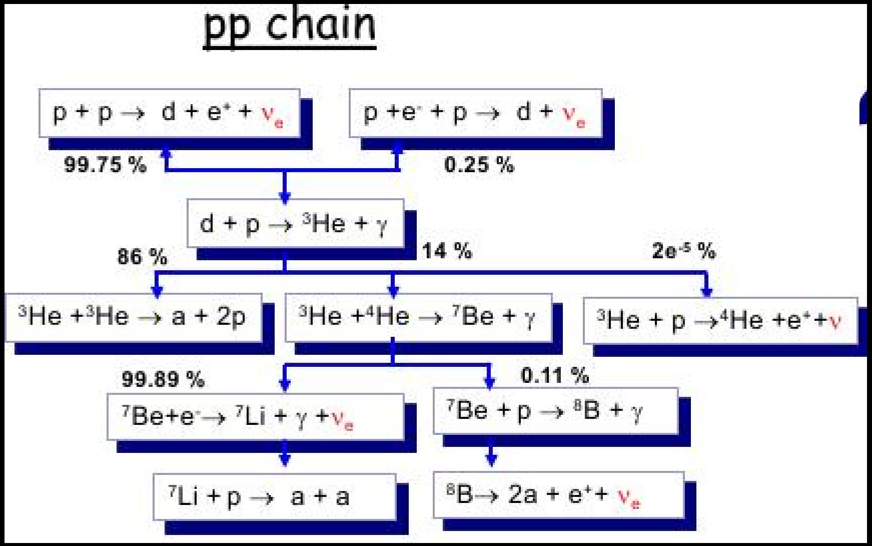
Wikipedia

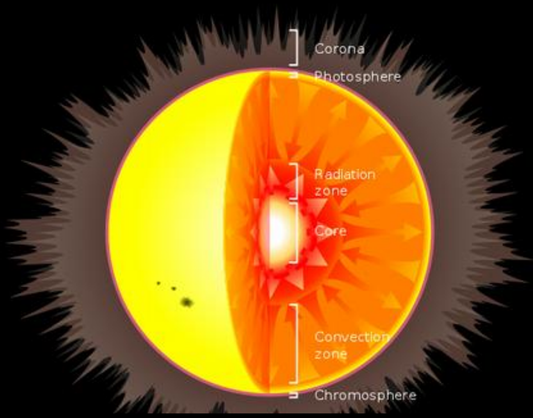
thermonuclear burning processes in the cosmos



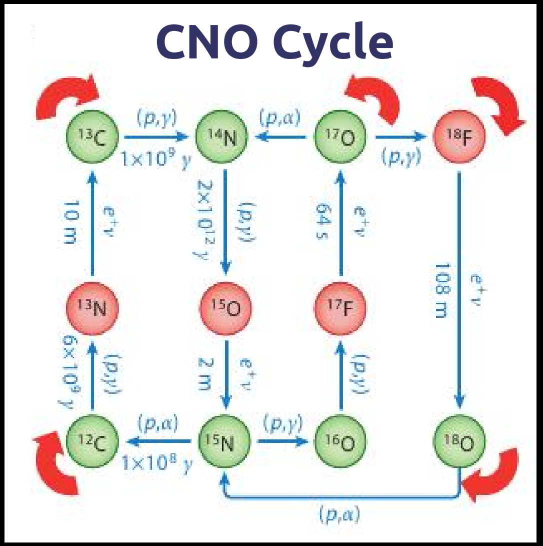
Timmes, Schatz, Smith, Wiescher, Greife 2005

