DURA Annual Meeting, March 5, 2013

Underground Accelerators

DIANA - Dual Ion Accelerators for Nuclear Astrophysics

Talk Outline:

- Introduction
- Nuclear Astrophysics
- Underground Accelerator
- DIANA Project Overview
- DIANA Low Energy Accelerator
- DIANA Project Status
- Summary (Cost & Schedule)

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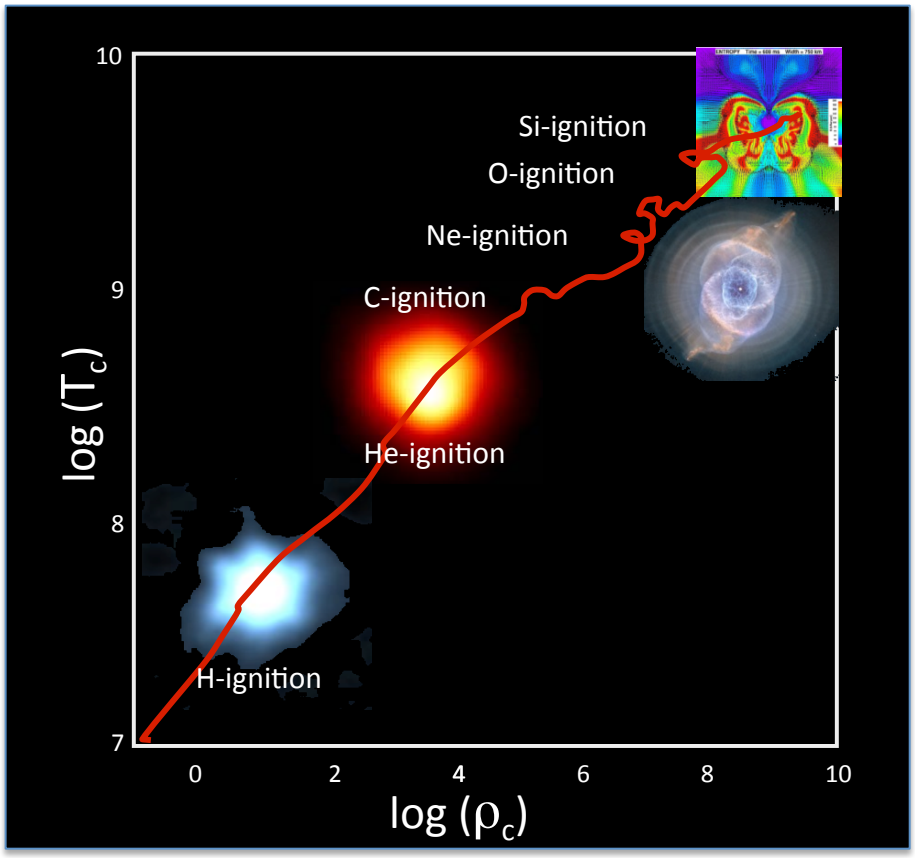
Introduction



- Today it is well known that stars are powered by nuclear reactions.
- Among the several key parameters (chemical composition, opacity, nuclei lifetimes, etc.) to model stars, reactions cross cross sections play an important role.
- They determines the origin of elements in the cosmos, stellar evolution and dynamic, etc.
- Many reactions ask for High Precision data.
- Many reactions don't have data at all and rely on theory.

Hydrogen Burning

p-p Chain

$p + p \rightarrow d + e^+ + \nu_e$

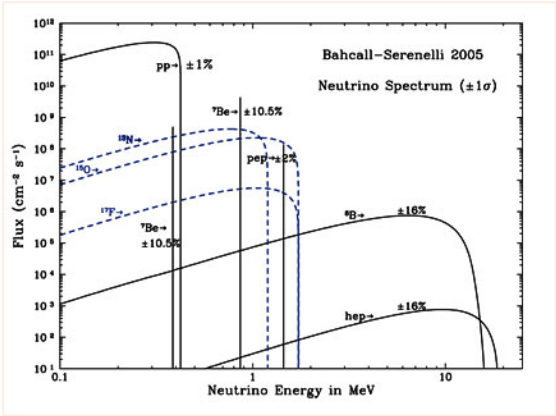
$d + p \rightarrow {}^3He + \gamma$

84.7 %: ${}^3He + {}^3He \rightarrow \alpha + 2p$

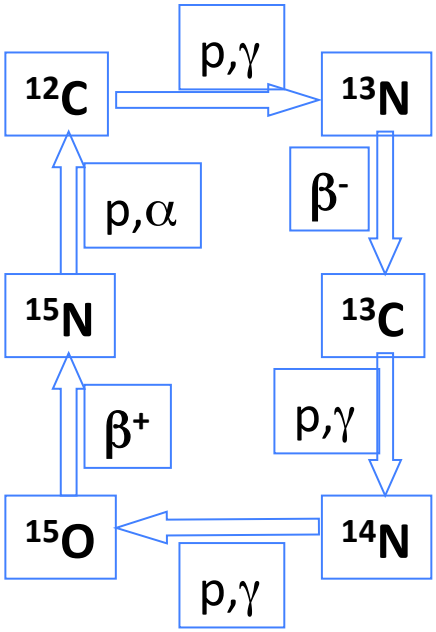
13.8 %: ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

13.78 %: ${}^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e$ → ${}^7Li + p \rightarrow \alpha + \alpha$

0.02 %: ${}^7Be + p \rightarrow {}^8B + \gamma$ → ${}^8B \rightarrow 2\alpha + e^+ + \nu_e$



