The n_TOF Collaboration, www.cern.ch/n_TOF

From n_TOF to Gamma-Factory, Nuclear Astrophysics challenging experimental approaches @ CERN

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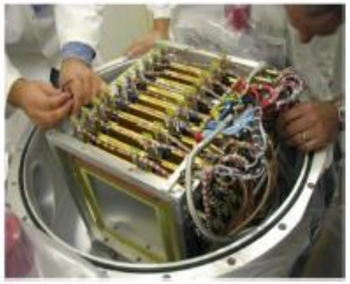
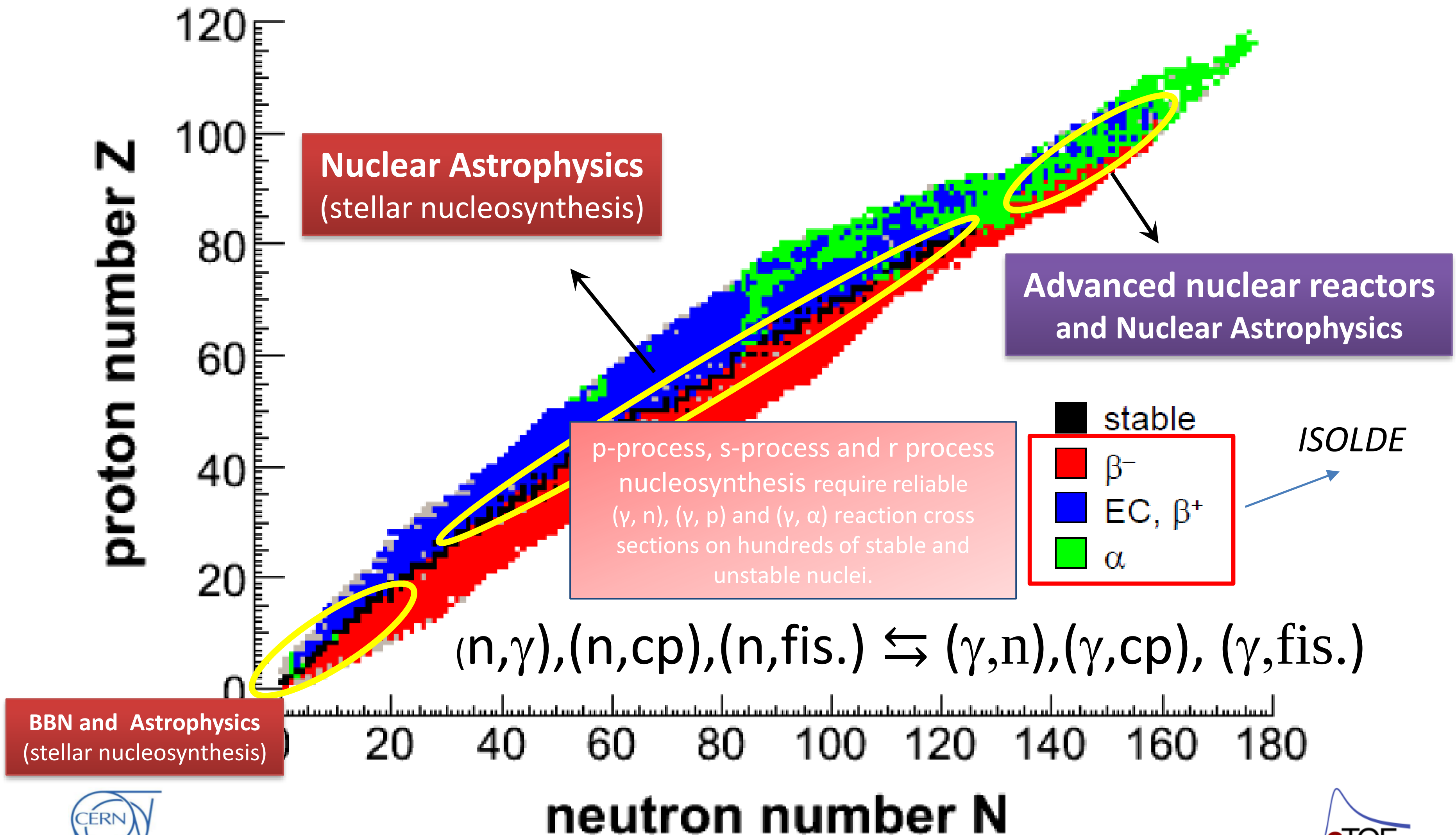


Neutron (Gamma) cross-section measurements



Gamma Factory fully synergize with n_TOF and ISOLDE in all the environments !

Consequently many physics cases have been described in white books/reports

The White Book of ELI Nuclear Physics
Bucharest-Magurele, Romania

The ELI-Nuclear Physics working groups

extreme light infrastructure

https://www.eli-np.ro/whitebook.php

ELSEVIER

Progress in Particle and Nuclear Physics
Volume 122, January 2022, 103903

Review

Photonuclear reactions—From basic research to applications

A. Zilges [a], D.L. Balabanski [b], J. Isaak [c], N. Pietralla [c]

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IOP Publishing
Journal of Physics G: Nuclear and Particle Physics
J. Phys. G: Nucl. Part. Phys. **49** (2022) 010502 (96pp)
https://doi.org/10.1088/1361-6471/ac2827

