DIANA & Underground Nuclear Astrophysics @ DUSEL Lab

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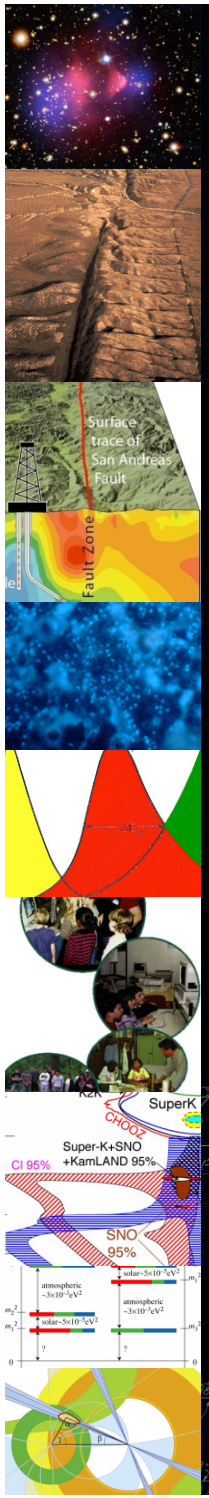


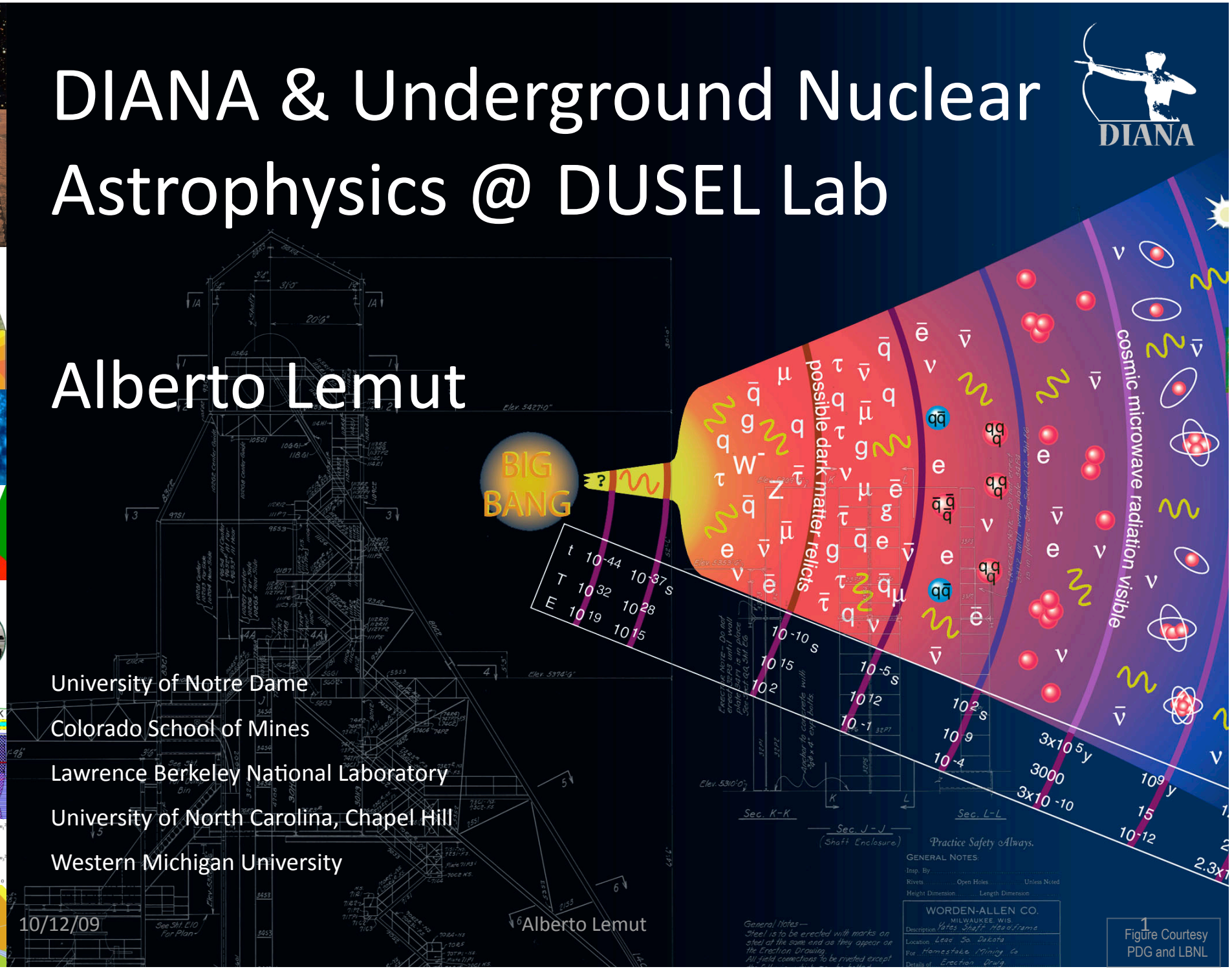
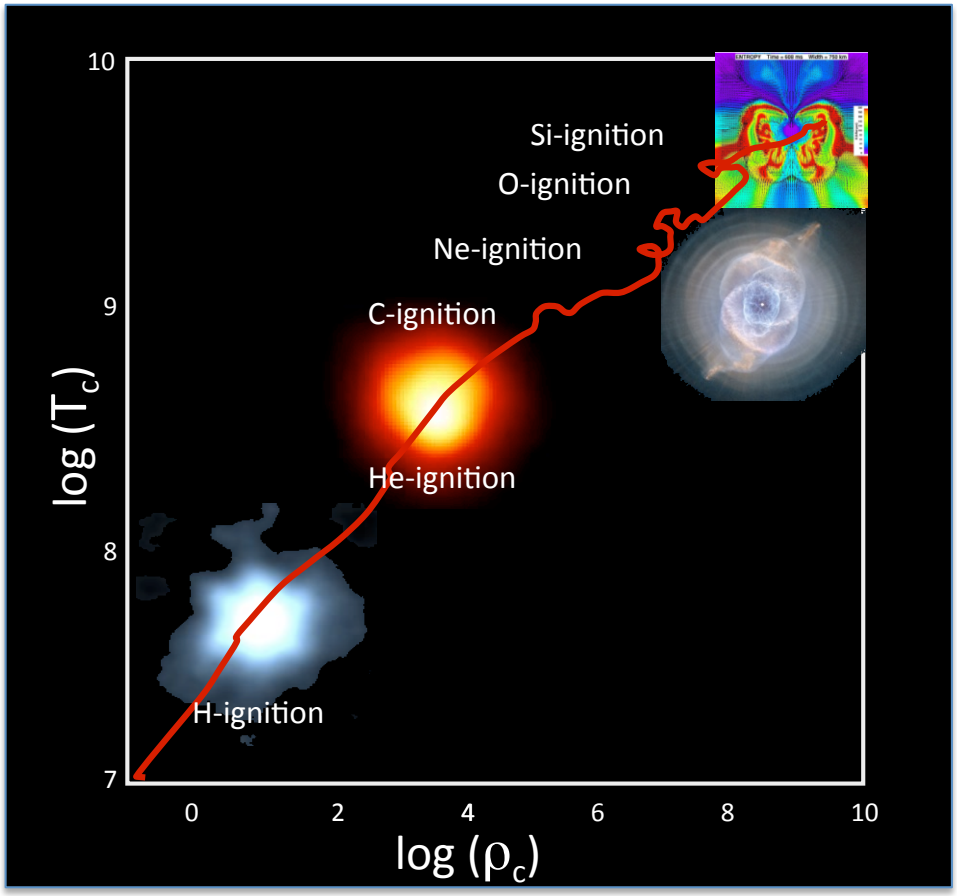