CNO cycle



$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e + 26.73\ MeV$$

Nuclear Astrophysics

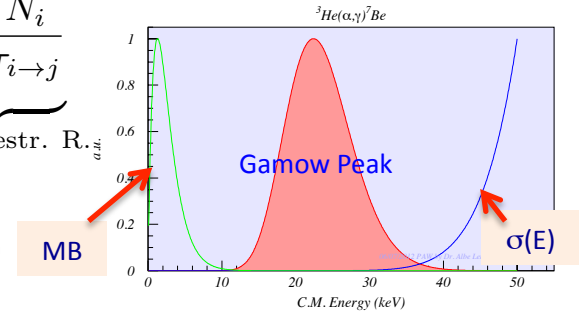
Isotopic Evolution (one eq. per each isotope):

$$\frac{dN_i}{dt} = \underbrace{\sum_{jk} \frac{N_j N_k}{1+\delta_{jk}} < \sigma v >_{jk\to i}}_{\text{Production Rate}} - \underbrace{\sum_{jk} \frac{N_i N_j}{1+\delta_{ij}} < \sigma v >_{ij\to k}}_{\text{Destruction Rate}} + \underbrace{\sum_{j\neq i} \frac{N_j}{\tau_{j\to i}}}_{\text{Dec. Prod. R.}} - \underbrace{\sum_{j\neq i} \frac{N_i}{\tau_{i\to j}}}_{\text{Dec. Destr. R.}}$$

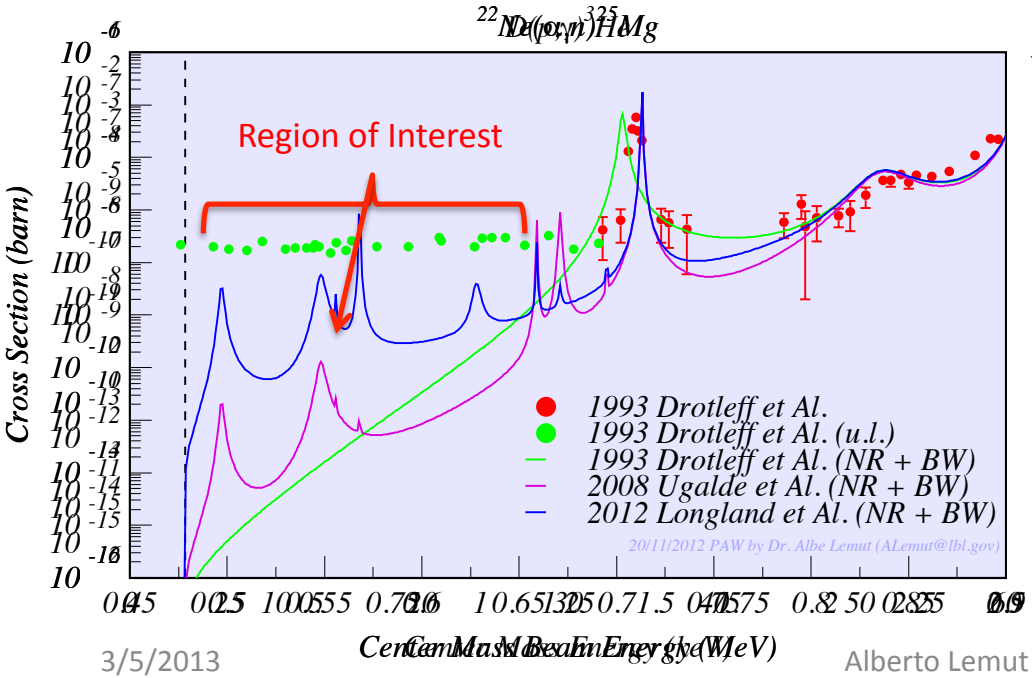
Maxwell-Boltzmann Averaged Cross Section:

$$< \sigma v > (T) = \sqrt{\frac{8}{\pi \mu (k_B T)^3}} \int_0^\infty \sigma(E) E e^{-E/(k_B T)} dE$$

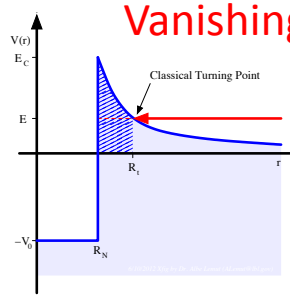
Gamow peak:



(Vanishing Small) Cross Section Measurements of Astrophysically Relevant Nuclear Reactions



Vanishing Small Cross Sections:

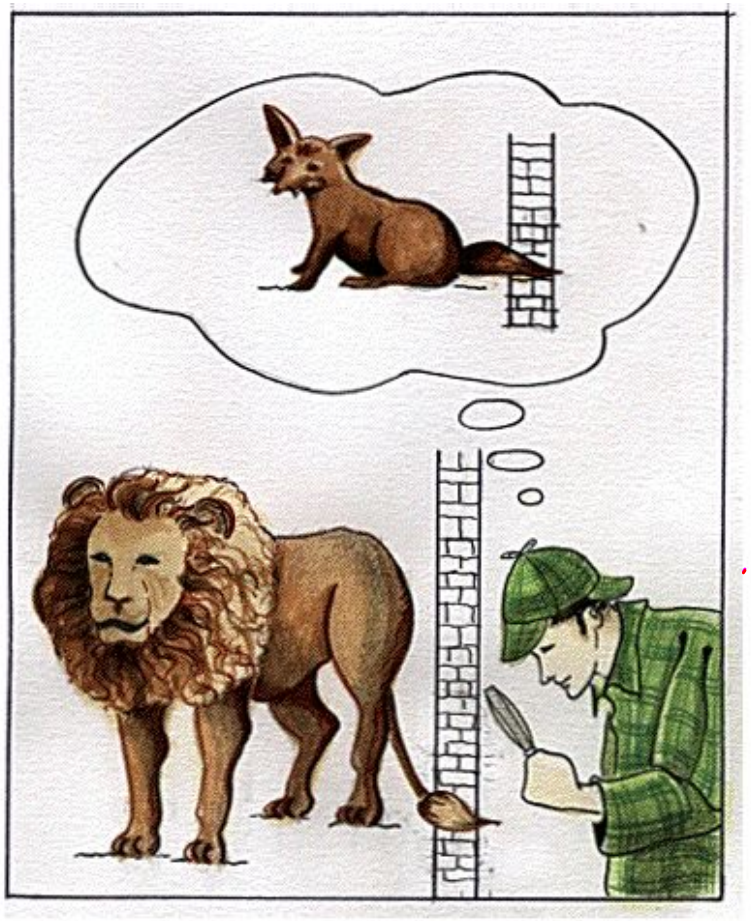


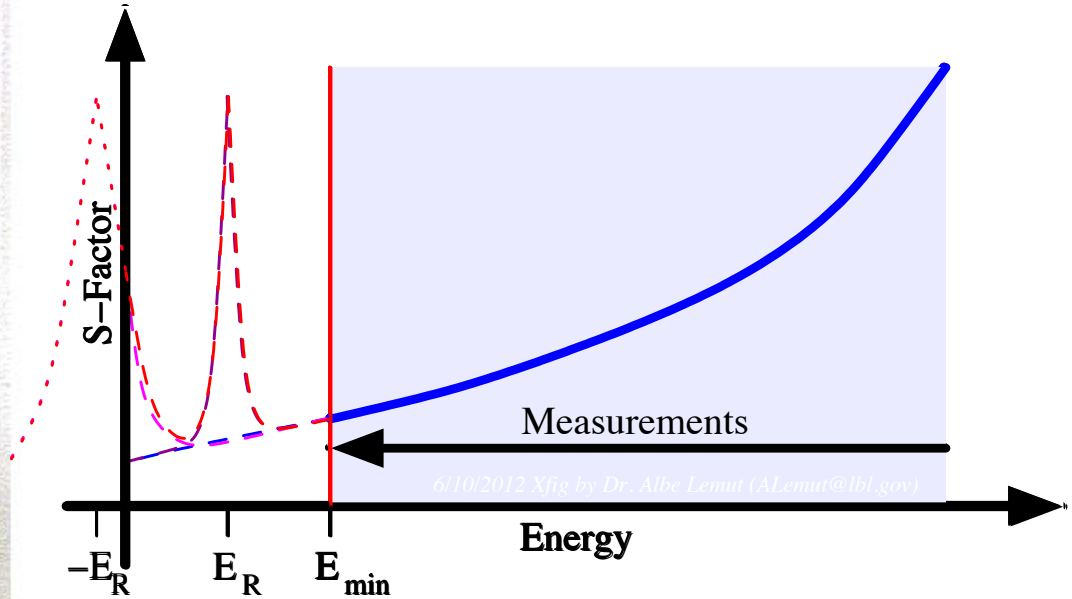
$$\sigma(E) = \frac{1}{E} e^{-\left(2\pi \frac{Z_T Z_p e^2}{\hbar} \sqrt{\frac{\mu}{2E}}\right)} S(E)$$

Low Laboratory Counting Rates:
1 counts/month – 1 counts/day.

Low Counting Facility for Nuclear Reactions Experiments!

What About Extrapolations?