Major Report

International workshop on next generation gamma-ray source

C R Howell[1,2], M W Ahmed[2,3,*], A Afanasev[4], D Alesini[5], J R M Annand[6], A Aprahamian[7], D L Balabanski[8], S V Benson[9], A Bernstein[10], C R Brune[11], J Byrd[12], B E Carlsten[13], A E Champagne[2,14], S Chattopadhyay[15], D Davis[2,16], E J Downie[4], J M Durham[13], G Feldman[4], H Gao[1,2], C G R Geddes[17], H W Grießhammer[4], R Hajima[18], H Hao[1,2], D Hornidge[19], J Isaak[20], R V F Janssens[2,14], D P Kendellen[1,2], M A Kovash[21], P P Martel[22], U-G Meißner[23], R Miskimen[24], B Pasquini[25], D R Phillips[11], N Pietralla[20], D Savran[26], M R Schindler[27], M H Sikora[2,4], W M Snow[28], R P Springer[1], C Sun[17], C Tang[29], B Tiburzi[30], A P Tonchev[31], W Tornow[3,18], C A Ur[8], D Wang[32], H R Weller[1,2], V Werner[20], Y K Wu[1,2], J Yan[1,2], Z Zhao[33], A Zilges[34] and F Zomer[35]

The *Cosmological Lithium Problem* and the Measurement of the ^{7}*Be(n,alpha)* Reaction at *n_TOF*-CERN.

Agatino Musumarra and Massimo Barbagallo

for the n_TOF@CERN Collaboration

DFA-University of Catania, INFN-Laboratori Nazionali del Sud
INFN-Bari

Looking for an «*unique*» experiment at CERN

Bing Bang Nucleosynthesis

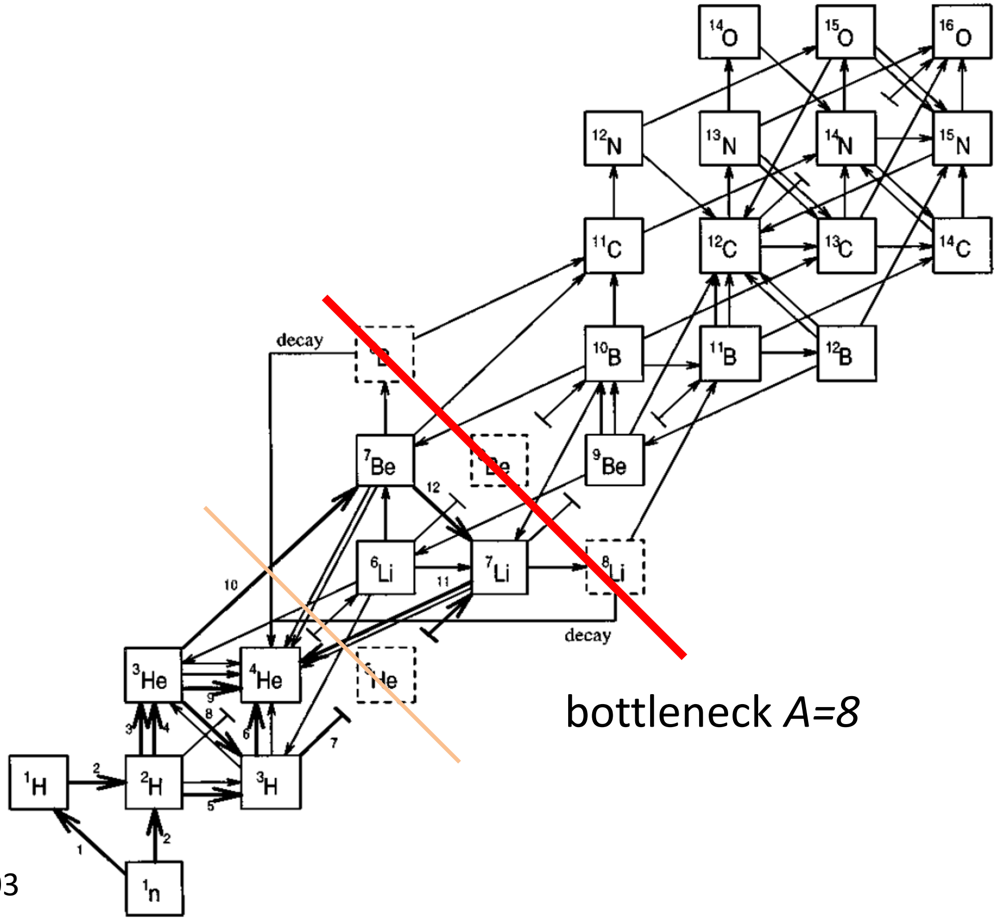
Bing Bang Nucleosynthesis (BBN), together with Hubble expansion and Cosmic Microwave Background Radiation is one of the cornerstones for Bing Bang Theory.

BBN gives the sequence of nuclear reactions leading to the synthesis of light elements up to Na* in the early stage of Universe (0.01-1000 sec)

At his first formulation, it depended on 3 parameters:

- -the baryon-to-photon ratio **η**,
- -the number of species of neutrino **ν**,
- -the lifetime of neutron **τ**.

Nowadays **BBN is a parameter free theory****, being the **cross-sections** of reactions involved the only input to the theory.



* A.Coc et al., The Astrophysical Journal, 744:158 (2012)

