Laboratory for Underground Nuclear Astrophysics (LUNA)

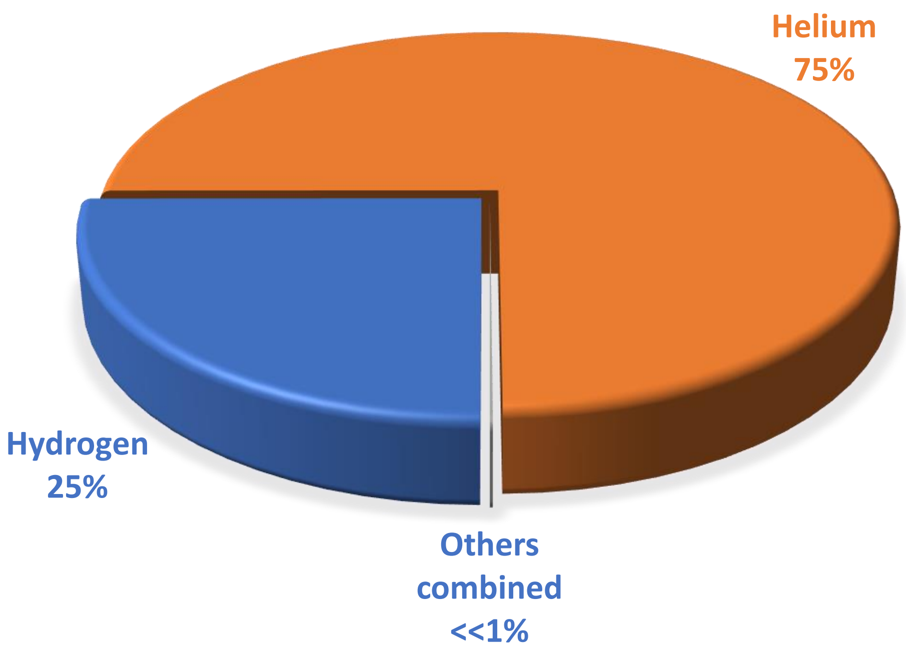
INAUGURAL WORKSHOP ON NUCLEAR ASTROCHEMISTRY
26 February 2024

Federico Ferraro
INFN - Laboratori Nazionali del Gran Sasso

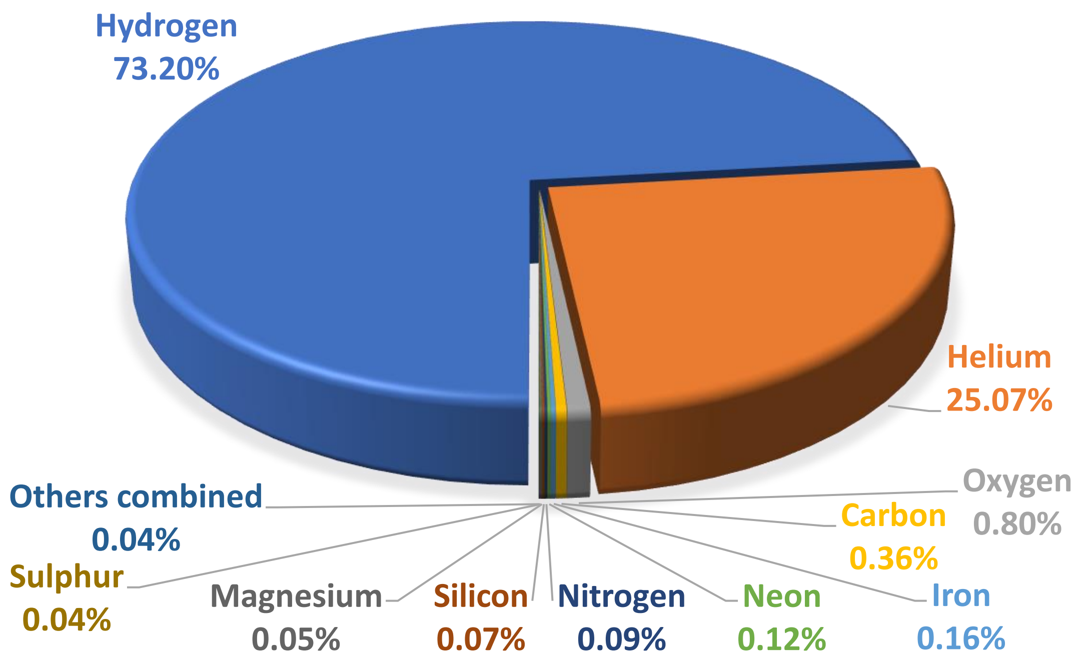
What is Nuclear Astrophysics about?

Where do elements come from?

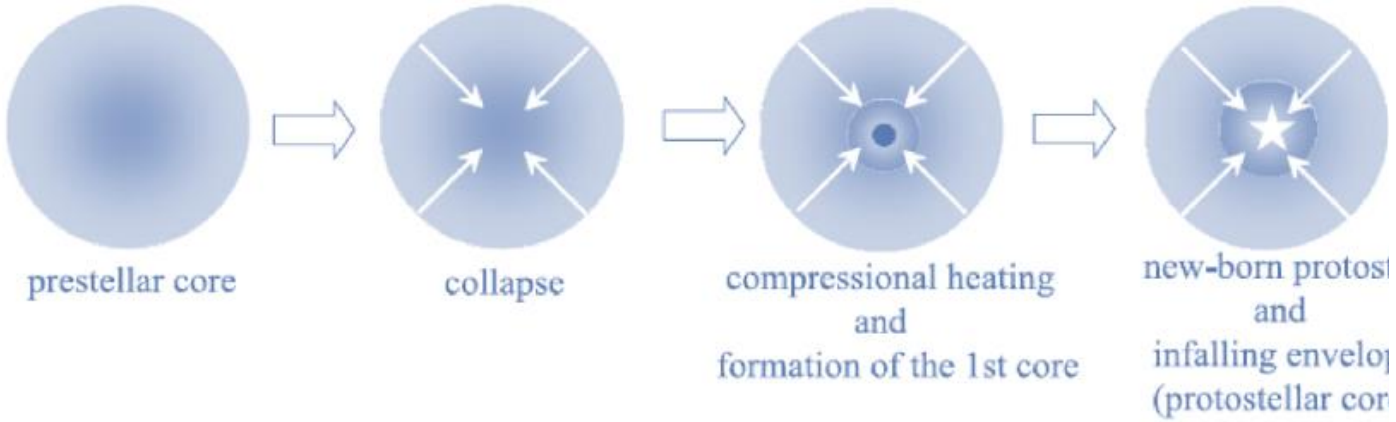
The universe
3 minutes after the Big Bang

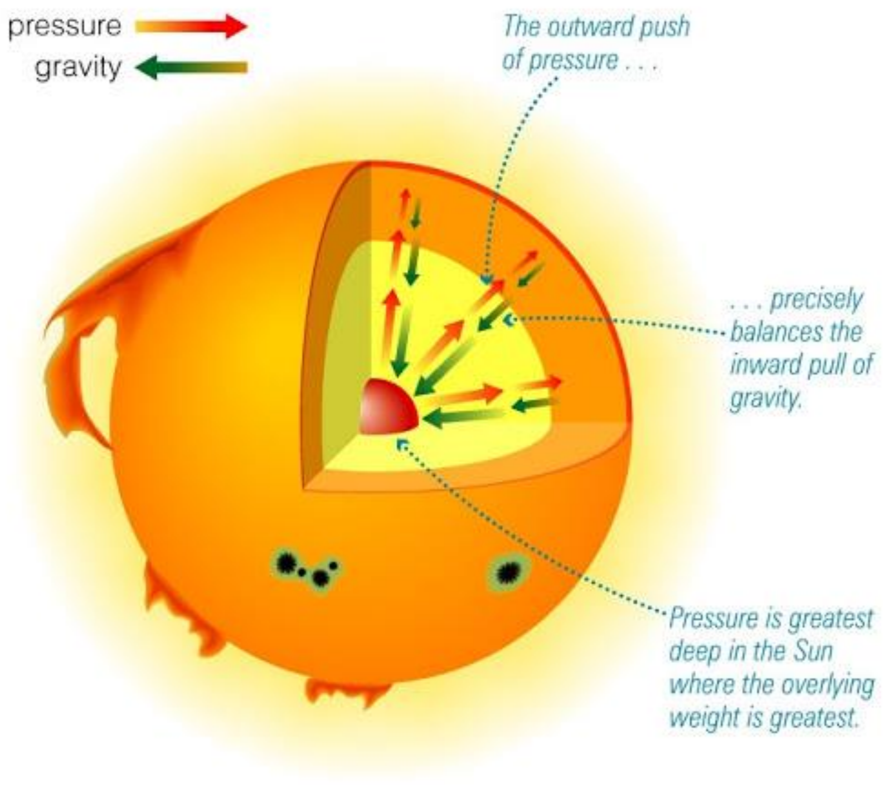


The Sun
today

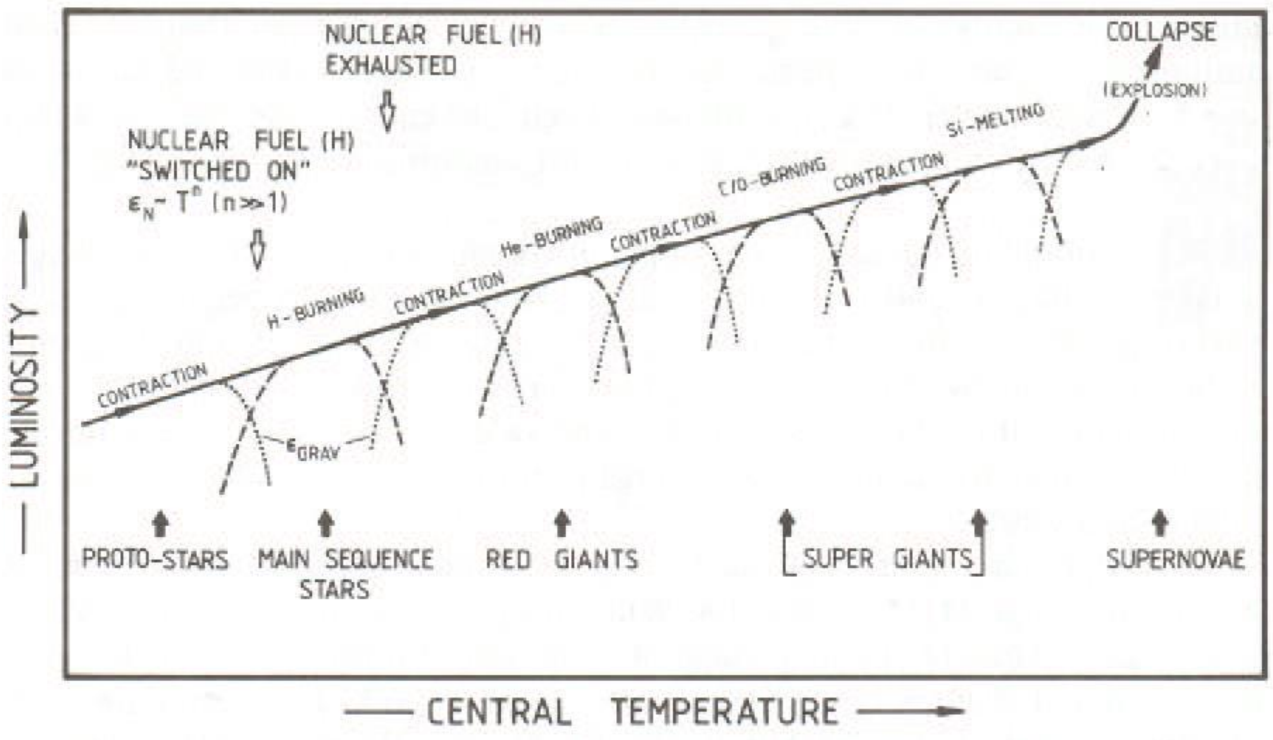


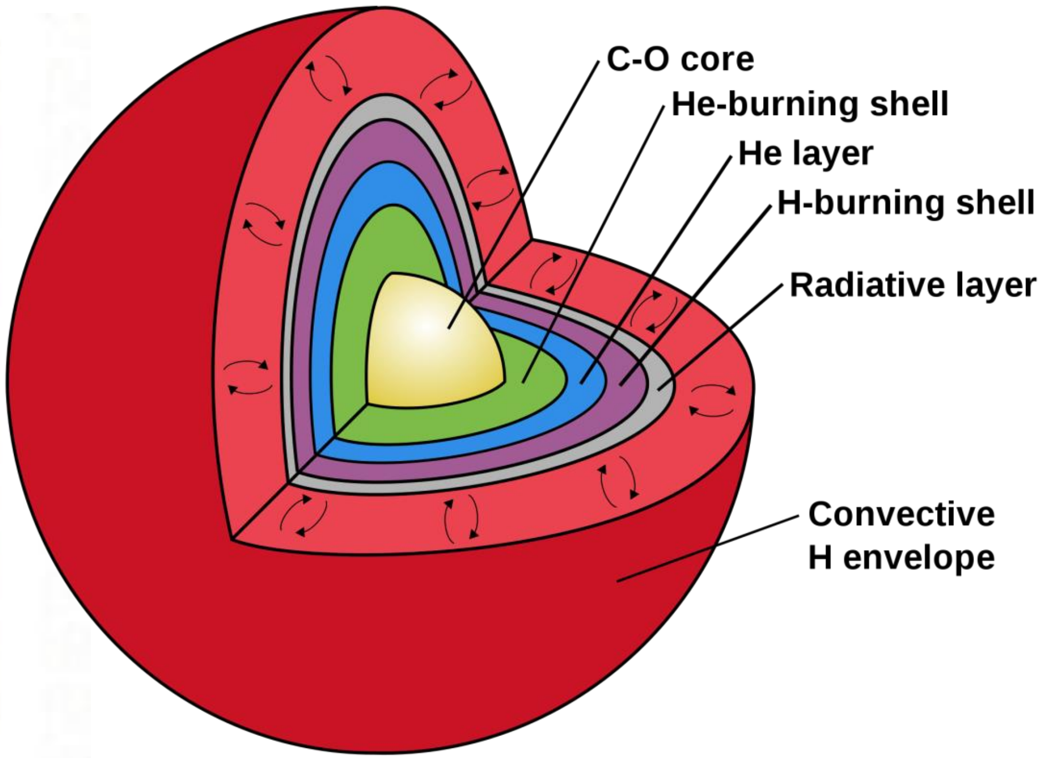
From a molecular cloud to a star...





…going through cyclic burning processes…





...to stellar explosions

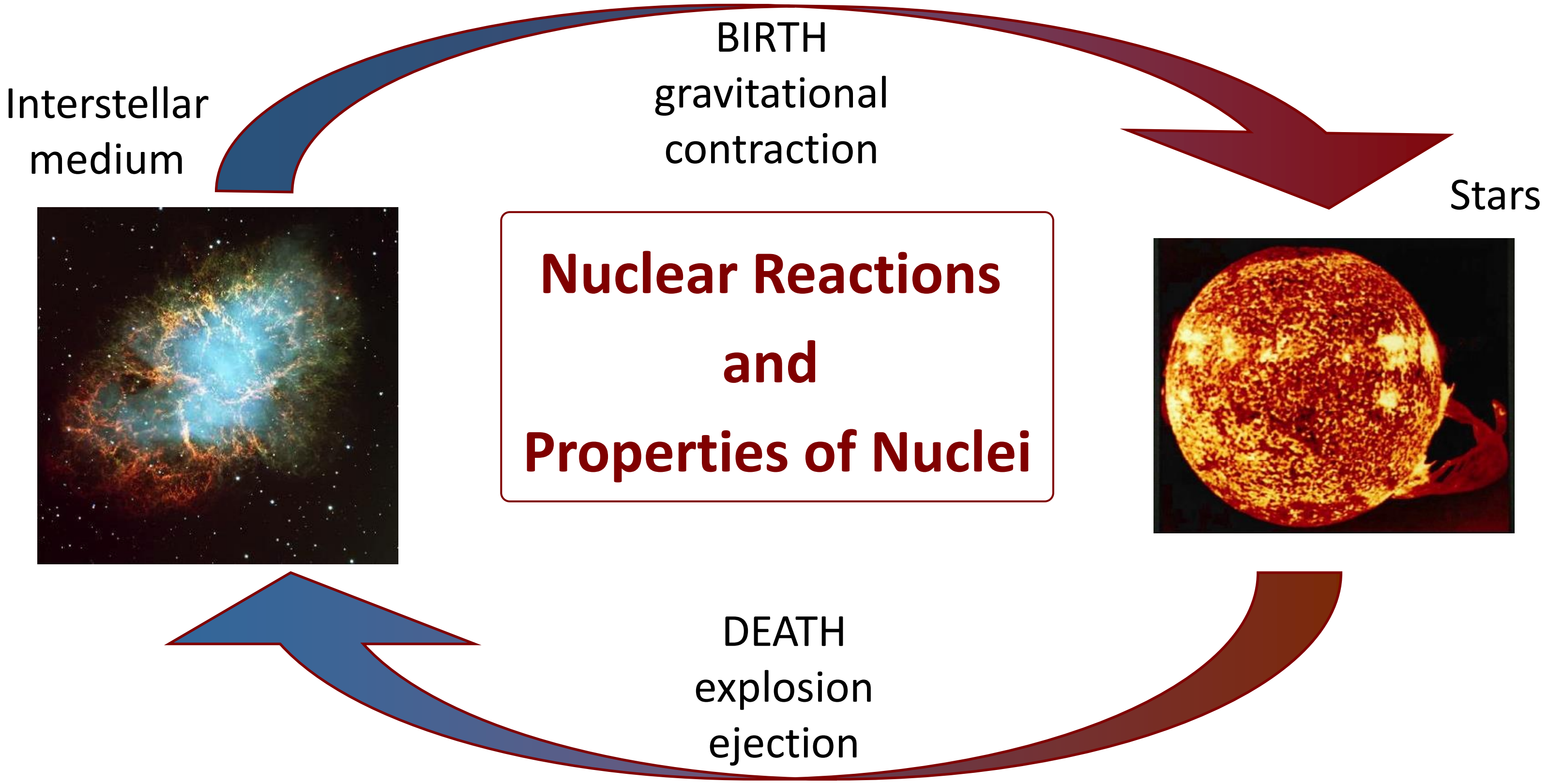
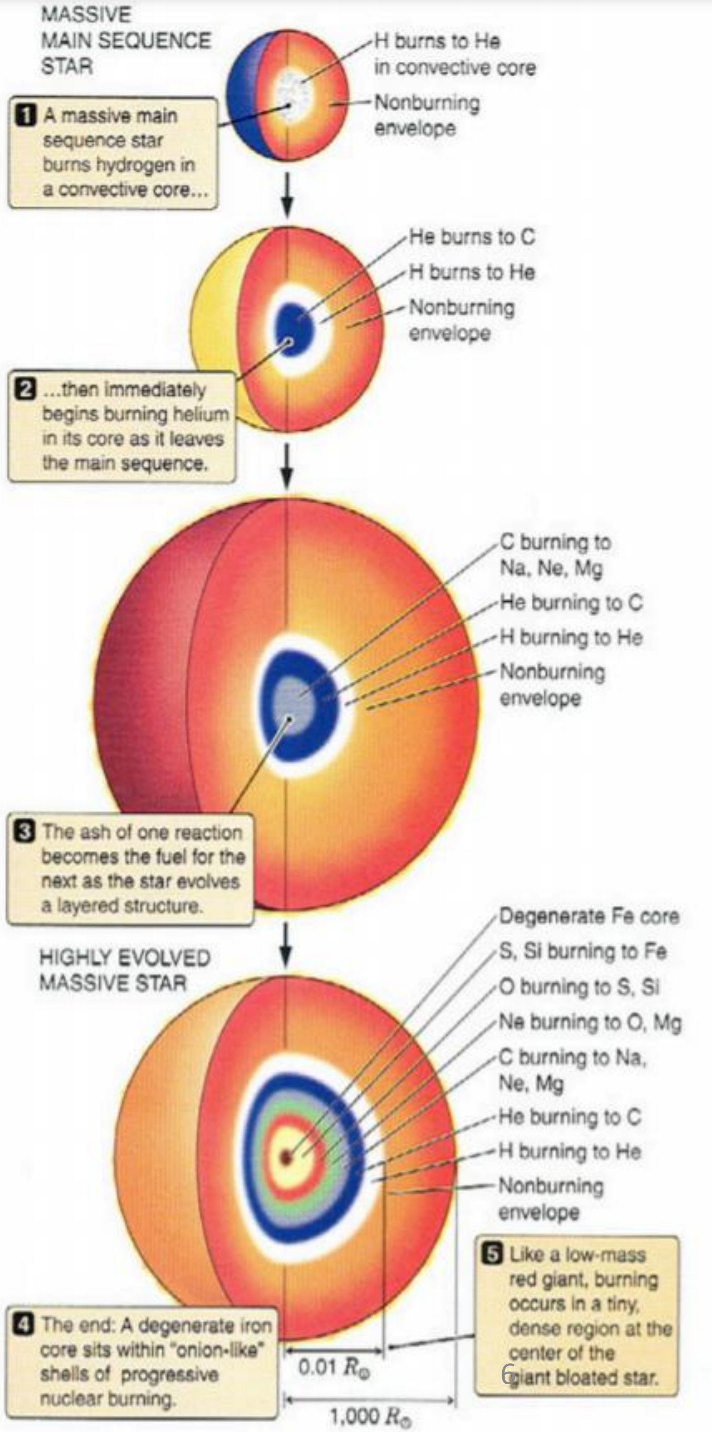
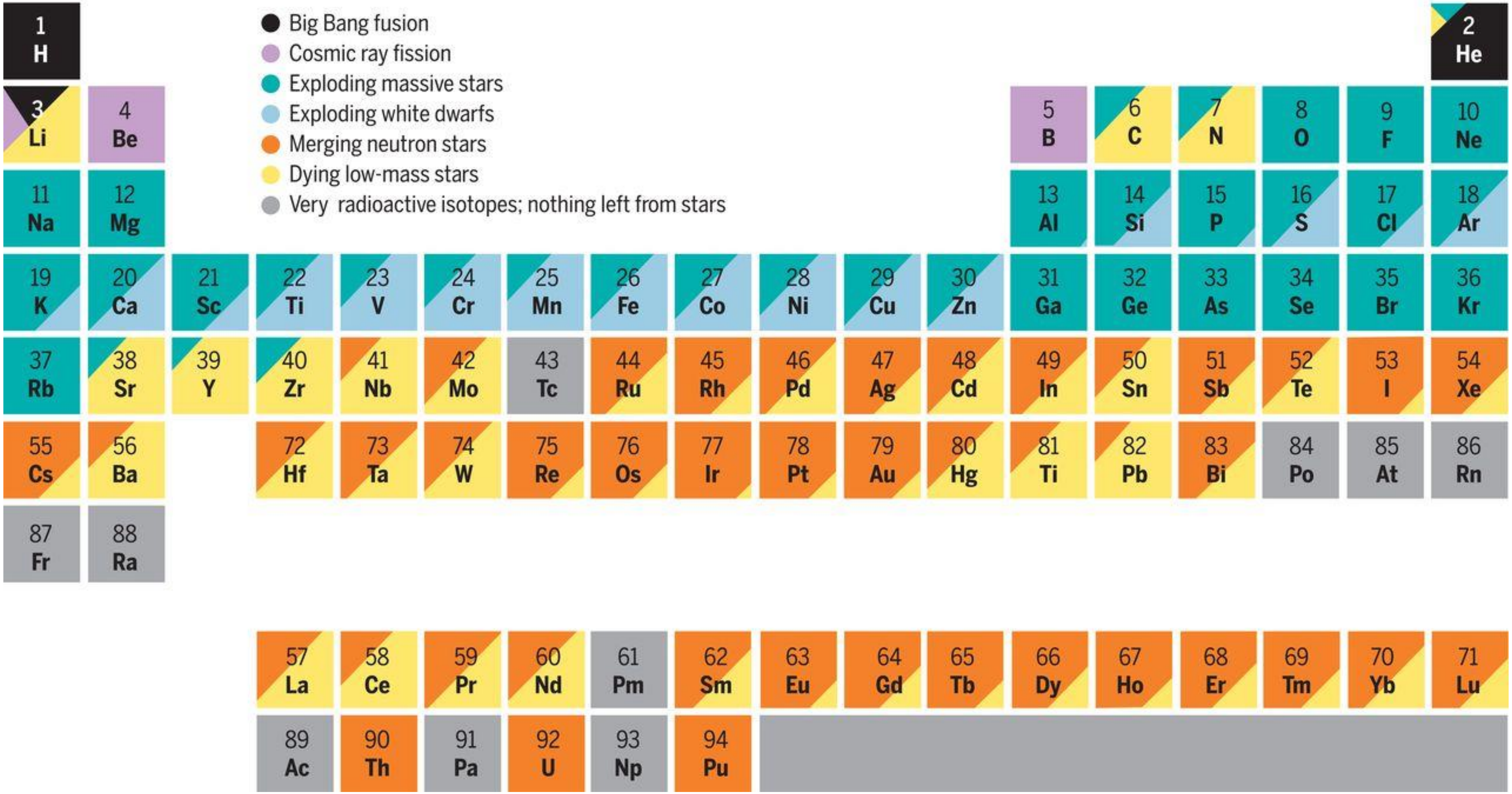


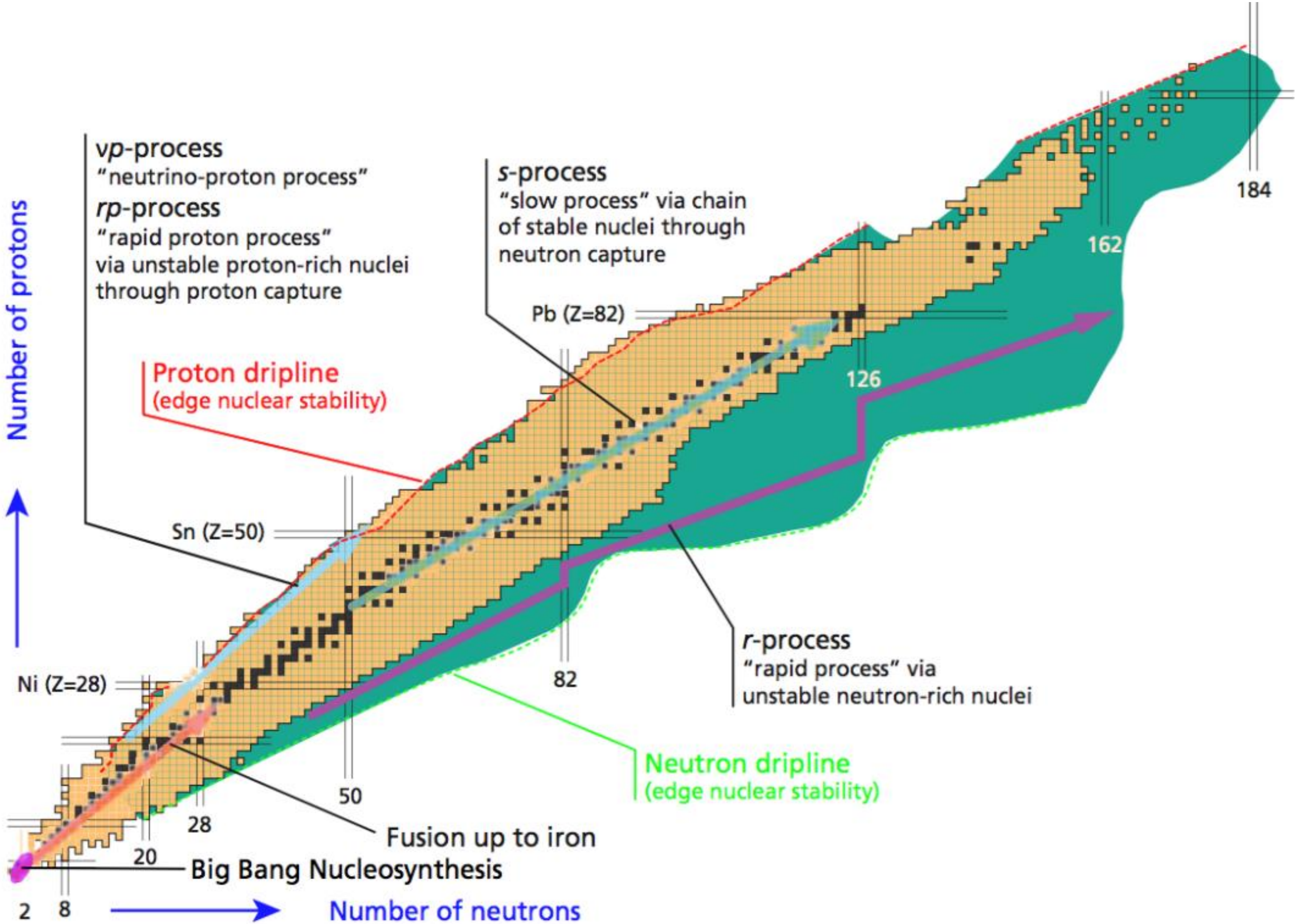
Image credit: https://montessorisecondplane.com/2020/03/04/first-great-lesson-stellar-nucleosynthesis/



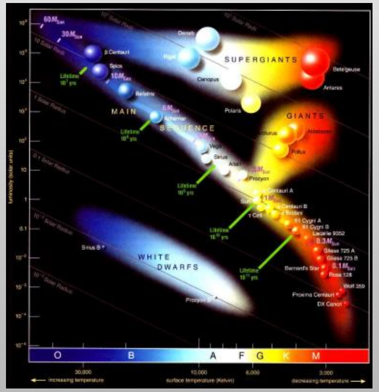
The evolving composition of the Universe



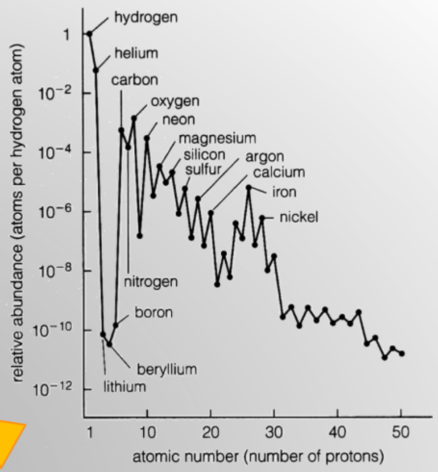
Jennifer A. Johnson, Populating the periodic table: Nucleosynthesis of the elements.*Science***363**, 474-478(2019).DOI:10.1126/science.aau9540


νp-process
"neutrino-proton process"
rp-process
"rapid proton process"
via unstable proton-rich nuclei
through proton capture
s-process
"slow process" via chain
of stable nuclei through
neutron capture
Proton dripline
(edge nuclear stability)
Pb (Z=82)
Sn (Z=50)
Ni (Z=28)
184
162
126
82
50
28
20
8
2
r-process
"rapid process" via
unstable neutron-rich nuclei
Neutron dripline
(edge nuclear stability)
Fusion up to iron
Big Bang Nucleosynthesis
Number of protons
Number of neutrons

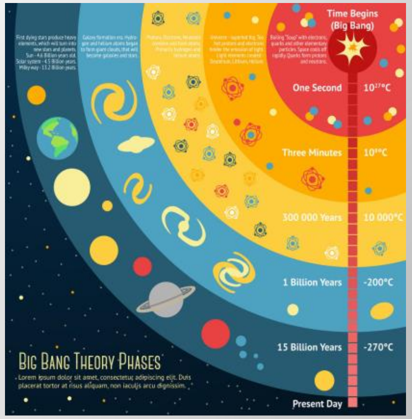
Stellar evolution



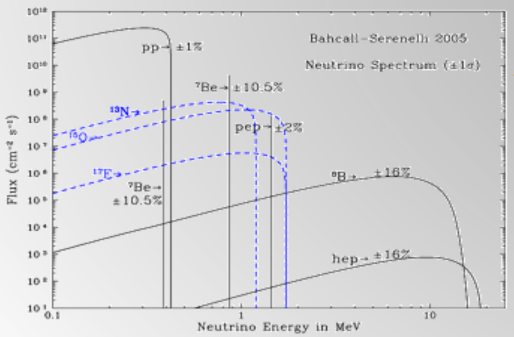
Nucleosynthesis



Evolution of early universe

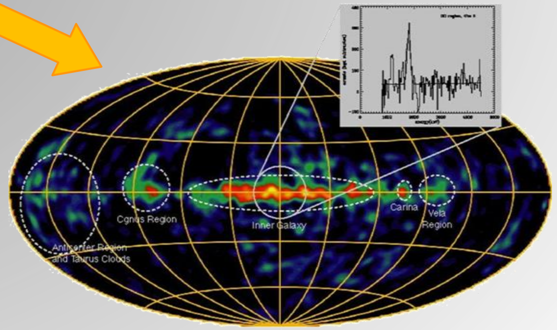


Nuclear cross sections



Solar neutrinos

Solar system



Astronomy

How do nuclear reactions take place?