Figure Courtesy PDG and LBNL

A Very Brief Introduction

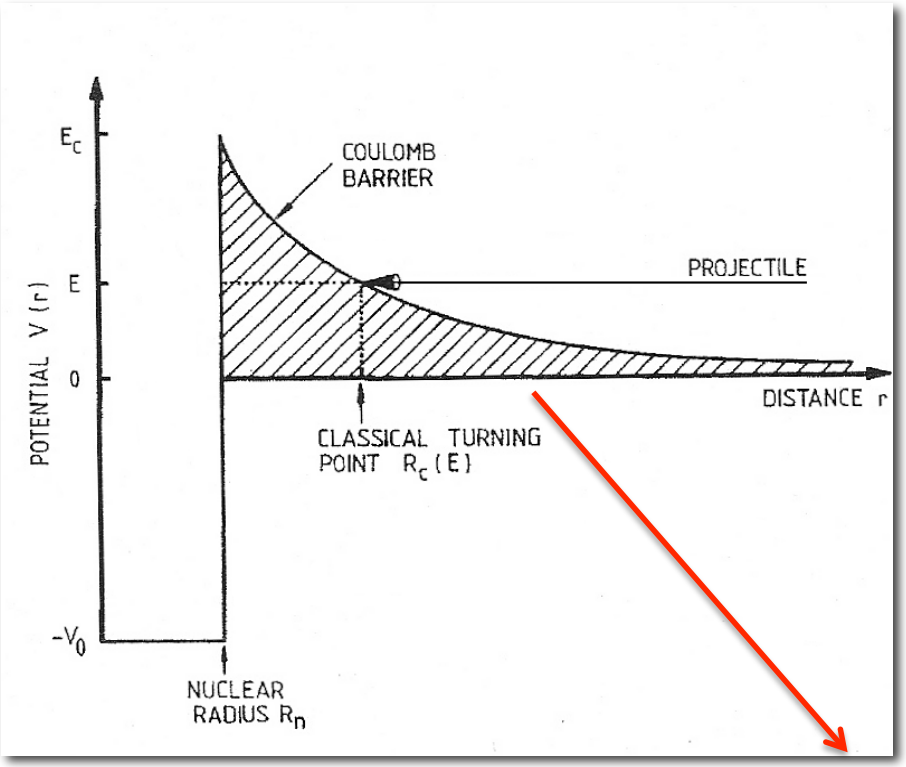


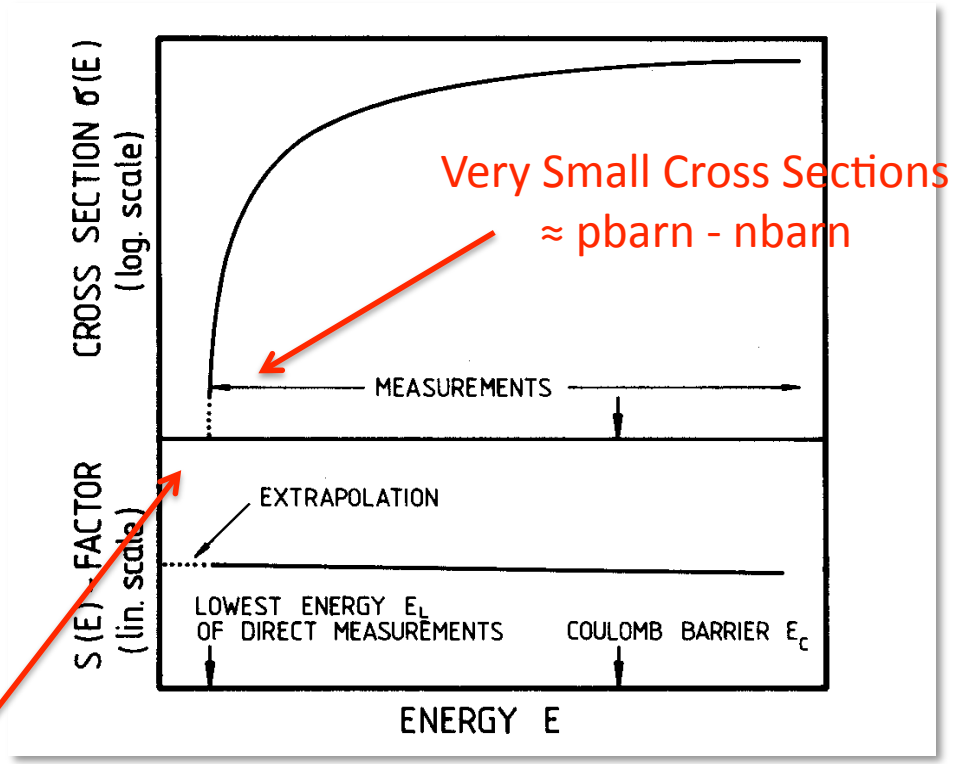
- Today is well known that stars are powered by nuclear reactions.
- Among the several key parameters (chemical composition, opacity, nuclei lifetimes, etc.) to model stars, reactions cross cross sections play an important role.
