Nuclear Astrophysics at Gran Sasso

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IAPS @ Gran Sasso – Gran Sasso Science Institute
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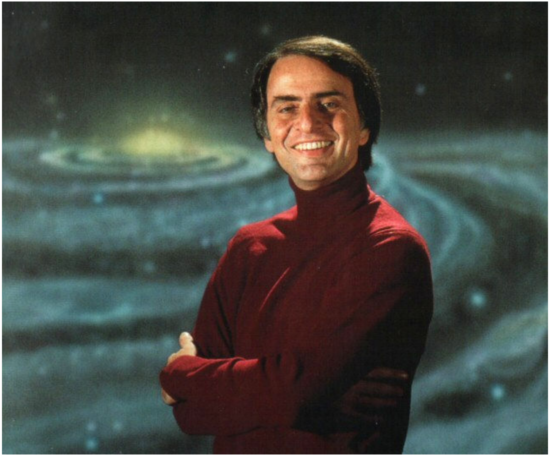
Outline

- Nuclear Astrophysics
- Why underground?
- LUNA at Gran Sasso
- Outlook

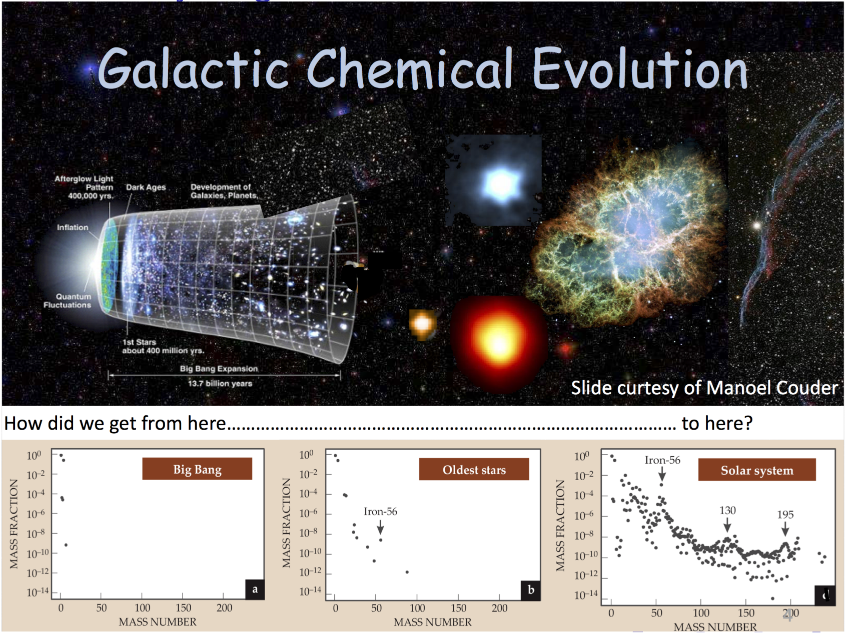
Starstuff

Starstuff



"The nitrogen in our DNA, the calcium in our teeth, the iron in our blood, the carbon in our apple pies were made in the interiors of collapsing stars. We are made of starstuff."

How was everything made?

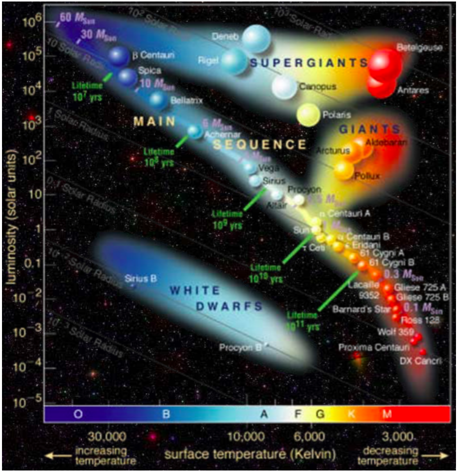


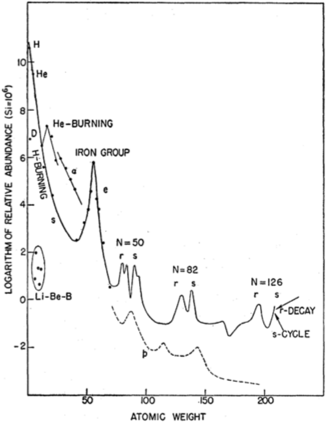
Galactic Chemical Evolution

Slide curtesy of Manoel Couder

How did we get from here……………………………………………………………… to here?