The energy of nuclei in a plasma follows a **Maxwell-Boltzmann distribution**

the **cross section** falls faster than exponentially as the energy decreases

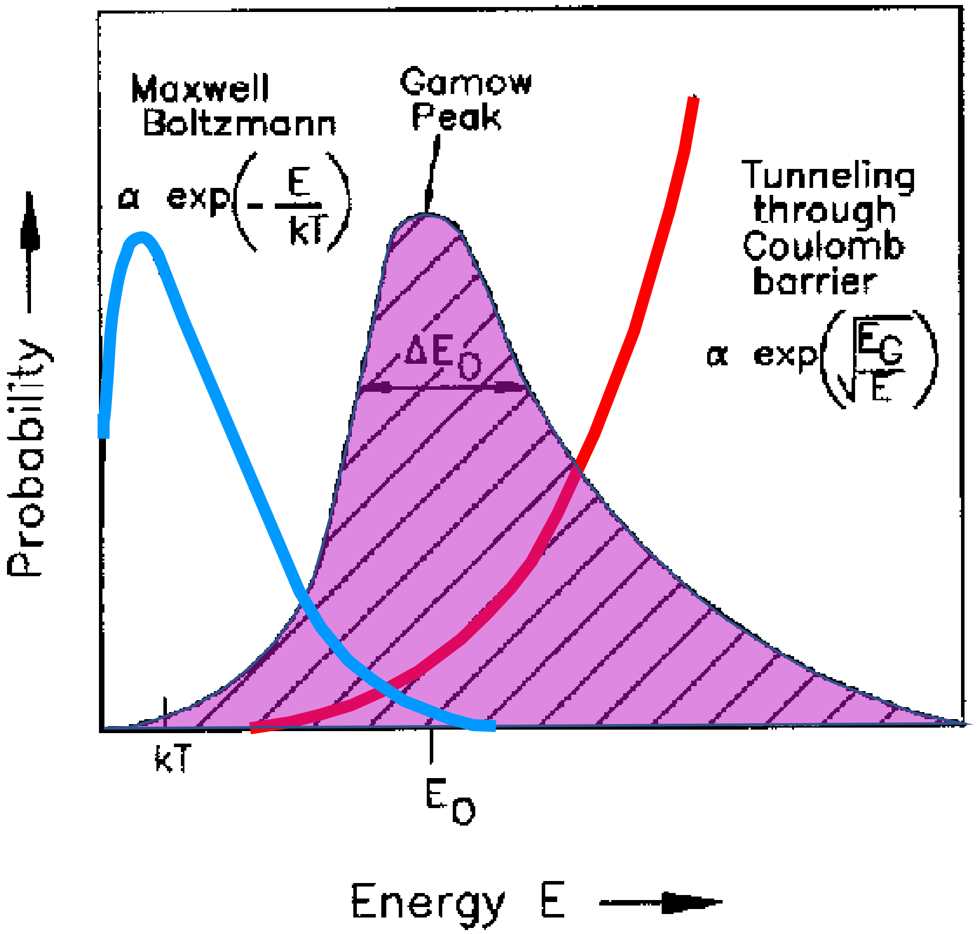
Consider a **reaction**

$$A + B \rightarrow C + D$$

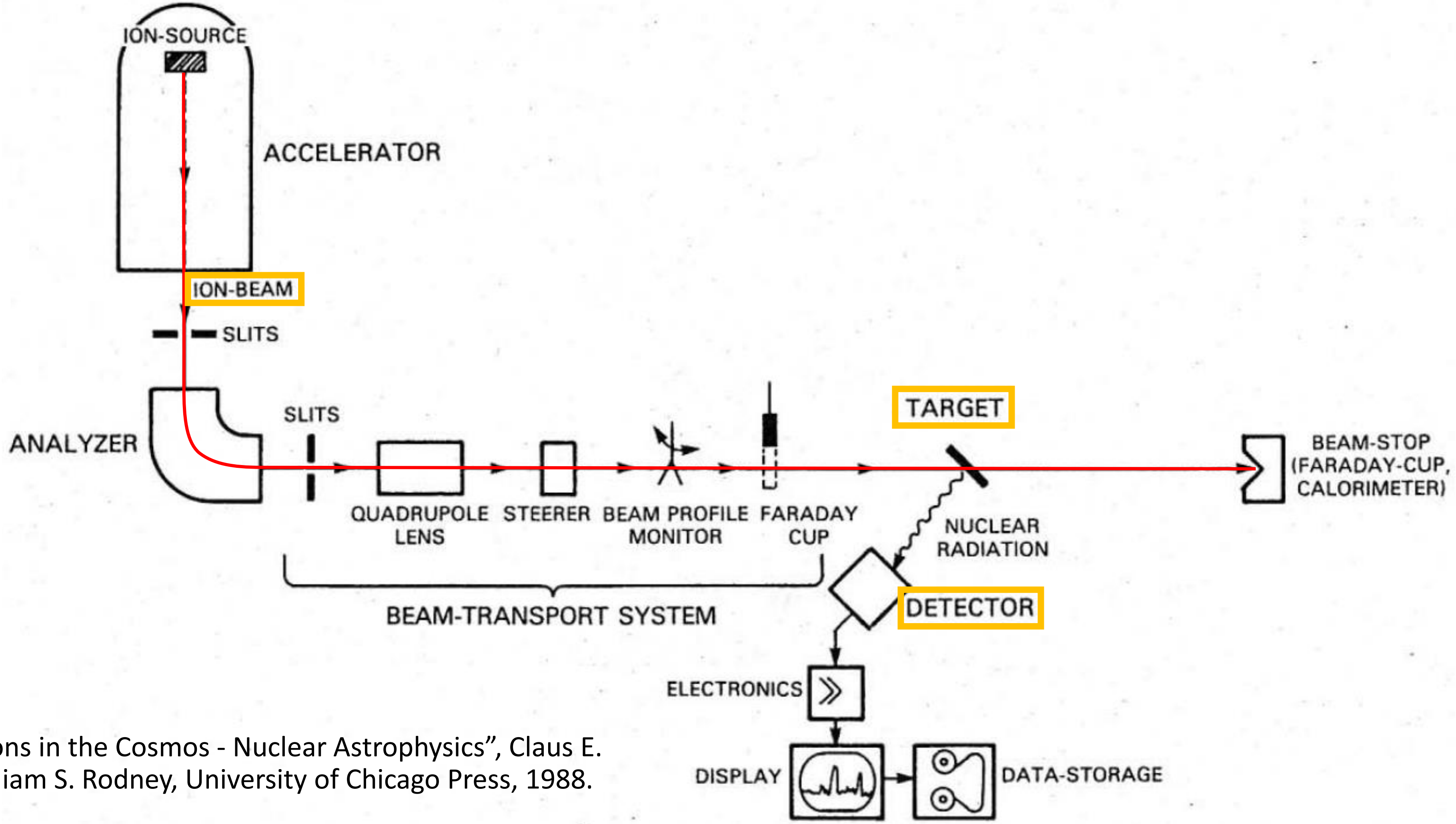
The reaction rate is given by

$$\langle r \rangle = N_A N_B \int_0^\infty \phi(v)\, \sigma(v)\, v\, dv$$

The **Gamow peak** defines the relevant energy range for this reaction to occur

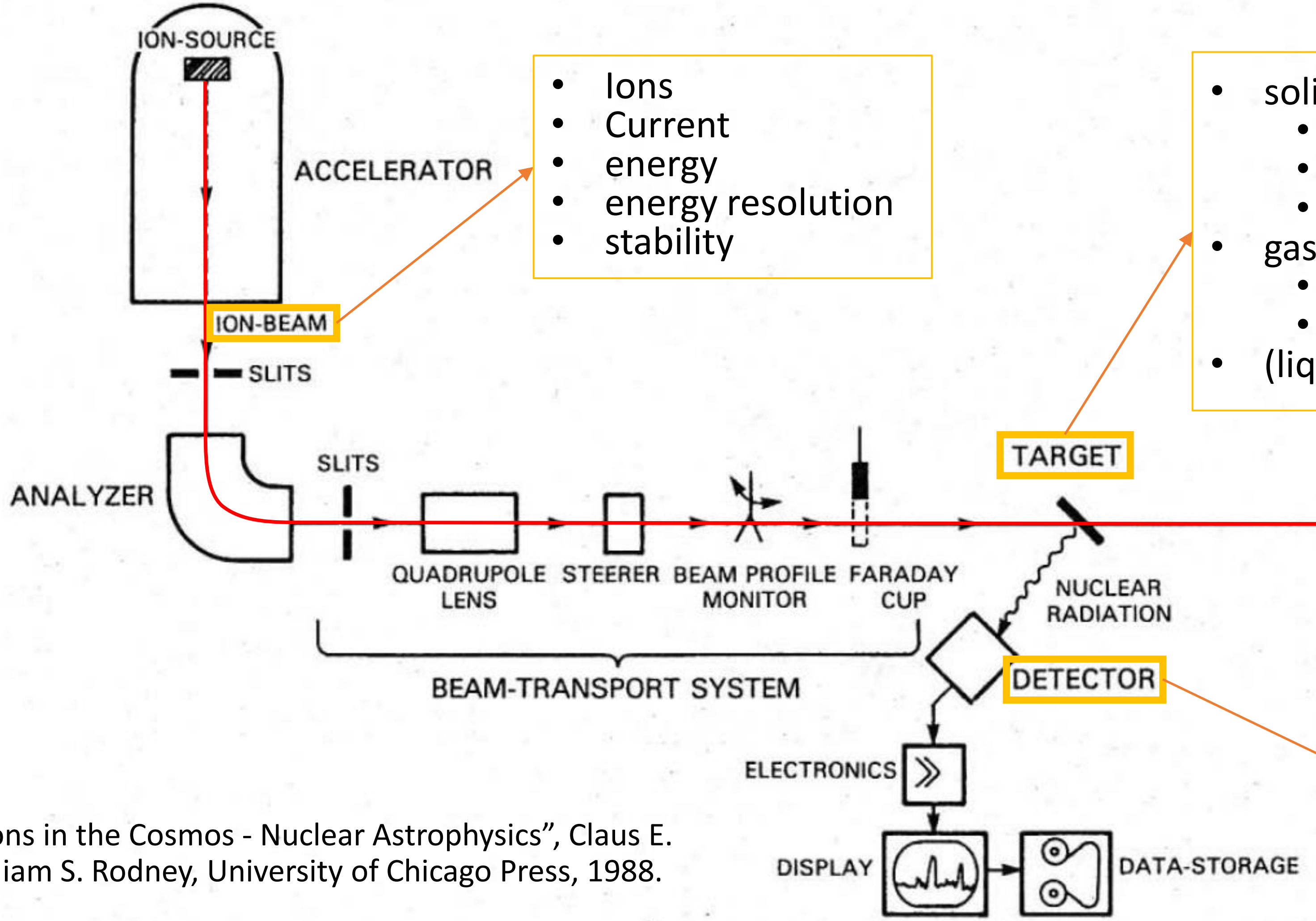


How to measure a nuclear cross section



From "Cauldrons in the Cosmos - Nuclear Astrophysics", Claus E. Rolfs and William S. Rodney, University of Chicago Press, 1988.

How to measure a nuclear cross section



- Ions
- Current
- energy
- energy resolution
- stability

- solid
  - implanted
  - evaporated
  - oxidized
- gas
  - extended
  - jet
- (liquid)

- HPGe
- NaI
- BGO
- Si
- Scintillators
- ^{3}He
- …

From "Cauldrons in the Cosmos - Nuclear Astrophysics", Claus E. Rolfs and William S. Rodney, University of Chicago Press, 1988.

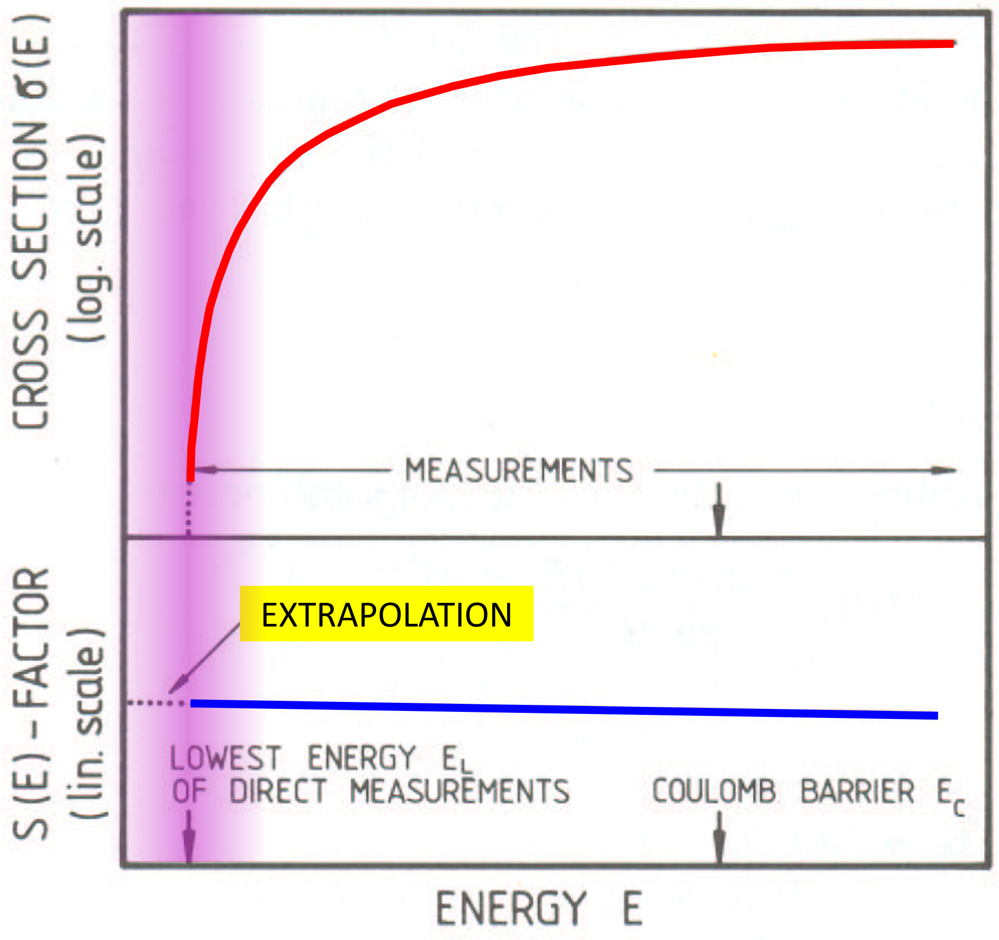
How to measure a low energy nuclear cross section

Below a certain energy, the counting rate is too low and the cosmic-ray induced background prevents the direct measurement of the cross section

Introducing the **astrophysical S-factor S(E)** and factorizing the **Coulomb interaction term** apart:

$$\boldsymbol{\sigma(E) = \frac{1}{E} e^{-2\pi\eta} S(E)}$$

it is possible to measure the cross section at high energy and extrapolate the astrophysical factor *S(E)* in the interesting energy range (Gamow window)



Challenges in Nuclear Astrophysics...

$$Counting\ rate = beam\ flux \times target\ nuclei\ areal\ density \times cross\ section \times detection\ efficiency$$

10^{14} pps (100 μA 1^{+} beam)

10^{19} atoms/cm^2 (often smaller)

10^{-36} cm^2 (often smaller)

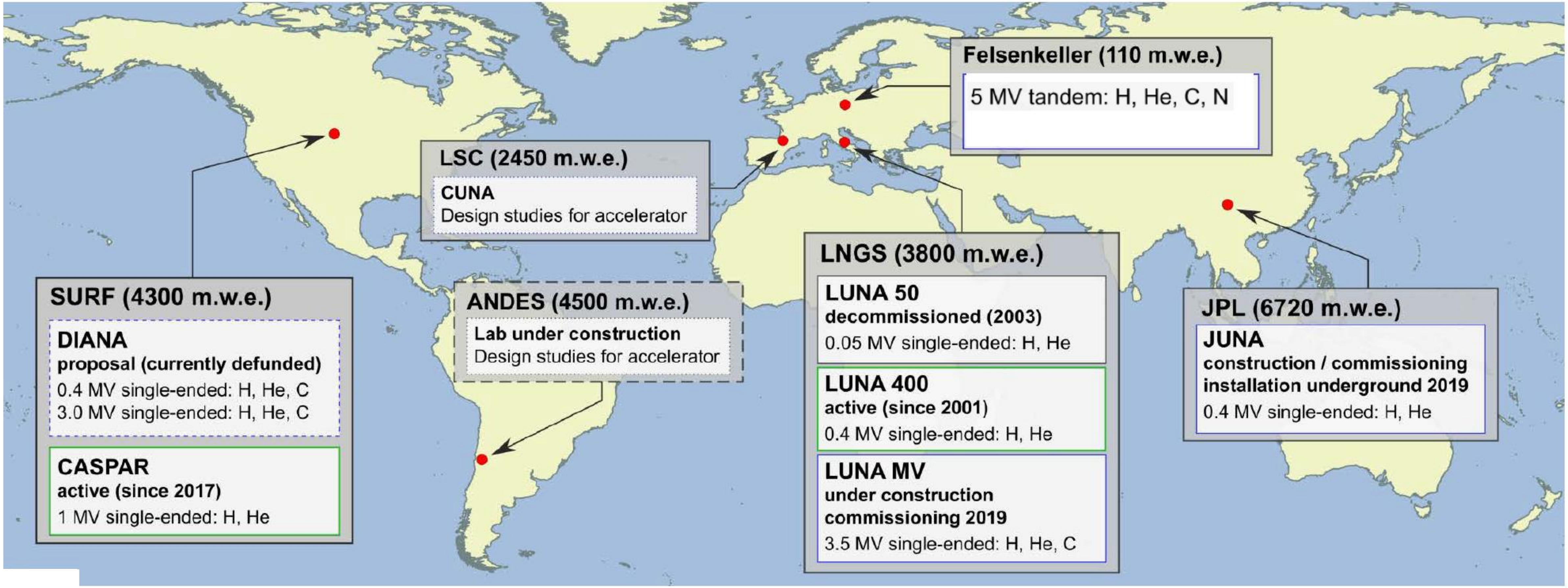
10^{-1} (often smaller)

a few counts/day

fundamental to strongly suppress the background!

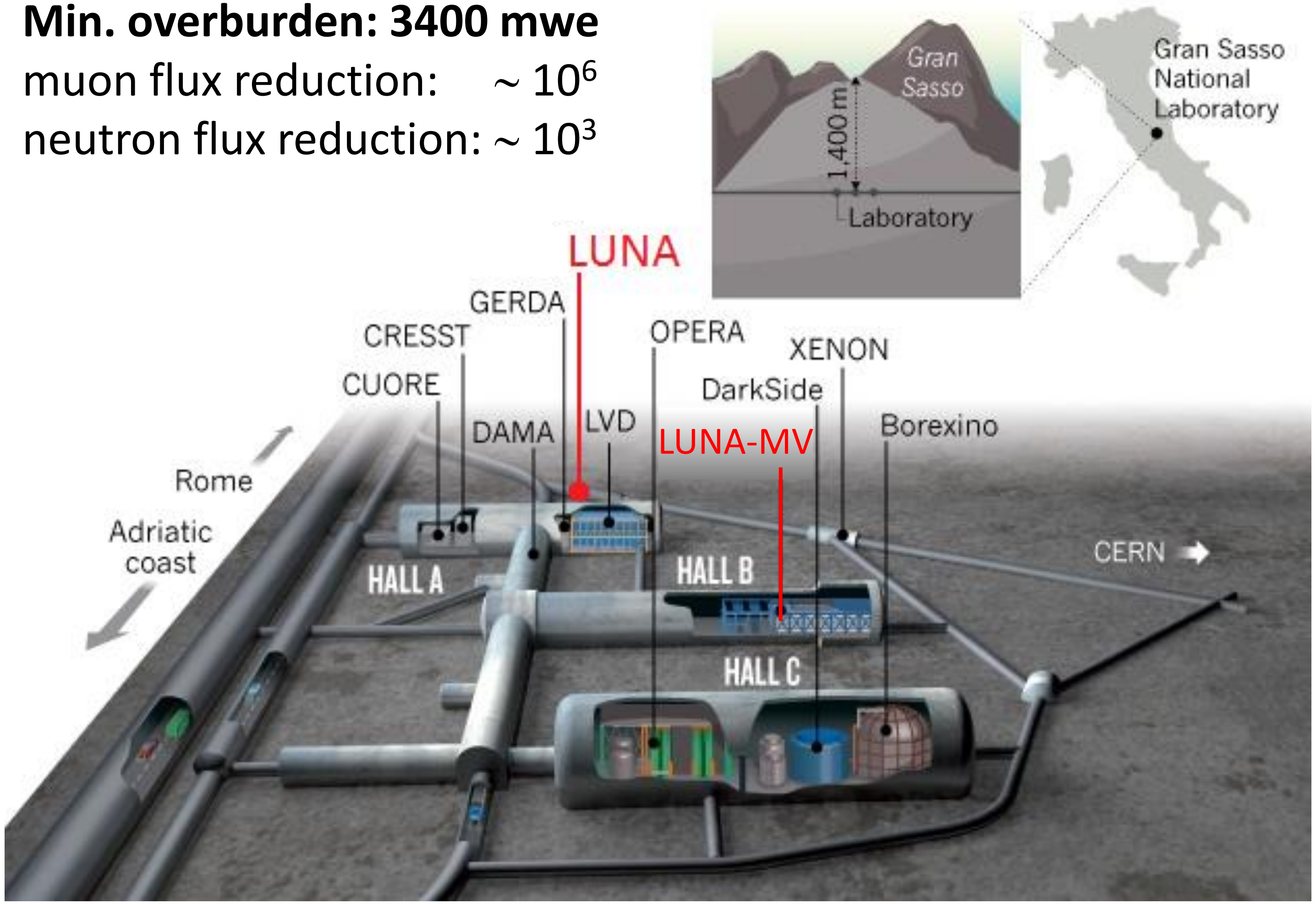
UNDERGROUND LABORATORIES

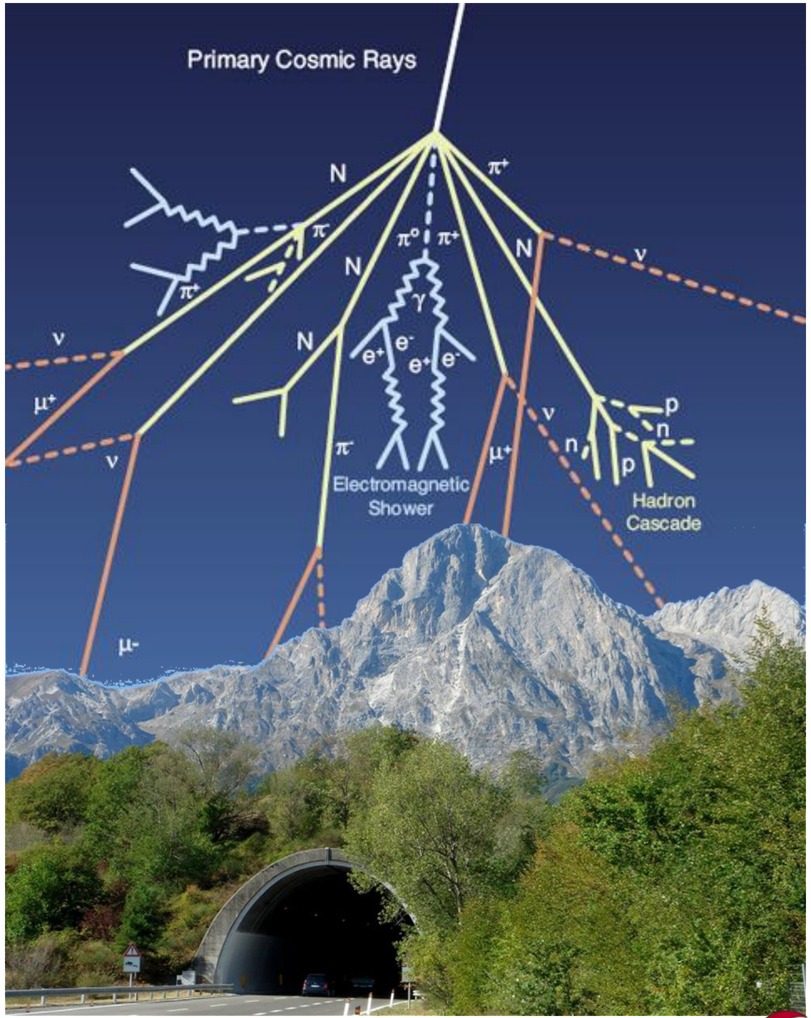
Nuclear Astrophysics Underground Laboratories