- They determines the origin of elements in the cosmos, stellar evolution and dynamic, etc.
- Many reactions ask for High Precision data.

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

Non Resonant Reaction Cross Section

At Sun $T = 15 \times 10^6$ K => $k_B T = 1.29$ keV << $E_c \approx$ MeV





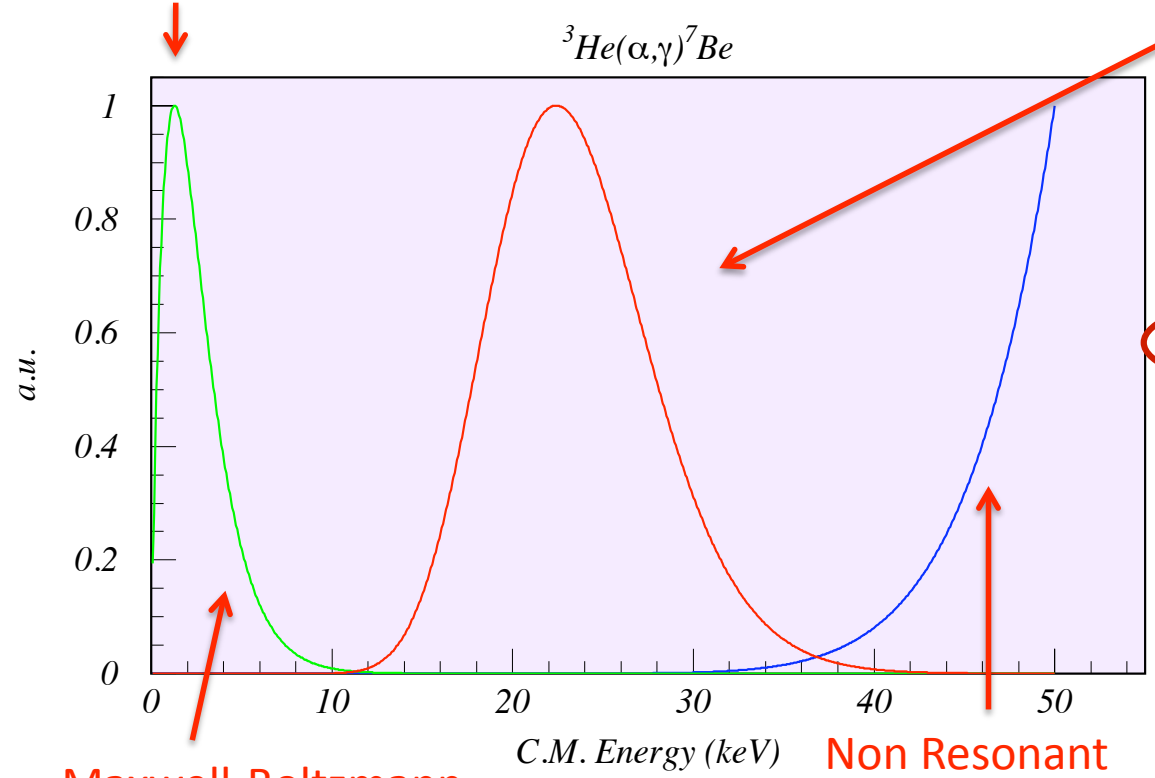
$$\sigma(E) = \frac{1}{E} e^{-\left(2\pi \frac{Z_T Z_p e^2}{\hbar} \sqrt{\frac{\mu}{2E}}\right)} S(E)$$