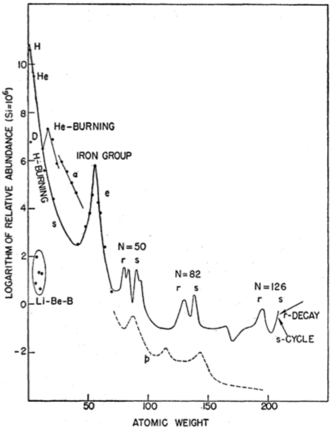
Nuclear Astrophysics





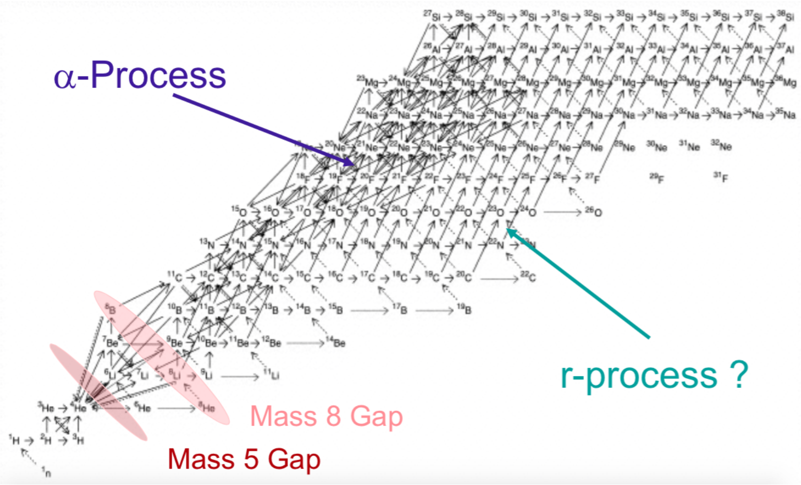
- Explain energy generation, life cycle of stars
- Origin of the elements

Synthesis of the elements in stars



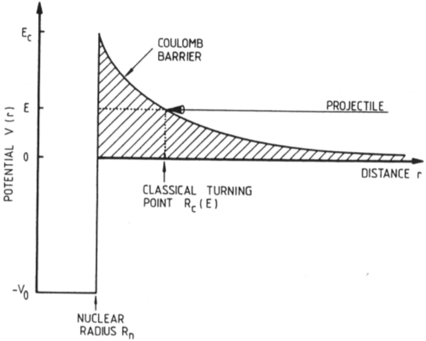
- H, D, He, some Li: Primordial Nucleosynthesis
- All other elements produced in stars
- Charged particle capture reactions
  - p-p, (hot)CNO, explosive burning, rp process
  - He burning
  - Advanced burning: C, Ne, O, Si
- Coulomb barrier prevents significant A $>$ 60 production via charged particles
- Neutron capture (s, r processes), some p process

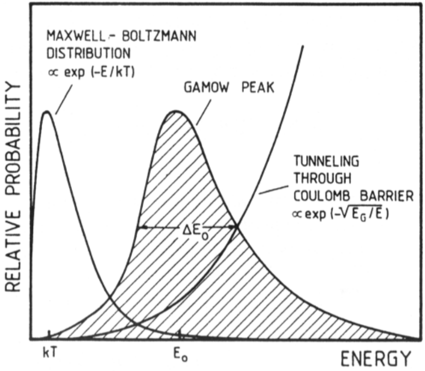
Putting the Nuclear in Astrophysics



- Give nuclear physics input for stellar models
- Hundreds of reactions, huge energy range