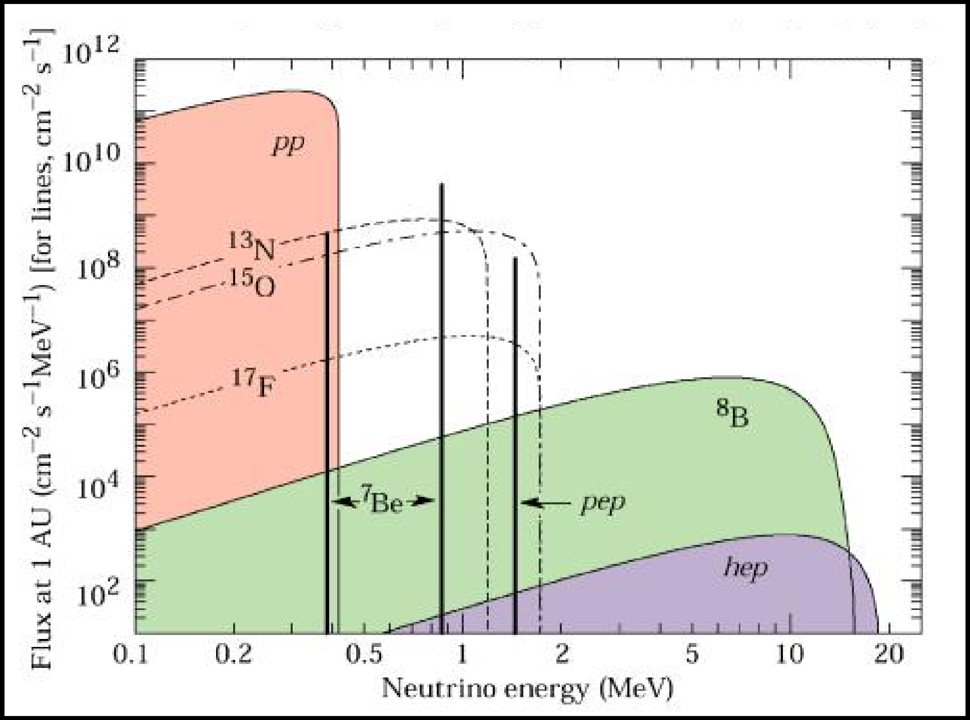
Hydrogen burning in main sequence stars

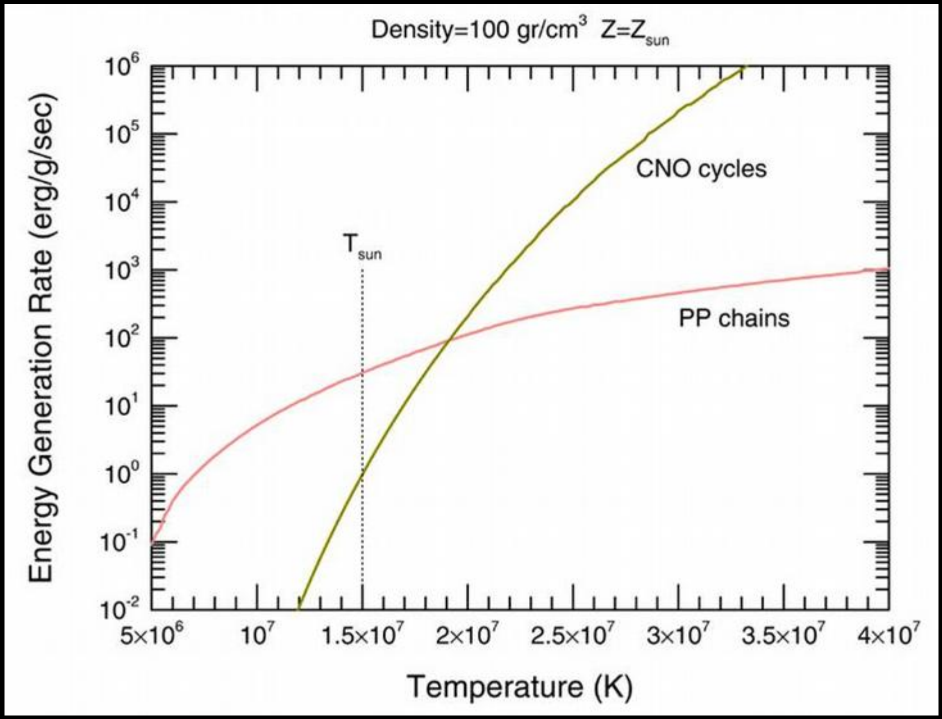




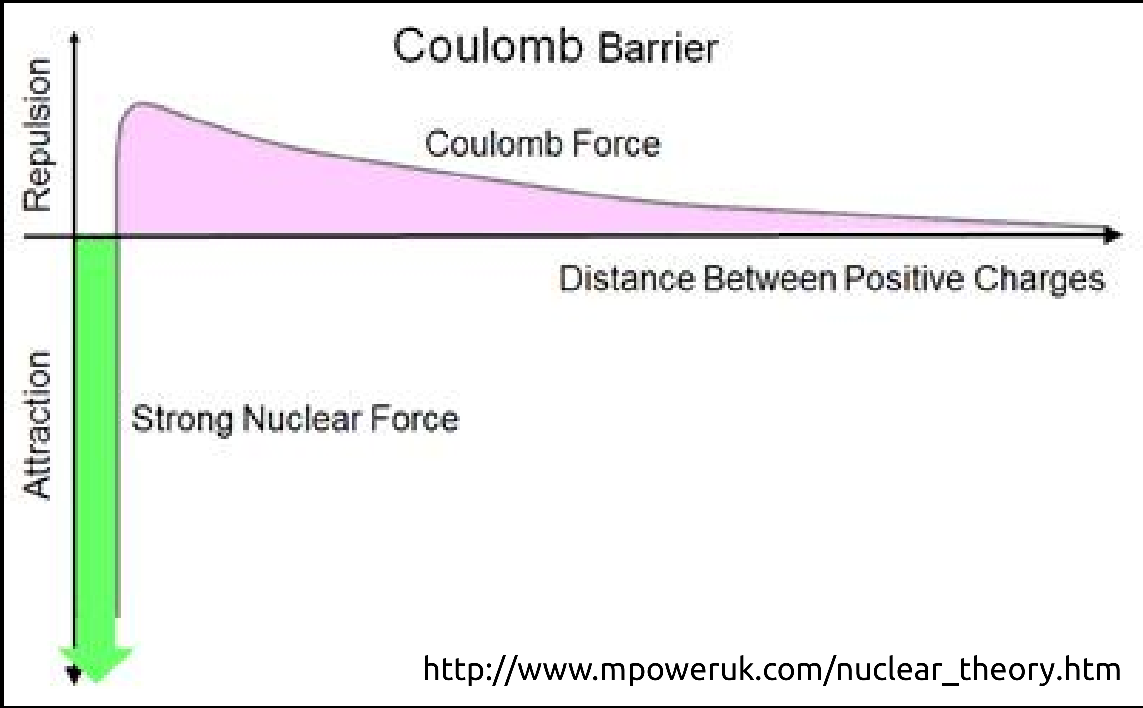
T ≈ 20 MK







Nuclear Fusion Reactions

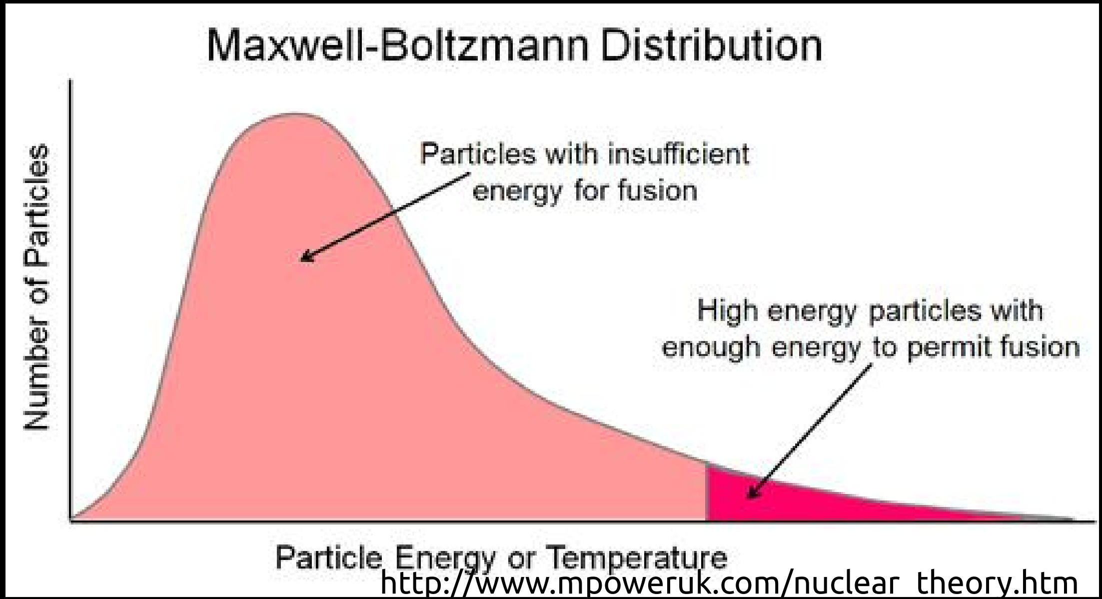


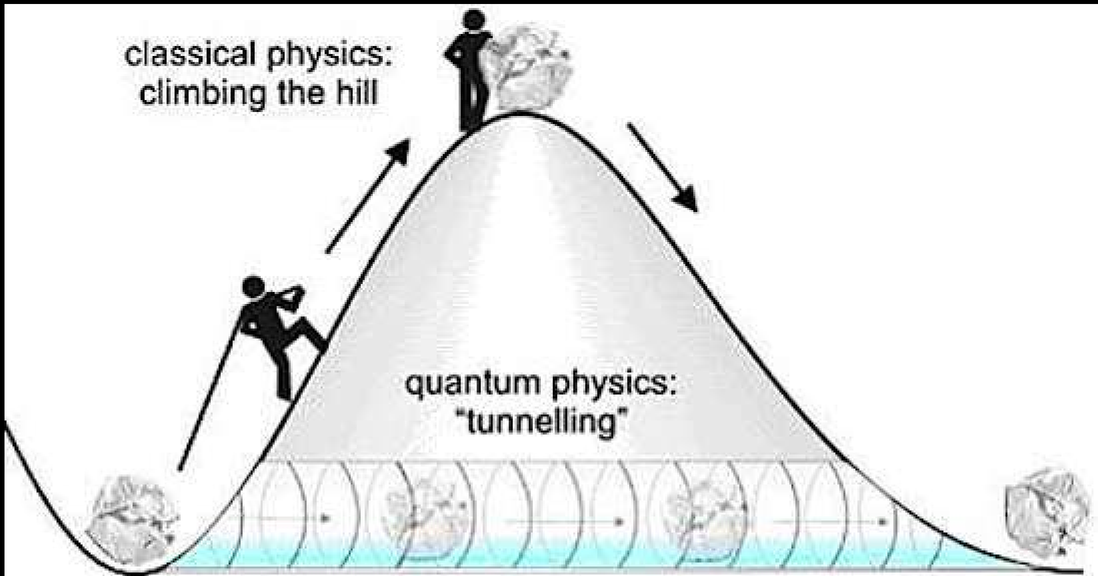
Coulomb Barrier values:

p + p	→	0,5 MeV
^{3}He + ^{3}He	→	1,7 MeV
^{14}N + p	→	2,5 MeV
^{23}Na + p	→	3,4 MeV
^{4}He + ^{12}C	→	4,6 MeV
^{12}C + ^{12}C	→	9,4 MeV