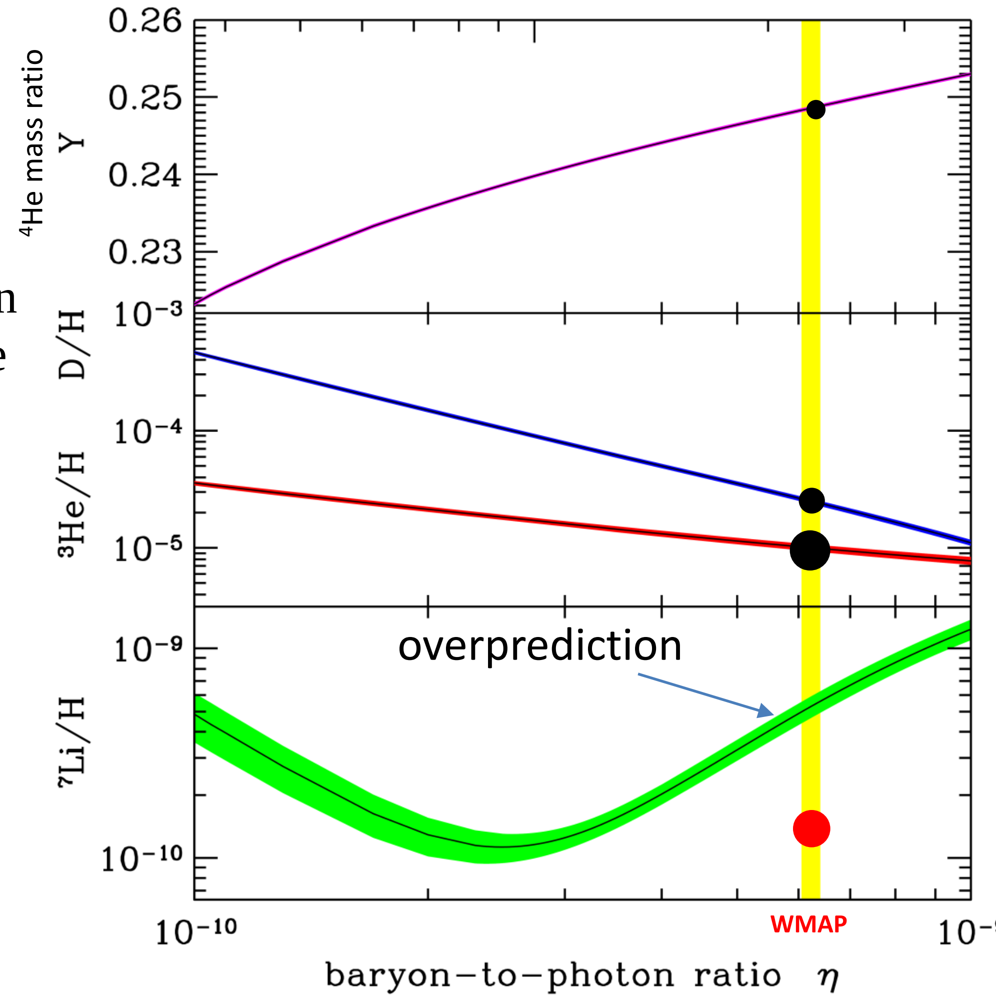
**D.N. Schramm and T.S Turner, Rev. Mod. Phys 70 (1998) 303

The Cosmological Lithium Problem

BBN successfully predicts the abundances of primordial elements such as ^{4}He, D and ^{3}He.

A serious discrepancy (factor 2-4) between the predicted abundance of **^{7}Li** and the value inferred by measurements (Spite et al, many others.)

Cosmological Lithium Problem (CLiP)



* R.H.Cyburt et al., Journal of Cosmology and Astroparticle Physics 11 (2008) 012
** A.Coc et al., The Astrophysical Journal, 744:158 (2012)

Solution to CLiP?

Approximately 95% of primordial ^{7}**Li** is produced from the Electron Capture *decay* of ***^{7}Be*** (*$T_{1/2}$=53.2 d ?*).

A higher destruction rate of ^{7}Be can solve or at least partially explain the **CLiP.**

as fas as we know ^{7}Be is destroyed via **(n,p)** **(~97%)** and **(n,α)** **(~2.5%)** reactions

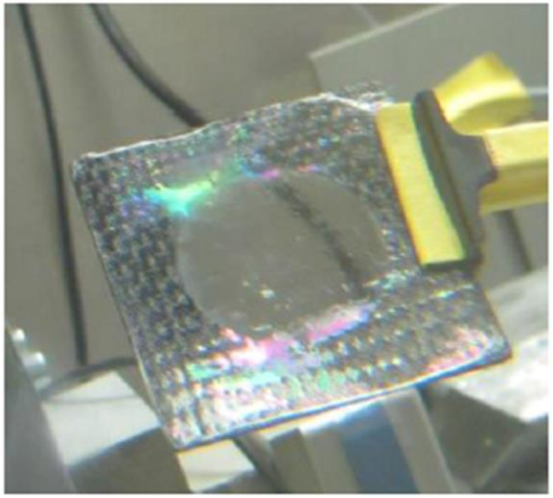
$n + {}^{7}Be \longrightarrow p + {}^{7}Li$ Q= 1.644 MeV

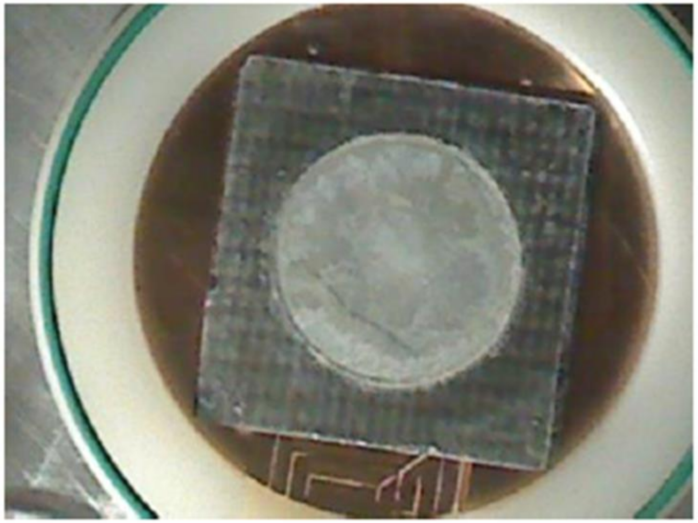
$n + {}^{7}Be \longrightarrow \alpha + \alpha$ Q= 19 MeV

^{7}Be available at PSI-Zurich !