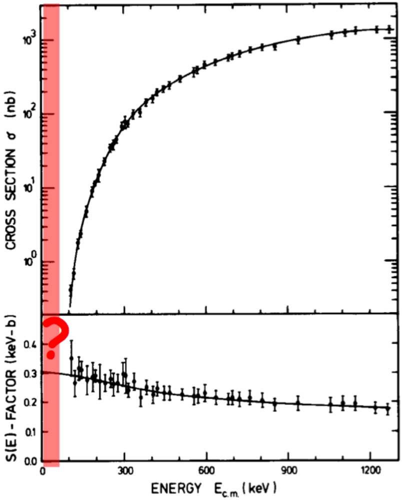
Effective energy of stellar burning





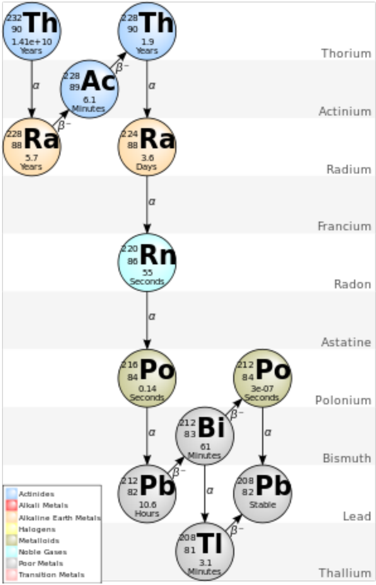
- Maxwell-Boltzmann energy distribution
- $f(E)dE = 2\sqrt{\frac{E}{\pi(kT)^3}} \exp\left(-\frac{E}{kT}\right) dE$
- combined with tunneling probability
- $P(E) = \exp\left(-\frac{2\pi}{\hbar} Z_1 Z_2 e^2 \sqrt{\frac{m}{2E}}\right)$
- $\rightarrow$ Reaction rate
- $\langle \sigma v \rangle = \left(\frac{8}{\pi\mu_{01}}\right)^{1/2} \frac{1}{kT^{3/2}} \int_0^\infty \sigma(E) E e^{-E/kT} dE$

Approaching stellar energies



- Thermal energies in stars in keV range, far below Coulomb energy
- $^{12}C(\alpha,\gamma)^{16}O$: kT $\approx$ 30 keV (T $=$ 0.2 GK), $E_G \approx$ 300 keV
- Very low energy: very low cross section
- Hard to approach stellar energy in the laboratory
- But: Need to know cross section in stellar ranges!

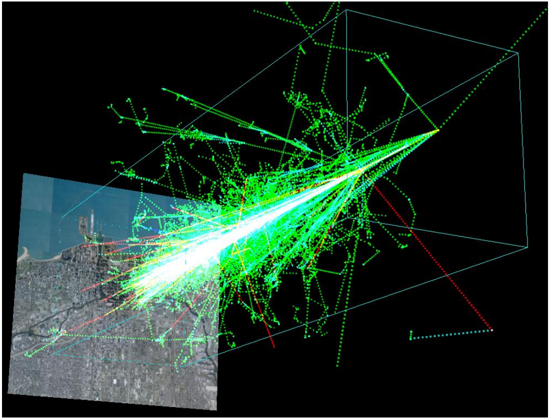
Background sources - Natural radioactivity



wikipedia

- Natural decay chains: Thorium, Uranium series
- Potassium-40
- Radon (from decay chains): gaseous
- Impact mostly gamma-ray measurements

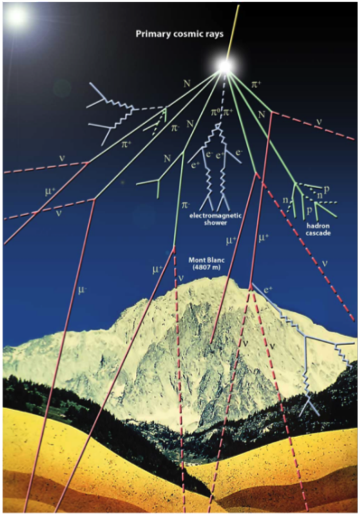
Background sources - Cosmic rays



http://astro.uchicago.edu/cosmus/projects/aires/

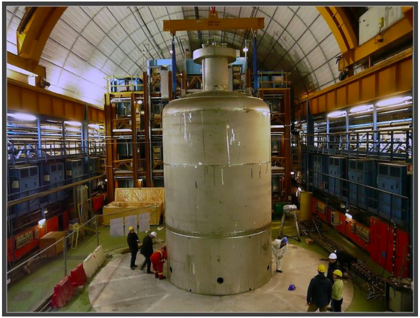
- Primary cosmic rays: mostly protons
- Create showers of secondary particles in atmosphere
- In the end muons and neutrons reach surface

Why don't we put a mountain around the experiment?