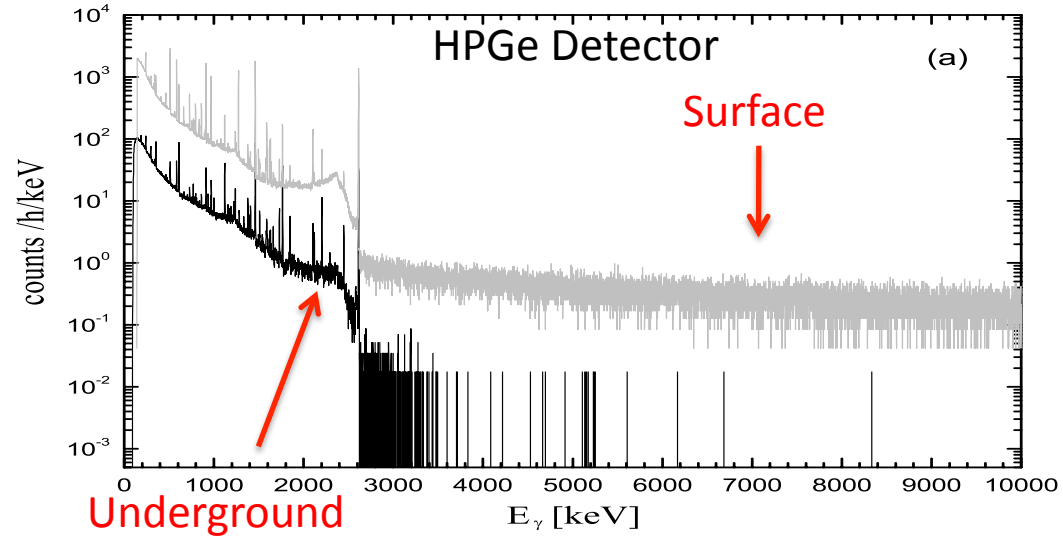


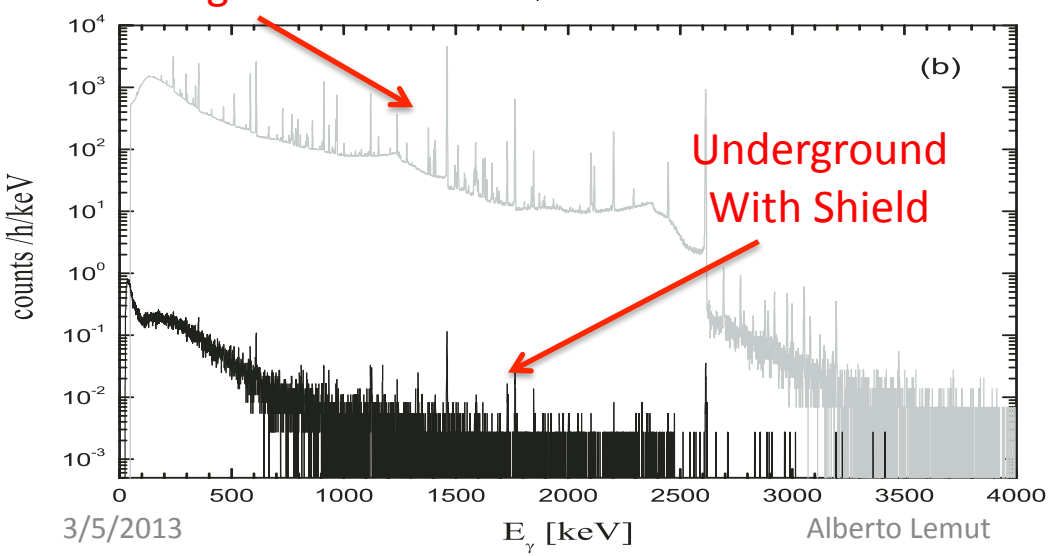


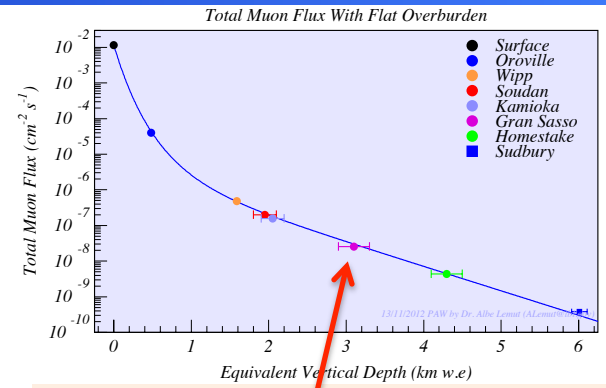
Extrapolations could (and do) fail!!

Underground Accelerator!

H. Costantini et. Al., Rep. Prog. Phys. **72 (2009) 086301**







Background reduction at the LUNA facility in the Gran Sasso National Laboratory 1400 m deep (= 3100 meter of water equivalent shielding)

Muon flux is reduced by 6 orders of magnitude

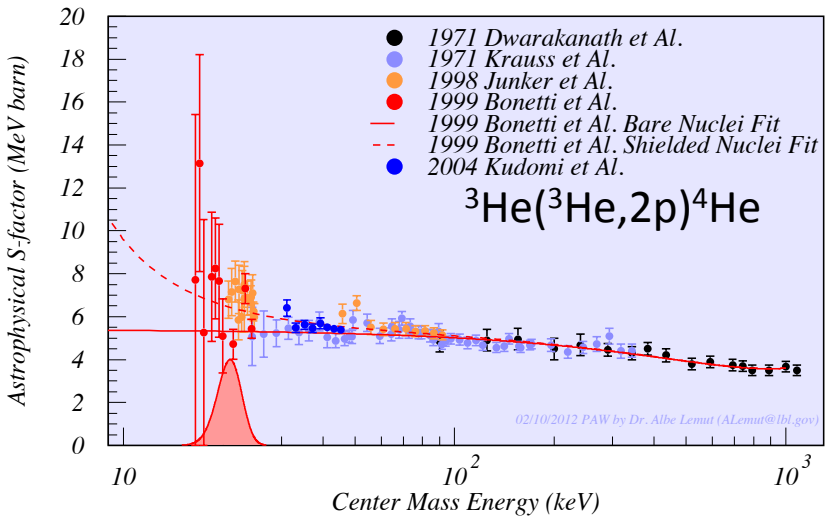
Neutron flux is reduced by 3 order of magnitude

Clear advantage for high Q-value reactions.

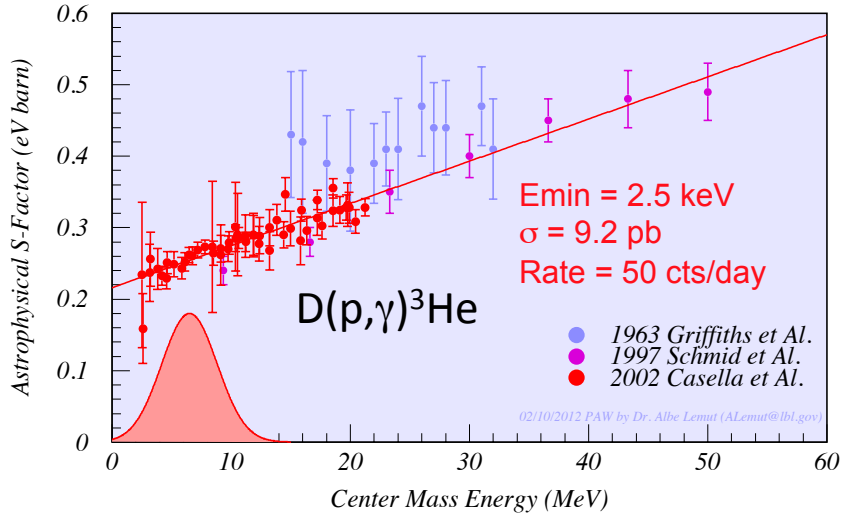
For low Q-value reaction: Passive shielding (Pb) is more effective when the muon flux is reduced

Was This Approach Successful?

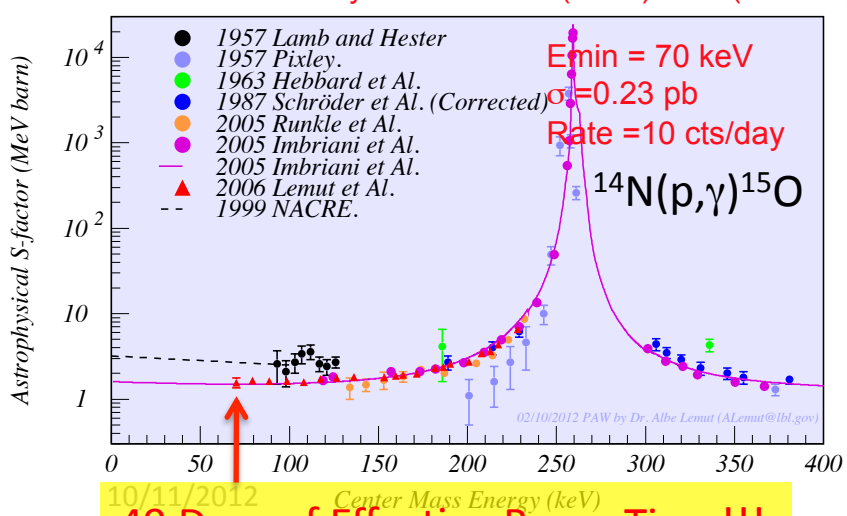
R. Bonetti et Al. Phys. Rev. Lett. 82 (1999) 5025 (TC 255)