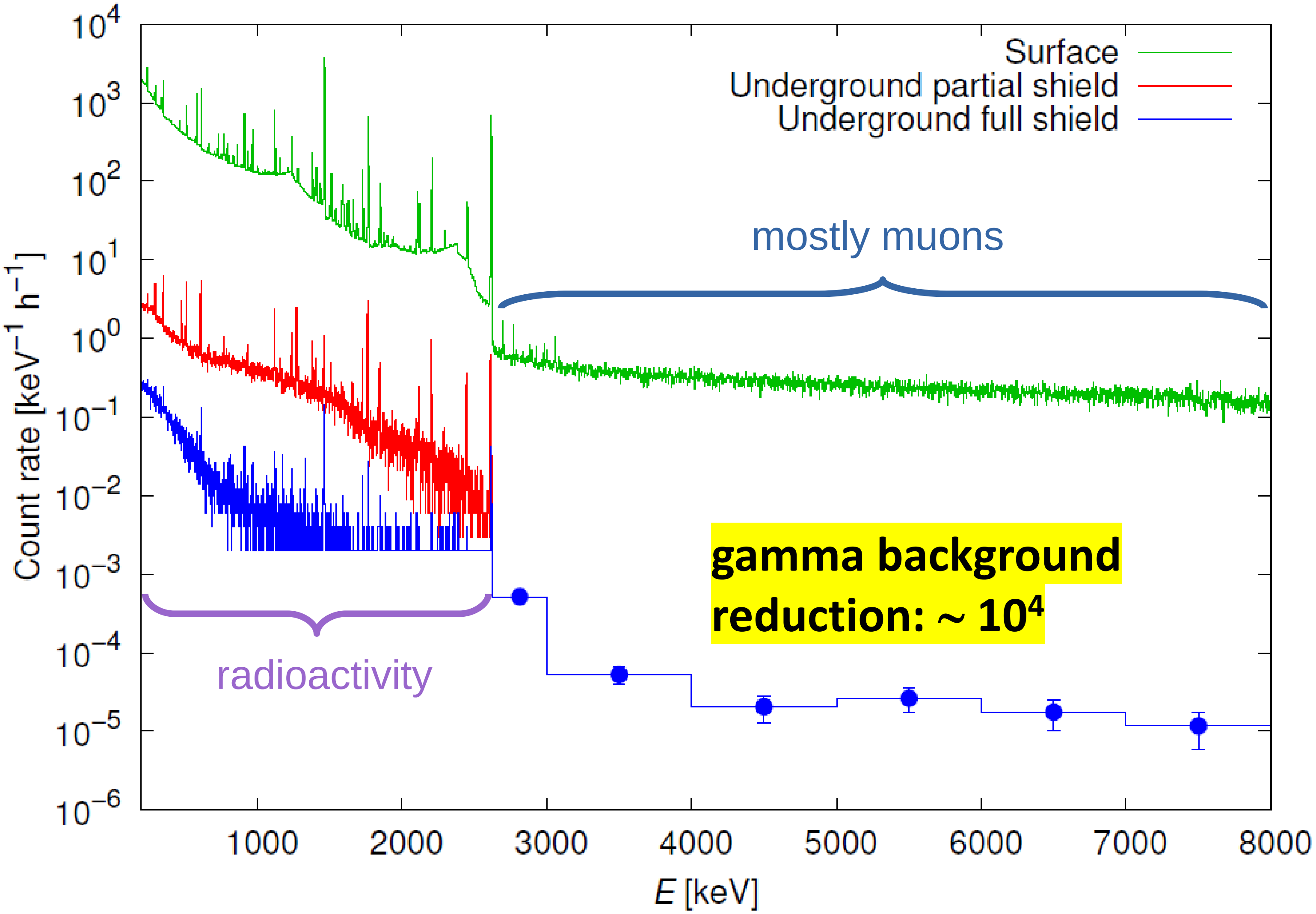
The Gran Sasso National Laboratory (LNGS)

Min. overburden: 3400 mwe
muon flux reduction: $\sim 10^6$
neutron flux reduction: $\sim 10^3$



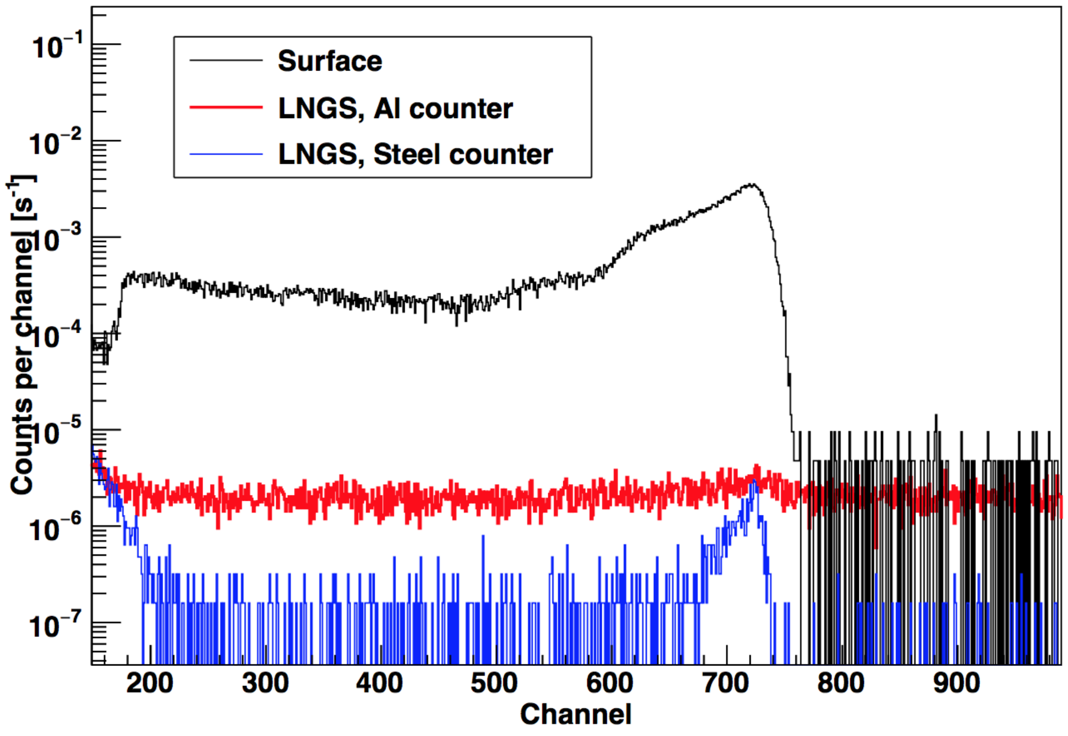


Gamma background reduction @ LNGS

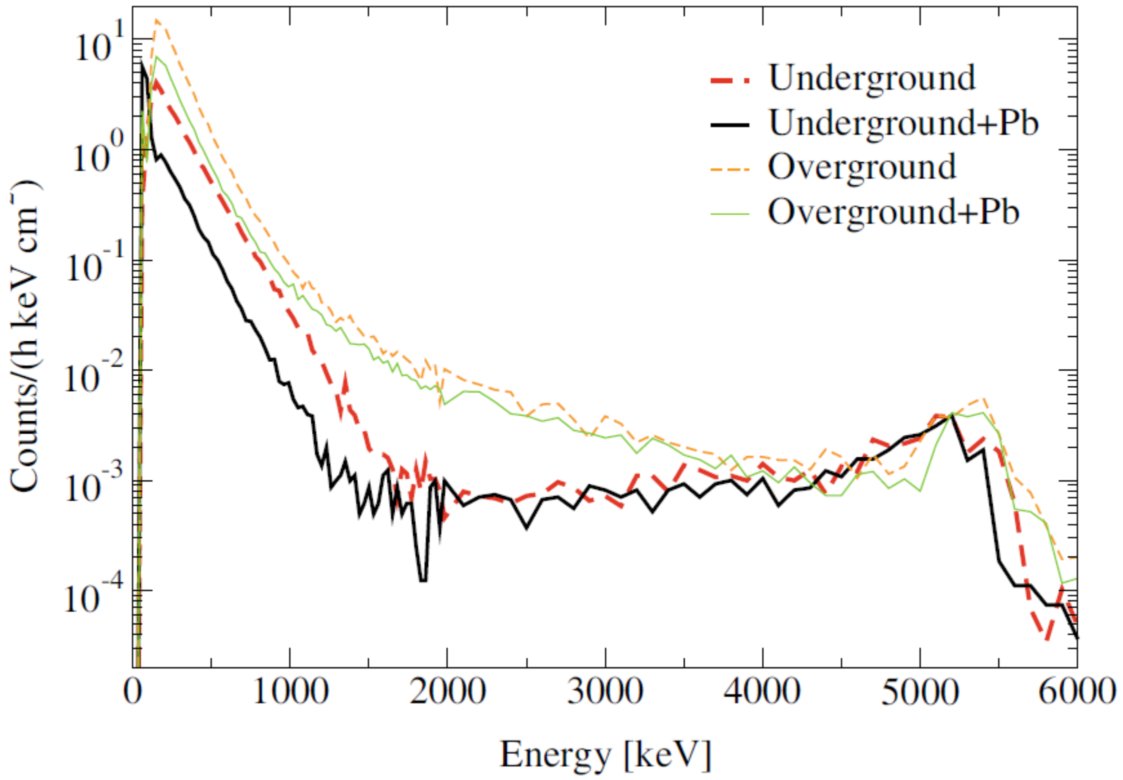


Reduction of particle background @ LNGS

Neutrons



Charged particles



The LUNA collaboration

Laboratori Nazionali del Gran Sasso, INFN, ASSERGI, Italy
F.Ferraro, M. Junker

GSSI, L'AQUILA, Italy
A. Compagnucci, R. Gesuè

Università degli Studi di Bari and INFN, BARI, Italy/*INFN Lecce, LECCE, Italy
F. Barile, G.F. Ciani

Konkoly Observatory, Hungarian Academy of Sciences, BUDAPEST, Hungary
M. Lugaro

Institute of Nuclear Research (ATOMKI), DEBRECEN, Hungary
L. Csedreki, Z. Elekes, Zs. Fülöp, Gy. Gyürky, T. Szücs

Helmholtz-Zentrum Dresden-Rossendorf, DRESDEN, Germany
D. Bemmerer, A. Boeltzig, E. Masha

University of Edinburgh, EDINBURGH, United Kingdom
M. Aliotta, L. Barbieri, C.G. Bruno, T. Davinson, J. Marsh, D. Robb, R. Sidhu

Università degli Studi di Genova and INFN, GENOVA, Italy
F. Casaburo, P. Corvisiero, P. Prati, S. Zavatarelli

Università degli Studi di Milano and INFN, MILANO, Italy
R. Depalo, A. Guglielmetti

Università degli Studi di Napoli "Federico II" and INFN, NAPOLI, Italy
A. Best, C. Ananna, D. Dell'Aquila, A. Di Leva, G. Imbriani, D. Rapagnani

Università degli Studi di Padova and INFN, PADOVA, Italy
C. Broggini, A. Caciolli, P. Marigo, R. Menegazzo, D. Piatti, J. Skowronski, S. Turkat

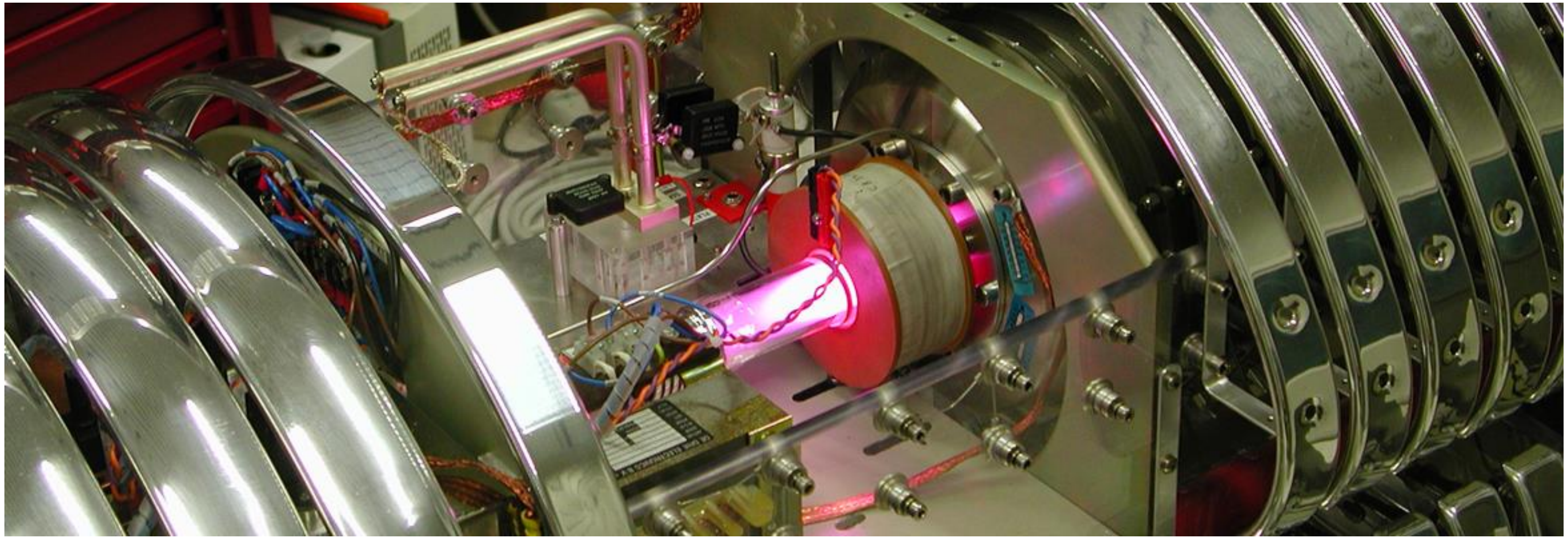
INFN Roma1, ROMA, Italy
A. Formicola, C. Gustavino

Laboratori Nazionali di Legnaro, Italy
M. Campostrini, V. Rigato

Osservatorio Astronomico di Collurania, TERAMO and INFN LNGS, Italy
O. Straniero

Università di Torino and INFN, TORINO, Italy
F. Cavanna, P. Colombetti, G. Gervino

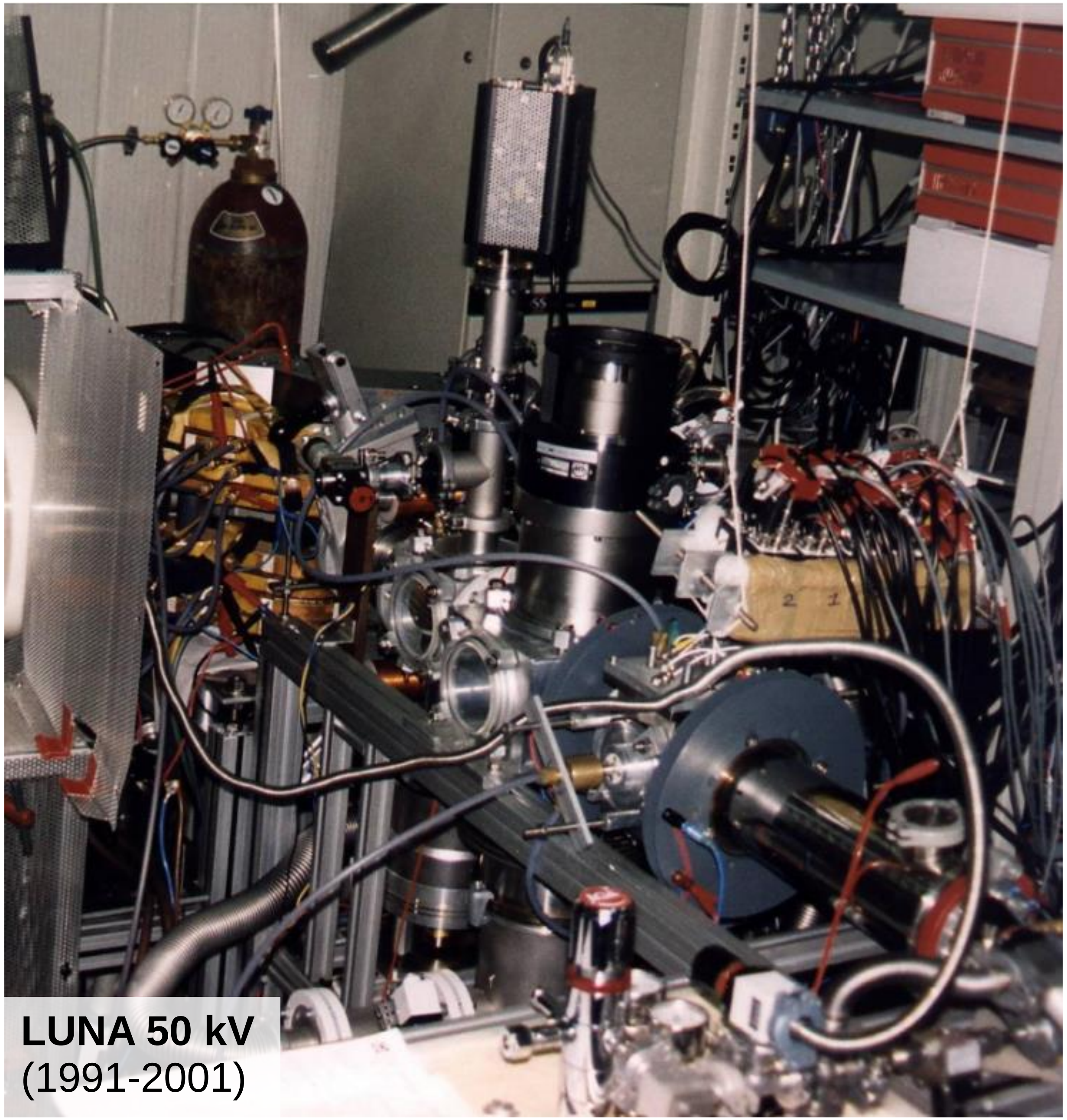
LUNA
Laboratory for Underground Nuclear Astrophysics

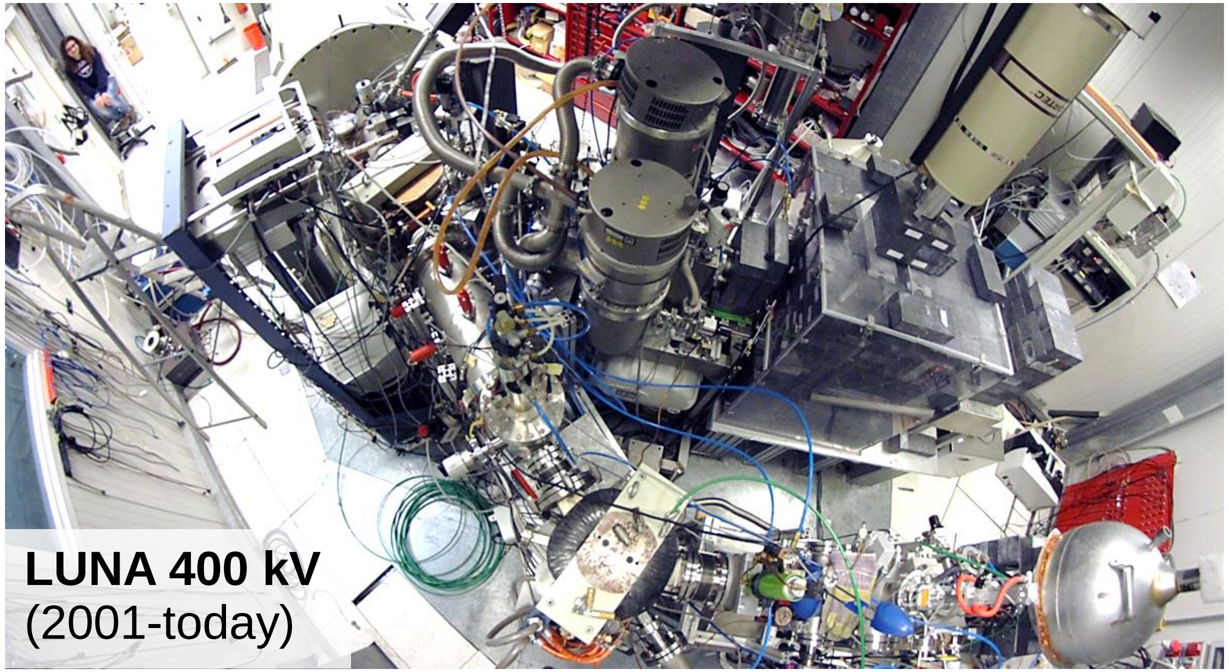


It has been the only underground accelerator for nuclear astrophysics for 25 years

Its results include

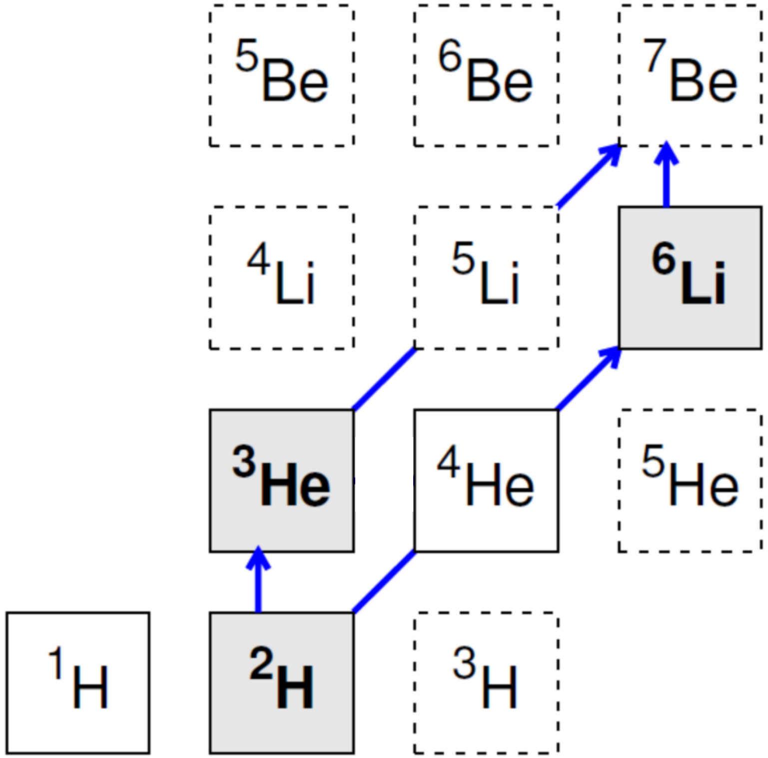
- solar physics (solar neutrinos)
- cosmological model
- big bang nucleosynthesis (BBN)
- stellar nucleosynthesis

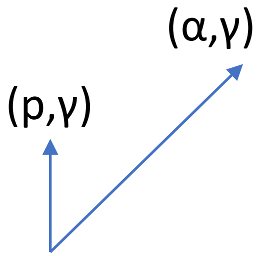

LUNA 50 kV
(1991-2001)


LUNA 400 kV
(2001-today)


LUNA-MV @ Bellotti IBF
(today-????)

Some reactions studied in the past by LUNA (BBN)





Some reactions studied in the past by LUNA (pp chain and CNO cycle)

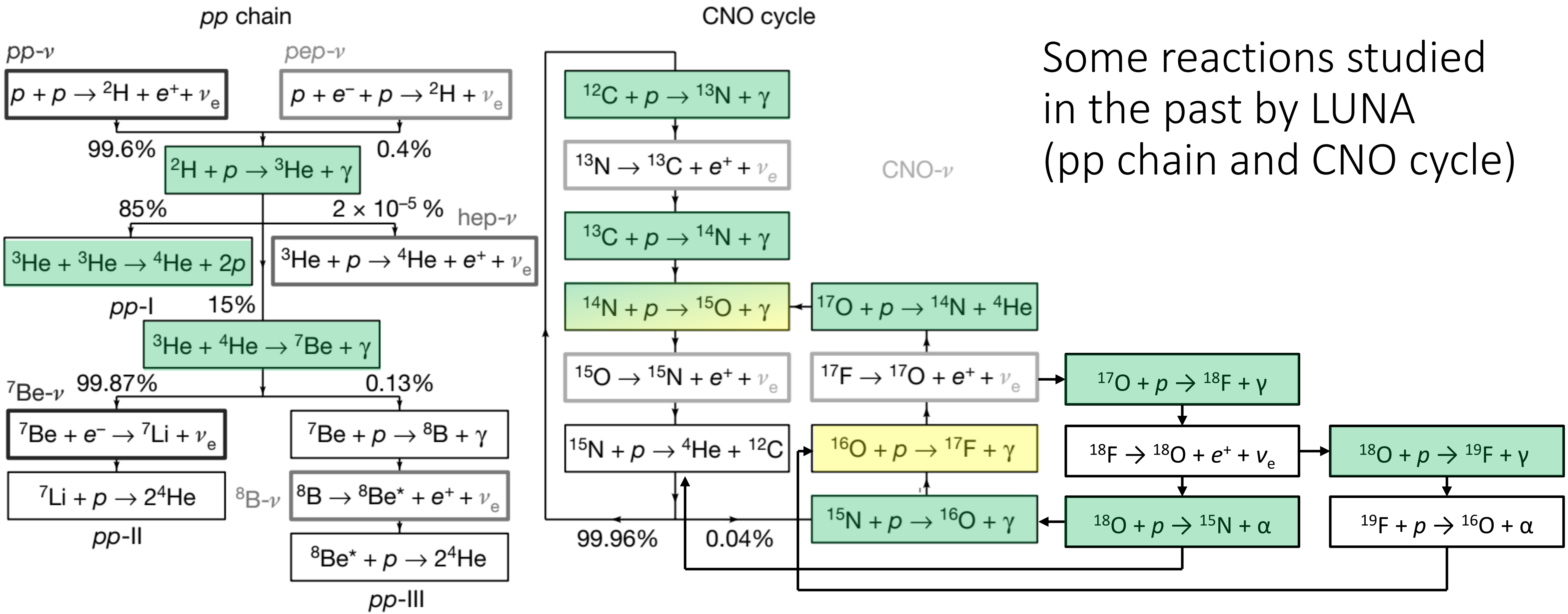
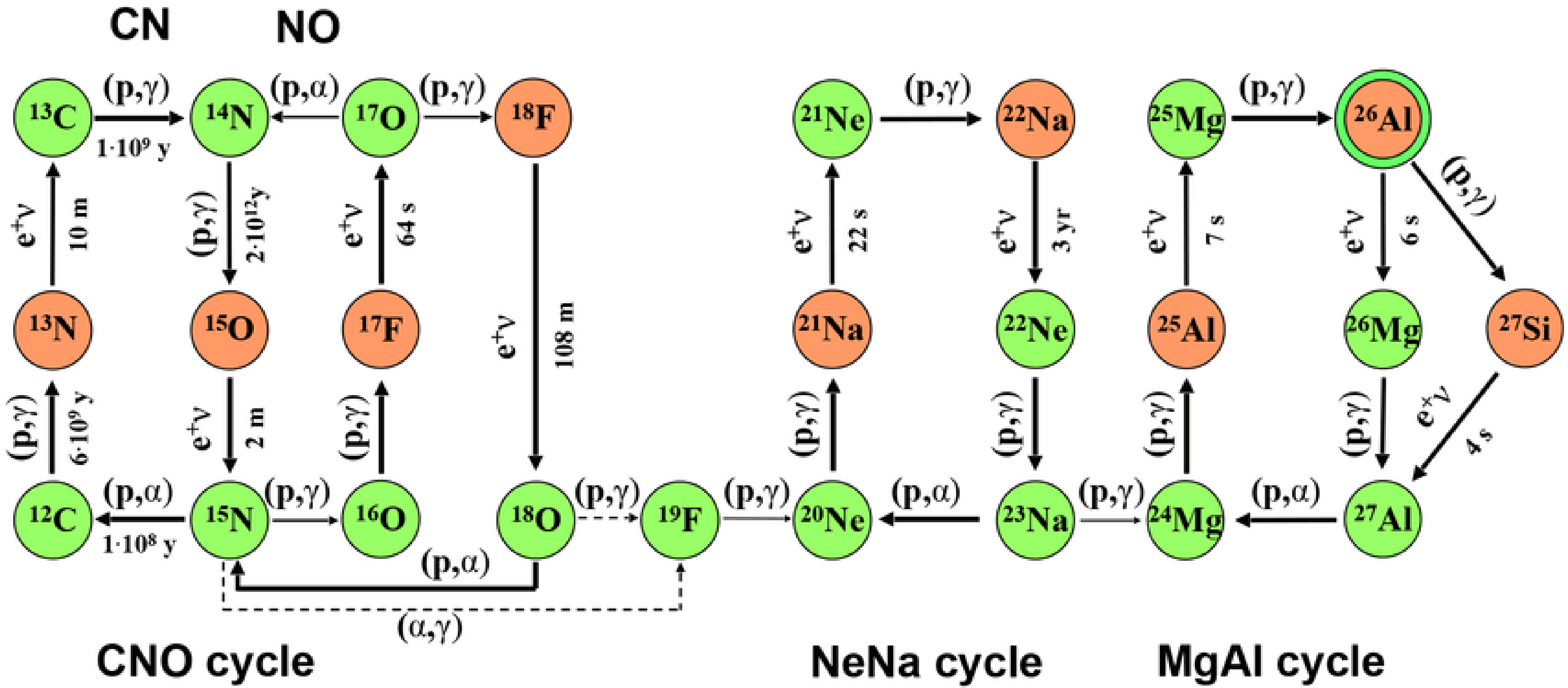
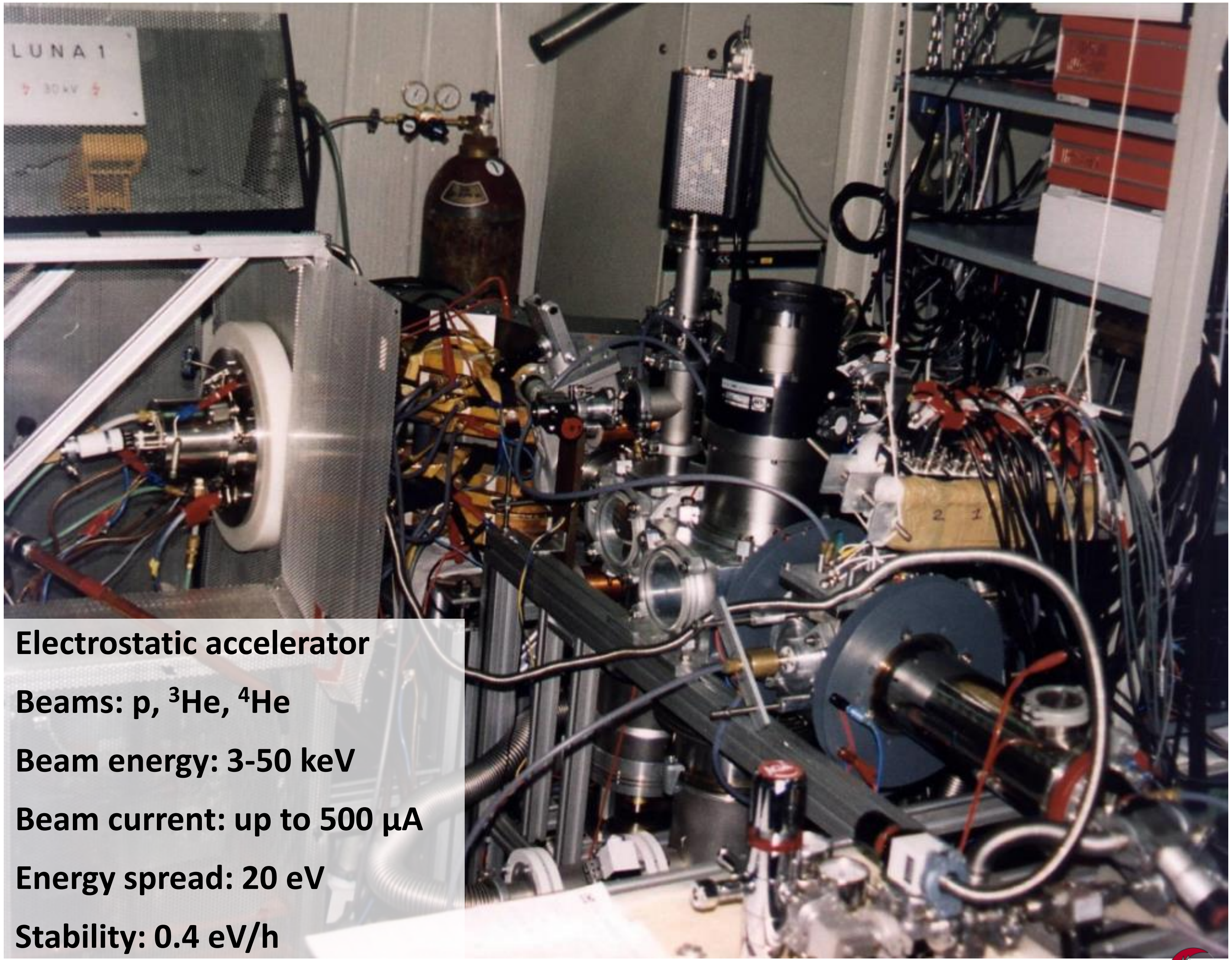