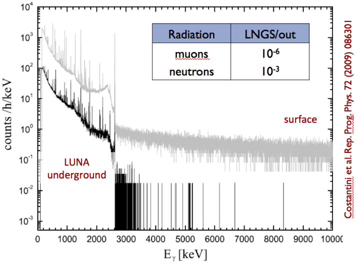
- Use natural (km thick) rock shielding by going underground
- Suppression of cosmic rays by factor 10^{-6}
- Lead shields can be much thicker (no secondaries induced in shield)
- Neutron flux dominated by natural radioactivity: 10^{-3} to 10^{-4}

LNGS



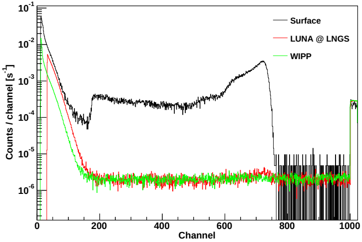
- Rock coverage of 3800 mwe
- Good accessibility (drive-in)
- Borexino, OPERA, LVD etc. . .
- Over 20 years underground nuclear astrophysics

Background @ LUNA



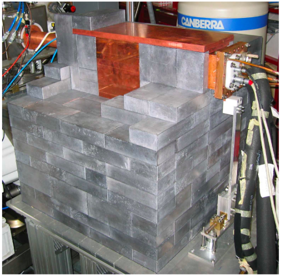
Radiation	LNGS/out
muons	10^{-6}
neutrons	10^{-3}

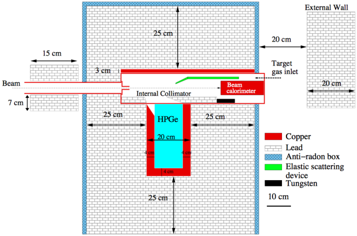
Costantini et al. Rep. Prog. Phys. 72 (2009) 086301



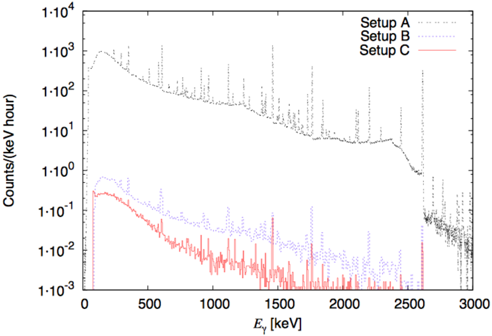
- Gammas: high energy part attenuated by 6 orders of magnitude
- Low-energy part? Next slide
- Neutrons: Down by 3-4 o.o.m.

LUNA gamma setup I



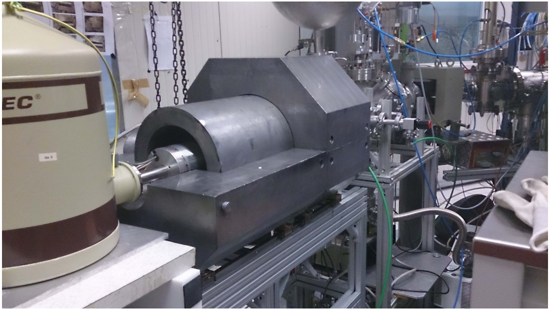


Caciolli et al. 2009



- Exploit low muon flux: build massive lead shield
- Flush detector surroundings with N_2 to get rid of radon
- Background reduction by 4-5 orders of magnitude (< 3 MeV)