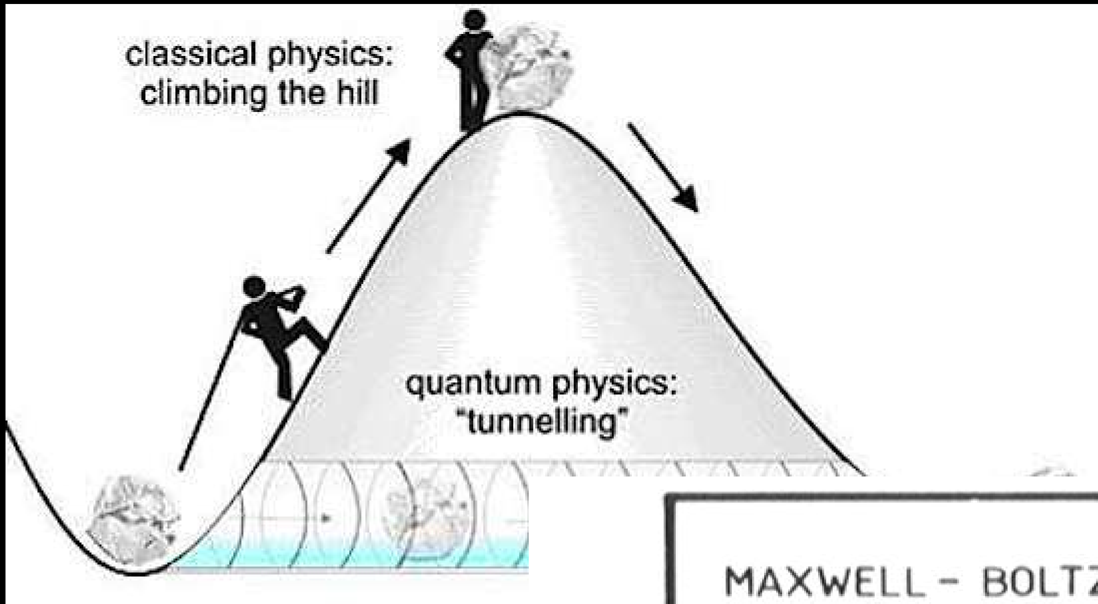
Energy of maximum of distrib.

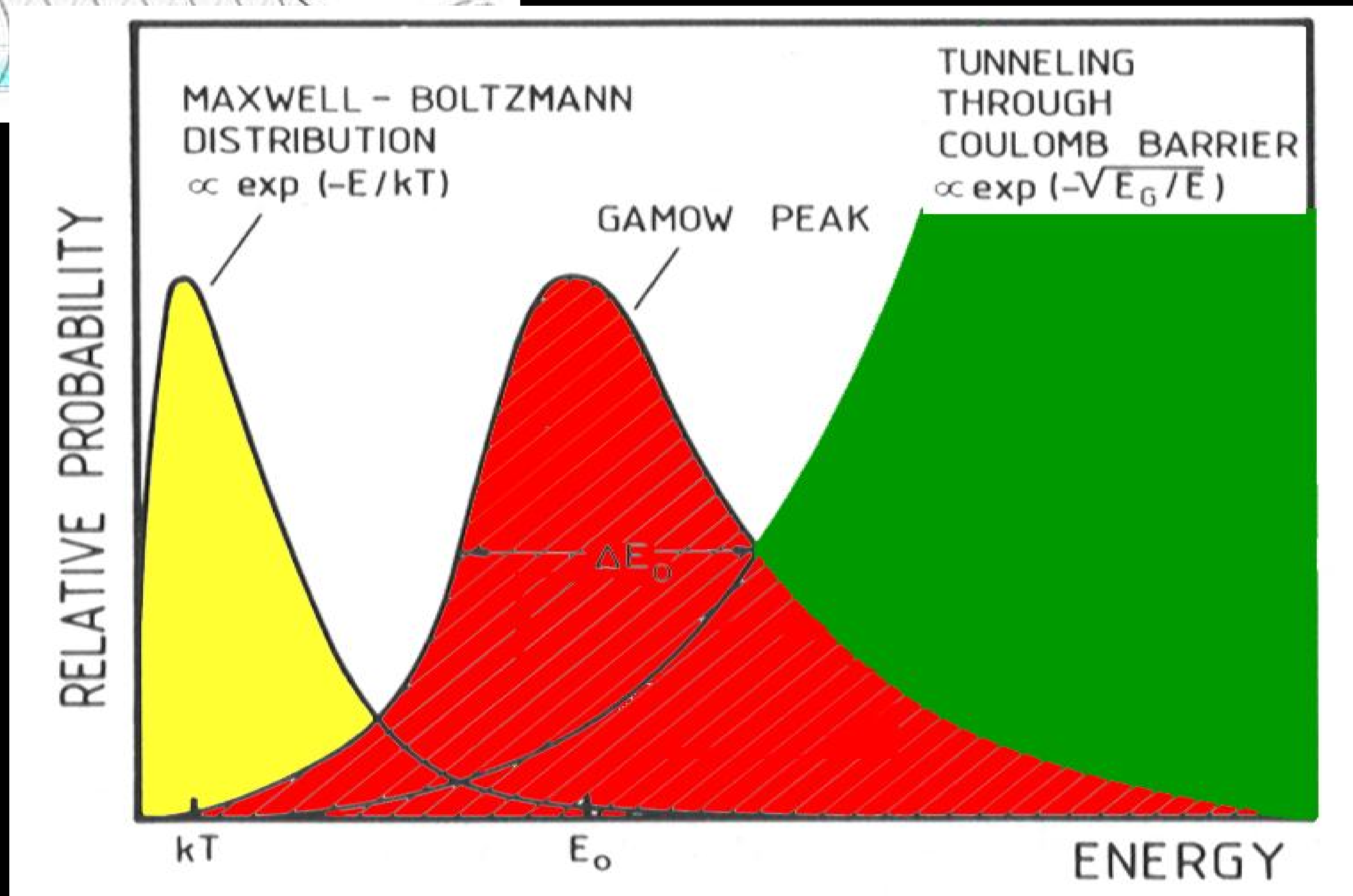
	T/GK	E/MeV
Sun	0,016	0,0014
AGB	0,300	0,026
Supernova	5	0,430