Stellar Reaction Rate

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

$k_B T_{Sun}$ = 1.29 keV

Gamow Peak = 22 keV



Maxwell-Boltzmann Distribution

Non Resonant Cross Section

Reactions	E_{Gamow}
$d(p,\gamma)^3He$	7 keV
$^3He(^3He,2p)^4He$	21 keV
$^3He(\alpha,\gamma)^7Be$	22 keV
$^{14}N(p,\gamma)^{15}O$	27 keV

Irradiated Energy by the Sun = 2×10^{39} MeV/s
Q value of pp-chain and CNO cycle = 26.73 MeV
Sun Reaction Rate = 10^{38}/s

Laboratory Reaction Rate

$$R = \rho x \sigma(E) \eta I_{beam}$$

Target Areal Density ρx = 10^{18} atoms/cm^2
Cross Sections $\sigma(E)$ = pbarn – nbarn
Absolute Detection Efficiency η = $10\ \%$
I_{beam} Beam Intensity = 1000 pμA

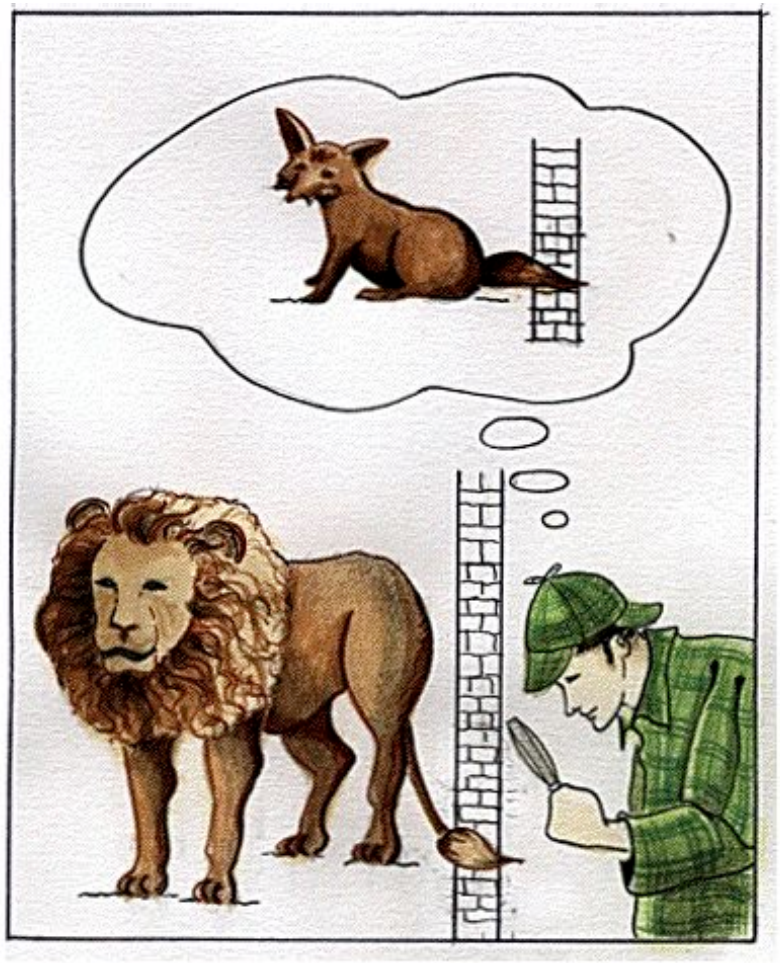
The Detection Rate Ranges from 1 event/month to 1 event/day