Image adapted from “The Borexino Collaboration. Comprehensive measurement of *pp*-chain solar neutrinos. *Nature* 562, 505–510 (2018). https://doi.org/10.1038/s41586-018-0624-y”

Some reactions studied in the past by LUNA (advanced H burning)



LUNA 50 kV
(1991-2001)



Electrostatic accelerator

Beams: p, ^{3}He, ^{4}He

Beam energy: 3-50 keV

Beam current: up to 500 μA

Energy spread: 20 eV

Stability: 0.4 eV/h

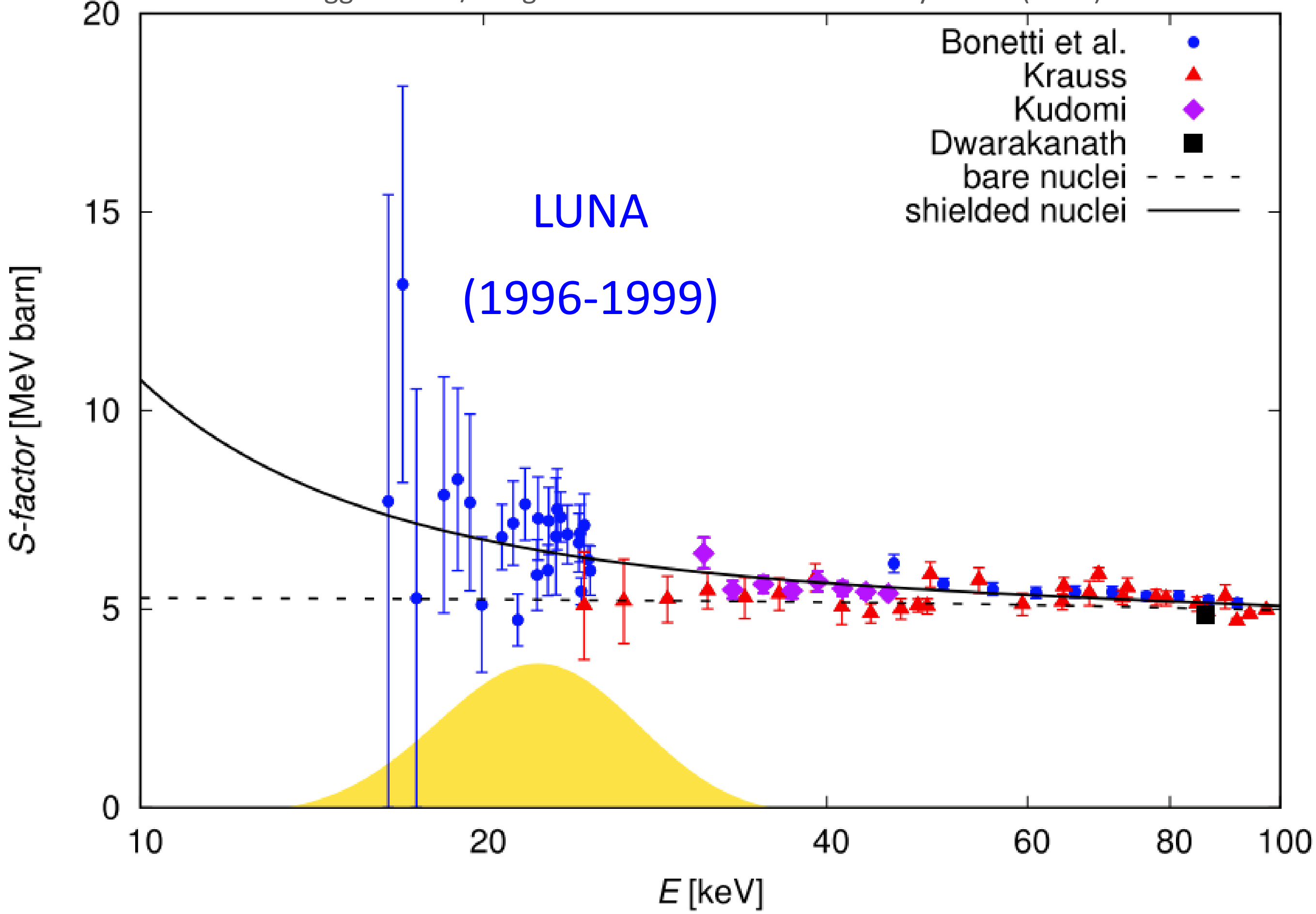
One historical measurement: $^{3}He(^{3}He,2p)^{4}He$

First direct measurement in the Gamow window

At 16.5 keV the cross section is 0.02 pb, corresponding to a reaction rate of approximately 2 events/month.

The absence of a resonance in the Gamow window allowed to discard a nuclear solution to the Solar Neutrino Problem

C. Broggini et al. / Progress in Particle and Nuclear Physics 98 (2018) 55–84



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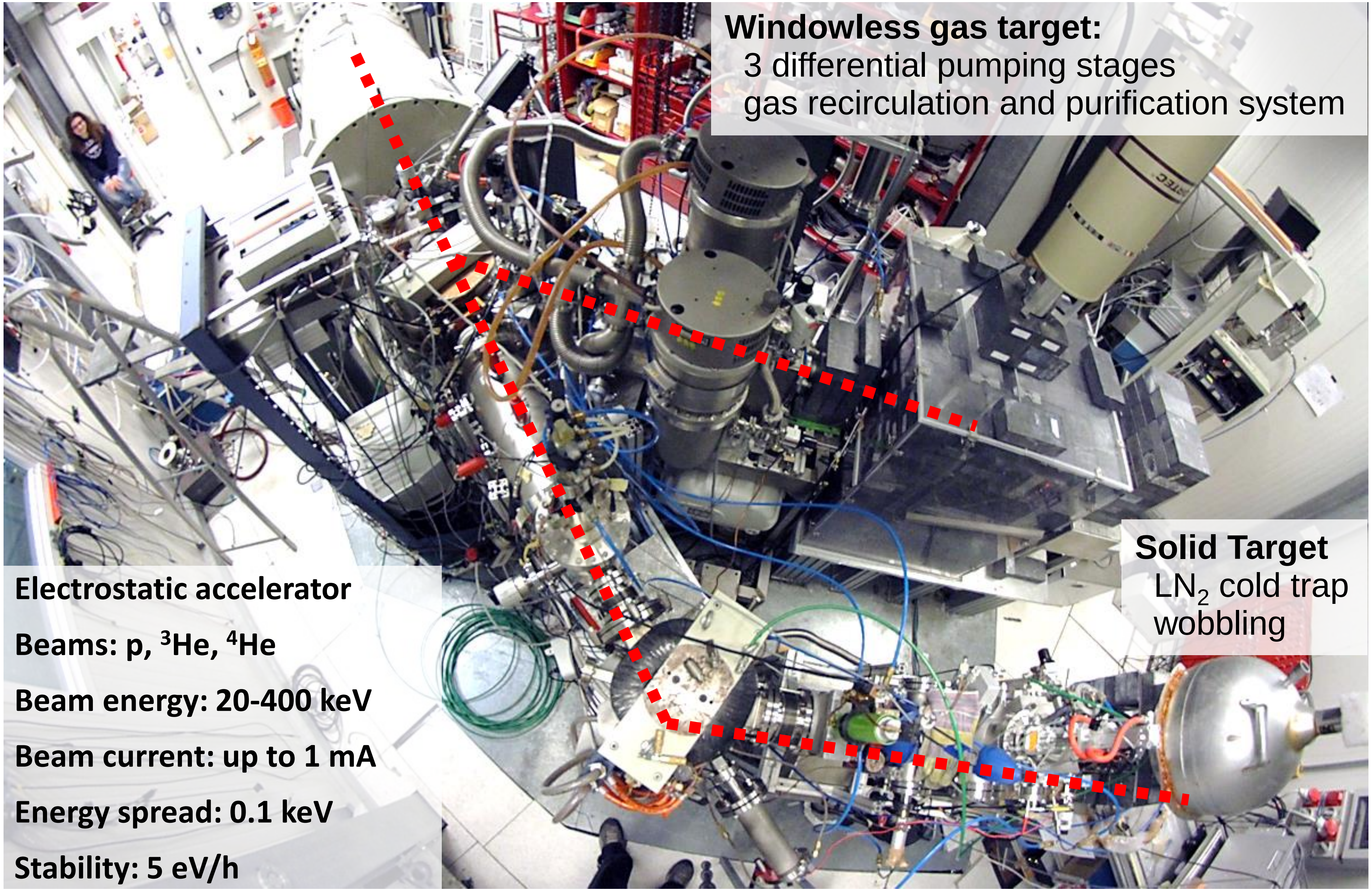
LUNA 400 kV
(2001-today)



One recent measurement: D(p,γ)^{3}He

It was the most uncertain nuclear physics input to BBN calculations

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Article | Published: 11 November 2020

The baryon density of the Universe from an improved rate of deuterium burning

V. Mossa, K. Stöckel, F. Cavanna, F. Ferraro, M. Aliotta, F. Barile, D. Bemmerer, A. Best, A. Boeltzig, C. Broggini, C. G. Bruno, A. Caciolli, T. Chillery, G. F. Ciani, P. Corvisiero, L. Csedreki, T. Davinson, R. Depalo, A. Di Leva, Z. Elekes, E. M. Fiore, A. Formicola, Zs. Fülöp, G. Gervino, A. Guglielmetti, C. Gustavino, G. Gyürky, G. Imbriani, M. Junker, A. Kievsky, I. Kochanek, M. Lugaro, L. E. Marcucci, G. Mangano, P. Marigo, E. Masha, R. Menegazzo, F. R. Pantaleo, V. Paticchio, R. Perrino, D. Piatti, O. Pisanti, P. Prati, L. Schiavulli, O. Straniero, T. Szücs, M. P. Takács, D. Trezzi, M. Viviani & S. Zavatarelli -Show fewer authors

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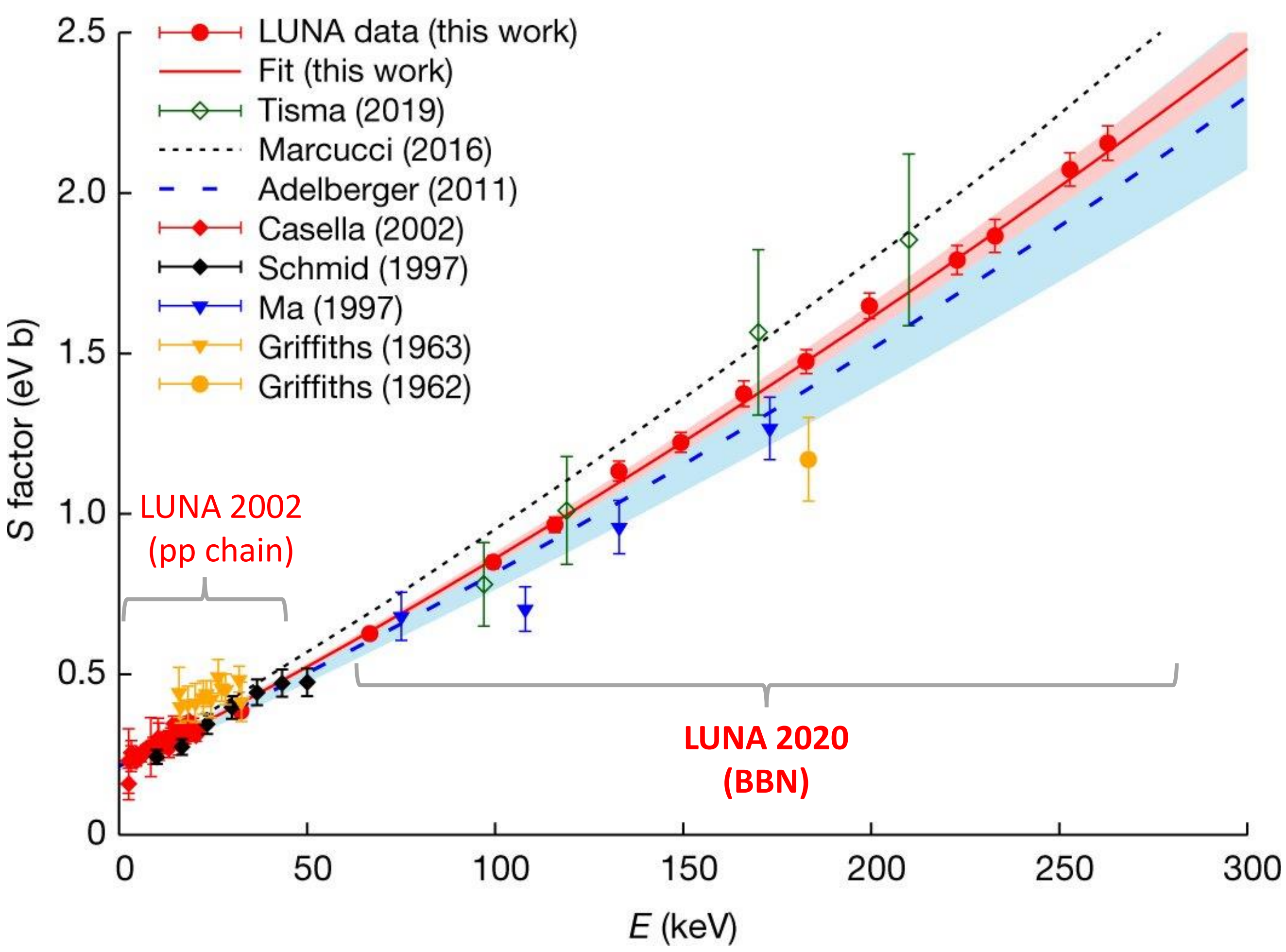
Our measurement improved the reliability in the use of primordial abundances as probes of the physics of the early Universe



One recent measurement: D(p,γ)^{3}He

"Big Bang nucleosynthesis studied at Felsenkeller and CRYRING"
Eliana Masha
Tuesday afternoon

It was the most uncertain nuclear physics input to BBN calculations

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Article | Published: 11 November 2020

The baryon density of the Universe from an improved rate of deuterium burning

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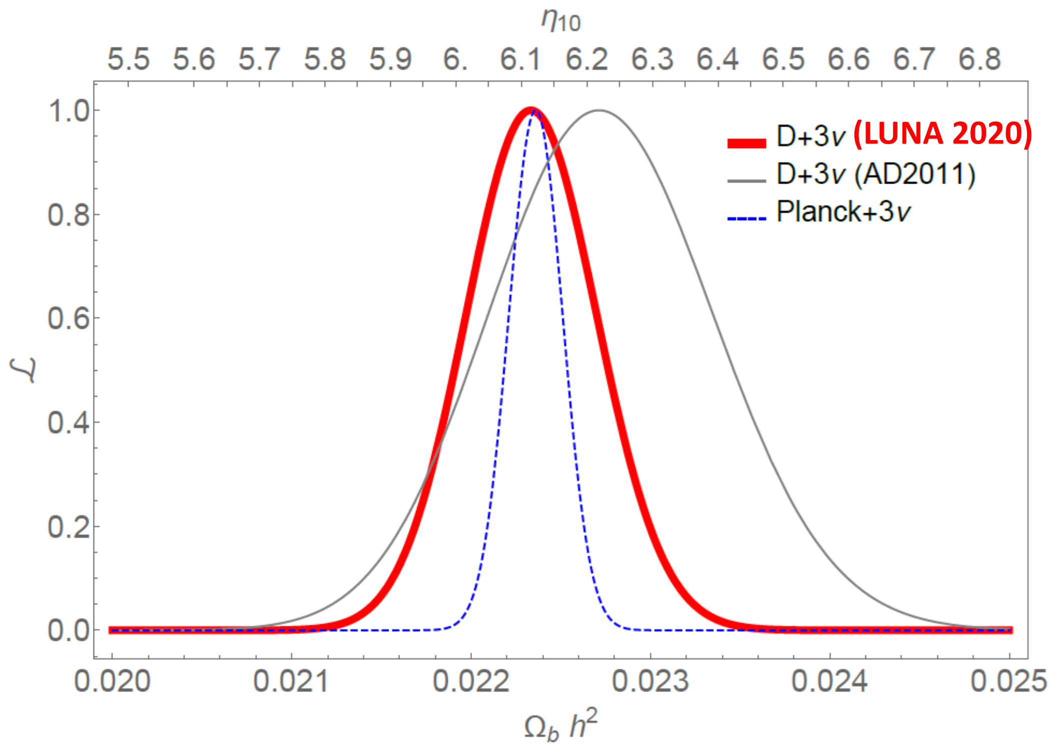
Our measurement improved the reliability in the use of primordial abundances as probes of the physics of the early Universe

Ω_b with PARTHENOPE code by comparing $[D/H]_{OBS}$ and $[D/H]_{BBN}$

N_{eff} from Standard Model

Comparison with Planck results



LUNA

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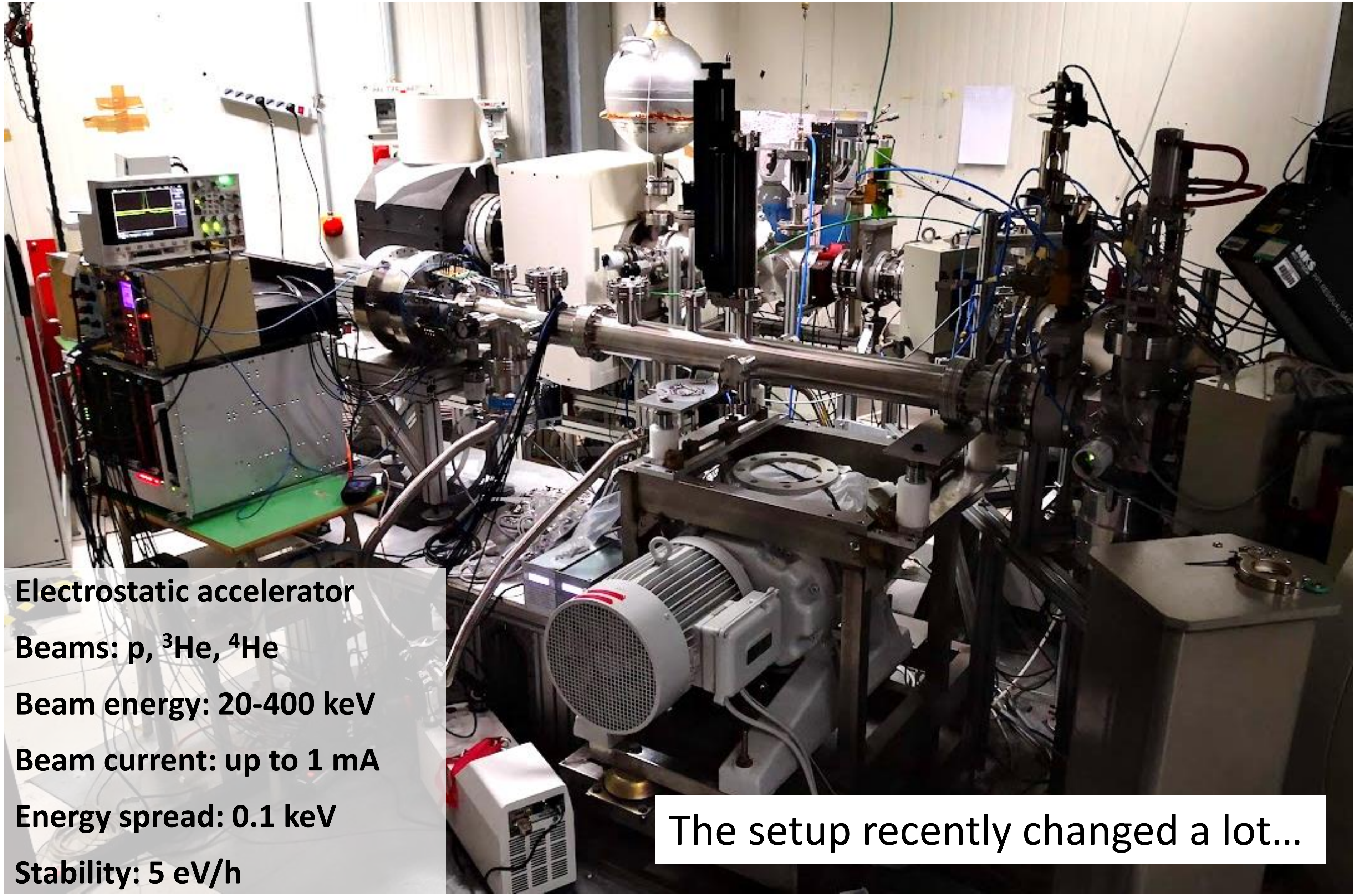
LUNA 400 kV
(2001-today)

recent picture (19/01/2024)



Electrostatic accelerator

Beams: p, ^{3}He, ^{4}He

Beam energy: 20-400 keV

Beam current: up to 1 mA

Energy spread: 0.1 keV

Stability: 5 eV/h

The setup recently changed a lot…

Present/future measurements @ LUNA 400 kV

in commissioning:

- $^{23}Na(p,\alpha)^{20}Ne$ — **ELDAR** — Elements in the Lives and Deaths of stARs

- $^{14}N(p,\gamma)^{15}O$ — **SoCIAL** — SOlar Composition Investigated At Luna

Present/future measurements @ LUNA 400 kV

in commissioning:

- $^{23}Na(p,\alpha)^{20}Ne$

ELDAR
Elements in the Lives and Deaths of stARs

- $^{14}N(p,\gamma)^{15}O$

SoCIAL
SOlar Composition Investigated At Luna

• $^{23}Na(p,\alpha)^{20}Ne$

ELDAR
Elements in the Lives and Deaths of stARs

This reaction is part of NeNa and MgAl cycles, active during H burning when the temperature exceeds ~ 50 MK.

Possible cause of O/Na **anti-correlation** (the best model of GC at present explains many observables but O and Na should be **correlated!**)

Uncertainties on the reaction rate are dominated by very weak resonances (too weak to be measured in surface laboratories)

"This discrepancy would be much alleviated if the cross-section of the sodium-destroying reaction $^{23}Na(p,\alpha)^{20}Ne$ were actually a factor of a few lower than currently estimated"

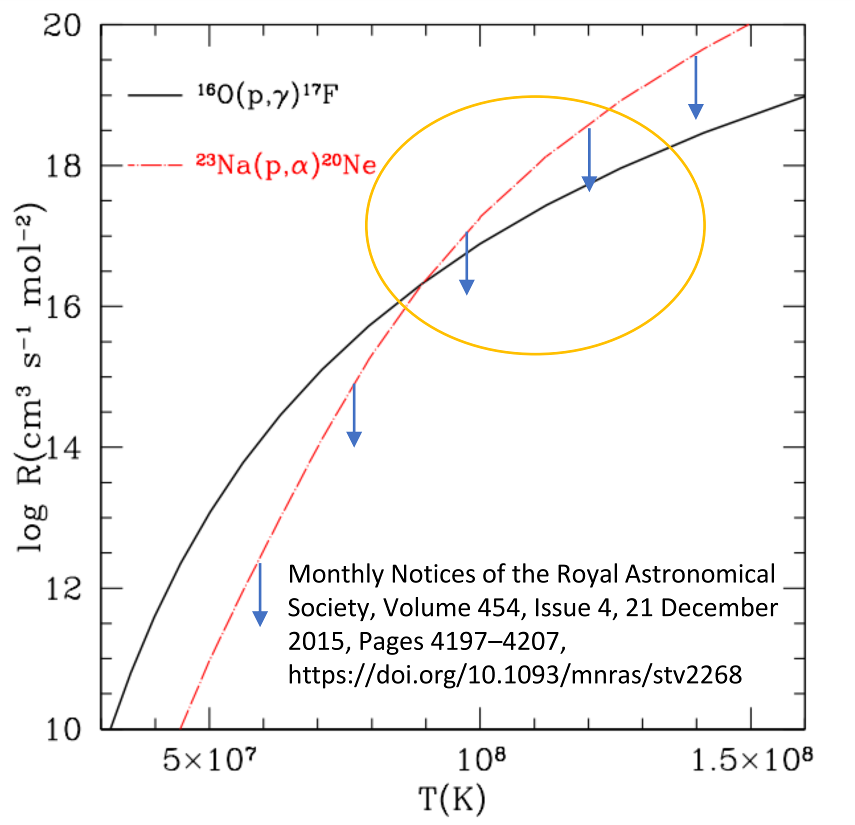


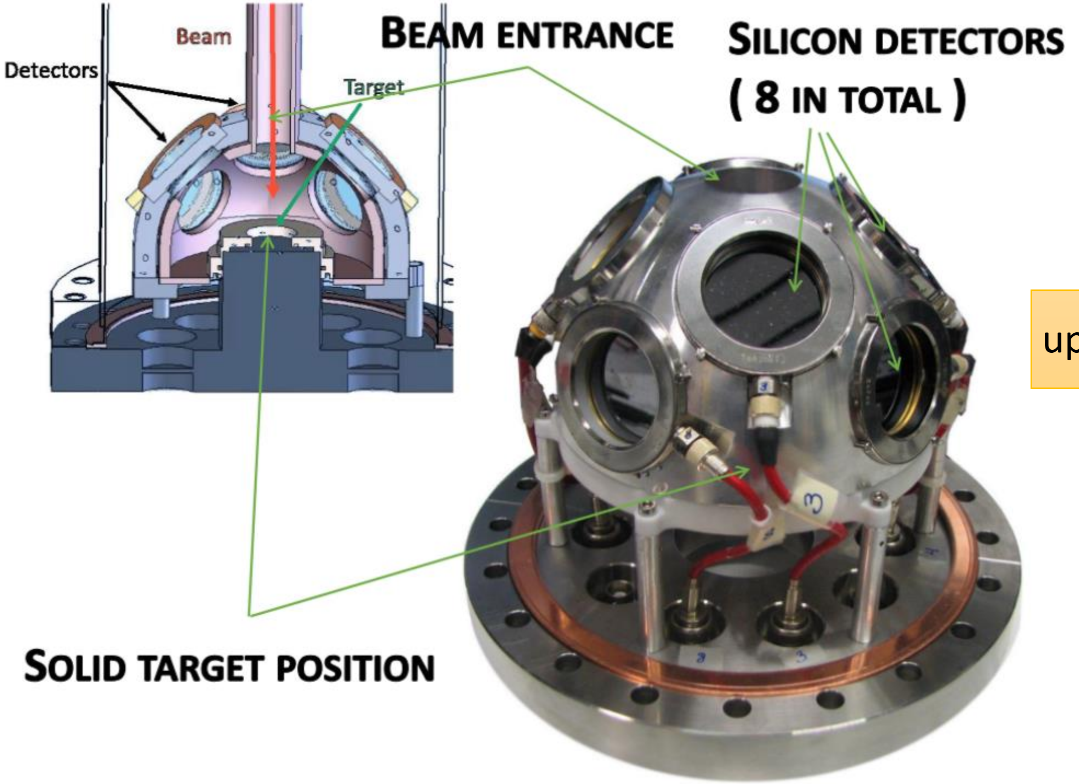
Figure 1. The rates of the $^{16}O(p,\gamma)^{17}F$ and $^{23}Na(p,\alpha)^{20}Ne$ reactions as a function of temperature, showing that for $T \lesssim 10^8$ K oxygen is destroyed faster than sodium, whereas sodium is destroyed faster above this temperature.