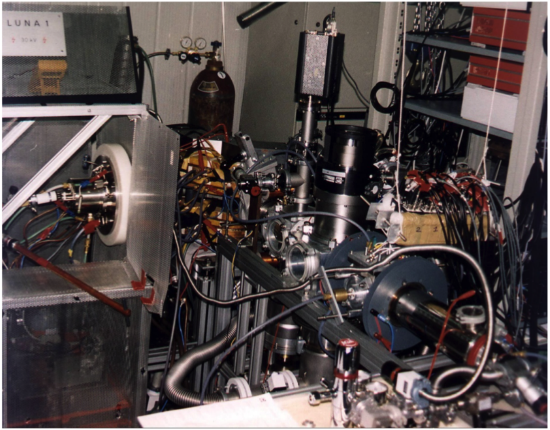
LUNA gamma setup II



- Recently constructed massive lead shield at solid target beamline
- Adaptable for HPGe (good resolution) or BGO (good efficiency)
- Looks nice

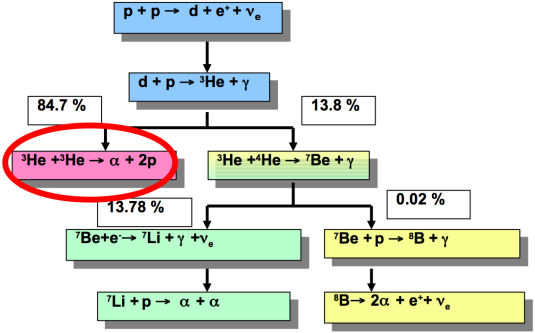
LUNA 1

LUNA 1



- 50 kV platform built by students
- Studied proton proton chain

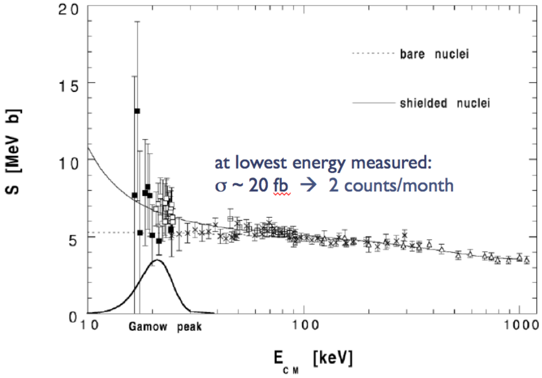
LUNA 1 - ^{3}He(^{3}He, 2p)^{4}He



- Solar neutrino puzzle:
  - Resonance in p-p 1 chain? lower ^{3}He$(\alpha, \gamma)^7$Be reaction flux
  - Fewer neutrinos might explain observed low solar flux

Junker et al. 1998, Bonetti et al. 1999

LUNA 1 - ^{3}He(^{3}He, 2p)^{4}He

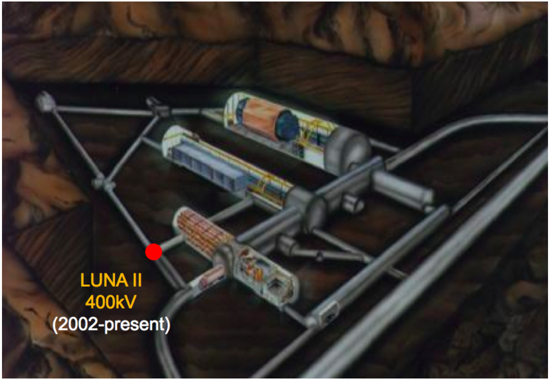


at lowest energy measured:
σ ~ 20 fb → 2 counts/month

- Solar neutrino puzzle:
  - Resonance in p-p 1 chain? lower ^{3}He$(\alpha, \gamma)^{7}$Be reaction flux
  - Fewer neutrinos might explain observed low solar flux
- First measurement at solar energies - exluded resonance