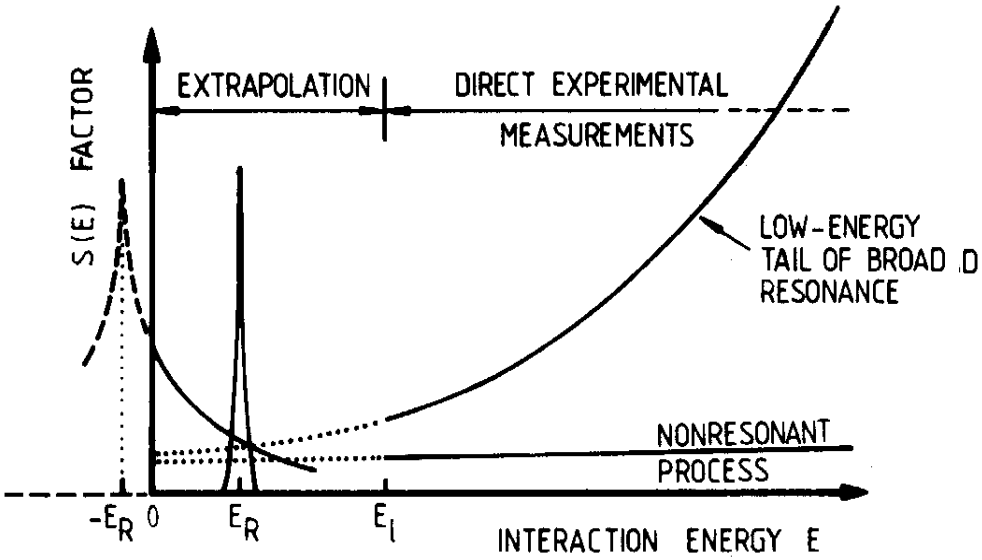
What Happens at Low Energies Where the Rate gets ≤ Background?

People Got Used to Extrapolate Using Several techniques!

A Comment on Extrapolations

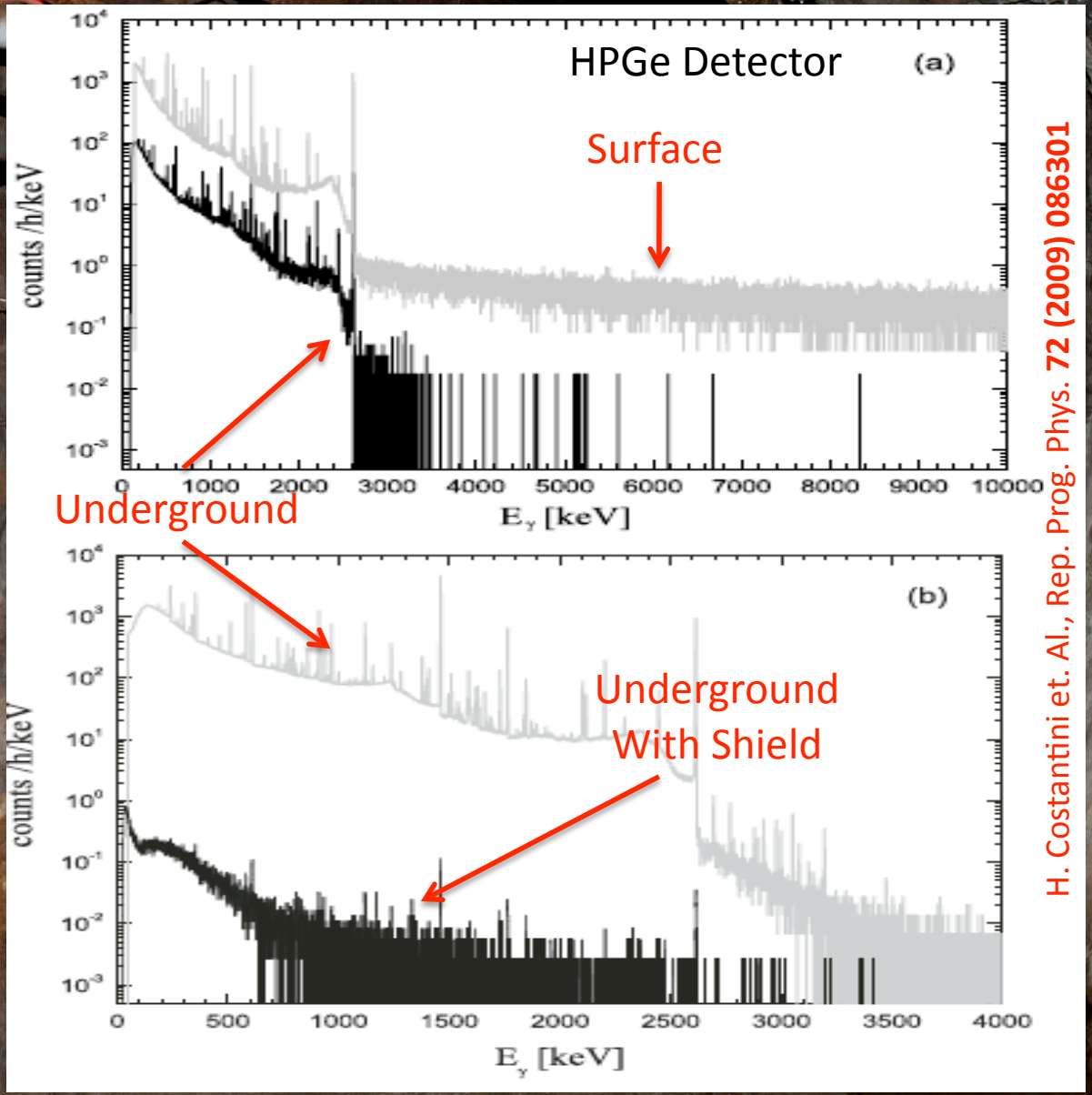
But…





Extrapolations could fail!!

Why Going Underground?