- $^{23}Na(p,\alpha)^{20}Ne$

ELDAR

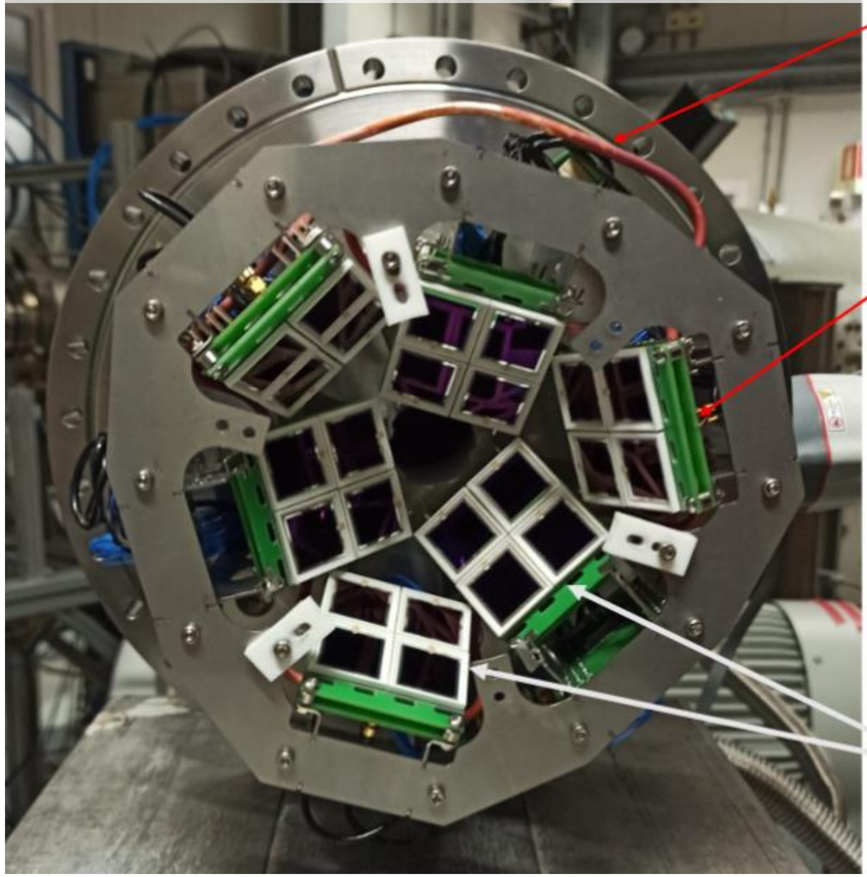
Elements in the Lives
and Deaths of stARs

Target chamber previously in use



upgrade

New target chamber design and detectors



Copper pipe for preamplifiers cooling

Hamamatsu PIN diodes

Each of the 3 external PCBs is connected to 8 diodes + 1 MSPAD (not mounted yet).

Present/future measurements @ LUNA 400 kV

in commissioning:

- $^{23}Na(p,\alpha)^{20}Ne$

ELDAR
Elements in the Lives and Deaths of stARs

- $^{14}N(p,\gamma)^{15}O$

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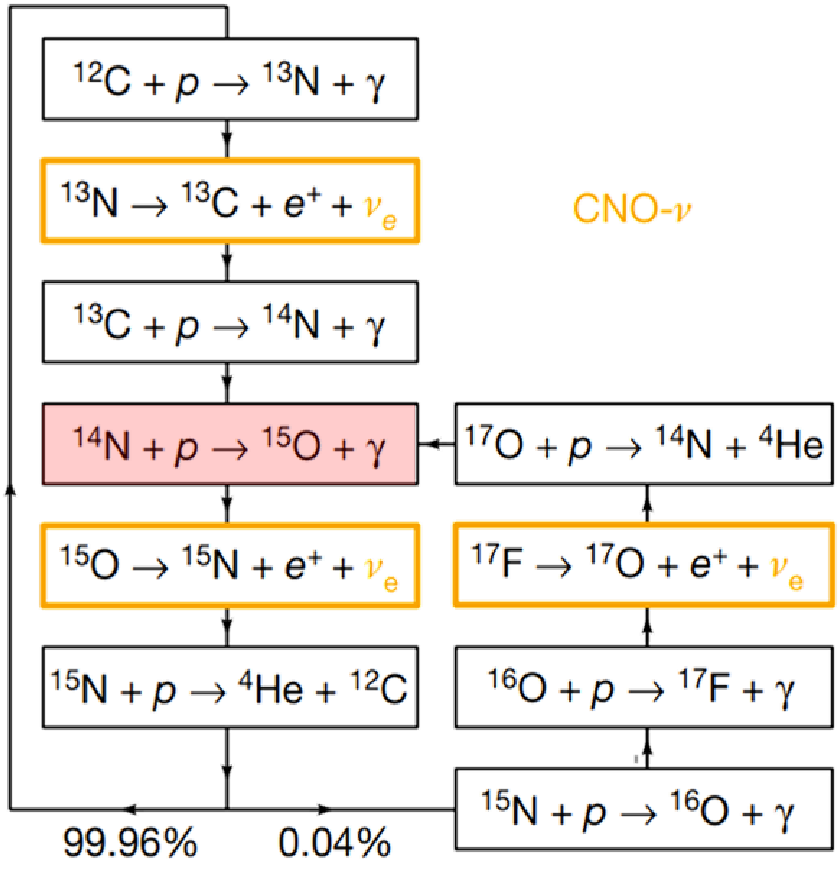
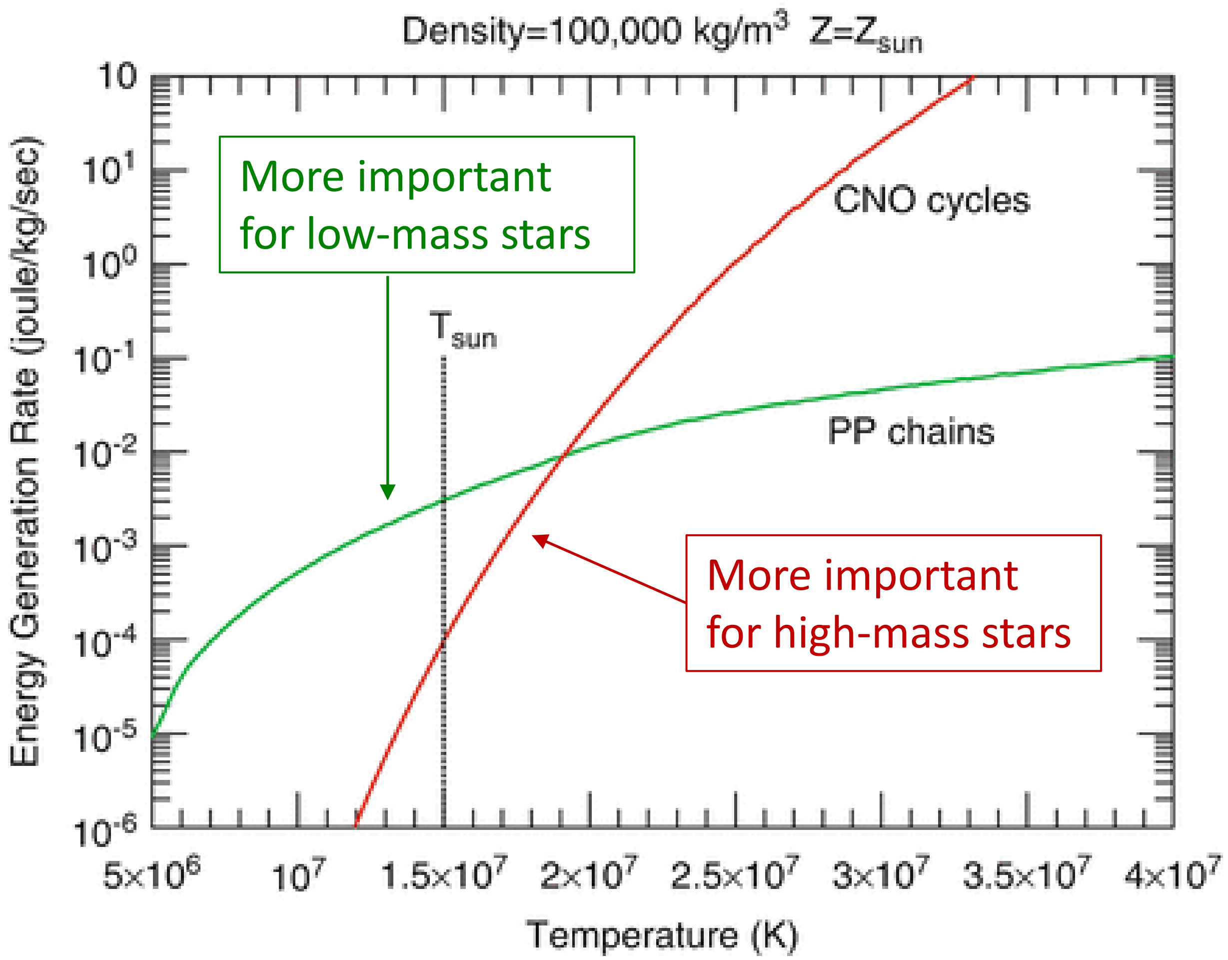
Part of a wider effort on the $^{14}N(p,\gamma)^{15}O$ that includes also measurements at the 3.5 MV accelerator

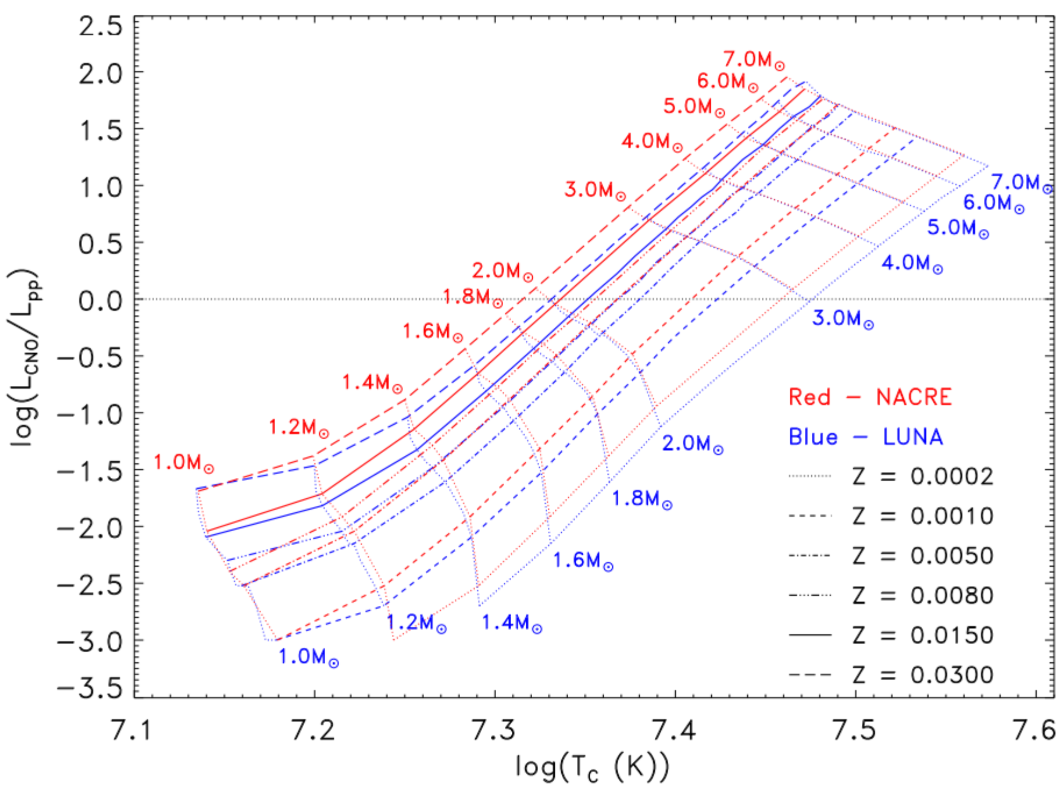
$^{14}N(p,\gamma)^{15}O$: the bottleneck of the CNO cycle

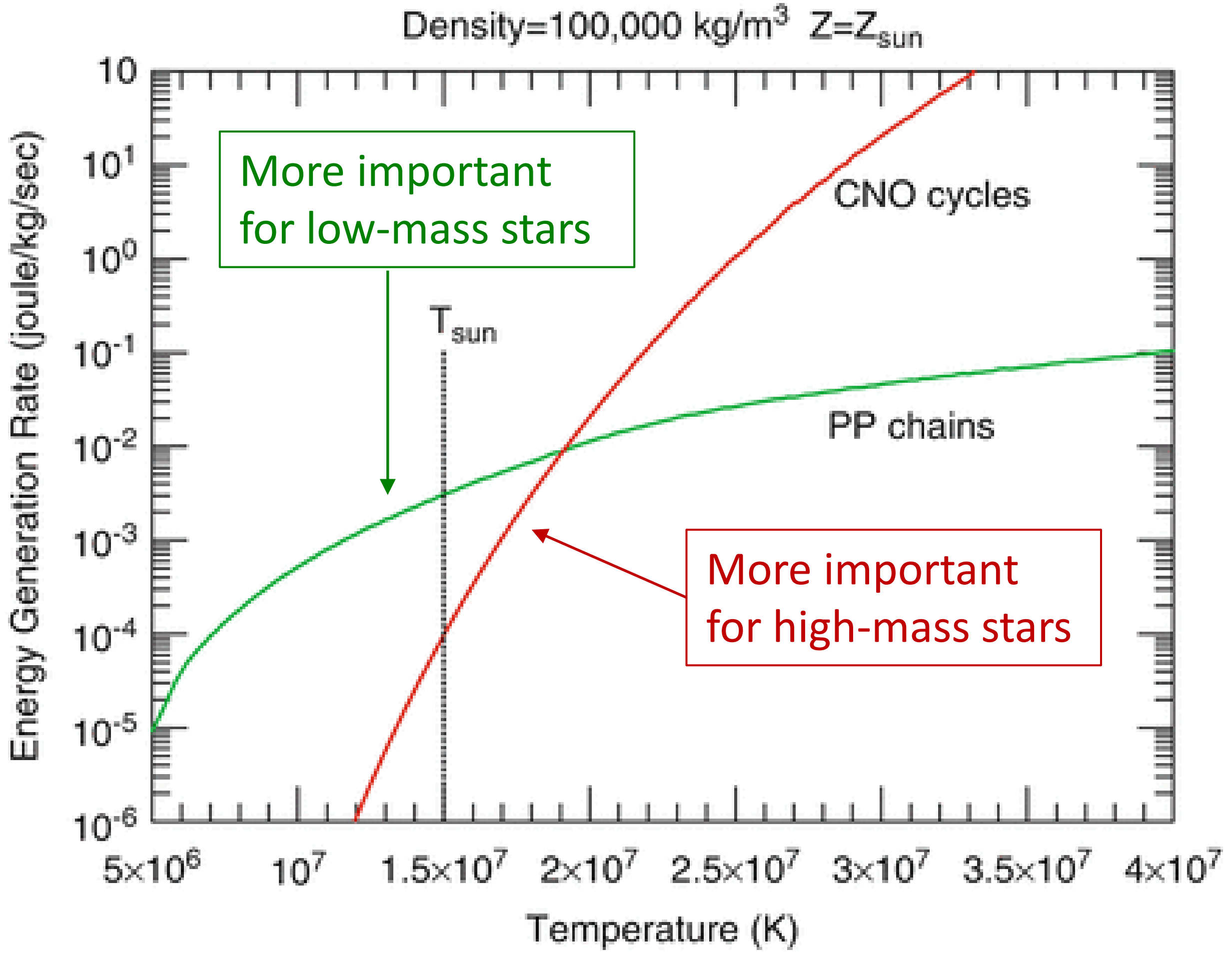




$^{14}N(p,\gamma)^{15}O$: the bottleneck of the CNO cycle

•Astronomy and Astrophysics 533(0004-6361)

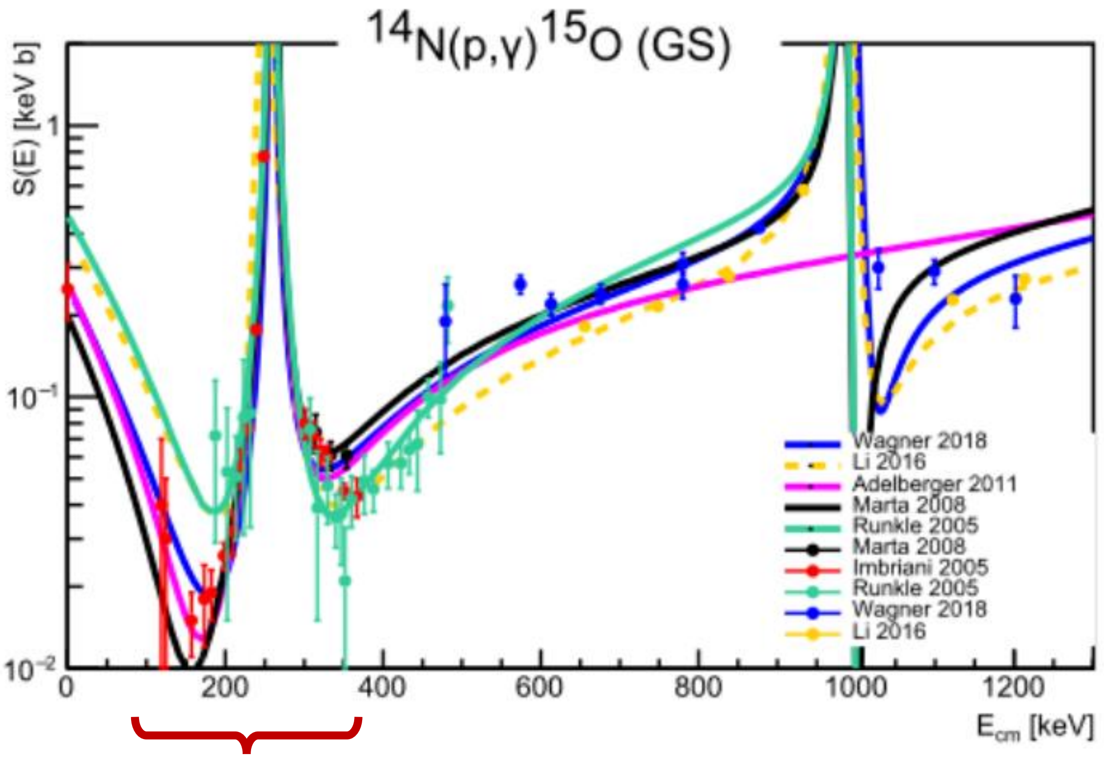




• $^{14}N(p,\gamma)^{15}O$

SoCIAL

SOlar Composition Investigated At Luna



LUNA-400
70-370 keV

A new study of the $^{14}N(p,\gamma)^{15}O$ reaction

- over a wide energy range
- with the capability of addressing all ^{15}O transitions with 5% precision

can provide a definitive solution to the **solar metallicity problem**

Goals of the SOCIAL project:

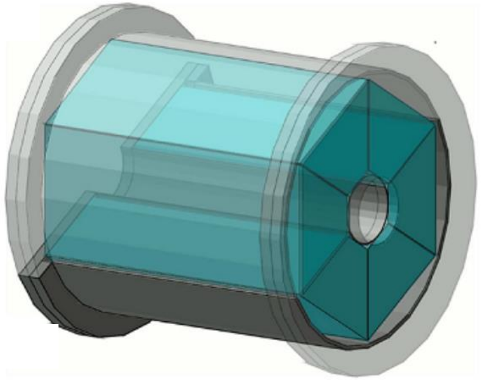
- below 100 keV → total cross section
- 100-370 keV → contribution of different excited states

using a segmented high-efficiency detector

- $^{14}N(p,\gamma)^{15}O$

SoCIAL

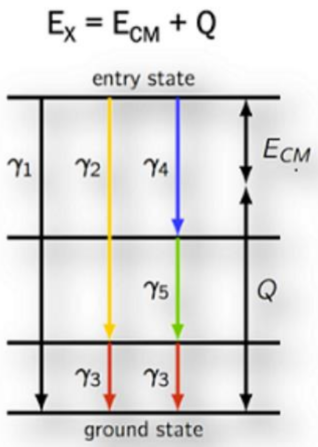
SOlar Composition Investigated At Luna

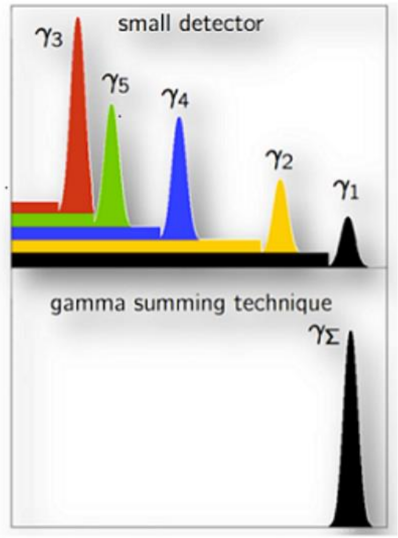


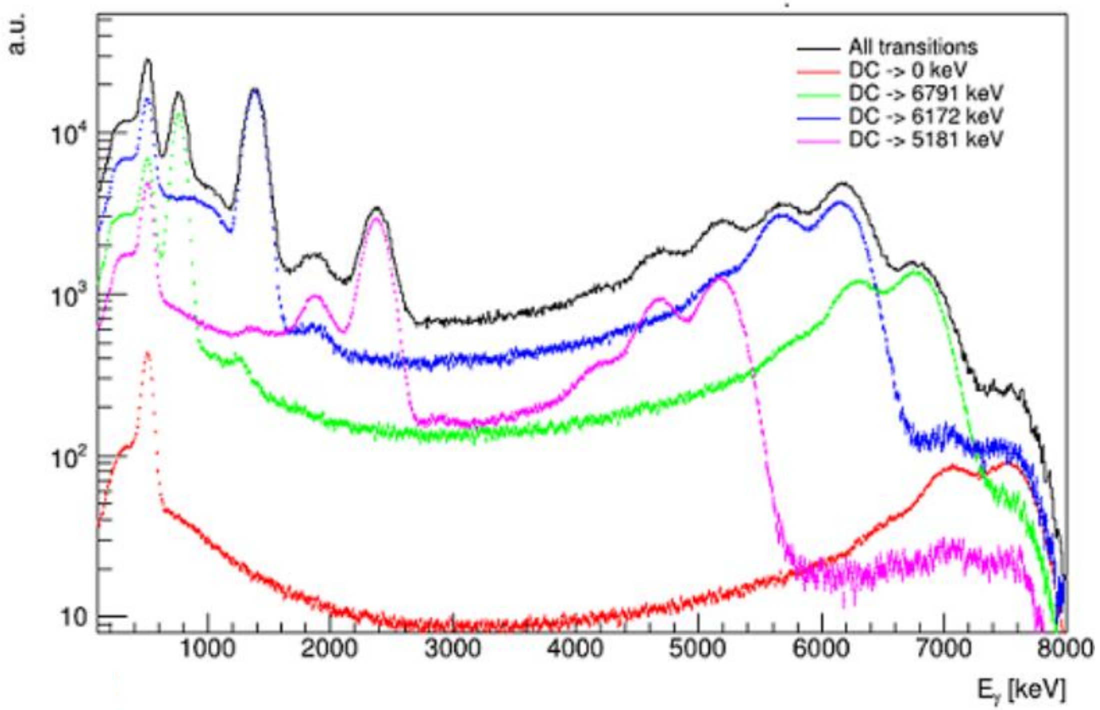
It is possible to see both the sum peak and the contribution from each gamma in the de-excitation of ^{15}O

so

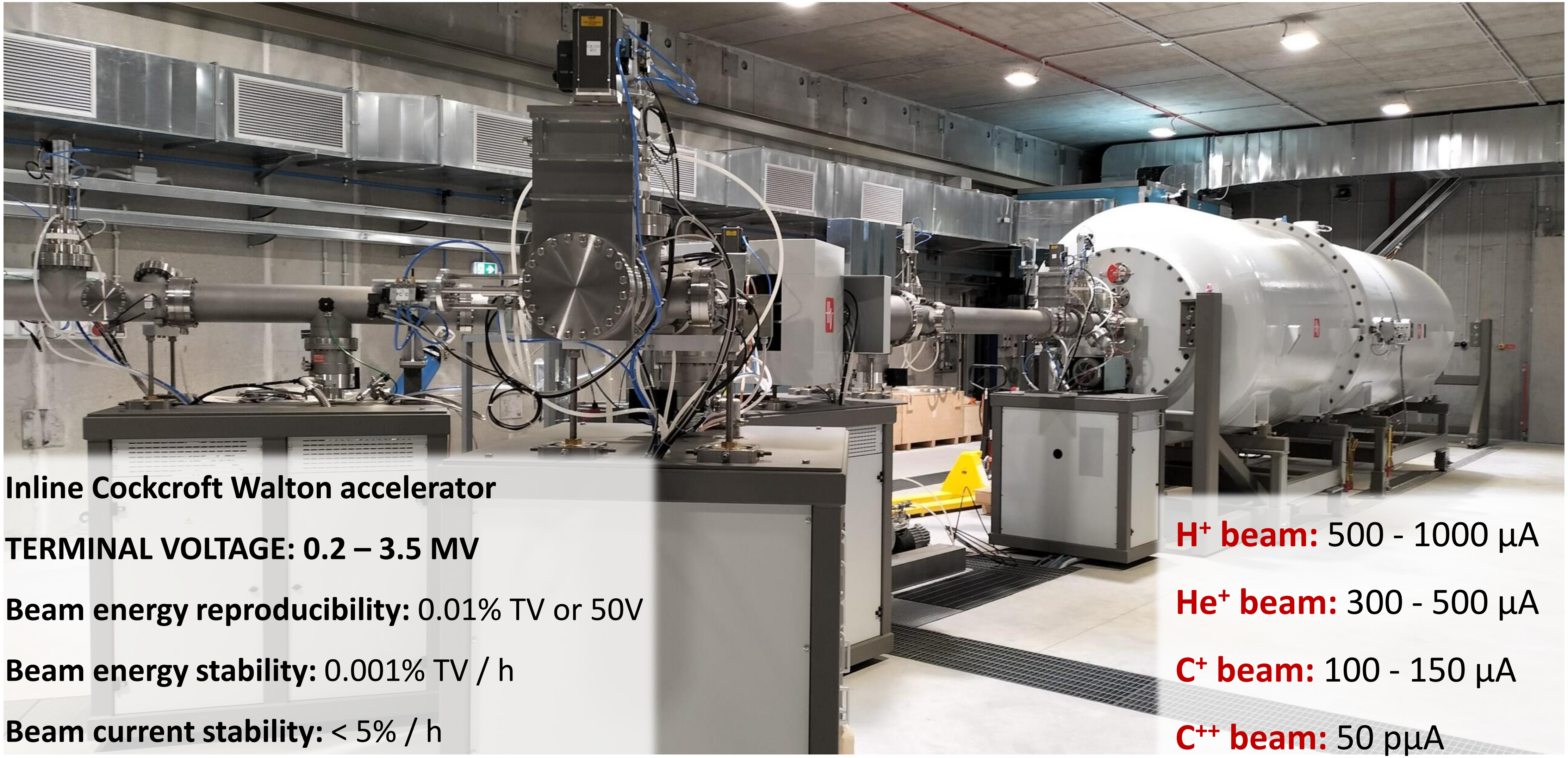
It is possible to determine the cross section more precisely (mitigating summing-in problems)







The new "Bellotti" Ion Beam Facility of LNGS



Inline Cockcroft Walton accelerator

TERMINAL VOLTAGE: 0.2 – 3.5 MV

Beam energy reproducibility: 0.01% TV or 50V

Beam energy stability: 0.001% TV / h

Beam current stability: < 5% / h

H^+ beam: 500 - 1000 μA

He^+ beam: 300 - 500 μA

C^+ beam: 100 - 150 μA

C^{++} beam: 50 pμA

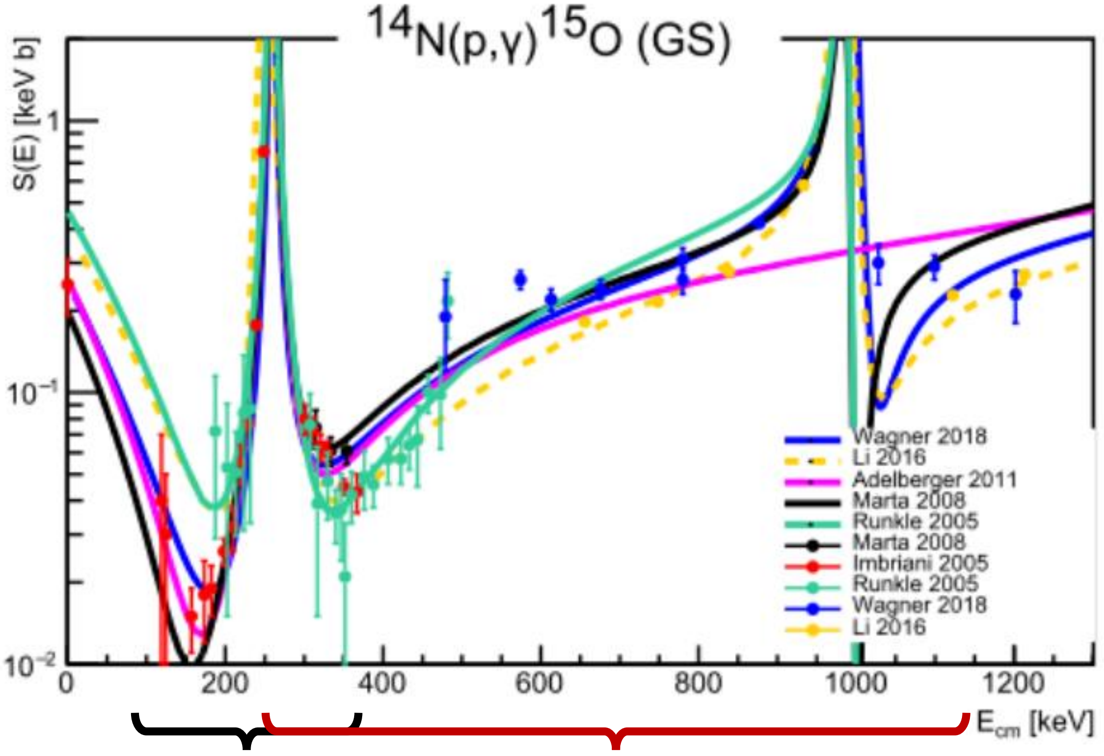
LUNA @ the new **IBF of LNGS** (2023-2024-????)