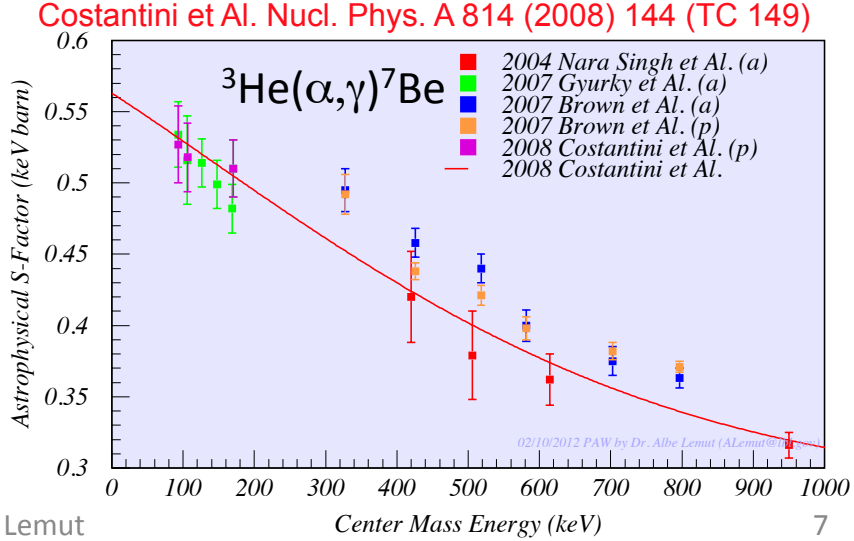
C. Casella et al. Nucl. Phys. A 706 (2002) 203-216 (TC 72)



A. Lemut et Al. Phys. Lett. B 634 (2006) 483 (TC 432)



Costantini et Al. Nucl. Phys. A 814 (2008) 144 (TC 149)



49 Days of Effective Beam Time!!!

Is There Anything Left to Do?

Many Reactions Need High Precision Data!

Hydrogen Burning

$^{3}He(\alpha,\gamma)^{7}Be$
$^{2}H(\alpha,\gamma)^{6}Li$
$^{3}He(^{3}He,2p)^{4}He$
$^{7}Be(p,\gamma)^{8}B$

$^{12}C(p,\gamma)^{13}N$
$^{14}N(p,\gamma)^{15}O$
$^{15}N(p,\gamma),(p,\alpha)^{16}O,^{12}C$

$^{17}O(p,\gamma),(p,\alpha)^{18}F,^{14}N$
$^{18}O(p,\gamma),(p,\alpha)^{19}F,^{15}N$
$^{19}F(p,\gamma),(p,\alpha)^{20}Ne,^{16}O$

Helium Burning

$^{12}C(\alpha,\gamma)^{16}O$
$^{16}O(\alpha,\gamma)^{20}Ne$
$^{20}Ne(\alpha,\gamma)^{24}Mg$

$^{18}O(\alpha,\gamma)^{22}Ne$
$^{22}Ne(\alpha,\gamma)^{26}Mg$
$^{24}Mg(\alpha,\gamma)^{28}Si$

Neutron Sources

$^{13}C(\alpha,n)^{16}O$
$^{22}Ne(\alpha,n)^{25}Mg$
$^{25}Mg(\alpha,n)^{28}Si$
$^{26}Mg(\alpha,n)^{29}Si$

Heavy Ion Burning

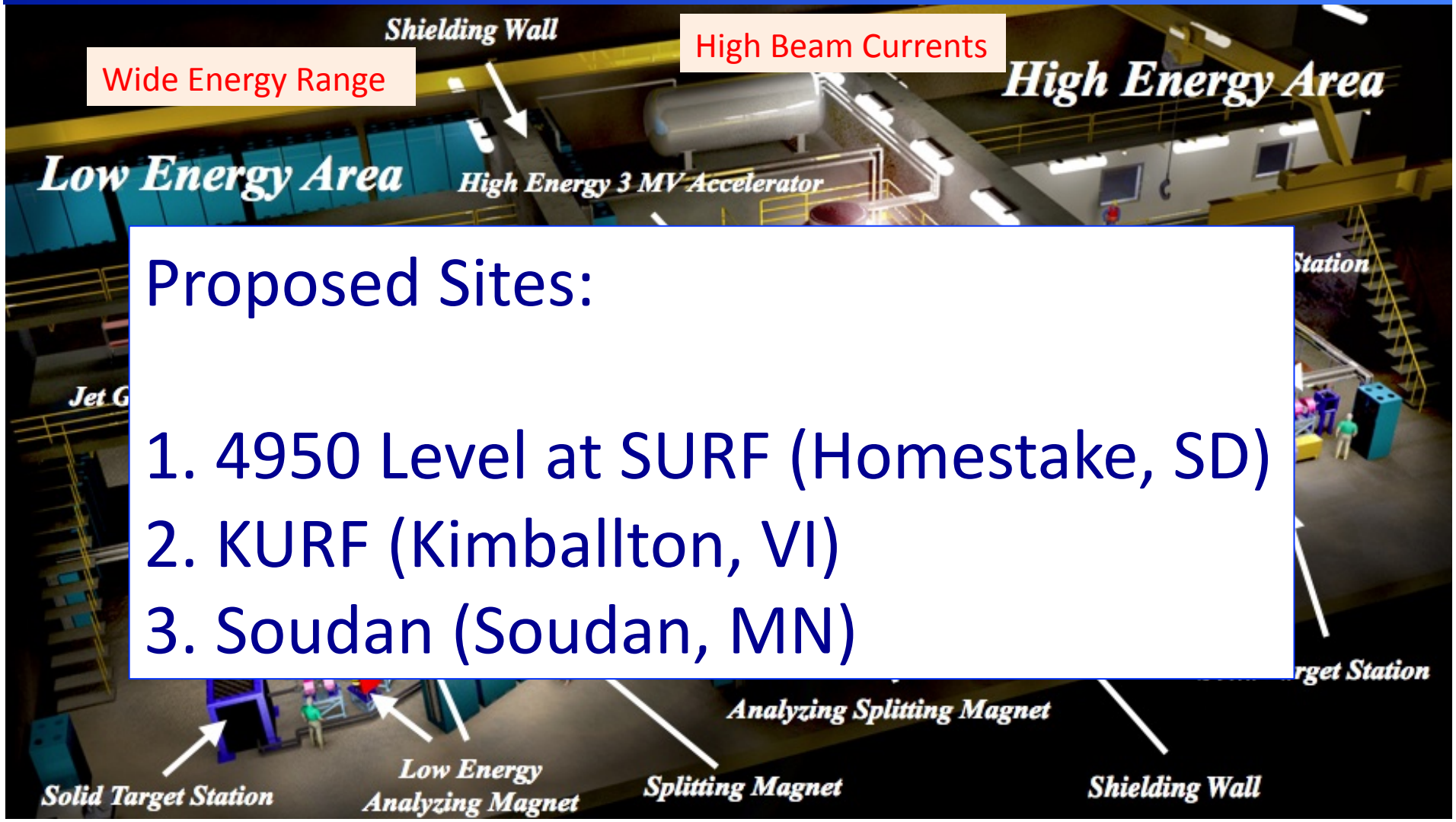
$^{12}C+^{12}C$
$^{12}C+^{16}O$
$^{16}O+^{16}O$