2 different samples: Molecular plating
(3.5 μg total mass) Vaporization of droplets

	Vaporization	Molecular Plating
Backing	Stretched PE (0.6 μm)	Aluminum (5 μm)
Activity	20 GBq	19 GBq
Diameter	30 mm	31.6 mm





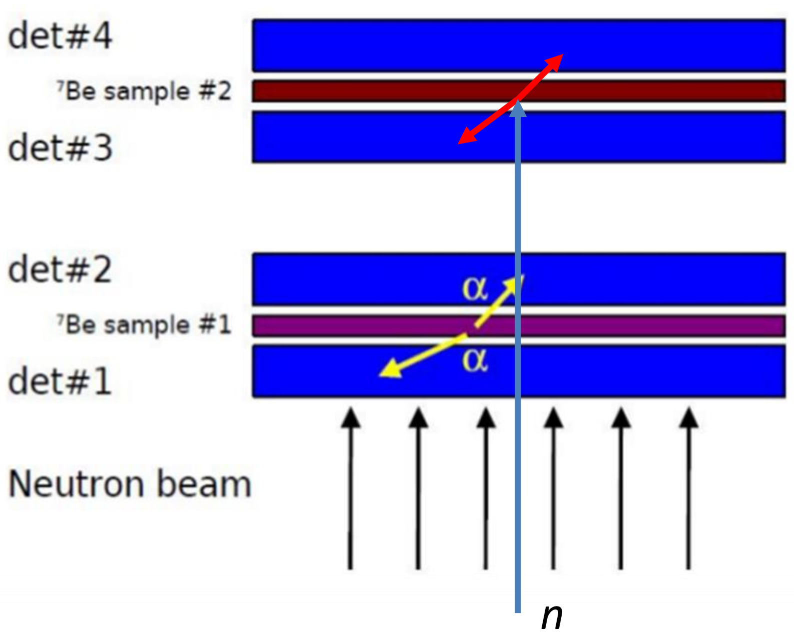
Thanks to E. Maugeri, D. Schumann (PSI Villigen)

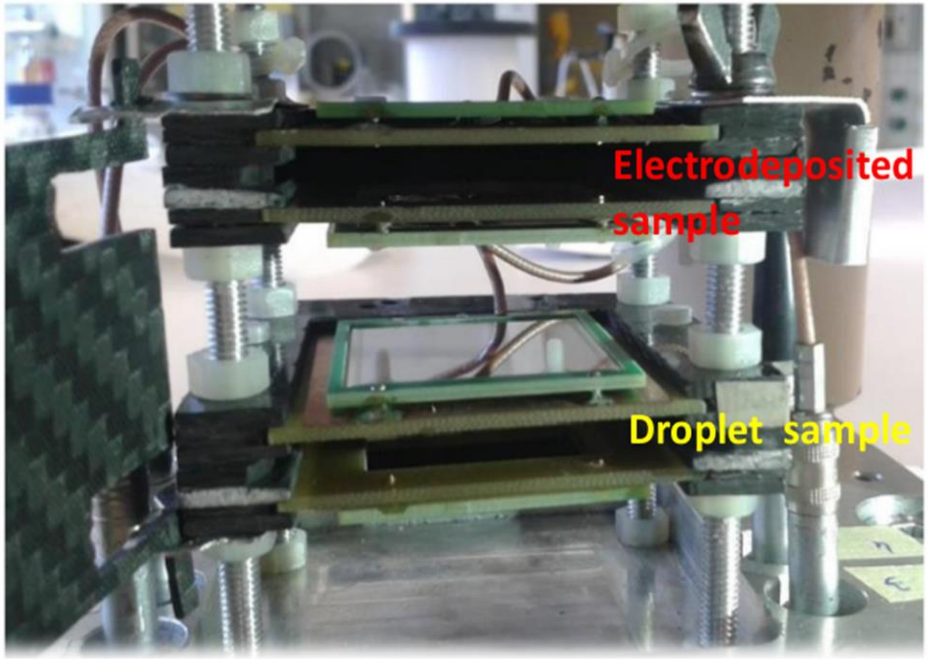
Experimental setup (INFN-LNS)

Silicon detectors directly inserted in the beam (3x3 cm^2 active area, 140 μm thickness)

Detection of high energy α-particles

Strong rejection of background (sample preparation)