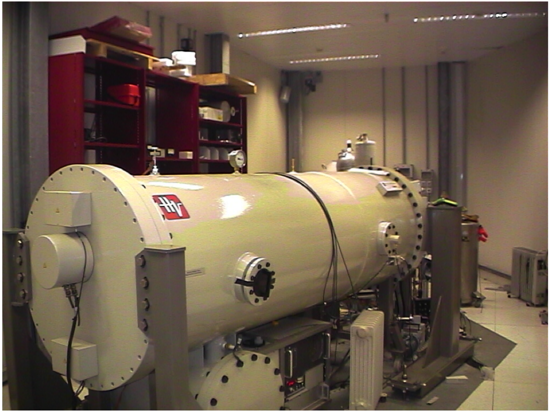
Junker et al. 1998, Bonetti et al. 1999

LUNA 2



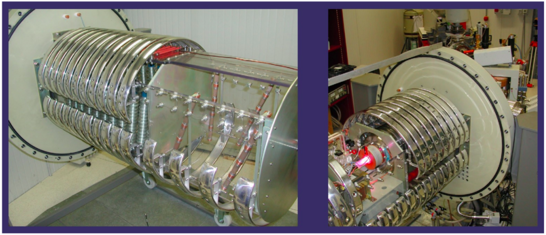
- Moved down the corridor a few meters
- In operation since 2002

LUNA 2



- Moved down the corridor a few meters
- In operation since 2002
- 50 - 400 kV accelerator
- CNO cycle reactions

LUNA 2



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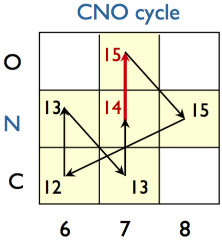
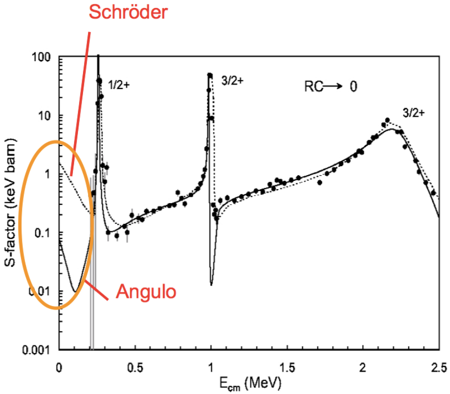
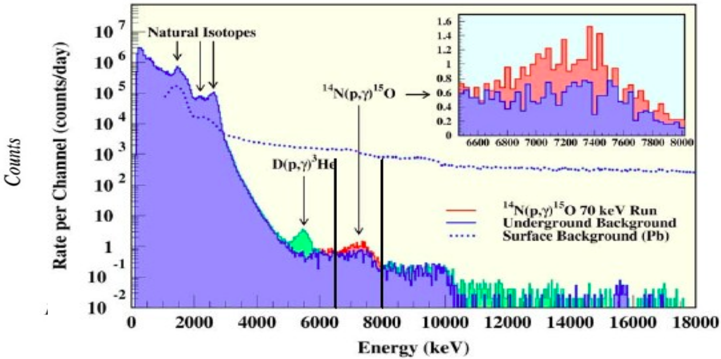
$^{14}N(p,\gamma)^{15}O$





- Bottleneck reaction in CNO cycle
- Age of globular clusters (turnoff from main sequence)
- Solar CNO neutrino flux
- Difference of factor 20 between extrapolations

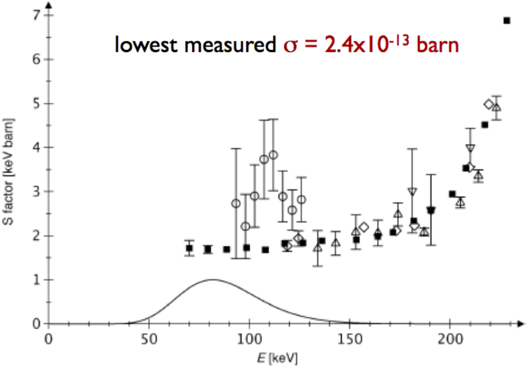
$^{14}N(p,\gamma)^{15}O$



- Measured using HPGe on solid target
- Low energy part with 4 π BGO and gas target

Lemut et al. 2006, Formicola et al. 2004 Imbriani et al. 2004

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



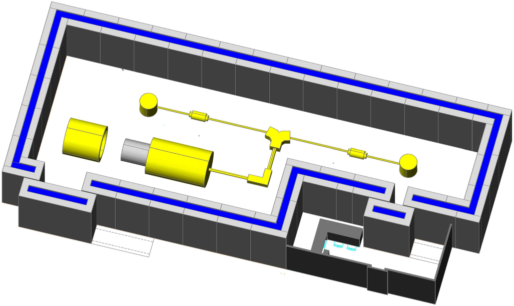
- Measured using HPGe on solid target
- Low energy part with 4 π BGO and gas target
- Covered Gamow energies
- Increased globular cluster age by $\sim$ 1 Gy
- Reduced solar CNO neutrino flux by factor 2