$^{17}O(\alpha,n)^{20}Ne$
$^{28}Si(\alpha,\gamma)^{32}S$
...
..
.

DIANA

NSF Funded Project

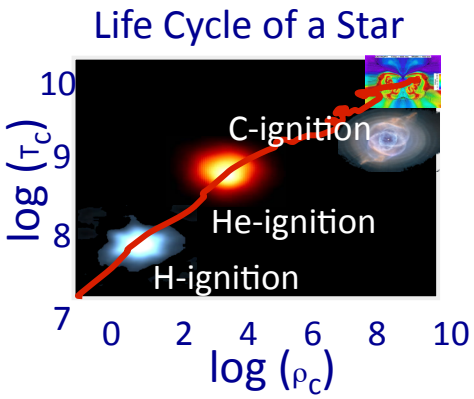
DIANA Facility Overview

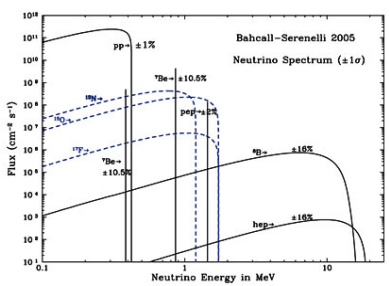


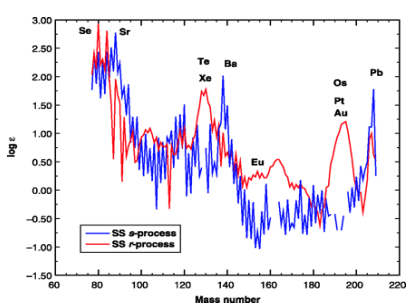
Proposed Sites:

1. 4950 Level at SURF (Homestake, SD)
2. KURF (Kimballton, VI)
3. Soudan (Soudan, MN)

DIANA Science Goal's







Two key questions of nuclear astrophysics:

1. **What is the origin of the elements in the cosmos?**
2. **What are the nuclear reactions that drive stellar explosions?**

DIANA will address three fundamental questions:

1. ***Solar neutrino sources and the metallicity of the Sun;***
2. ***Carbon-based nucleosynthesis;***
3. ***Neutron sources for the production of trans-Fe elements in stars.***

- **DIANA will support a long, high level research program ≥ 20 years.**
- **Ideal E&O opportunities on all levels (under-graduate, grad students, and post-docs).**

DIANA Project Work-chart

DIANA
(Dual Ion Accelerators for Nuclear Astrophysics)

Ernest Orlando Lawrence Berkeley National Laboratory

- Low Energy Accelerator
- Calorimeter
- Overall Engineering
- Low Energy Gas-Jet detector Integration

University of Notre Dame

- High Energy Accelerator
- High Energy Beam Optics
- Solid Target Stations
- Neutron Detector

The University of North Carolina at Chapel Hill

- Ultra-low Background Gamma Detectors

University of Michigan

- High Radio-purity Passive Shields
- Radio-protection

Colorado School of Mines

- Gas-Jet Targets

Michigan State University

- High Beam Intensity Developments with Gas-Jet Target

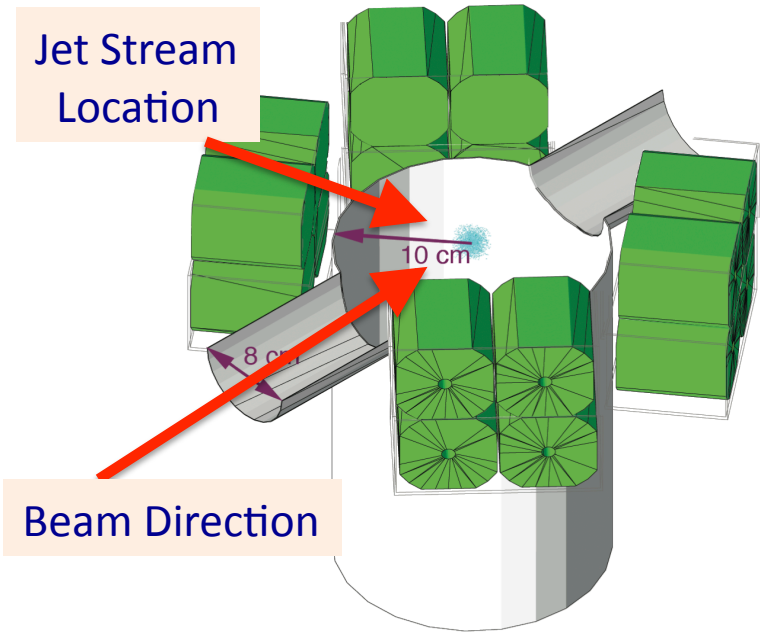
DIANA Low Energy Accelerator

Main Features:

- High Intensity ECR ion source.
- Open platform.
- Accelerator tube with movable screening electrode.
- Two beam lines:
  - Gas-Jet Target.
  - Solid Target.
- Target stations are integrated into beam line design and high radio-purity passive shields.
- High voltage platform is enclosed in grounded Faraday cage.