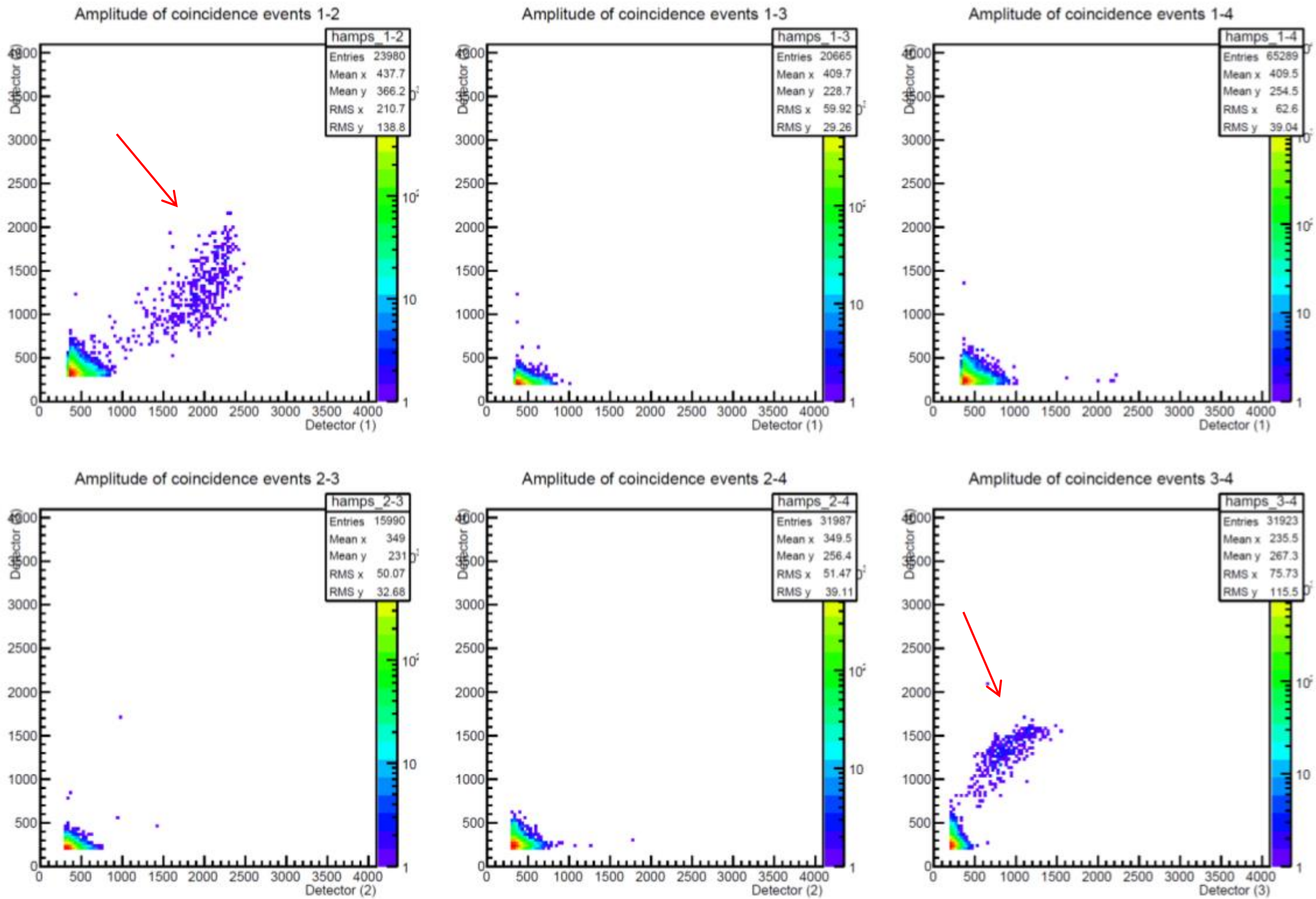




The double alpha signature is the key ***capability of the Si-detector to survive***

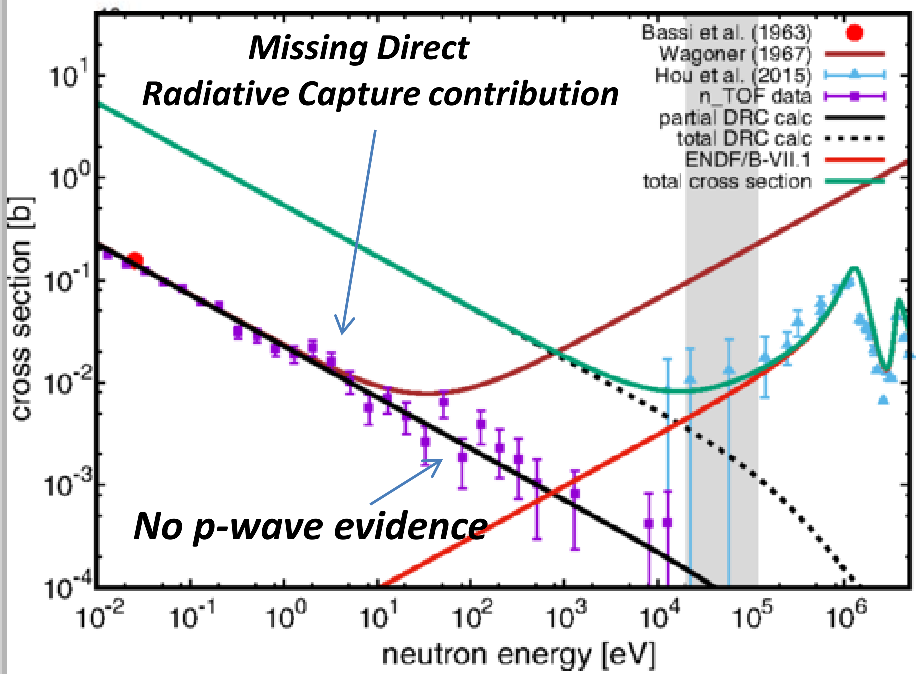
Many colleagues were very skeptical

$^{7}Be(n,\alpha)$ data analysis



Possible to evaluate random coincidences comparing uncorrelated couples of detectors

Impact on Cosmological Lithium Problem



The ^{7}Be$(n,\alpha)^4$He reaction and the Cosmological Lithium Problem: measurement of the cross section in a wide energy range at n_TOF (CERN)