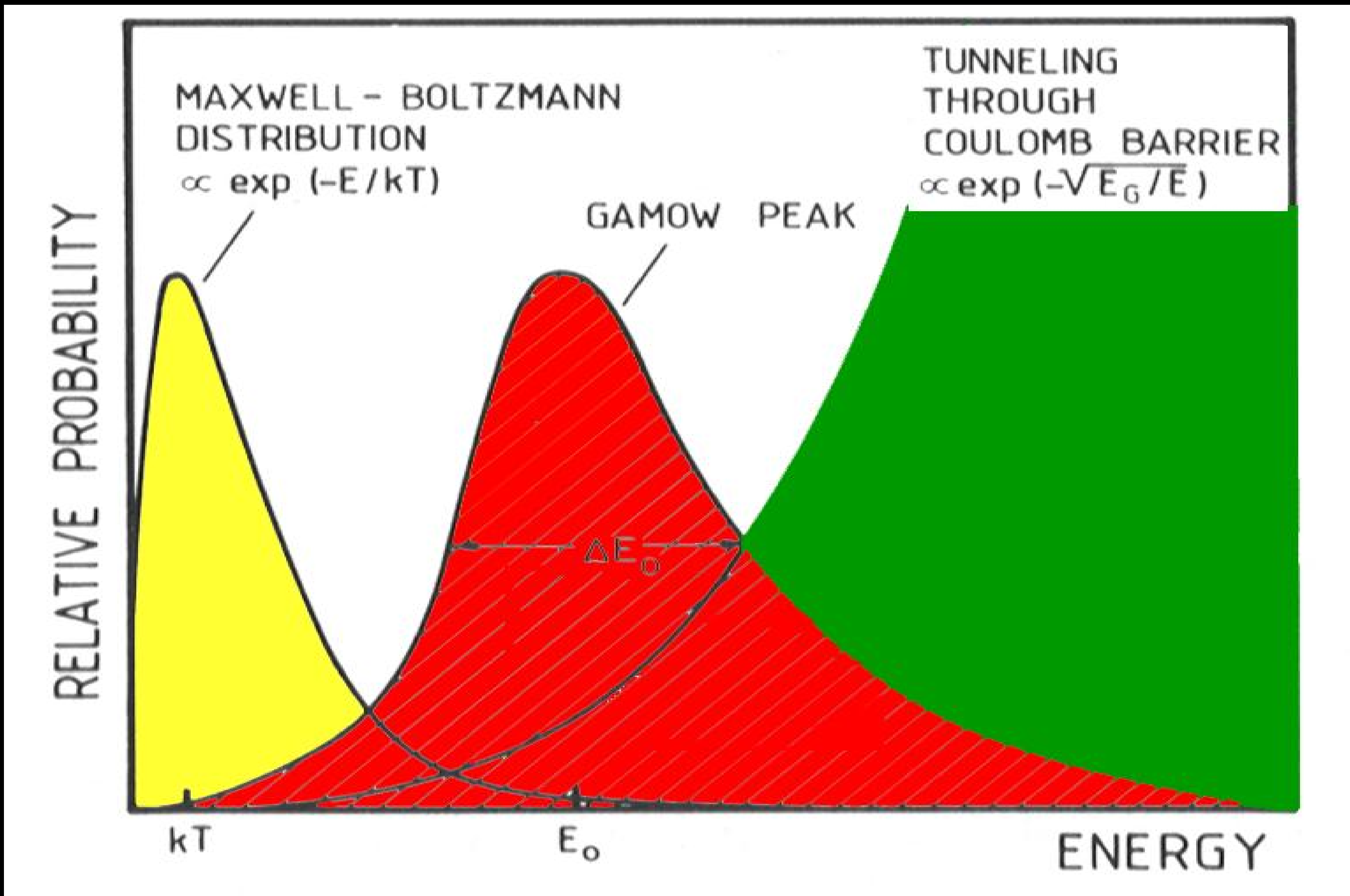
Justin Grayer, Missouri


classical physics:
climbing the hill
quantum physics:
"tunnelling"

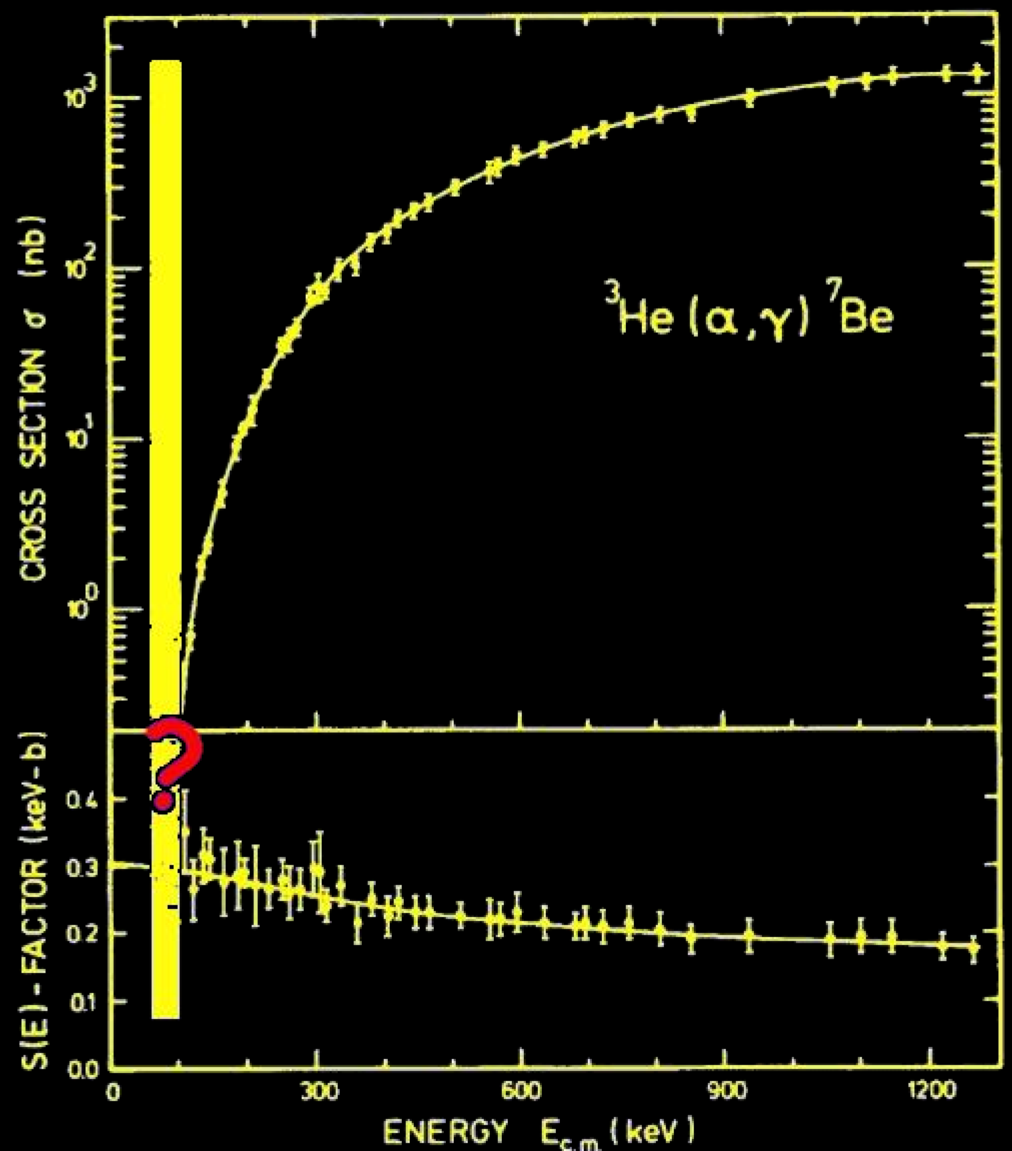

MAXWELL – BOLTZMANN
DISTRIBUTION
∝ exp (−E/kT)
TUNNELING
THROUGH
COULOMB BARRIER
∝ exp (−√(E_G/E))
GAMOW PEAK
RELATIVE PROBABILITY
ΔE₀
kT
E₀
ENERGY

Stellar Fusion Reactions

	Gamow Energy [keV]	Astrophys Environment	Cross section [barn]	Lowest measured Energ
$^{3}He(^{3}He,2p)\,^{4}He$	21	Sun	$7\ 10^{-13}$	16,5
$^{3}He(a,g)^{7}Be$	22	Sun	$9\ 10^{-18}$	107
$^{14}N(p,g)^{15}O$	26	Sun	$4\ 10^{-21}$	200



The astrophysical S-factor



$$\sigma(E) = S(E)\cdot\exp(-2\pi\eta)/E$$

$$S(E) = E\cdot\sigma(E)\cdot\exp(2\pi\eta)$$

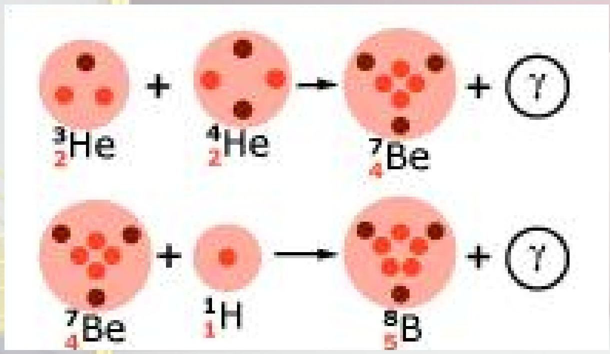
$$2\pi\eta = 31.29\, Z_1 Z_2 (\mu/E)^{0.5}$$

Extrapolations by orders of magnitude not always safe (resonances)