Targets & Detectors

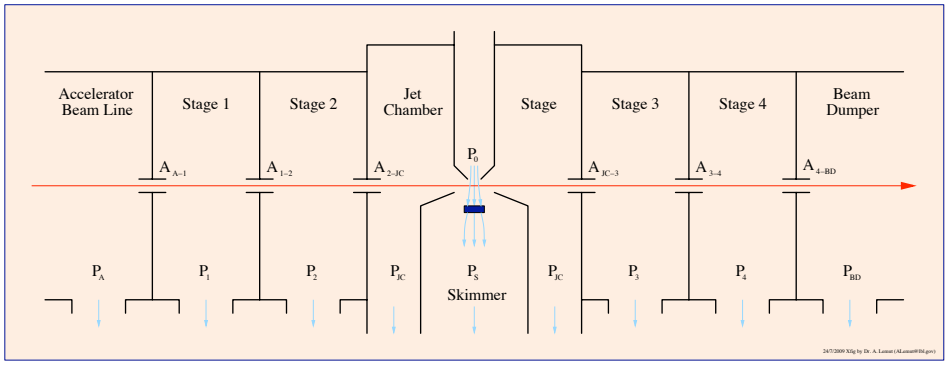
HP Germanium Detector Array (Clover type)



Four 70 mm × 70 mm HPGe Clover Detectors:
- High energy resolution.
- High detection efficiency.

LE and HE Target Stations

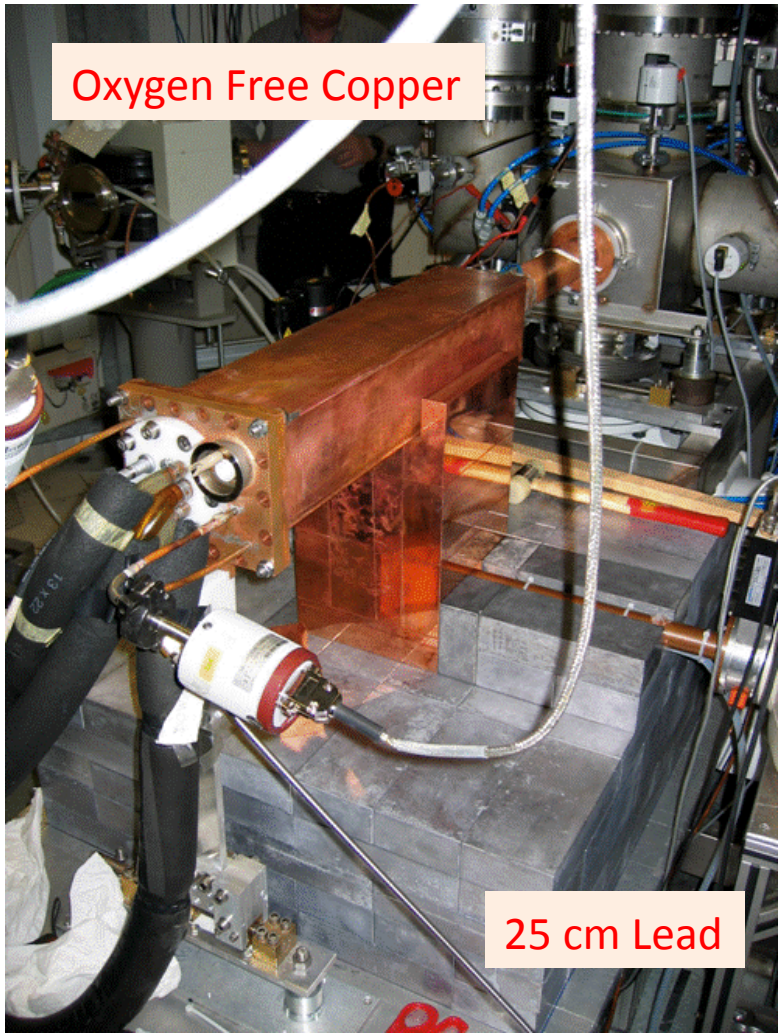
1) High Areal Density Supersonic Jet Gas Target: Goal 10^{18} atoms/cm^2 (0.2-0.4 x 10^{18} appear really feasible).
2) A second beam line for a Solid Target Station and/or extended gas target.



Neutron Detector (^{3}He type) under Development

Jet gas target constrains the Low Energy beam diameter to be ≤ 1 cm

Passive Detector Shielding



Pictures from LUNA $^{3}He(\alpha,\gamma)^{7}Be$ Setup

High Purity, Ultra Low Activity Materials

Radon Box Flushed with High Purity Nitrogen

DIANA Project Status

FY 2010-2012: NSF S4 Preliminary Design:

- All components have been designed, specified, quoted:
  - **Low energy accelerator (50-400 kV, up to 100 mA)**
  - **High energy accelerator (0.3-3.0 MV, up to 1 mA)**
  - Beam lines (magnets, vacuum stations, beam diagnostics, etc).
  - Target stations (solid and jet-gas target).
  - Gamma and neutron detectors (low intrinsic background).
  - High radio-purity passive shields.