M. Barbagallo,[1] A. Musumarra,[2] L. Cosentino,[3] E. Maugeri,[4] S. Heinitz,[4] N. Colonna,[1,*] F. Käppeler,[5] P. Finocchiaro,[3] A. Mengoni,[6] D. Schumann,[4] L. Damone,[1] O. Aberle,[7] S. Altstadt,[8] J. Andrzejewski,[9] L. Audouin,[10] M. Bacak,[11] S. Barros,[12] V. Bécares,[13] F. Bečvář,[14] F. Belloni,[15] E. Berthoumieux,[16] J. Billowes,[17] V. Boccone,[7] D. Bosnar,[18] M. Brugger,[7] M. Calviani,[7] F. Calviño,[19] D. Cano-Ott,[13] C. Carrapiço,[12] F. Cerutti,[7] E. Chiaveri,[7] M. Chin,[7] G. Cortés,[19] M.A. Cortés-Giraldo,[20] M. Diakaki,[21] C. Domingo-Pardo,[22] R. Dressler,[4] I. Duran,[23] C. Eleftheriadis,[24] A. Ferrari,[7] K. Fraval,[16] S. Ganesan,[25] A.R. García,[13] G. Giubrone,[22] M.B. Gómez-Hornillos,[19] I.F. Gonçalves,[12] E. González-Romero,[13] E. Griesmayer,[11] C. Guerrero,[7] F. Gunsing,[16] P. Gurusamy,[25] D.G. Jenkins,[26] E. Jericha,[11] D. Karadimos,[21] N. Kivel,[4] M. Kokkoris,[21] M. Krtička,[14] J. Kroll,[14] C. Langer,[8] C. Lederer,[8] H. Leeb,[11] L.S. Leong,[10] S. Lo Meo,[6] R. Losito,[7] A. Manousos,[24] J. Marganiec,[9] T. Martínez,[13] C. Massimi,[27] P. Mastinu,[28] M. Mastromarco,[1] E. Mendoza,[13] P.M. Milazzo,[29] F. Mingrone,[27] M. Mirea,[30] W. Mondalaers,[15] A. Pappalardo,[3] C. Paradela,[15] A. Pavlik,[31] J. Perkowski,[9] M. Piscopo,[3] A. Plompen,[15] J. Praena,[20] J. Quesada,[20] T. Rauscher,[32,33] R. Reifarth,[8] A. Riego,[19] F. Roman,[7] C. Rubbia,[7] R. Sarmento,[12] A. Saxena,[25] P. Schillebeeckx,[15] S. Schmidt,[8] G. Tagliente,[1] J.L. Tain,[22] D. Tarrío,[23] L. Tassan-Got,[10] A. Tsinganis,[7] S. Valenta,[14] G. Vannini,[27] V. Variale,[1] P. Vaz,[12] A. Ventura,[34] R. Versaci,[7] M.J. Vermeulen,[26] V. Vlachoudis,[7] R. Vlastou,[21] A. Wallner,[35,31] T. Ware,[17] M. Weigand,[8] C. Weiß,[7] T. Wright,[17] and P. Žugec[18]

(The n_TOF Collaboration (www.cern.ch/ntof))

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PRL **117,** 152701 (2016) PHYSICAL REVIEW LETTERS week ending 7 OCTOBER 2016

^{7}Be$(n,\alpha)^4$He Reaction and the Cosmological Lithium Problem: Measurement of the Cross Section in a Wide Energy Range at n_TOF at CERN

of the cross section estimates currently used in BBN calculations. Although new measurements at higher neutron energy may still be needed, the present results hint to a minor role of this reaction in BBN, leaving the long-standing Cosmological Lithium problem unsolved.

Spokesperson: *a risky job*

branching electronics
in EAR II

https://home.cern/news/news/experiments/ntof-plays-hide-and-seek-cosmological-lithium

BBN and Photonuclear Reactions

Eur. Phys. J. A (2023) 59:165
https://doi.org/10.1140/epja/s10050-023-01082-9

THE EUROPEAN PHYSICAL JOURNAL A

Review

Photonuclear reactions with charged particles detection for nuclear astrophysics studies

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[2] Extreme Light Infrastructure - Nuclear Physics, Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering, 077125 Bucharest-Magurele, Romania
[3] Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
[4] Department of Engineering and Mathematics, Sheffield Hallam University, Sheffield S1 1WB, UK

«The nuclear astrophysics program with ELI-NP includes studies of (γ,p) and (γ,α) photo-disintegration reactions on light nuclei for Big Bang nucleosynthesis (2H, 6−7Li)»

The Gamma Factory provides larger intensity and wider energy range (> 20 MeV)

7Be destruction by photo-disintegration ?
(just at CERN-PSI)

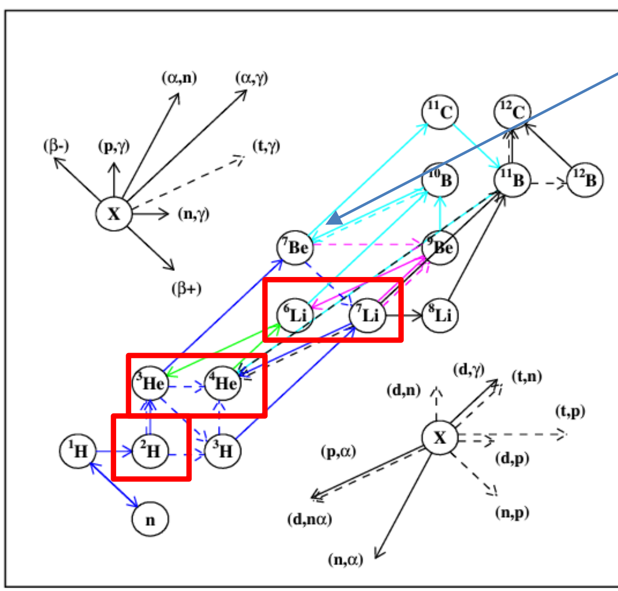


Figure 22. Reduced network displaying the important reactions for ^{4}He, D, ^{3}He, and ^{7}Li (blue), ^{6}Li (green), ^{9}Be (pink), ^{10,11}B (cyan), and CNO (black) production. Note that CNO production is via ^{11}B but follows a different path than primordial ^{11}B formation through the late-time ^{11}C decay.