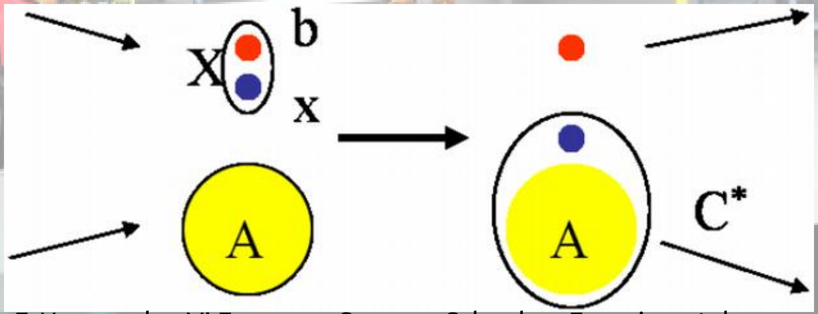
A. Bettini

Experimental Techniques

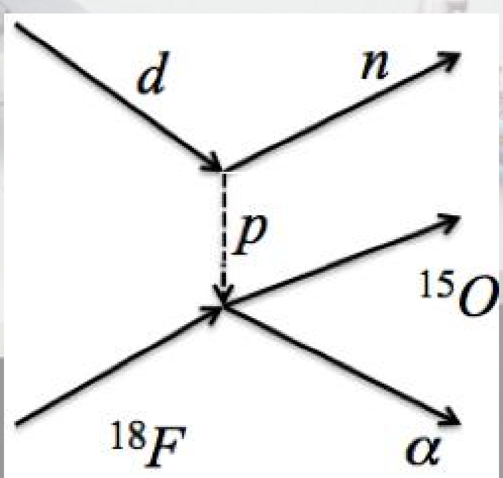
- Direct measurements
  - Stable ion beams → Quiescent burning phase (e.g. Sun, AGB, ...)
  - Radioactive beam → Explosive burning phases



- Indirect measurements
  - Transfer reactions
  - Trojan horse measurements
  - Coulomb breakup
  - ...



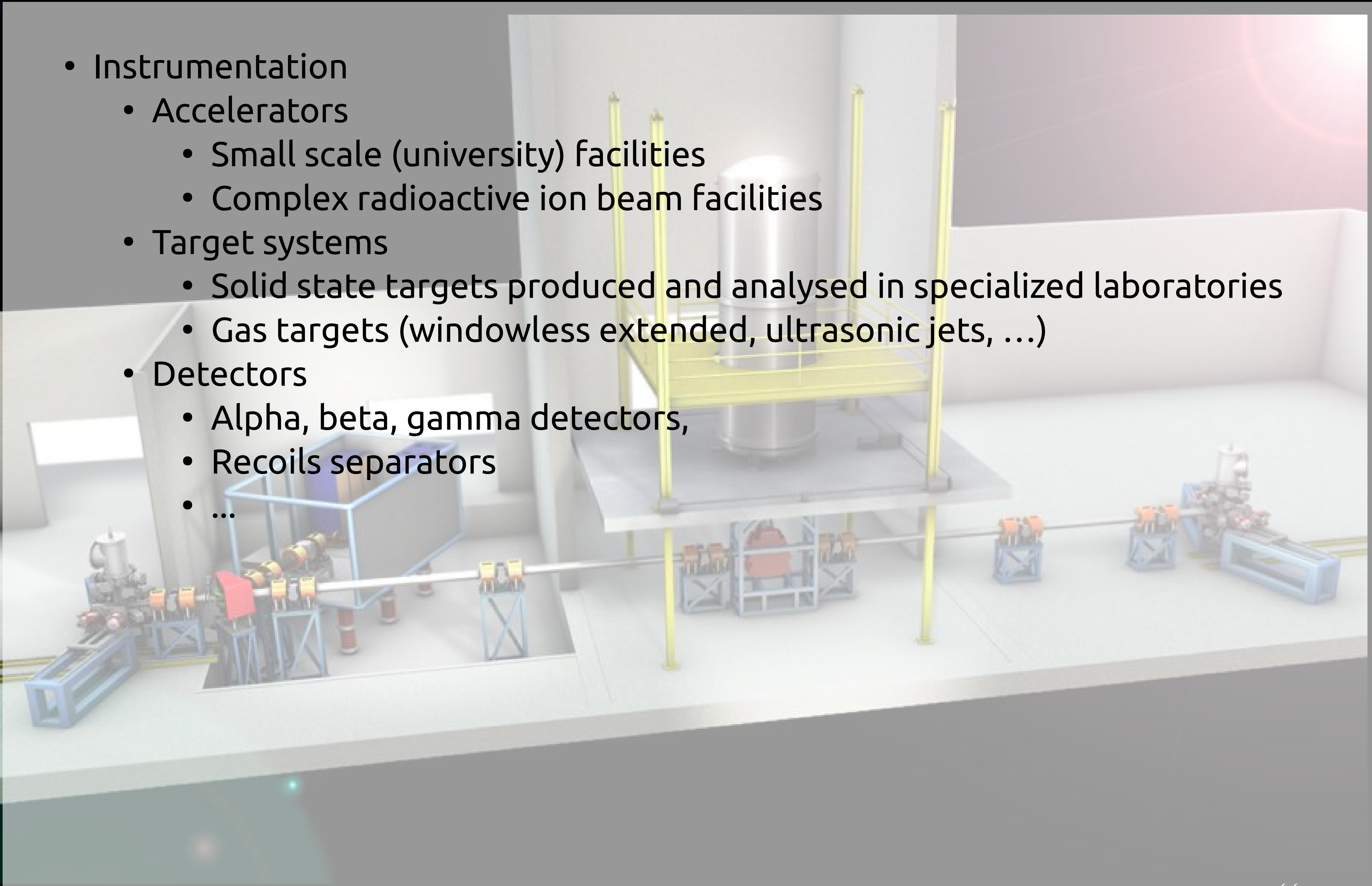
F. Hammache, VI European Summer School on Experimental Nuclear Astrophysics, ENAS 6September 18-27, 2011Acireale Italy



$^{18}F(p,\alpha)^{15}O$

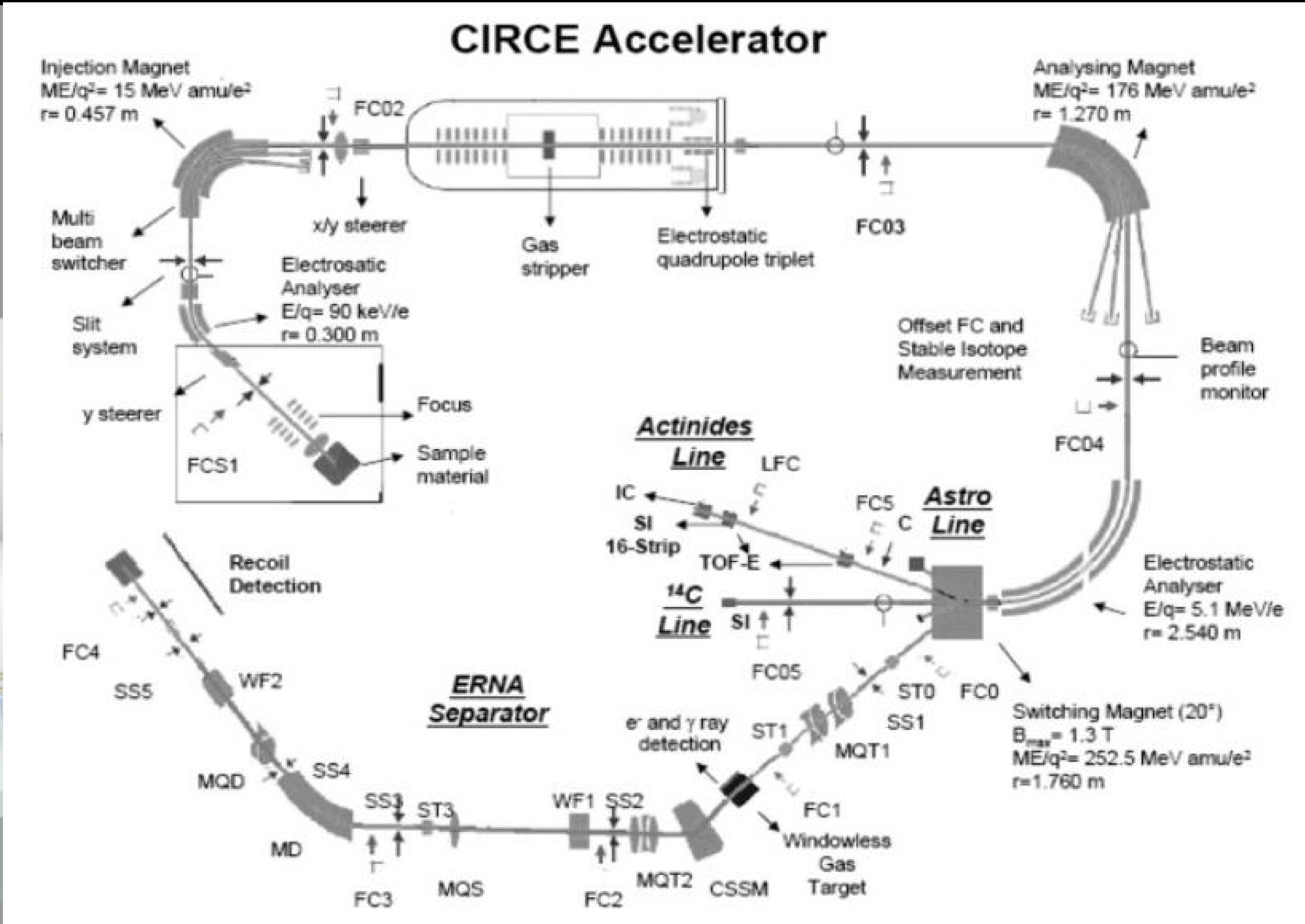
Gulino,. doi:10.1088/1742-6596/420/1/012149