Measurements proposed to the PAC (Program Advisory Committee):

- $^{14}N(p,\gamma)^{15}O$ → approved and started → perfect as **commissioning measurement**
  - interesting science case
  - well known targets
  - well known resonance at low E
- $^{22}Ne(\alpha,n)^{25}Mg$ → approved and started → erc **SHADES** Scintillator-He3 Array for Deep-underground Experiments on the S-process
- $^{12}C+^{12}C$ → approved, starting soon → MUR Ministero dell'Università e della Ricerca **CaBS** Carbon Burning in Stars

$^{14}N(p,\gamma)^{15}O$: the bottleneck of the CNO cycle

$^{14}N(p,\gamma)^{15}O$: the bottleneck of the CNO cycle



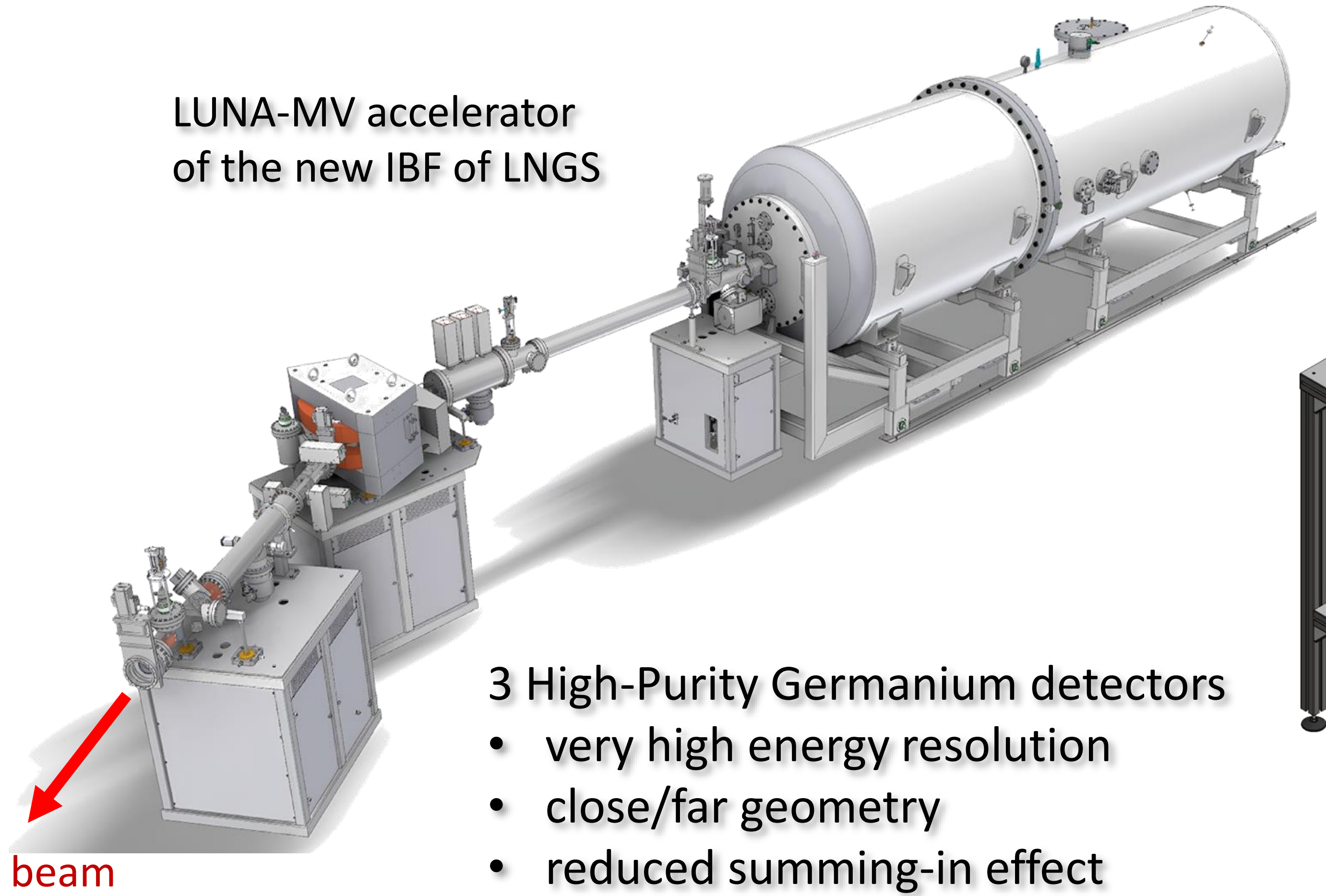
LUNA-400
70-370 keV

LUNA-MV
250-1 keV

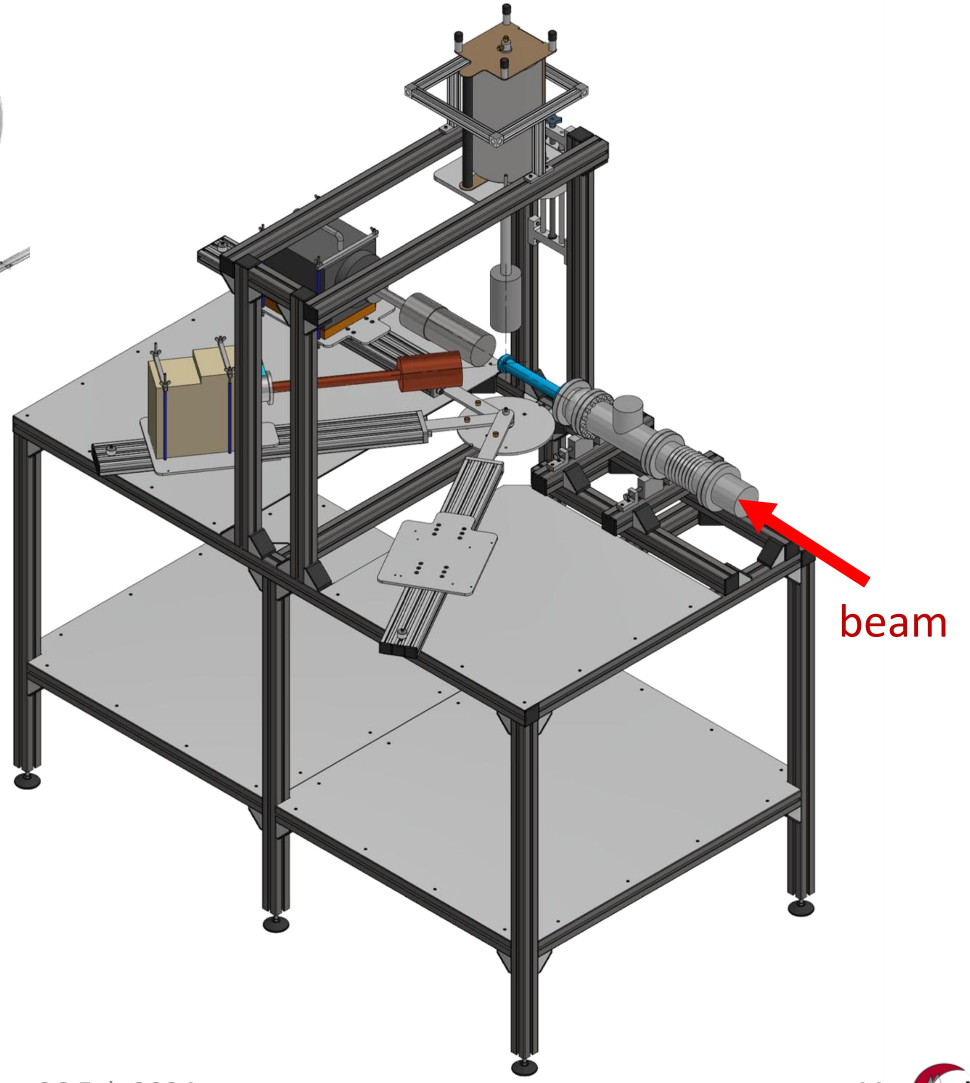
Goals of the high-energy experiment
- non-resonant component
- weak transitions (to ground state)
- summing-in corrections
- angular distribution

… all of this in a wide energy range!

$^{14}N(p,\gamma)^{15}O$: experimental setup @ Bellotti IBF



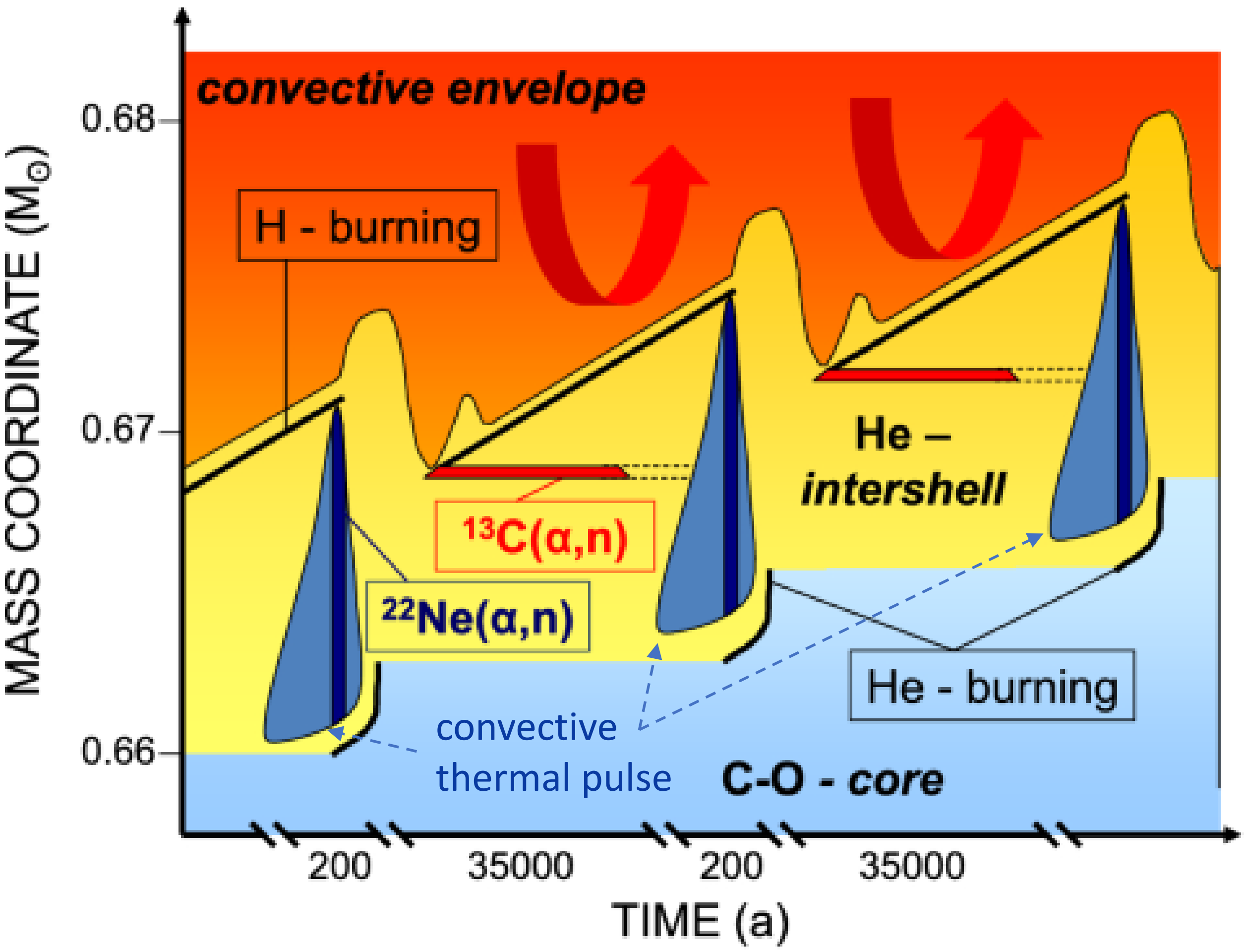
3 High-Purity Germanium detectors
- very high energy resolution
- close/far geometry
- reduced summing-in effect
- sensitivity to angular distribution




ICS
BERRA

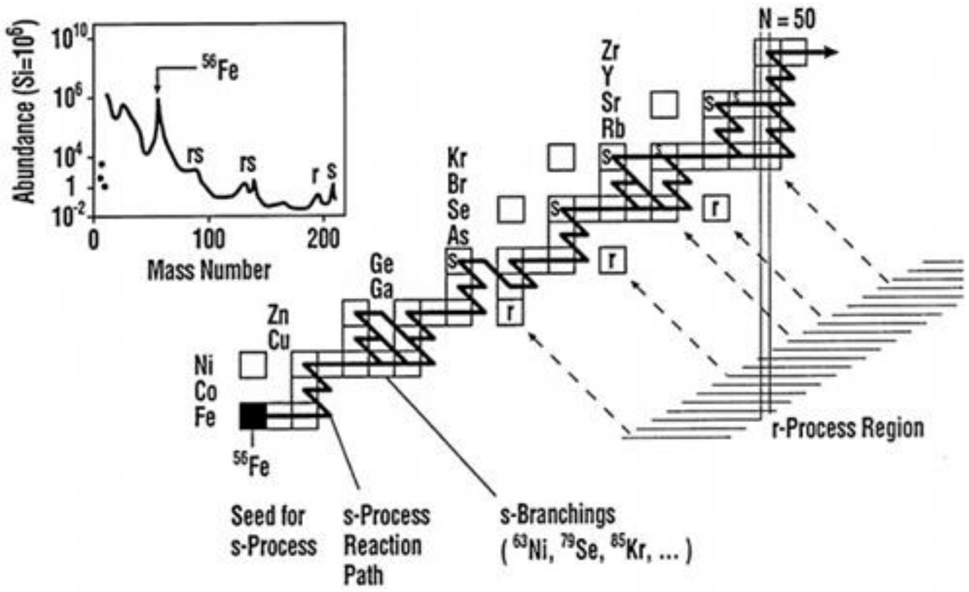
$^{22}Ne(\alpha,n)^{25}Mg$: neutron source for the s-process

^{22}Ne(α,n)^{25}Mg: neutron source for the s-process

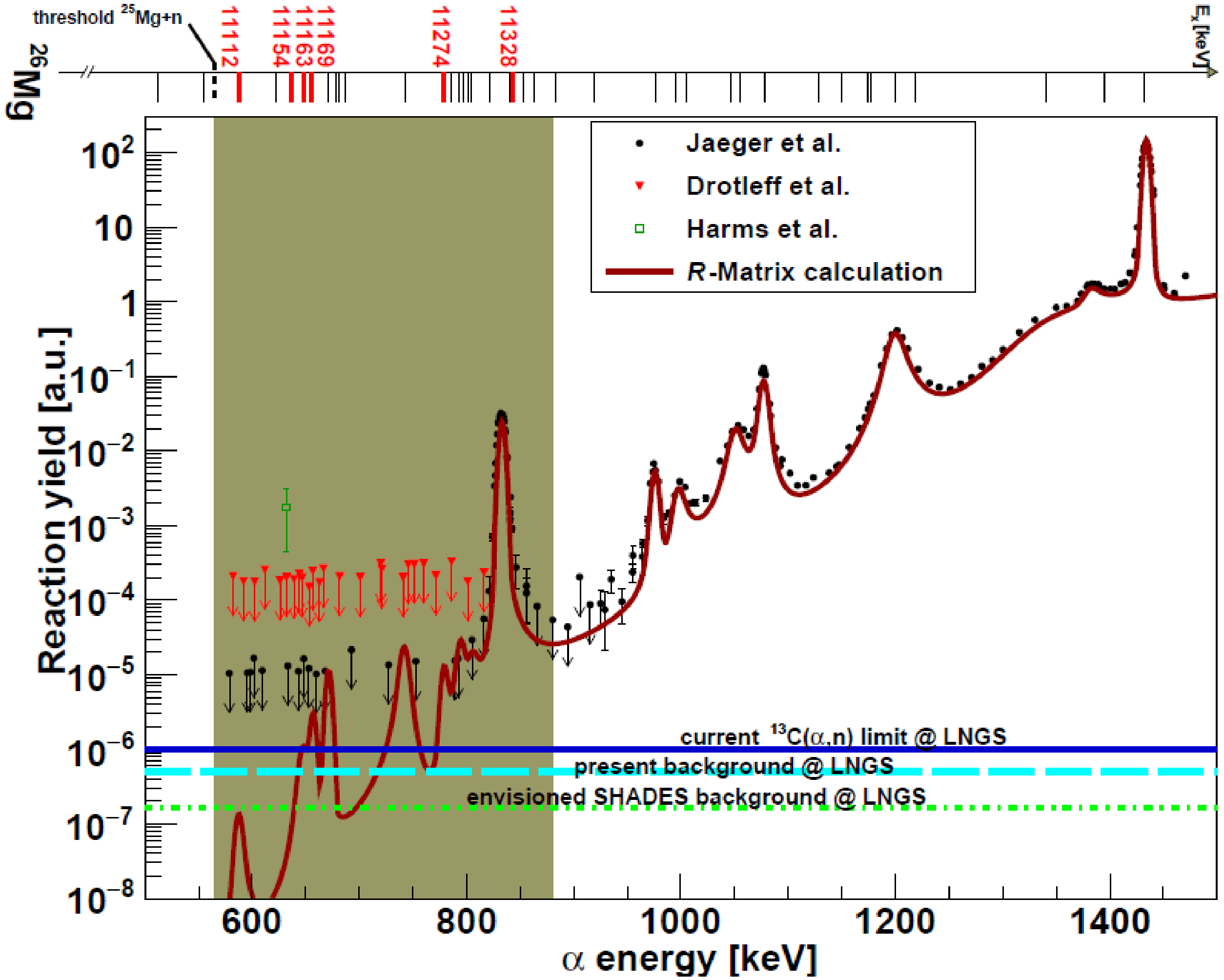


~ half the elements between Fe and Y (56≲A≲90) are produced via the weak s-process in massive stars (M > 8M$_{⊙}$)

^{22}Ne(α,n)^{25}Mg is a neutron source for the weak s-process



$^{22}Ne(\alpha,n)^{25}Mg$: need for data!



R matrix courtesy of R. J. deBoer, University of Notre Dame/JINA

Cross section is highly uncertain: no direct data in vast part of Gamow window!

Capabilities on surface labs exhausted (20 years since last direct measurement)

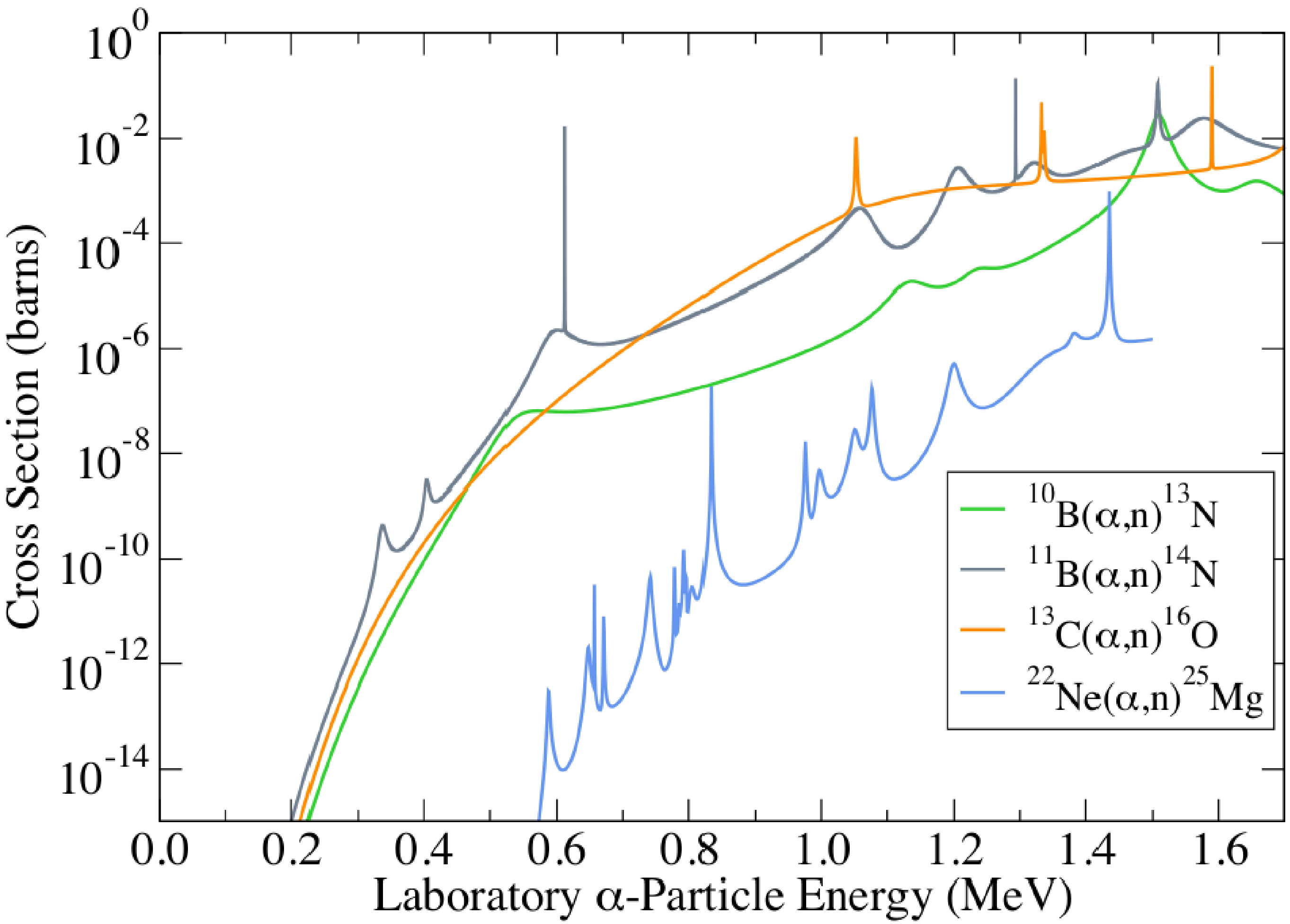
Current lowest rate: 2 reactions/minute

One resonance close to Gamow peak

upper limits spanning ≈ 300 keV

Many states can contribute to the cross section

$^{22}Ne(\alpha,n)^{25}Mg$: background



Q-values:

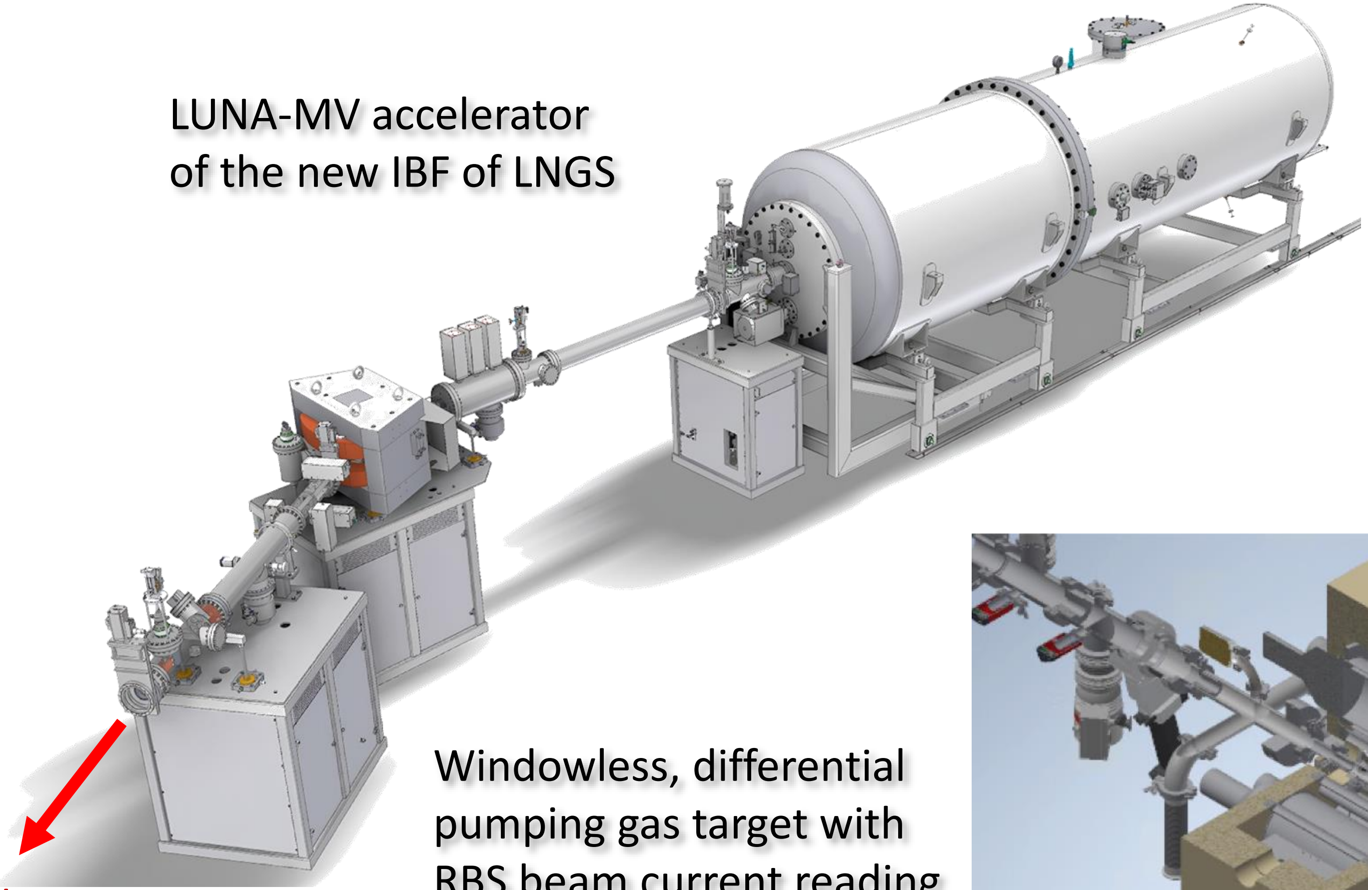
- **$^{22}Ne(\alpha,n)^{25}Mg$ = - 478 keV**
- $^{10}B(\alpha,n)^{13}N$ = 1059 keV
- $^{11}B(\alpha,n)^{14}N$ = 158 keV
- $^{13}C(\alpha,n)^{16}O$ = 2216 keV