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 (= 3800 meter of water equivalent shielding)

Muon flux is reduced by 6 orders of magnitude

Neutron flux is reduced by 3 order of magnitude

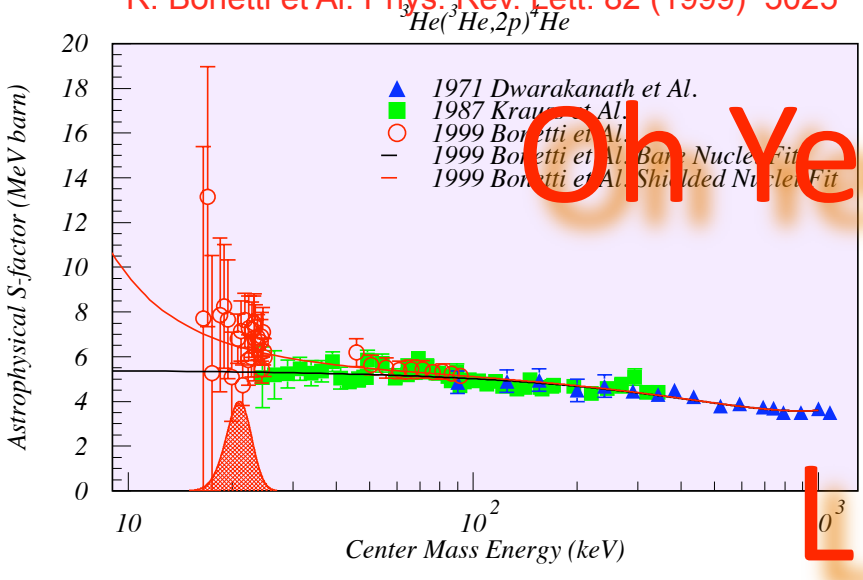
Clear advantage for high Q-value reactions.

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

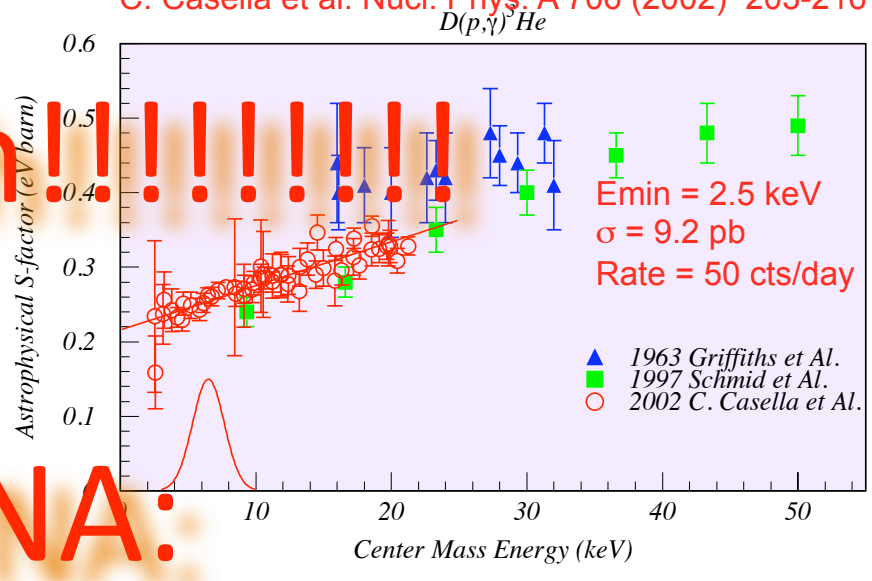
Was This Approach Successful?

DIANA

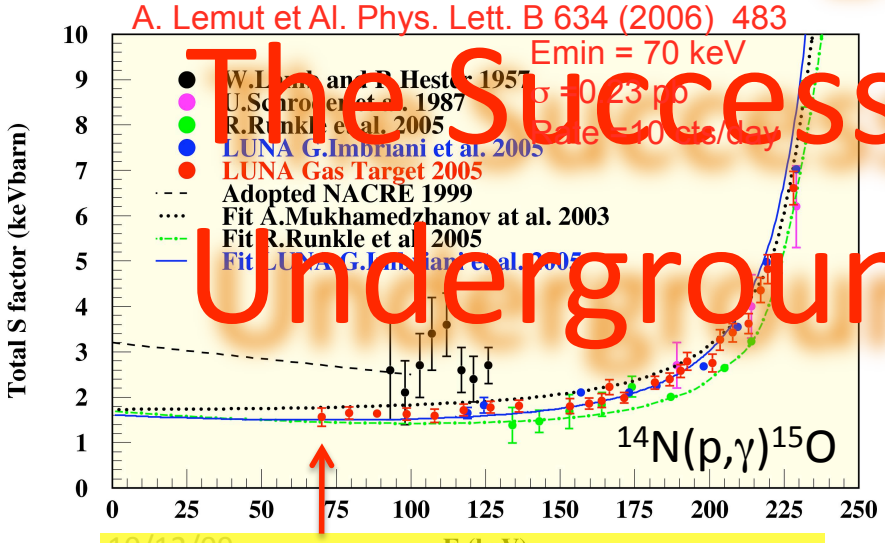
R. Bonetti et Al. Phys. Rev. Lett. 82 (1999) 5025