Experimental Techniques



- Instrumentation
  - Accelerators
    - Small scale (university) facilities
    - Complex radioactive ion beam facilities
  - Target systems
    - Solid state targets produced and analysed in specialized laboratories
    - Gas targets (windowless extended, ultrasonic jets, …)
  - Detectors
    - Alpha, beta, gamma detectors,
    - Recoils separators
    - …

Experimental Techniques

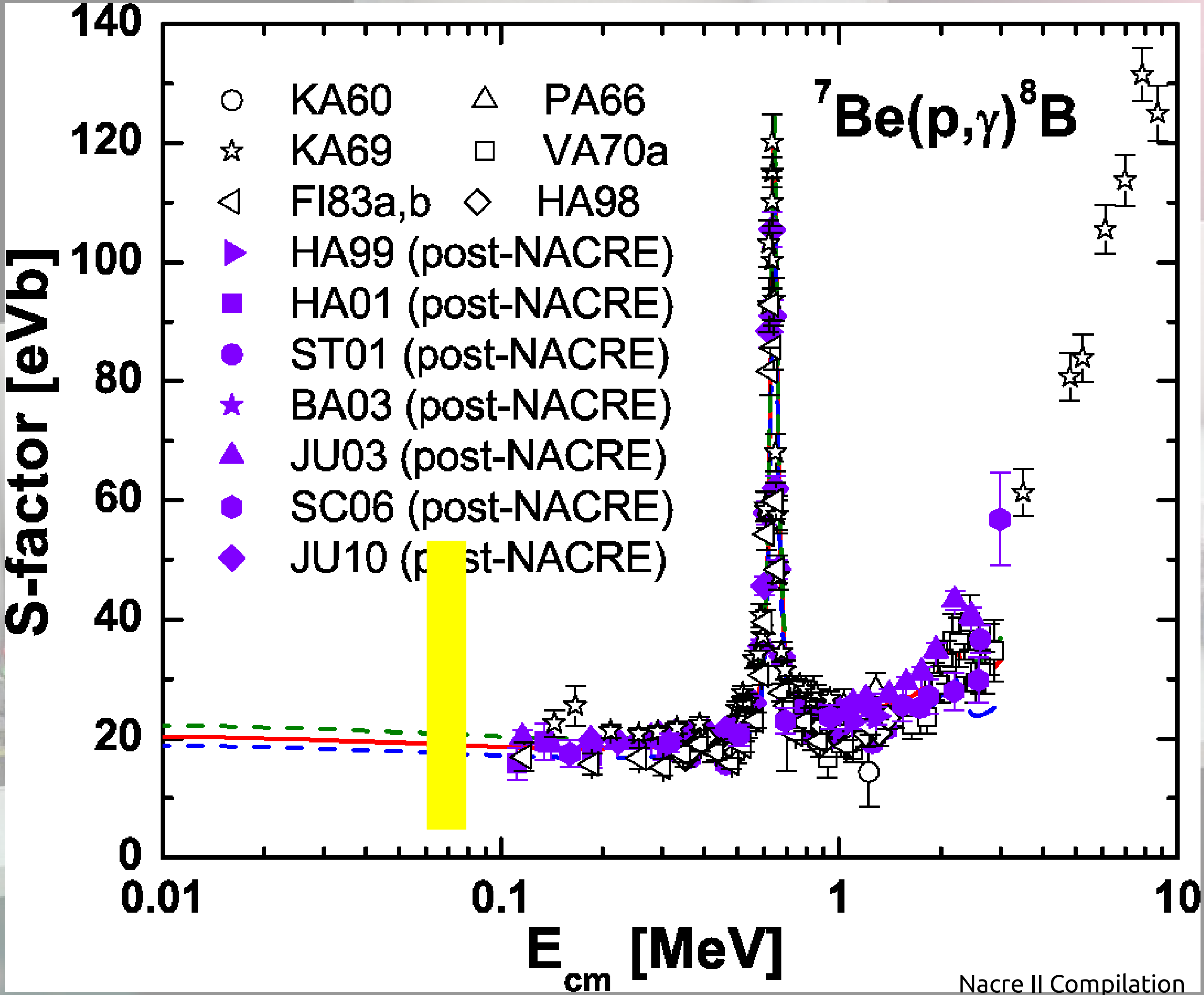


Experimental Techniques

- Example: The reaction $^{7}Be(p,\gamma)^{8}B$

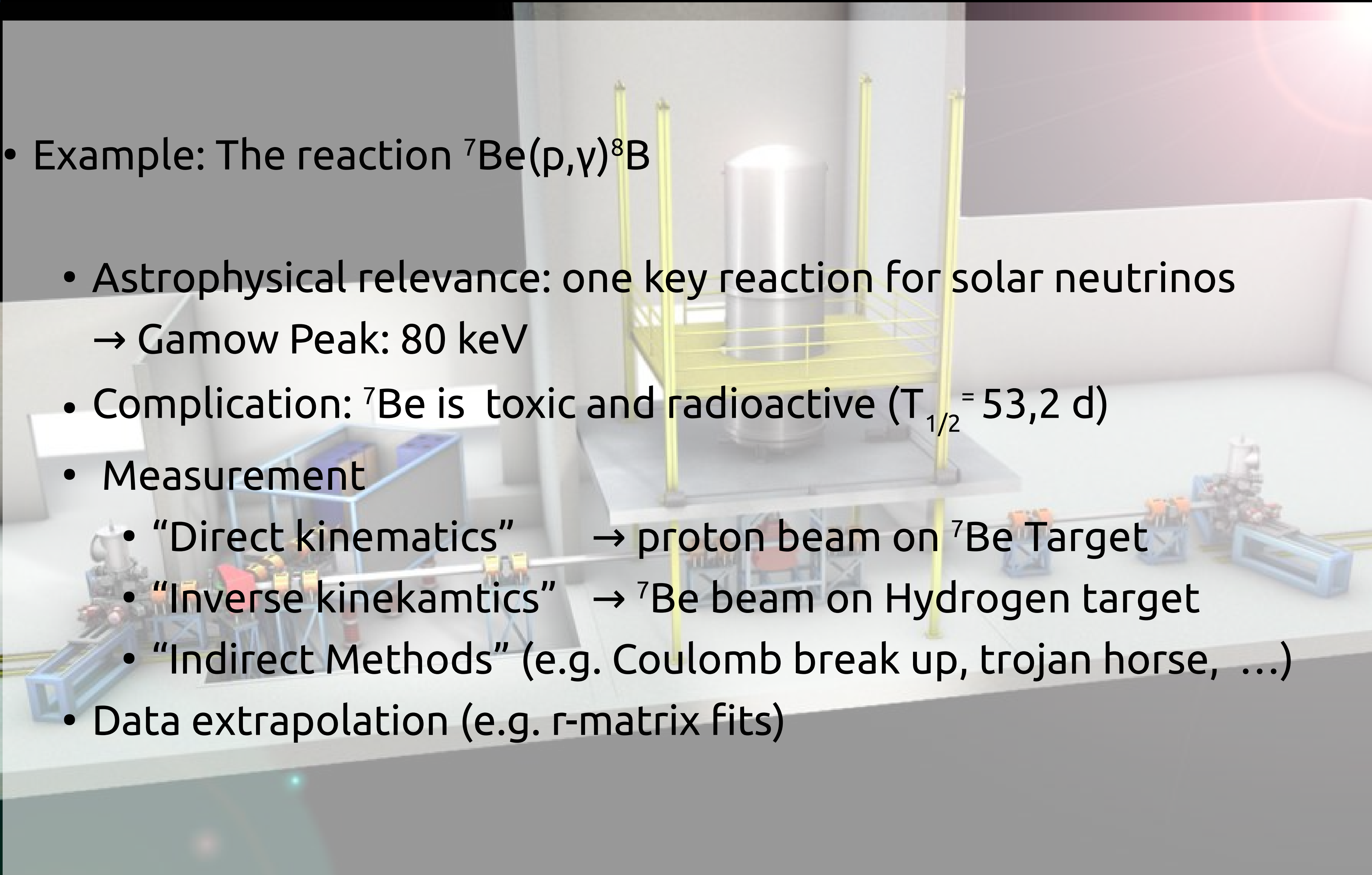
  - Astrophysical relevance: one key reaction for solar neutrinos
    → Gamow Peak: 80 keV
  - Complication: ^{7}Be is toxic and radioactive ($T_{1/2}$ = 53,2 d)
  - Measurement