To minimize the Beam-Induced background:

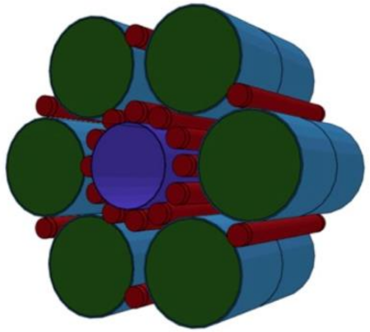
- ^{22}Ne gas target
- energy sensitivity (LS)

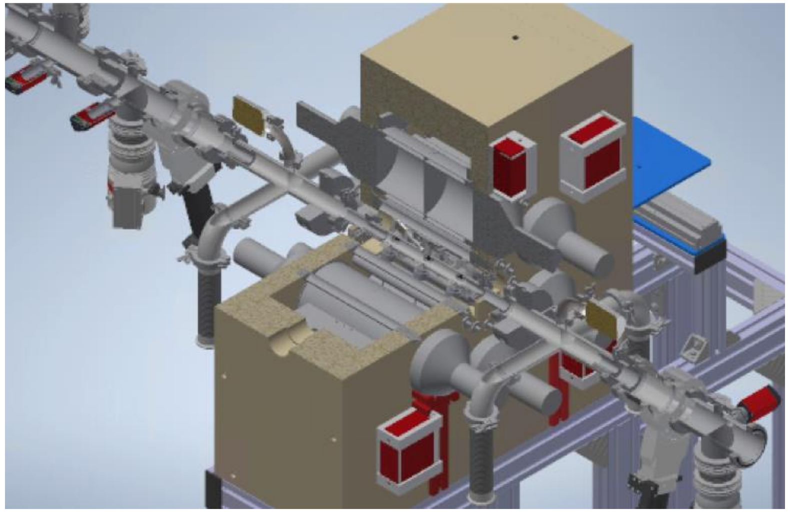
$^{22}Ne(\alpha,n)^{25}Mg$: experimental setup @ Bellotti IBF

LUNA-MV accelerator
of the new IBF of LNGS

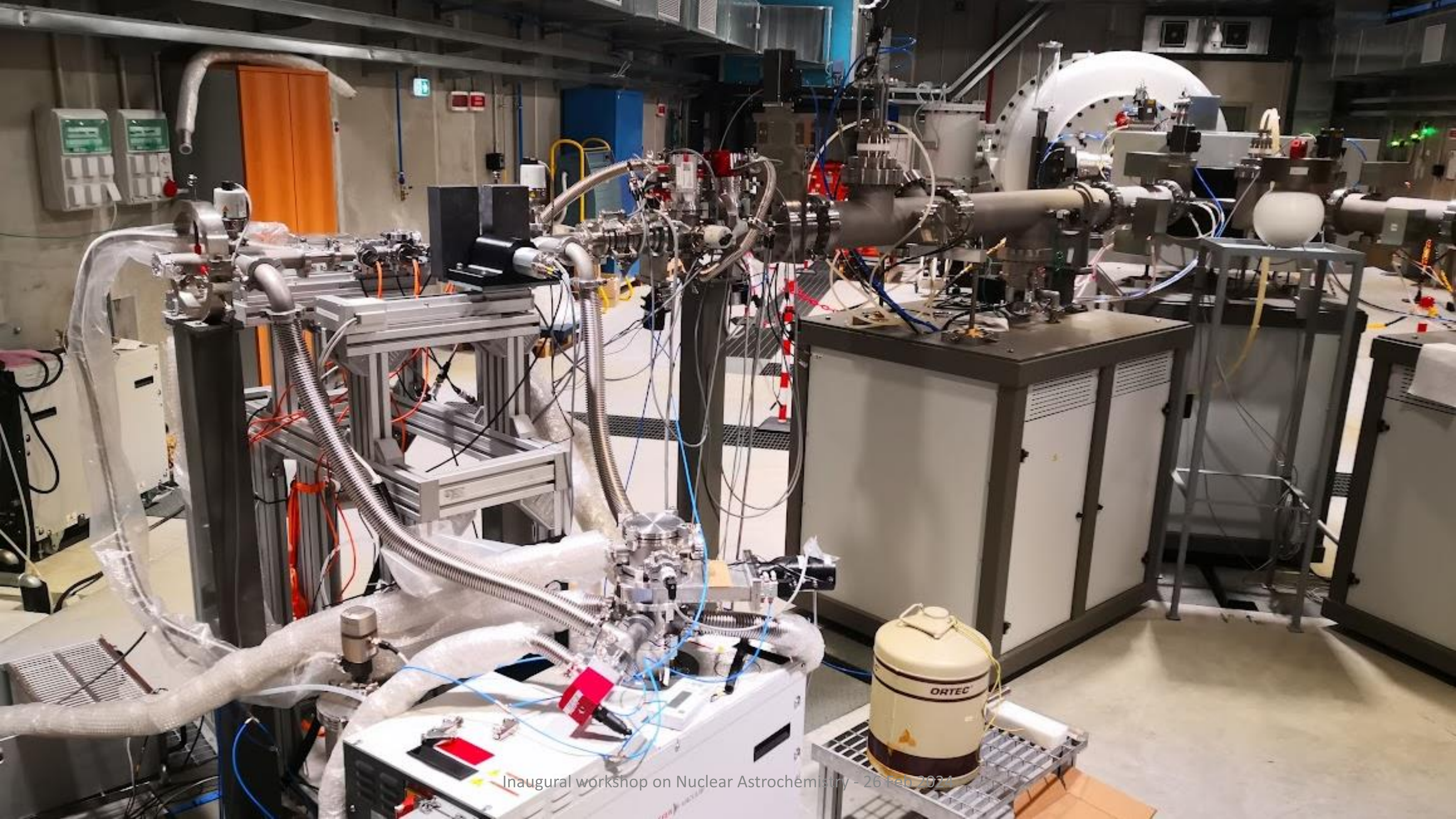


Windowless, differential
pumping gas target with
RBS beam current reading
high purity
high stability



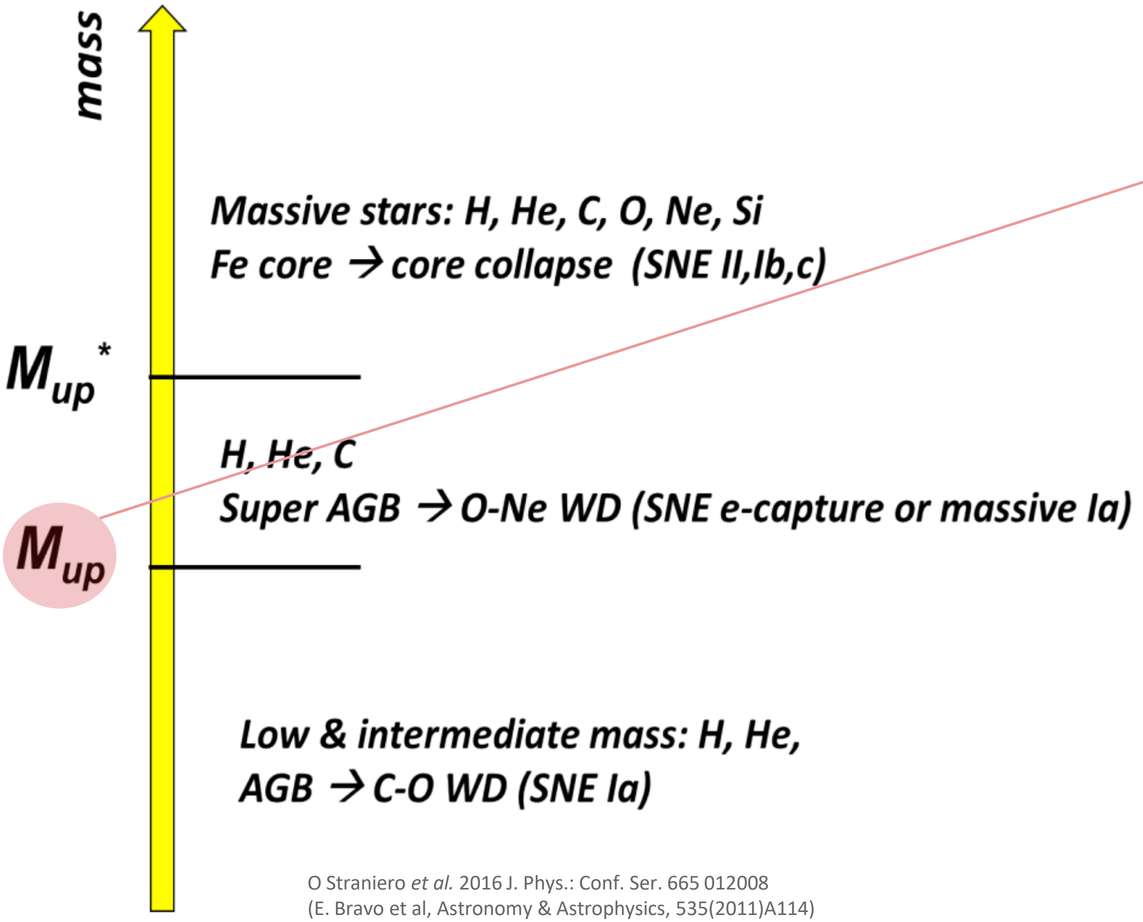


3He + LS neutron detector
- high neutron detection intrinsic efficiency
- large solid angle coverage


ORTEC

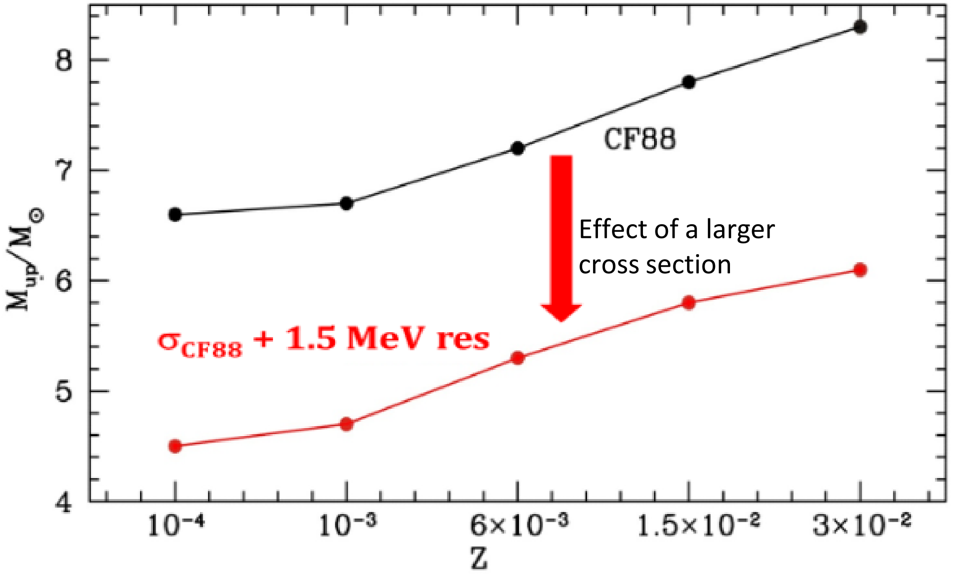
$^{12}C+^{12}C$: trigger of C burning in the stars

$^{12}C+^{12}C$: trigger of C burning in the stars



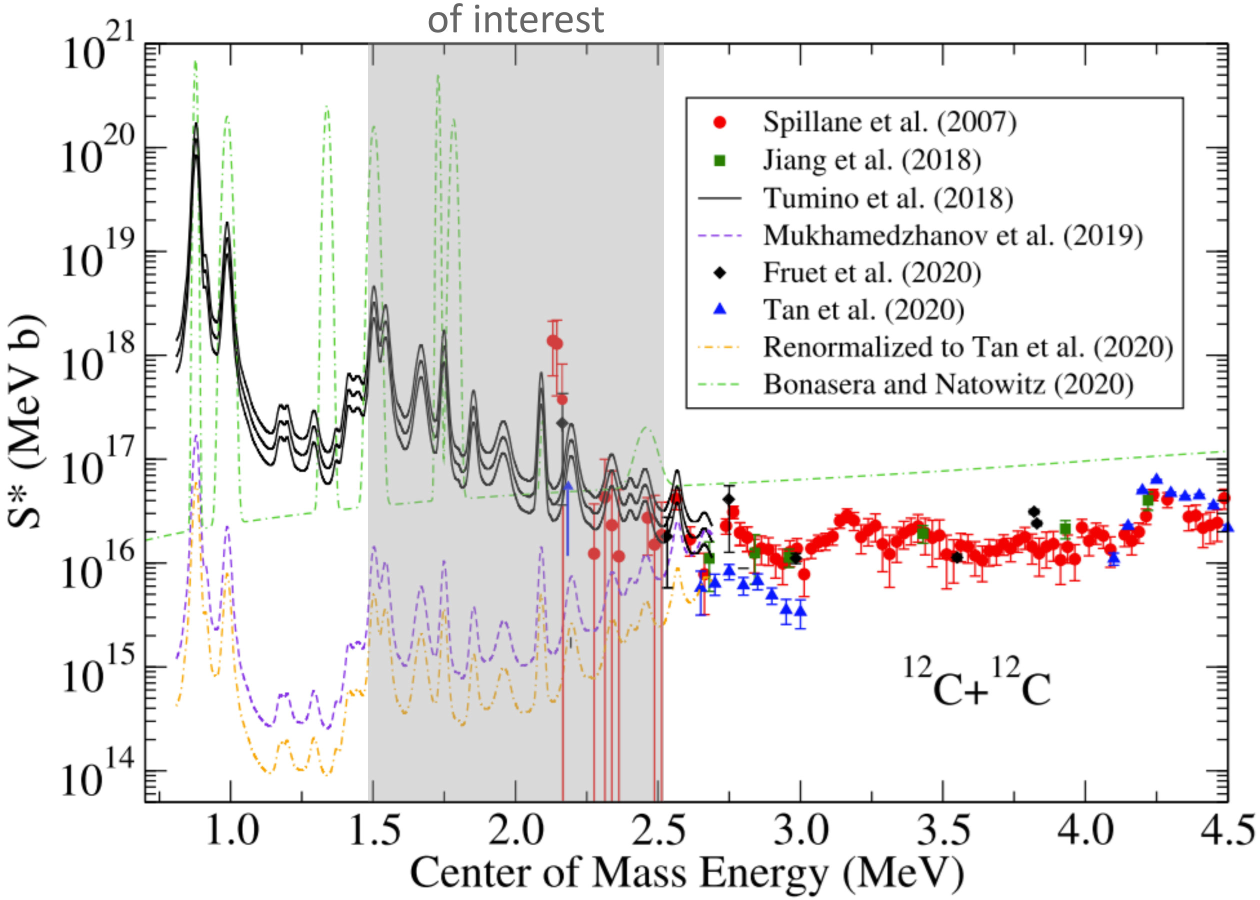
$M > M_{up}$	⇒	quiescent C burning (ONe-WD, CC-SN, NS, BH)
$M < M_{up}$	⇒	no C burning (CO-WD, Novae, **SN-Ia**)

O Straniero *et al.* 2016 J. Phys.: Conf. Ser. 665 012008
(E. Bravo et al, Astronomy & Astrophysics, 535(2011)A114)



$^{12}C+^{12}C$: need for data!

Energy range of interest



Several datasets and models exist

Direct measurements above 2.1 MeV (large scattering, large uncertainties)

Indirect measurements below 2.1 MeV (some criticism with normalization and the treatment of Coulomb interactions)

Very intersting to measure below 2.5 MeV (energy range of astrophysical interest)

$^{12}C+^{12}C$: experimental method

To measure the cross section it is possible to count emitted charged particles

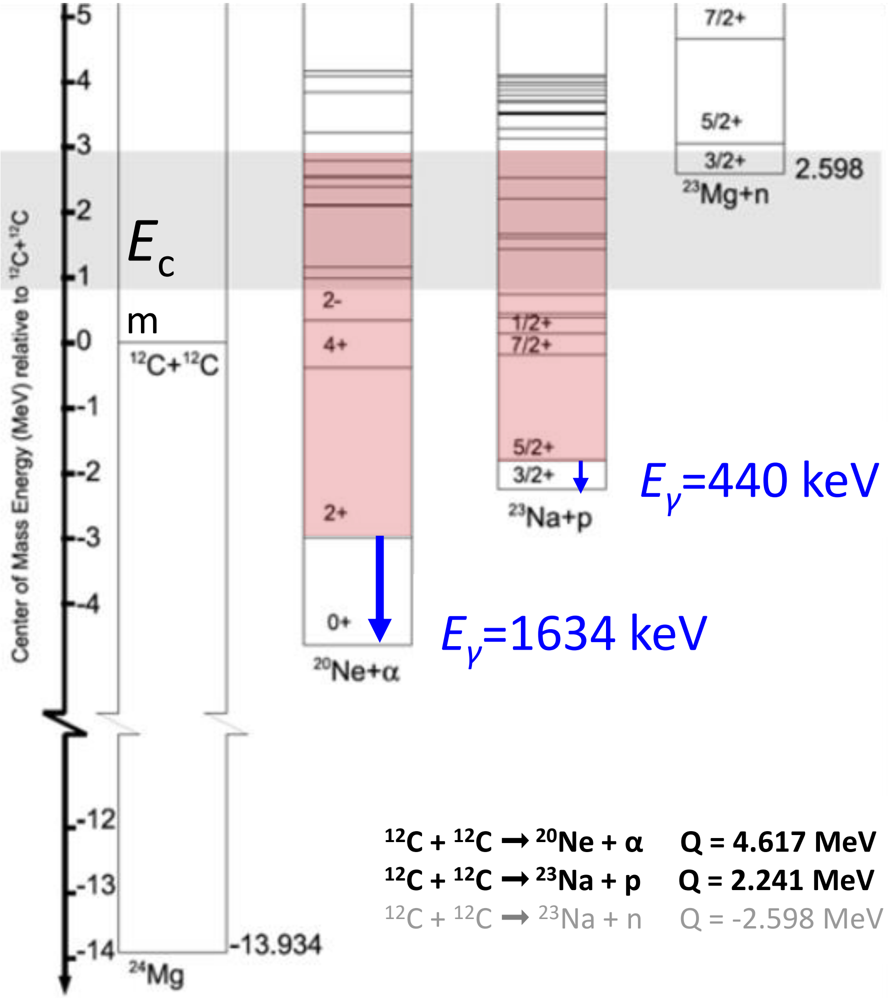
but

~50% of the reactions leave the final nucleus in an excited state

so

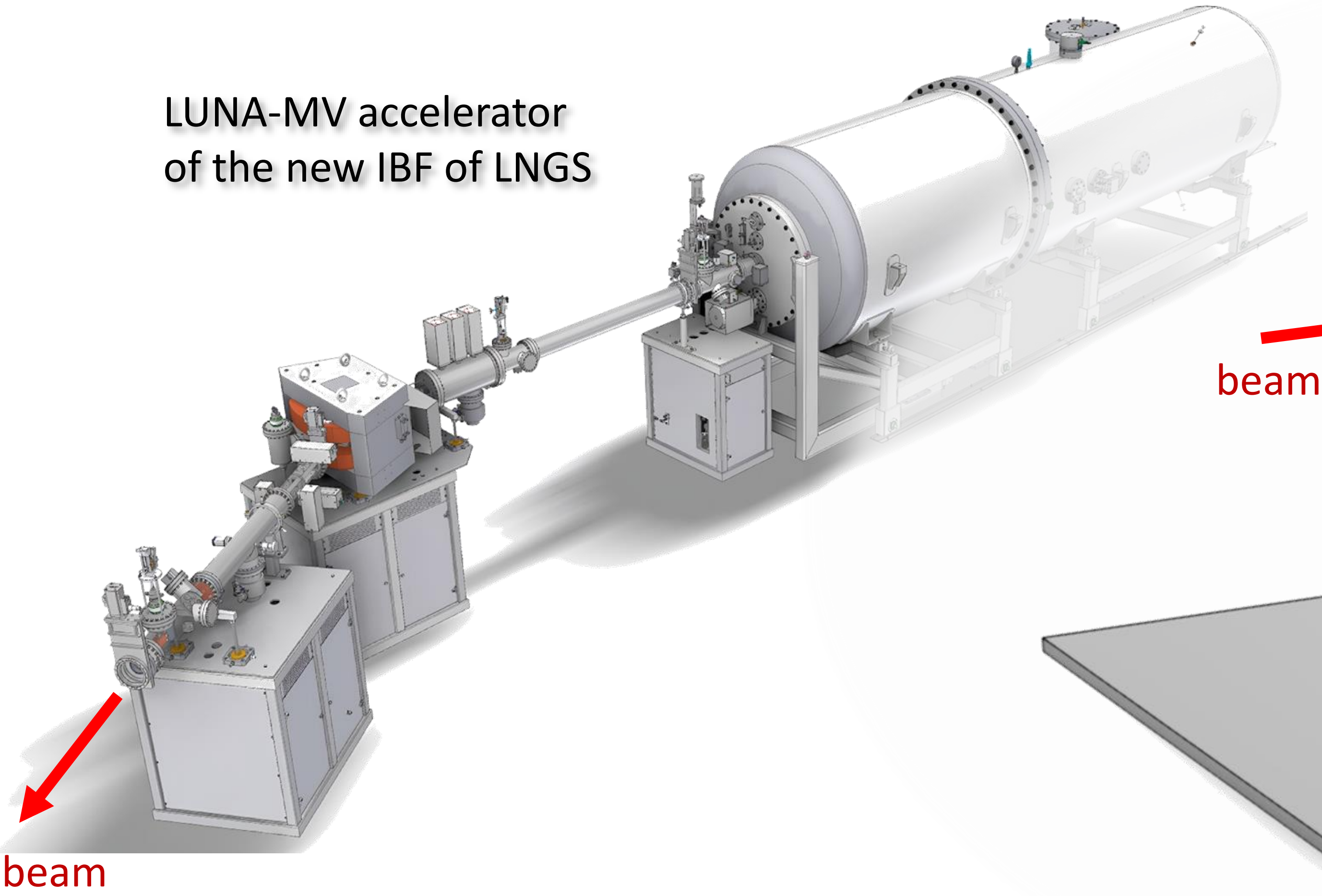
it is also possible to count photons emitted (isotropically) in the **de-excitation of the final nucleus**

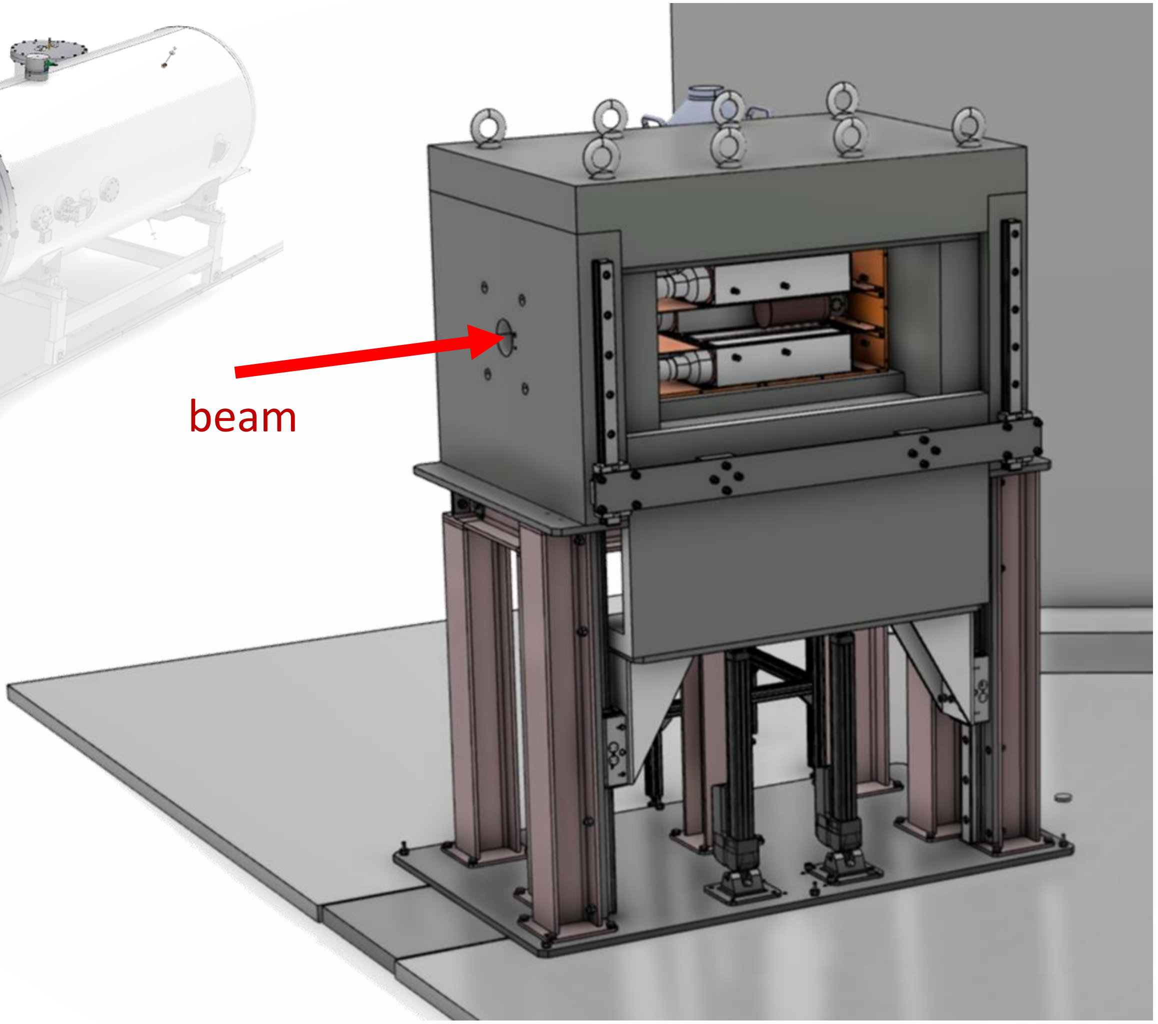
very often involves the **transitions from the 1st excited state to the GS**



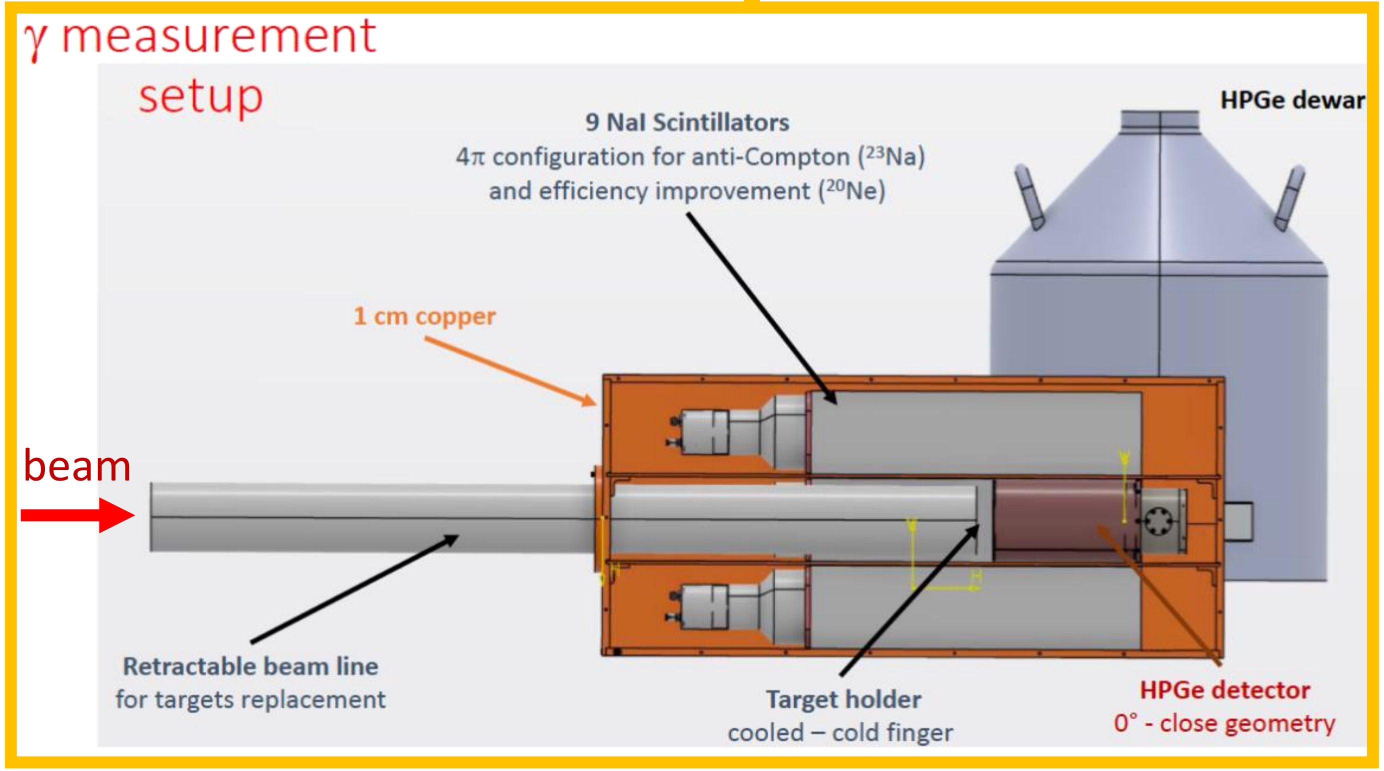
$^{12}C + ^{12}C \rightarrow ^{20}Ne + \alpha$ Q = 4.617 MeV
$^{12}C + ^{12}C \rightarrow ^{23}Na + p$ Q = 2.241 MeV
$^{12}C + ^{12}C \rightarrow ^{23}Na + n$ Q = -2.598 MeV