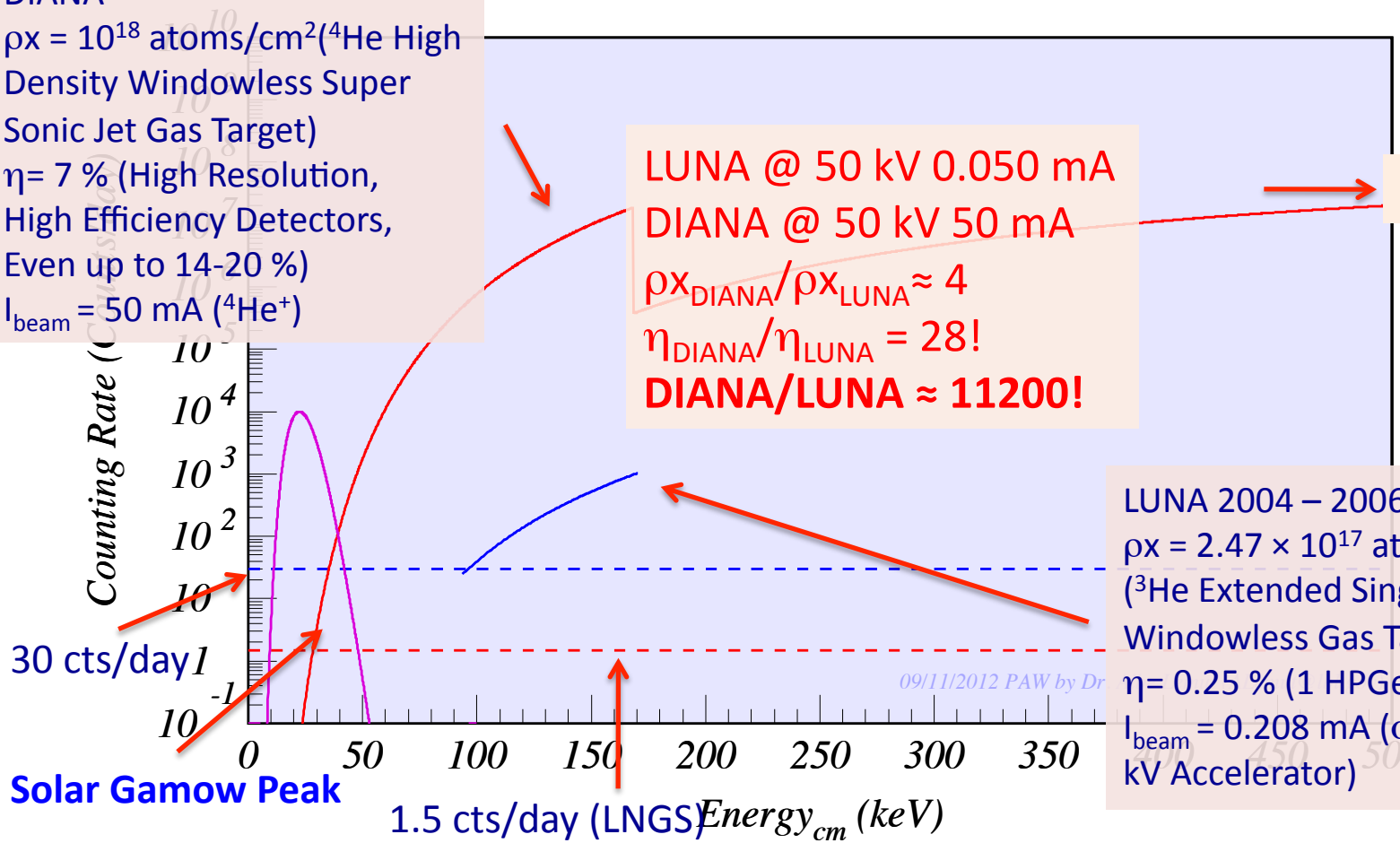
May 1st 2012, DIANA proposal submitted to NSF call:

- NSF Awarded the DIANA team a one year extension (FY 2013) to develop engineering design and detailed cost estimates with proposed underground site teams.
- The process for the site selection is underway.

$^3He(\alpha,\gamma)^7Be$: DIANA vs LUNA

LBL Has a High Experience in High Beam Intensity Ion Source Design!

DIANA
$\rho x = 10^{18}$ atoms/cm^2(^{4}He High Density Windowless Super Sonic Jet Gas Target)
η= 7 % (High Resolution, High Efficiency Detectors, Even up to 14-20 %)
I_{beam} = 50 mA ($^4He^+$)



LUNA @ 50 kV 0.050 mA
DIANA @ 50 kV 50 mA
$\rho x_{DIANA}/\rho x_{LUNA} \approx 4$
η_{DIANA}/η_{LUNA} = 28!
DIANA/LUNA ≈ 11200!

Up to 1.4 MeV

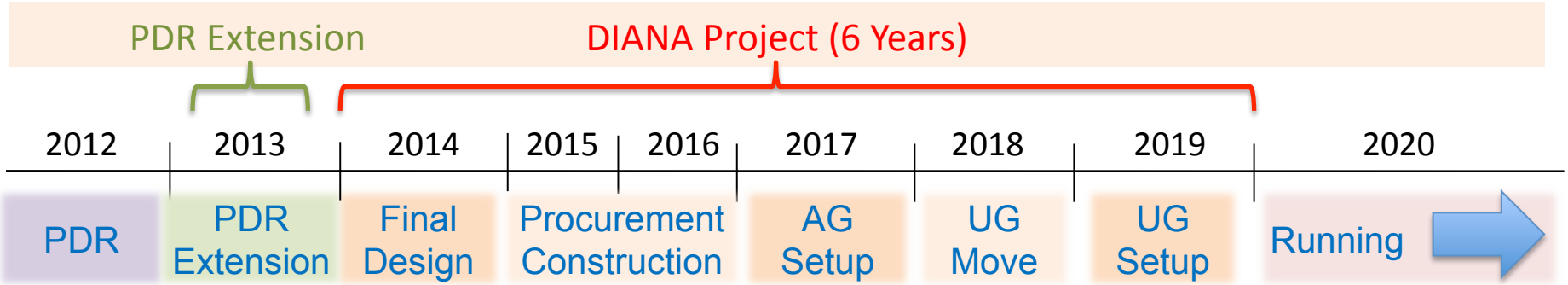
LUNA 2004 – 2006:
$\rho x = 2.47 \times 10^{17}$ atoms/cm^2 (^{3}He Extended Single Ended Windowless Gas Target)
η= 0.25 % (1 HPGe Detector)
I_{beam} = 0.208 mA (α, LUNA 400 kV Accelerator)

30 cts/day

Solar Gamow Peak

1.5 cts/day (LNGS)

Summary (Cost & Schedule)



Estimated cost: ≈ 46 M$ (Underground Site Cost not Included)

Summary:

- The underground approach for measuring nuclear reaction of astrophysical interest has been proved to be successful.
- DIANA will be the next generation underground accelerator facility for nuclear astrophysics experiments.
- DIANA Will support a broad low energy nuclear astrophysics program (≥ 20 years).
- DIANA Will be a unique deep underground accelerator facility with beam intensities never available before (i.e. LUNA at Gran Sasso).