    - "Direct kinematics" → proton beam on ^{7}Be Target
    - "Inverse kinekamtics" → ^{7}Be beam on Hydrogen target
    - "Indirect Methods" (e.g. Coulomb break up, trojan horse, ...)

Experimental Techniques



Nacre II Compilation

Experimental Techniques



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  - Data extrapolation (e.g. r-matrix fits)

Nuclear Astrophysics…. The full story at GSSI

- Lectures in Nuclear Astrophysics

  Theoretical N.A.
- L. Marcucci (Pisa)

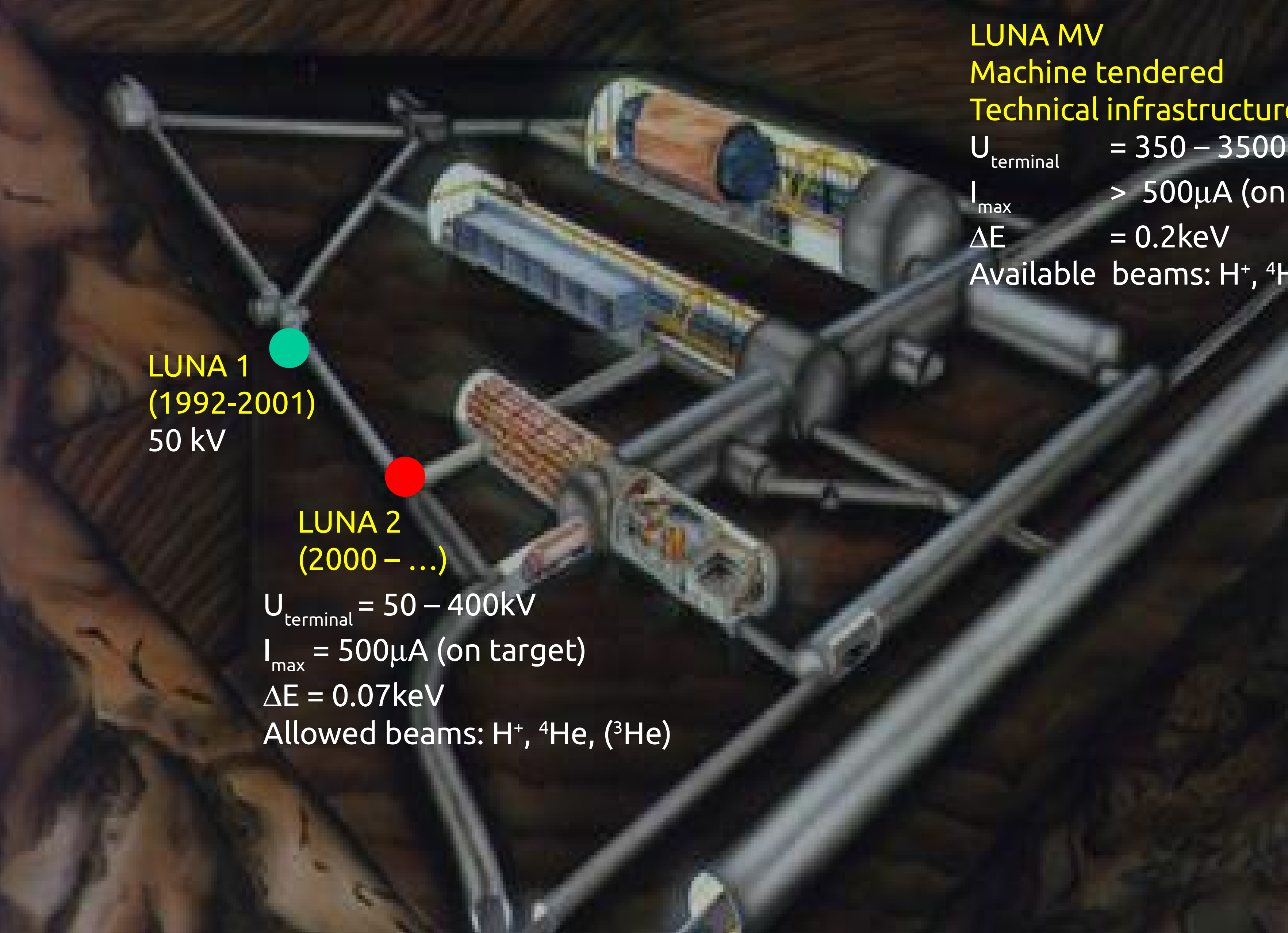
- Integrating seminars

  Experimental aspects of N.A.

  M. Wiescher (U. Notre Name, In, USA)

Nuclear Astrophysics at LNGS …

LUNA (Lab. for Underground Nuclear Astrophysics) at LNGS (Laboratori Nazionali del Gran Sasso)