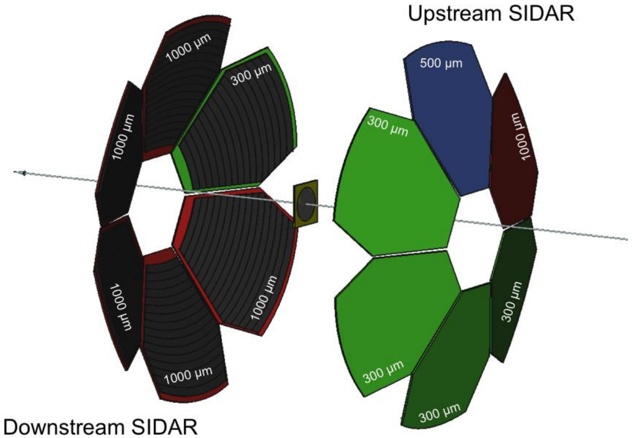
TABLE I. The relevant photodissociation reactions and their respective threshold energies are listed in the table below, and their cross sections are listed in the Appendix.

Reaction	Threshold ($E_{\gamma,\mathrm{th}}$)
$d(\gamma,n)p$	2.2246 MeV
$t(\gamma,n)d$	6.2572 MeV
$t(\gamma,np)n$	8.4818 MeV
^{3}He$(\gamma,p)d$	5.4935 MeV
^{3}He$(\gamma,np)p$	7.7181 MeV
^{4}He$(\gamma,p)t$	19.8139 MeV
^{4}He(γ,n) ^{3}He	20.5776 MeV
^{4}He$(\gamma,d)d$	23.8465 MeV
^{4}He$(\gamma,np)d$	26.0711 MeV
^{6}Li(γ,np) ^{4}He	3.6989 MeV
^{6}Li(γ,X) ^3A	15.7947 MeV
^{7}Li(γ,t) ^{4}He	2.4670 MeV
^{7}Li(γ,n) ^{6}Li	7.2400 MeV
^{7}Li$(\gamma,2np)$ ^{4}He	10.9489 MeV
^{7}Be$(\gamma,{}^3$He$)$ ^{4}He	1.5866 MeV
^{7}Be(γ,p) ^{6}Li	5.6058 MeV
^{7}Be$(\gamma,2pn)$ ^{4}He	9.3047 MeV

PHYSICAL REVIEW D 67(2003)103521

^{7}Li(γ,t)^{4}He @ HIγS   Eγ= 4.4-10 MeV

Phys. Rev. C 101, 055801 – 2020



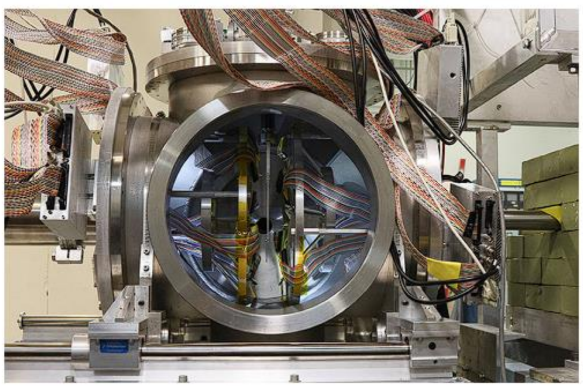


Photo of the setup for the ^{7}Li(γ, t)^{4}He measurement at HIγS. The vacuum chamber contains two lampshade configurations of YY1 detectors of the SIDAR array, symmetrically mounted upstream and downstream of the target. Beam enters from the right, via an extended pipe upstream with an entrance window to the vacuum system, shielded from the setup by a lead castle

Again back-to-back coincidences

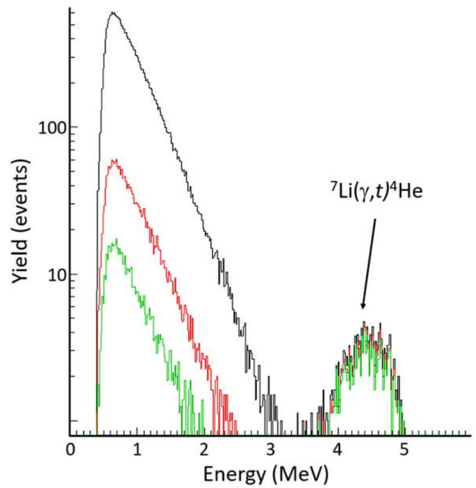


Fig. 3 Summed energy spectrum from SIDAR detectors from the ^{7}Li(γ, t)^{4}He experiment, with no geometric conditions (black), with a back-to-back detector coincidence (red) and a back-to-back strip coincidence (green). These spatial cuts suppress the uncorrelated electron backgrounds, with negligible loss of the genuinely coincident ejectiles from ^{7}Li(γ, t)^{4}He events

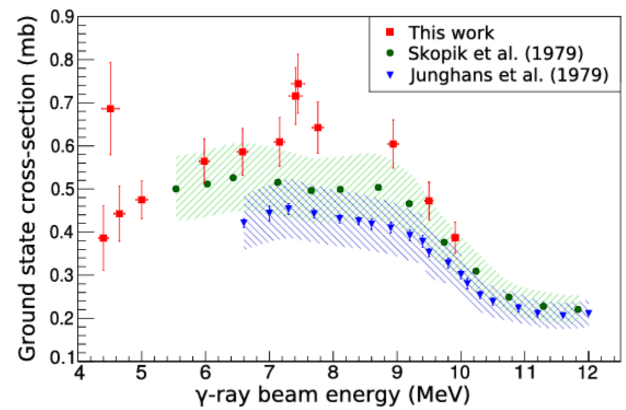


FIG. 12. The ^{7}Li(γ, t)^{4}He ground-state cross section result from the present measurement. The error bars represent both statistical and systematic uncertainties added in quadrature. Experimental results from Refs. [7,8] are also shown (including 15% systematic uncertainty band).