$^{12}C+^{12}C$: experimental setup @ Bellotti IBF



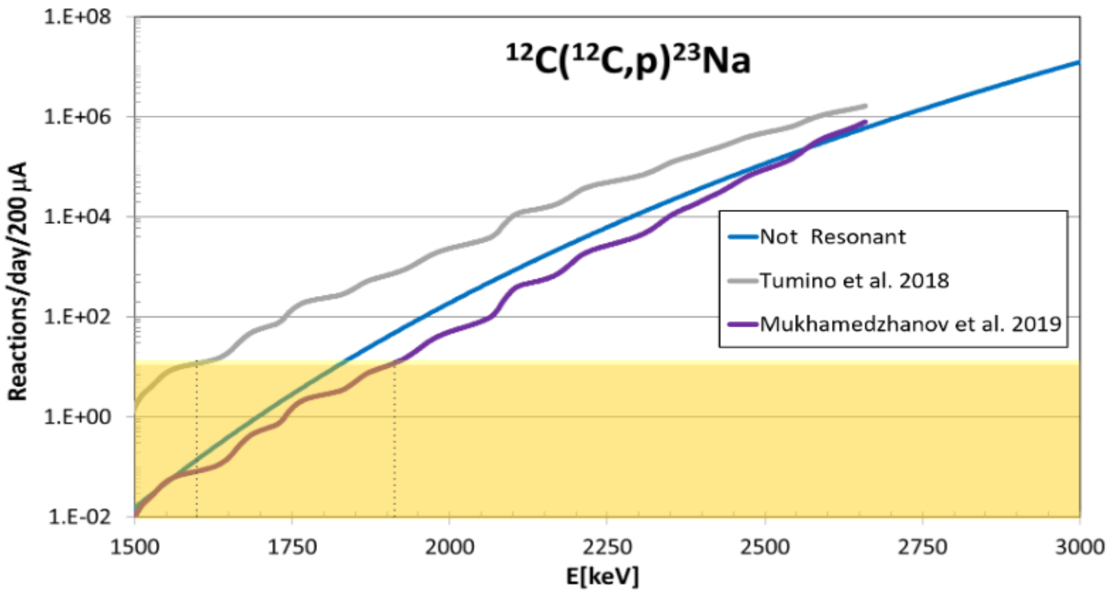


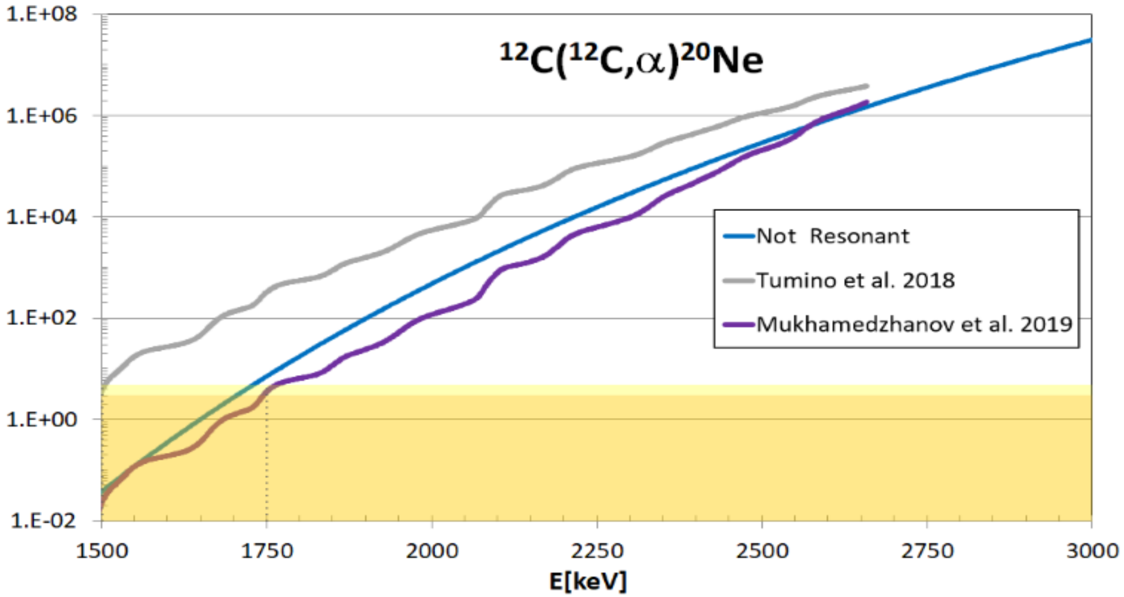
$^{12}C+^{12}C$: experimental setup @ Bellotti IBF



$^{12}C+^{12}C$: expected sensitivity

Minimum daily reaction rate to reach 50% statistical uncertainty considering detection efficiency, beam current (100 pμA) and data taking time (120 days)	
$^{12}C + ^{12}C \rightarrow ^{23}Na + p$ E_γ=440 keV	**$^{12}C + ^{12}C \rightarrow ^{20}Ne + \alpha$** E_γ=1634 keV
11 reactions/day	**3** reactions/day





H burning
He burning

C burning
BBN

n sources

Present and future measurements

	0-3 years	3-5 years	5-7 years
400 kV	$^{23}Na(p,\alpha)^{20}Ne$	$^{19}F(p,\alpha)^{16}O$	$^{6}Li(\alpha,\gamma)^{10}B$
	$^{27}Al(p,\alpha)^{24}Mg$	$^{19}F(p,\gamma)^{20}Ne$	$^{7}Li(\alpha,\gamma)^{11}B$
	$^{14}N(p,\gamma)^{15}O$	$^{30}Si(p,\gamma)^{31}P$	$^{10}B(\alpha,{}^{2}H)^{12}C$
			$^{10}B(\alpha,p)^{13}C$
			$^{10}B(\alpha,n)^{13}N$
			$^{11}B(\alpha,n)^{14}N$
3.5MV	$^{14}N(p,\gamma)^{15}O$	$^{18}O(\alpha,\gamma)^{22}Ne$	$^{2}H(p,\gamma)^{3}He$
	$^{22}Ne(\alpha,n)^{25}Mg$	$^{17}O(\alpha,\gamma)^{21}Ne$	$^{2}H(\alpha,\gamma)^{6}Li$
	$^{12}C+^{12}C$ (gammas)	$^{15}N(\alpha,\gamma)^{19}F$	$^{3}He(\alpha,\gamma)^{7}Be$
	$^{13}C(\alpha,n)^{16}O$	$^{14}N(\alpha,\gamma)^{18}F$	$^{12}C(\alpha,\gamma)^{16}O$
		$^{22}Ne(\alpha,\gamma)^{26}Mg$	$^{12}C+^{12}C$ (particles)

Conclusions

- LUNA has pioneered underground studies in Nuclear Astrophysics for over three decades
- The LUNA underground accelerator allowed direct measurements at the lowest possible energies (Hydrogen Burning, Big Bang Nucleosynthesis, s-process)
- Interesting measurements soon to be performed at the new IBF of the LNGS (s-process, Hydrogen burning, Helium burning, Carbon burning)
- (Session on Nuclear Astrophysics Tuesday afternoon)

LUNA
Laboratory for Underground Nuclear Astrophysics

Thank you for your attention!

Other slides

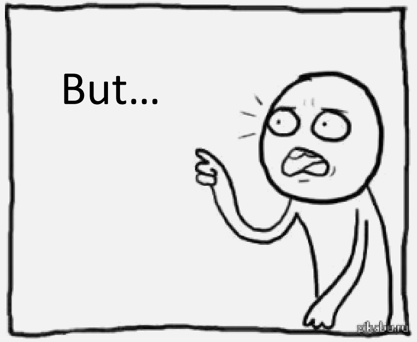
Challenges in Nuclear Astrophysics

Below a certain energy, the counting rate is too low and the cosmic-ray induced background prevents the direct measurement of the cross section

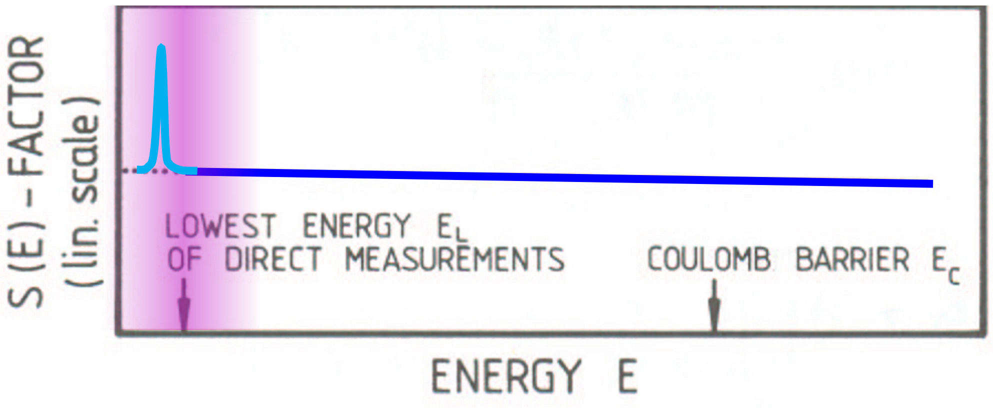
introducing the **astrophysical S-factor S(E)** and factorizing the **Coulomb interaction term** apart:

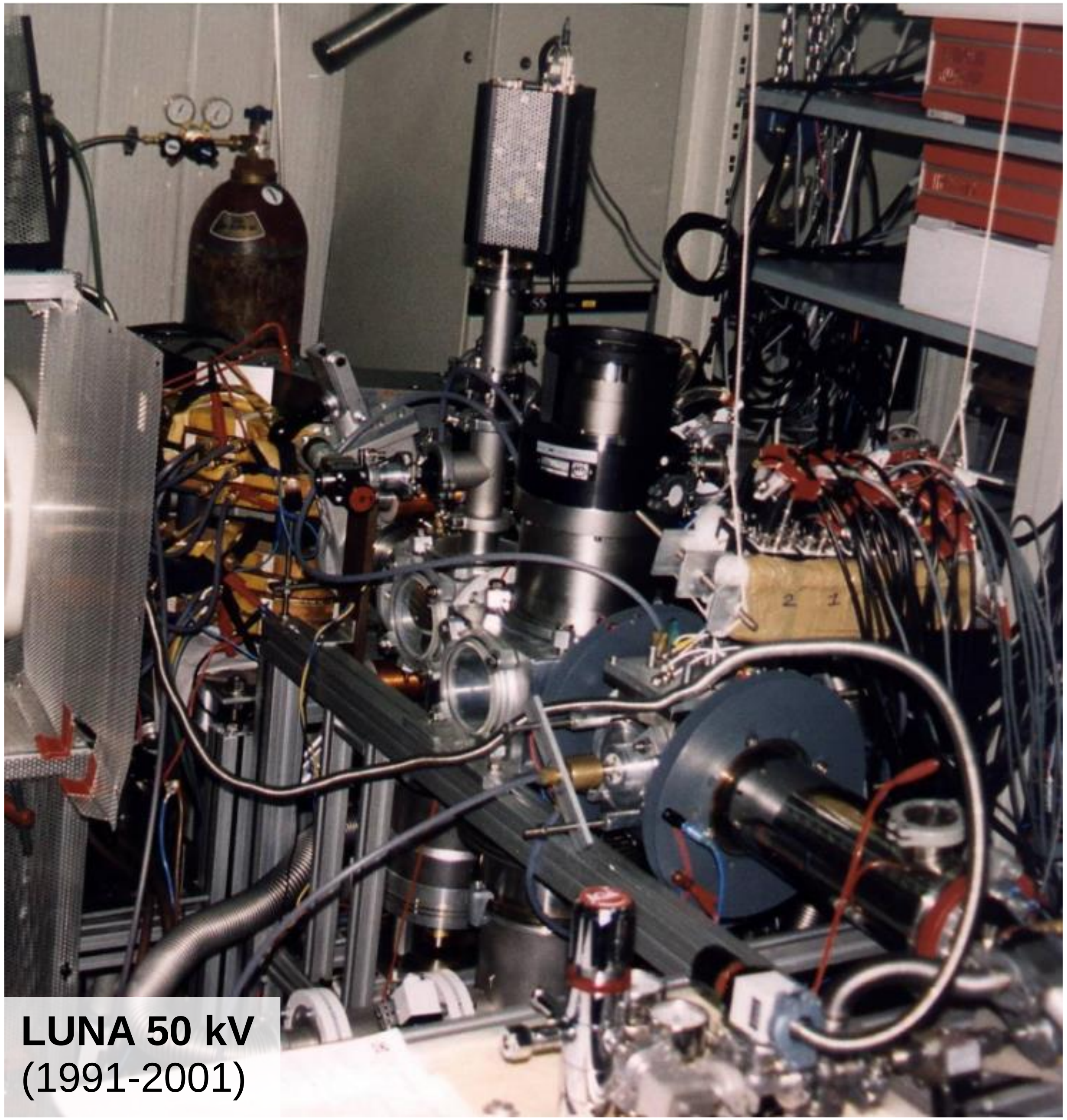
$$\sigma(E) = \frac{1}{E} e^{-2\pi\eta} S(E)$$

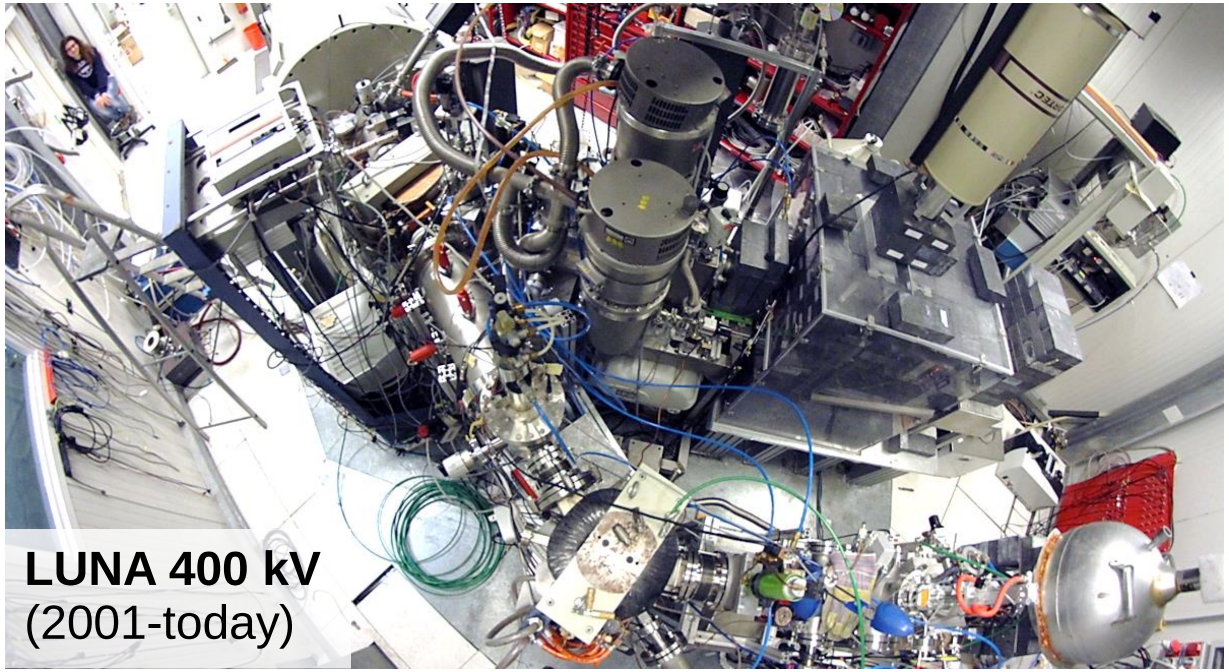
it is possible to measure the cross section at high energy and extrapolate the astrophysical factor *S(E)* in the interesting energy range (Gamow window)



unexpected low-energy resonances may be present in the extrapolation region!

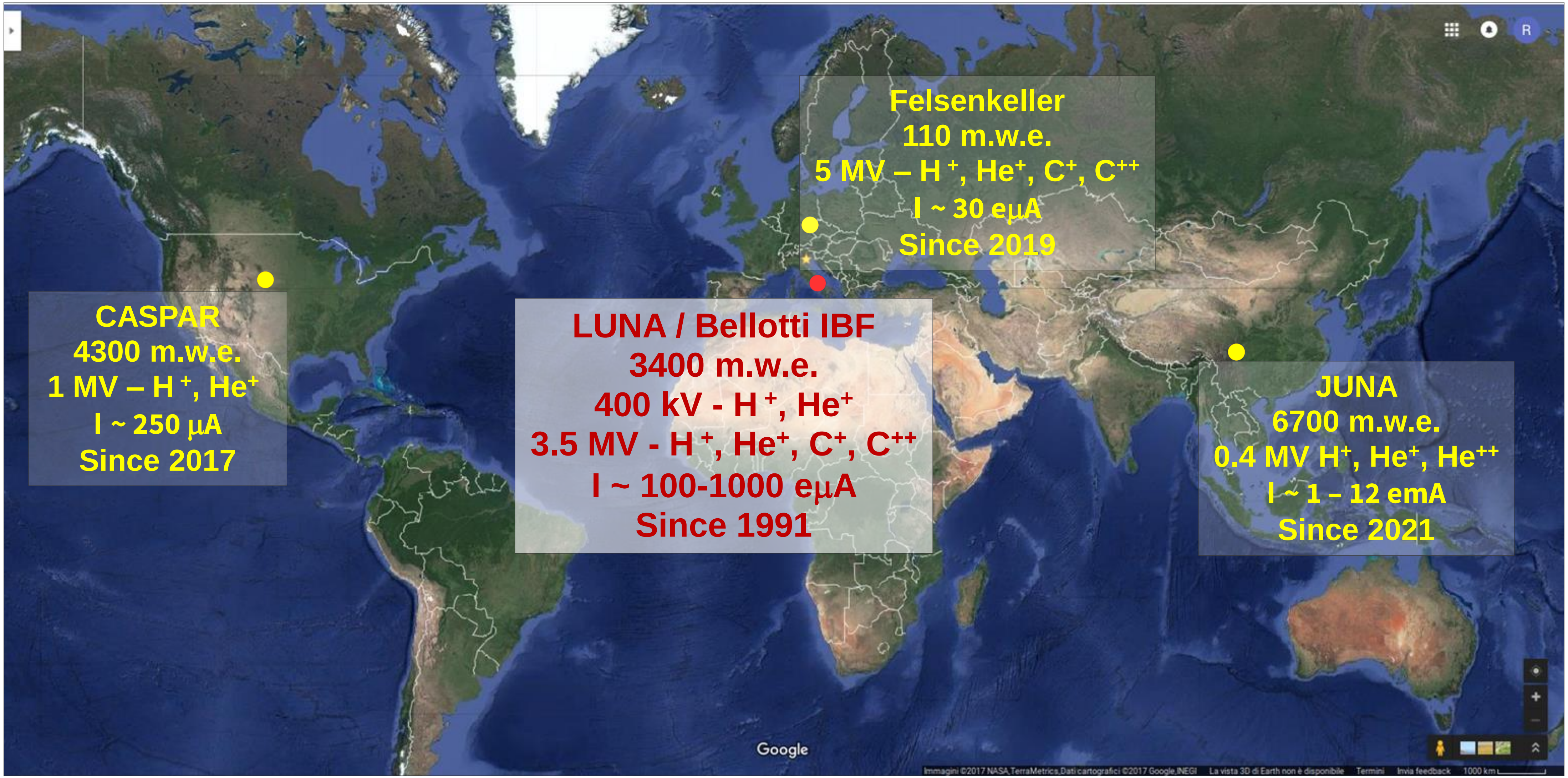



LUNA 50 kV
(1991-2001)


LUNA 400 kV
(2001-today)

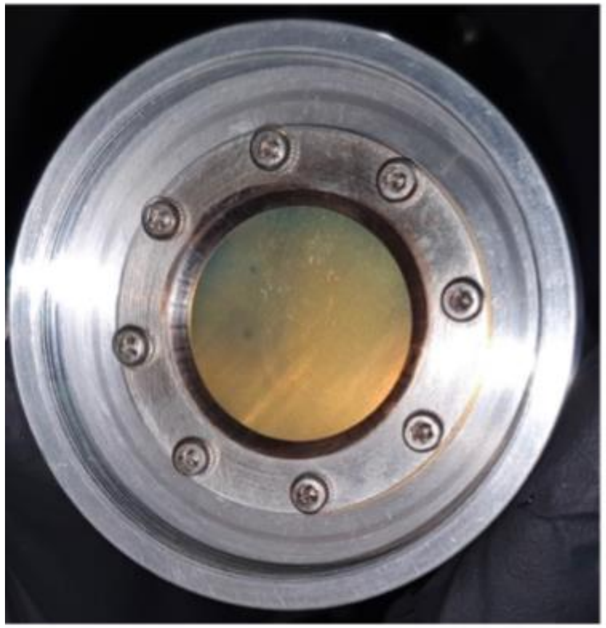

LUNA-MV @ Bellotti IBF
(today-????)

Underground laboratories for Nuclear Astrophysics

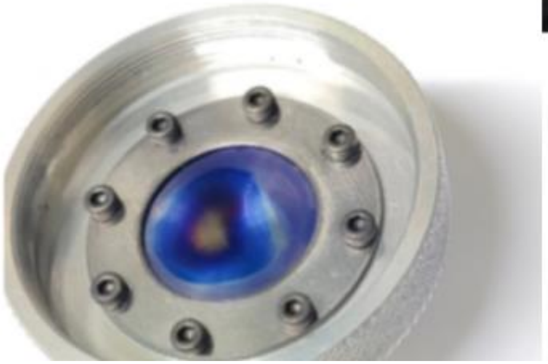


2 NaNbO sputtered targets from Legnaro
(unknown stoichiometry)

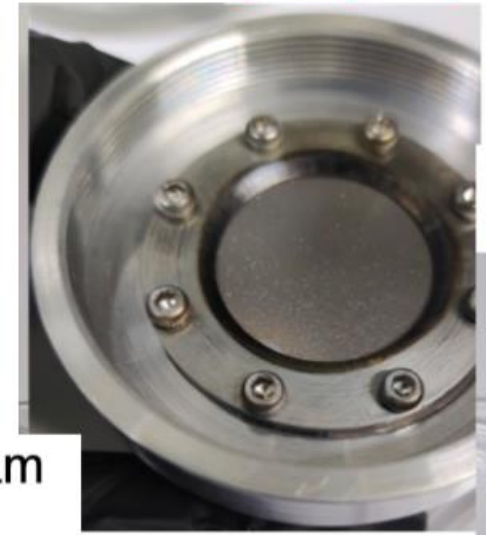
Before beam



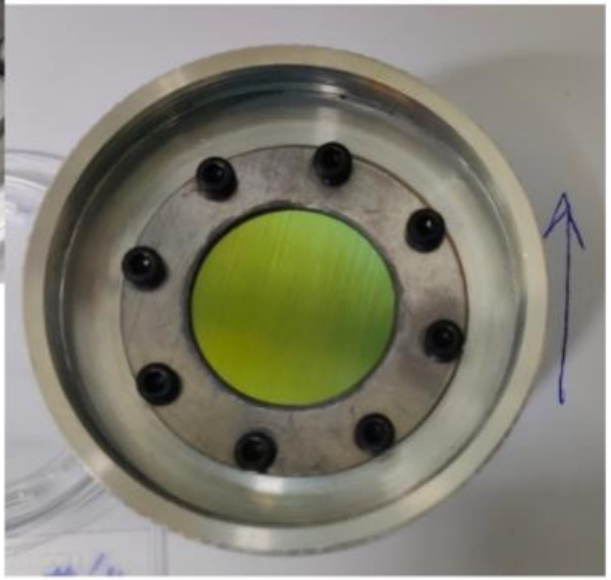
After beam



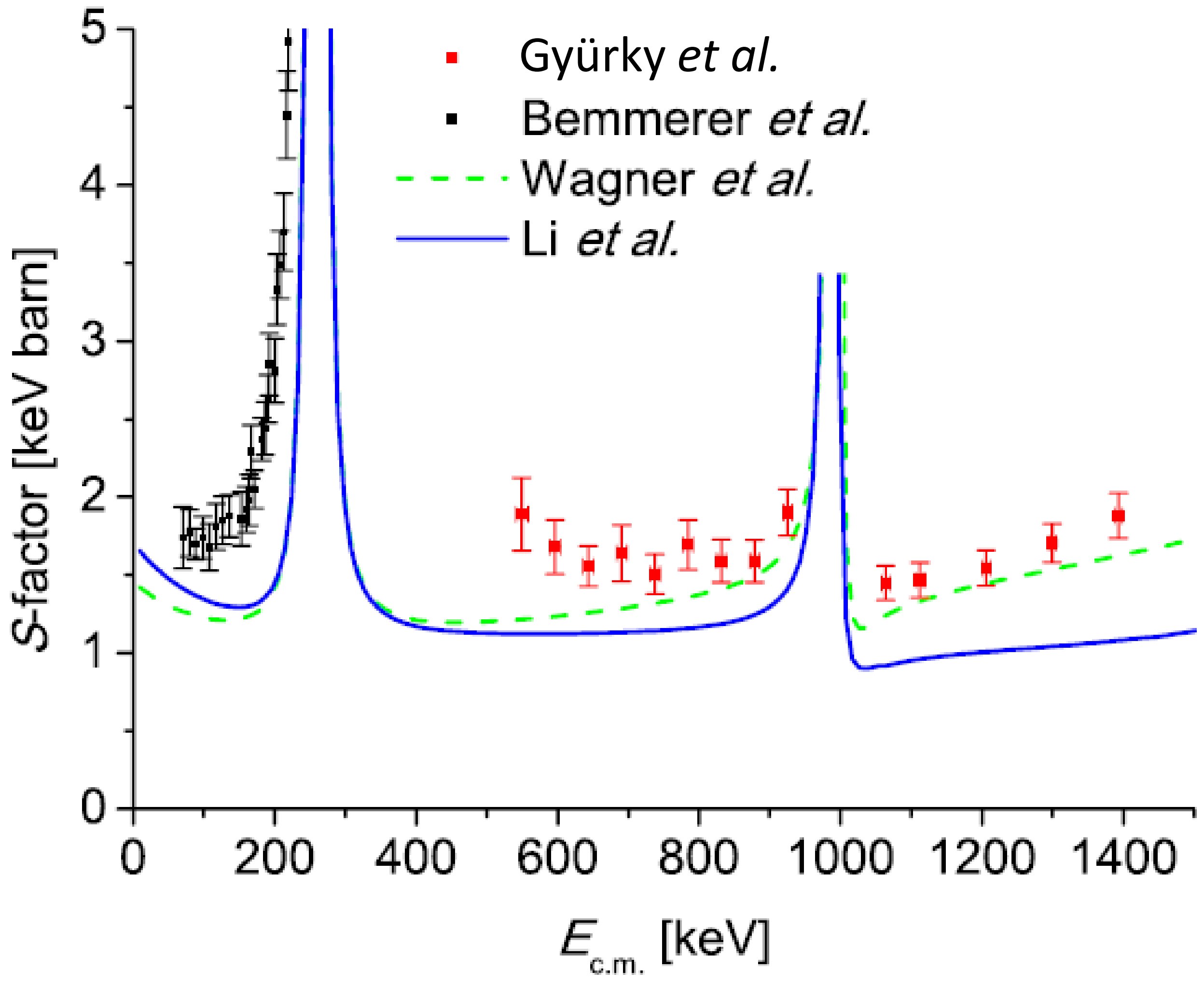
3 Na_2WO_4 evaporated targets from Atomki



Before beam



$^{14}N(p,\gamma)^{15}O$: the bottleneck of the CNO cycle



To be investigated:

- non-resonant component
- weak transitions (to ground state)
- summing-in corrections
- angular distribution

… all of this in a wide energy range!