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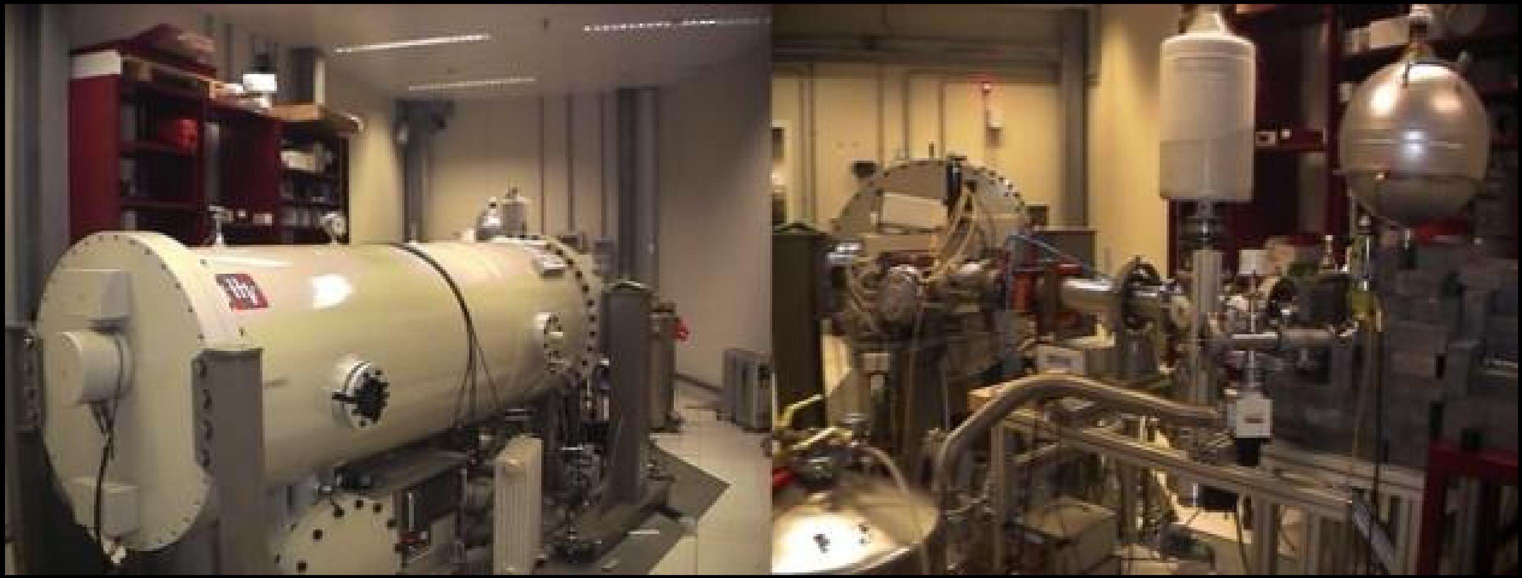
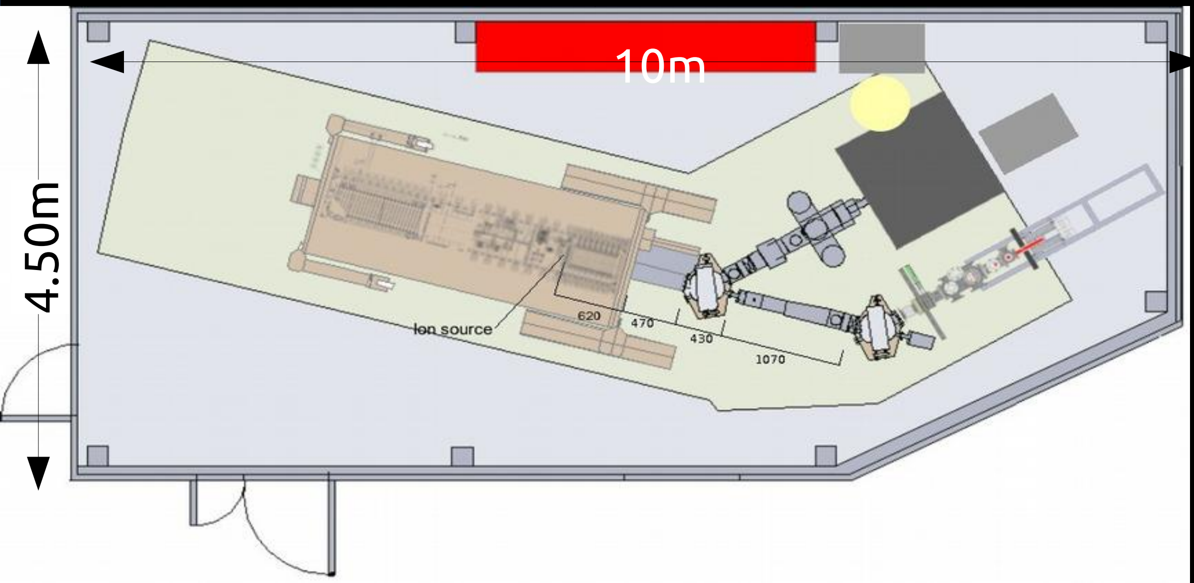
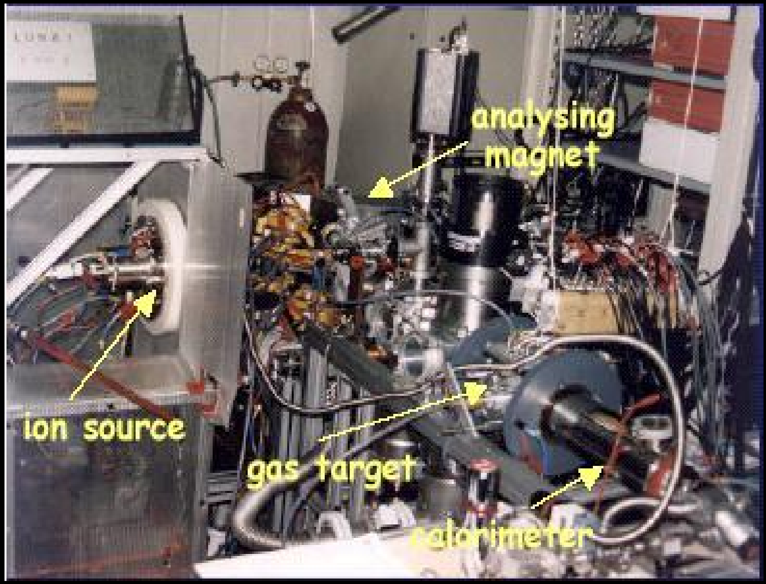






Laboratory
Underground
Nuclear
Astrophysics

LUNA MV

Partecipating Institutions:

Laboratori Nazionali del Gran Sasso, INFN, Assergi, Italy

Gran Sasso Science Institute, L'Aquila, Italy

INFN, Padova, Italy

INFN, Roma La Sapienza, Italy

Università di Genova and INFN, Genova, Italy

Università di Milano and INFN, Milano, Italy

Università di Napoli "Federico II", and INFN, Napoli, Italy

Università di Torino and INFN, Torino, Italy

Università di Bari and INFN, Bari, Italy

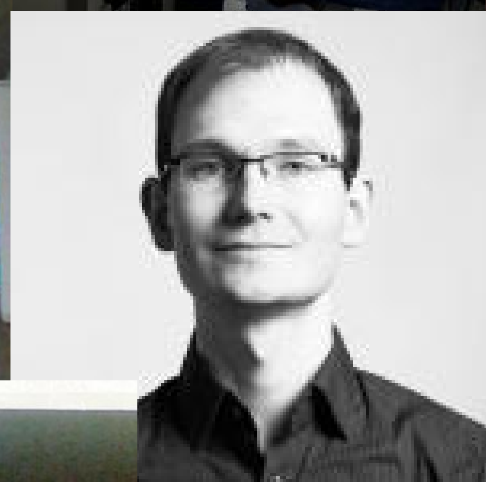
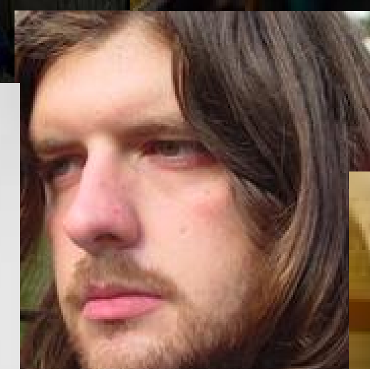
Osservatorio Astronomico di Collurania, Teramo, and LNGS, Italy

The University of Edinburgh, UK

Institute of Nuclear Research (ATOMKI), Debrecen, Hungary

Forschungszentrum Dresden-Rossendorf, Germany





LUNA @ LNGS

Matthias Junker, Alba Formicola, Giovanni Ciani, Axel Boeltzig, Alessandro Razeto, Oscar Straniero, Matthias Laubenstein, Laura Leonzi Stefano Gazzana, Iza Kochanek