Lemut et al. 2006, Formicola et al. 2004 Imbriani et al. 2004

Current measurements

- BGO phase at solid and gas target beam line
- Solid target:
  - ^{23}Na(p, γ)^{24}Mg
  - ^{18}O(p, γ)^{19}F
- Gas target:
  - ^{22}Ne(p, γ)^{23}Na
  - d(p, γ)t

LUNA-MV



- 3.5 MV single-ended accelerator
- Two target stations
- Explore helium burning and heavy element production
- First beam 2018

Conclusion

- Nuclear Astrophysics is interesting ("starstuff"!)
- 20+ years track record of underground nuclear astrophysics @ LUNA
- Measured key reactions in stellar energy range
- Growing field: 3 new facilites world wide, one upgrade:
  - LUNA
  - JUNA: Jinping Underground Nuclear Astrophysics
  - CASPAR (long acronym)
  - Felsenkeller Dresden
  - LUNA-MV
- Underground NA has a fruitful future

Conclusion

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  - LUNA
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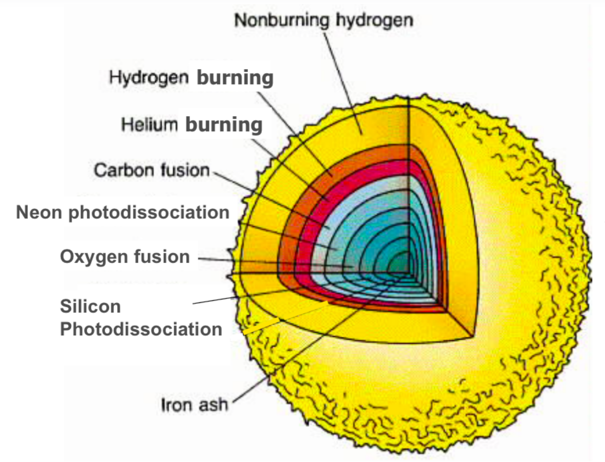
  - Felsenkeller Dresden
  - LUNA-MV
- Underground NA has a fruitful future
- We are always looking for grad students

LUNA collaboration

- INFN - Laboratori Nazionali del Gran Sasso, Italy
  A. Best, A. Boeltzig (GSSI), G. Ciani A. Formicola, S. Gazzana, M. Junker, I. Kochanek, L. Leonzi, A. Razeto
- Helmholtz-Zentrum Dresden-Rossendorf, Germany
  D. Bemmerer, M. Takacs, T. Szucs
- Università di Padova and INFN Padova, Italy
  C. Broggini, A. Caciolli, R. Depalo, R. Menegazzo, D. Piatti
- INFN, Roma I, Italy
  C. Gustavino
- Institute of Nuclear Research (MTA-ATOMKI), Debrecen, Hungary
  Z. Elekes, Zs. Fülöp, Gy. Gyürky
- Osservatorio Astronomico di Collurania Teramo and INFN Napoli, Italy
  O. Straniero
- Università di Genova and INFN Genova, Italy
  F. Cavanna, P. Corvisiero, F. Ferraro, P. Prati, S. Zavatarelli
- Universit di Milano and INFN Milano, Italy
  A. Guglielmetti (Spokesperson), D. Trezzi
- Università di Napoli “Federico II”, and INFN Napoli, Italy
  A. Di Leva, G. Imbriani
- Università di Torino and INFN Torino, Italy
  G. Gervino
- University of Edinburgh, UK
  M. Aliotta, C. Bruno, T. Davinson
- University of Bari Aldo Moro and INFN Bari
  G. D’Erasmo, E.M. Fiore, V. Mossa, F. Pantaleo, V. Paticchio, R. Perrino, L. Schiavulli, A. Valentini

Thanks!
Questions?



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