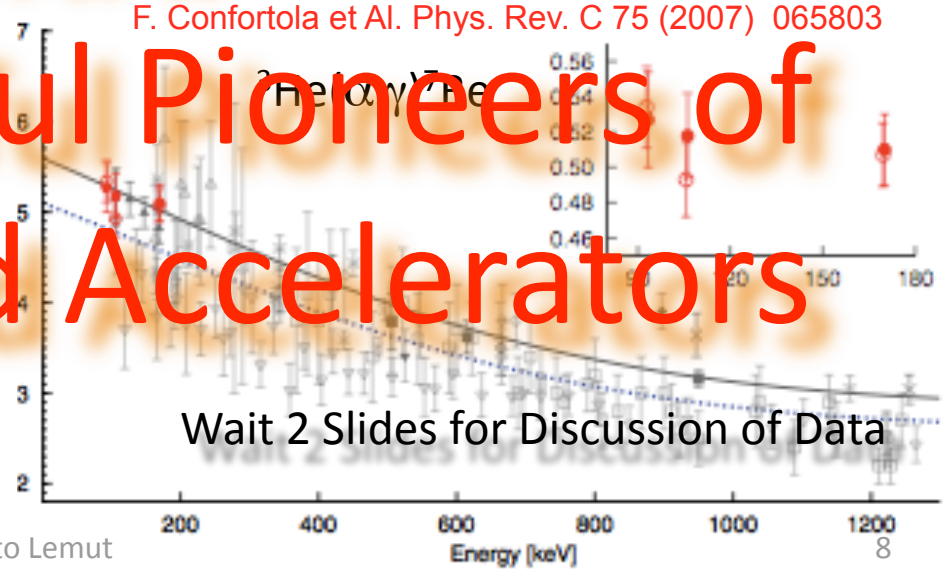
C. Casella et al. Nucl. Phys. A 706 (2002) 203-216



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



F. Confortola et Al. Phys. Rev. C 75 (2007) 065803



Wait 2 Slides for Discussion of Data

Oh Yeah!!!!!!!!

LUNA:

The Successful Pioneers of Underground Accelerators

49 Days of Effective Beam Time!!!

Is There Anything Left to Do?