Theory

Journal of Cosmology and Astroparticle Physics

M. Kawasaki et al JCAP12(2020)048

Reaction	Error	Reference
$\gamma + \mathrm{D} \to n + p$	6 %	[54]
$\gamma + \mathrm{T} \to n + \mathrm{D}$	14%	[55, 56]
$\gamma + \mathrm{T} \to p + n + n$	7%	[56]
$\gamma + {}^3\mathrm{He} \to p + \mathrm{D}$	10%	[57]
$\gamma + {}^3\mathrm{He} \to p + p + n$	15%	[57]
$\gamma + {}^4\mathrm{He} \to p + \mathrm{T}$	4%	[58]
$\gamma + {}^4\mathrm{He} \to n + {}^3\mathrm{He}$	5%	[59, 60]
$\gamma + {}^4\mathrm{He} \to p + n + \mathrm{D}$	14%	[58]
$\gamma + {}^6\mathrm{Li} \to$ anything	4%	[61]
$\gamma + {}^7\mathrm{Li} \to n + {}^6\mathrm{Li}$	4%	[62]
$\gamma + {}^7\mathrm{Li} \to$ anything	9%	[63]
$\gamma + {}^7\mathrm{Be} \to {}^3\mathrm{He} + {}^4\mathrm{He}$	9%	[64]
$\gamma + {}^7\mathrm{Be} \to p + {}^6\mathrm{Li}$	4%	[16]
$\gamma + {}^7\mathrm{Be} \to p + p + n + {}^4\mathrm{He}$	9%	[16]

R.H.Cyburt et al. Updated nucleosynthesis constraints on unstable relic particles, Phys. Rev. D 67(2003)103521

H. Ishida, M. Kusakabe, and H. Okada

Phys. Rev. D 90 (2014)083519

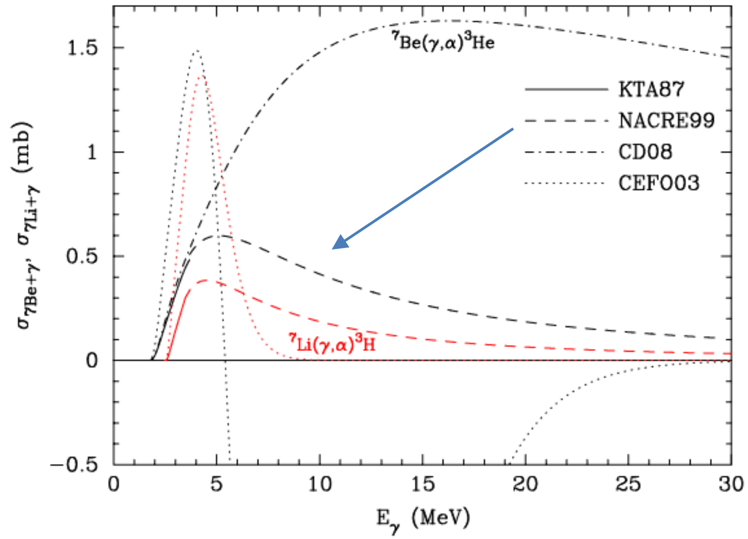


FIG. 1 (color online). Cross sections of reactions $^7\mathrm{Be}(\gamma,\alpha)^3\mathrm{He}$ and $^7\mathrm{Li}(\gamma,\alpha)^3\mathrm{H}$ as a function of the photon energy. They are estimated from the detailed balance relation with the forward radiative capture cross sections. Solid lines correspond to polynomial fits to theoretical calculations in the low energy regions [82]. Dashed lines correspond to constant S factors in the high energy regions [83]. The dot-dashed line is from a fit to experimental data on $^3\mathrm{He}(\gamma,\alpha)^7\mathrm{Be}$ [92]. Dotted lines show fitted functions of Ref. [44].

Key problem: the BBN photon spectrum should be modified without altering the rest of the network

Big-bang nucleosynthesis with sub-GeV massive decaying particles

Masahiro Kawasaki,[a,b] Kazunori Kohri,[c,d,b] Takeo Moroi,[e,b] Kai Murai[a,b] and Hitoshi Murayama[f,g,b,1]

JCAP12(2020)048

Importantly, the threshold energy of the photon for the process ${}^7\mathrm{Be}(\gamma, {}^3\mathrm{He}){}^4\mathrm{He}$ is $E^{(\mathrm{th})}_{^7\mathrm{Be}} \simeq 1.59$ MeV, which is lower than that of the photodissociation of D ($E^{(\mathrm{th})}_{\mathrm{D}} \simeq 2.22$ MeV) and ^{4}He (~ 20 MeV). Thus, if the energy of the injected photons is in the range of $E^{(\mathrm{th})}_{^7\mathrm{Be}} < \epsilon_0 < E^{(\mathrm{th})}_{\mathrm{D}}$, the photodissociation of ^{7}Be may occur to solve the ^{7}Li problem without significantly affecting the abundances of other light elements, as mentioned in [35, 64].

PRL **114,** 091101 (2015) PHYSICAL REVIEW LETTERS week ending 6 MARCH 2015

Loophole to the Universal Photon Spectrum in Electromagnetic Cascades and Application to the Cosmological Lithium Problem

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(Received 13 November 2014; revised manuscript received 8 January 2015; published 2 March 2015)

The standard theory of electromagnetic cascades onto a photon background predicts a quasiuniversal shape for the resulting nonthermal photon spectrum. This has been applied to very disparate fields, including nonthermal big bang nucleosynthesis (BBN). However, once the energy of the injected photons falls below the pair-production threshold the spectral shape is much harder, a fact that has been overlooked in past literature. This loophole may have important phenomenological consequences, since it generically alters the BBN bounds on nonthermal relics; for instance, it allows us to reopen the possibility of purely electromagnetic solutions to the so-called "cosmological lithium problem," which were thought to be excluded by other cosmological constraints. We show this with a proof-of-principle example and a simple particle physics model, compared with previous literature.

DOI: 10.1103/PhysRevLett.114.091101 PACS numbers: 95.30.Cq, 14.60.St, 26.35.+c