DIANA

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

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

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

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

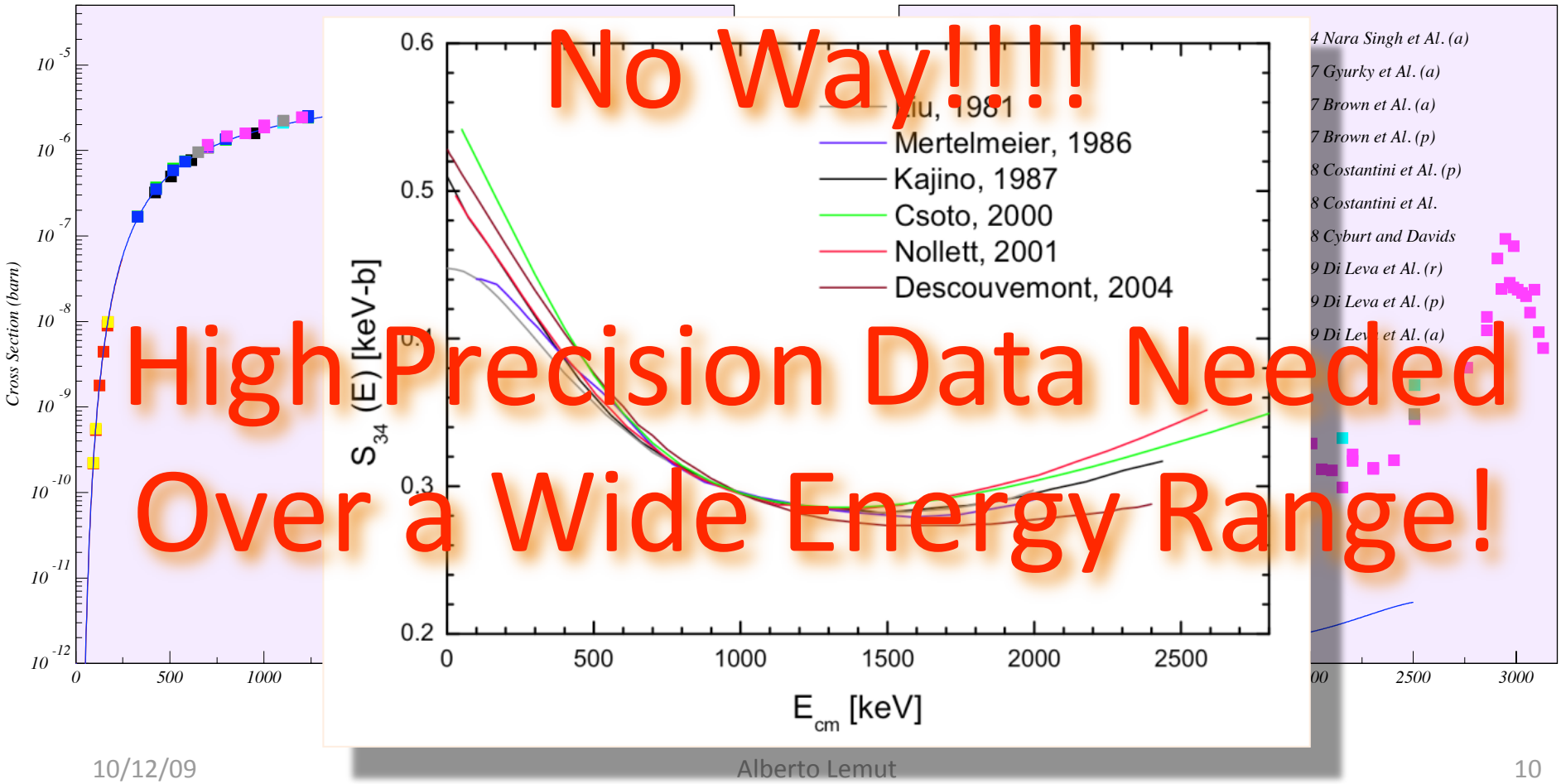
Heavy Ion Burning

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

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

Why DIANA?

A Physics Case Example: $^{3}He(\alpha,\gamma)^{7}Be$

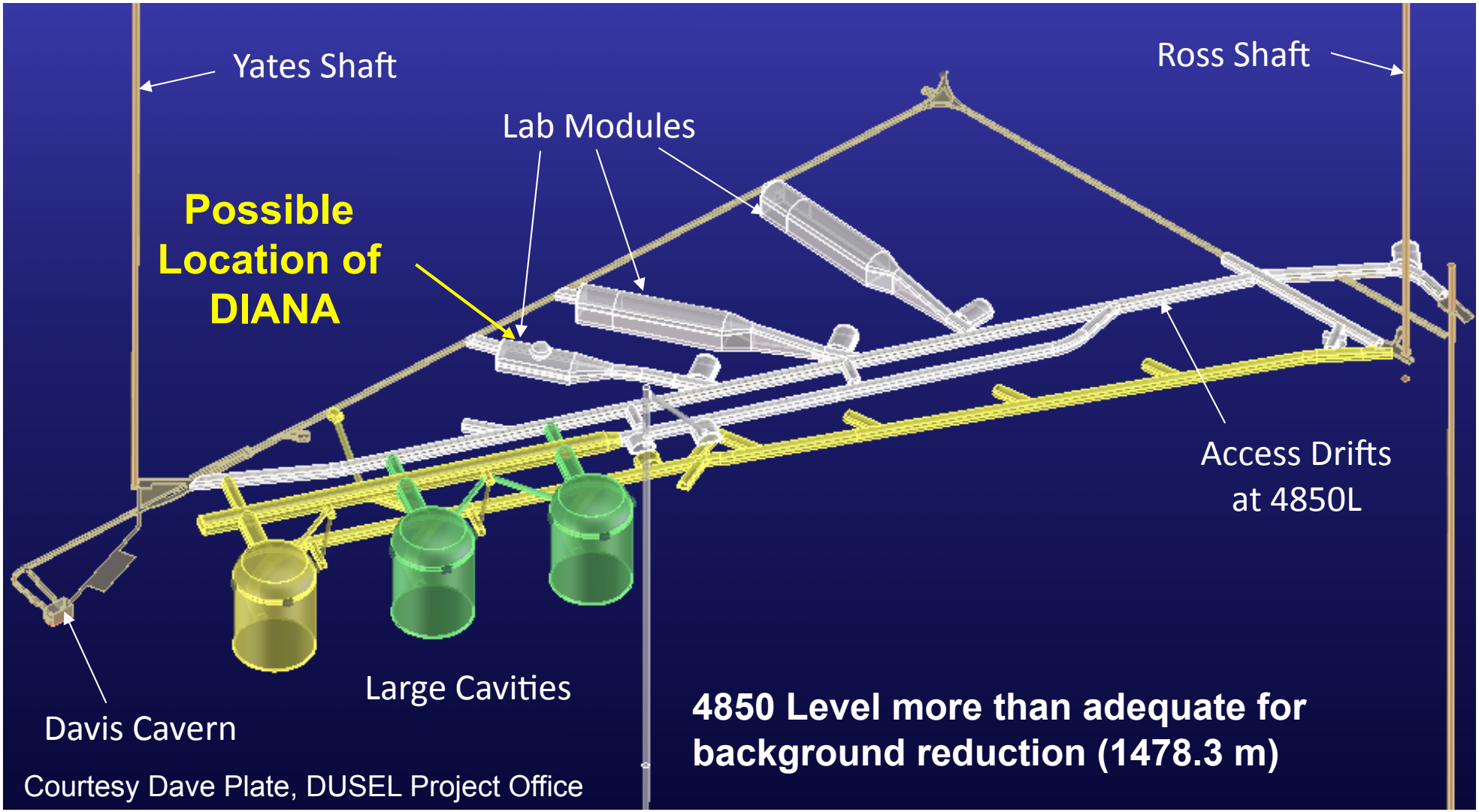


No Way!!!!

High Precision Data Needed Over a Wide Energy Range!

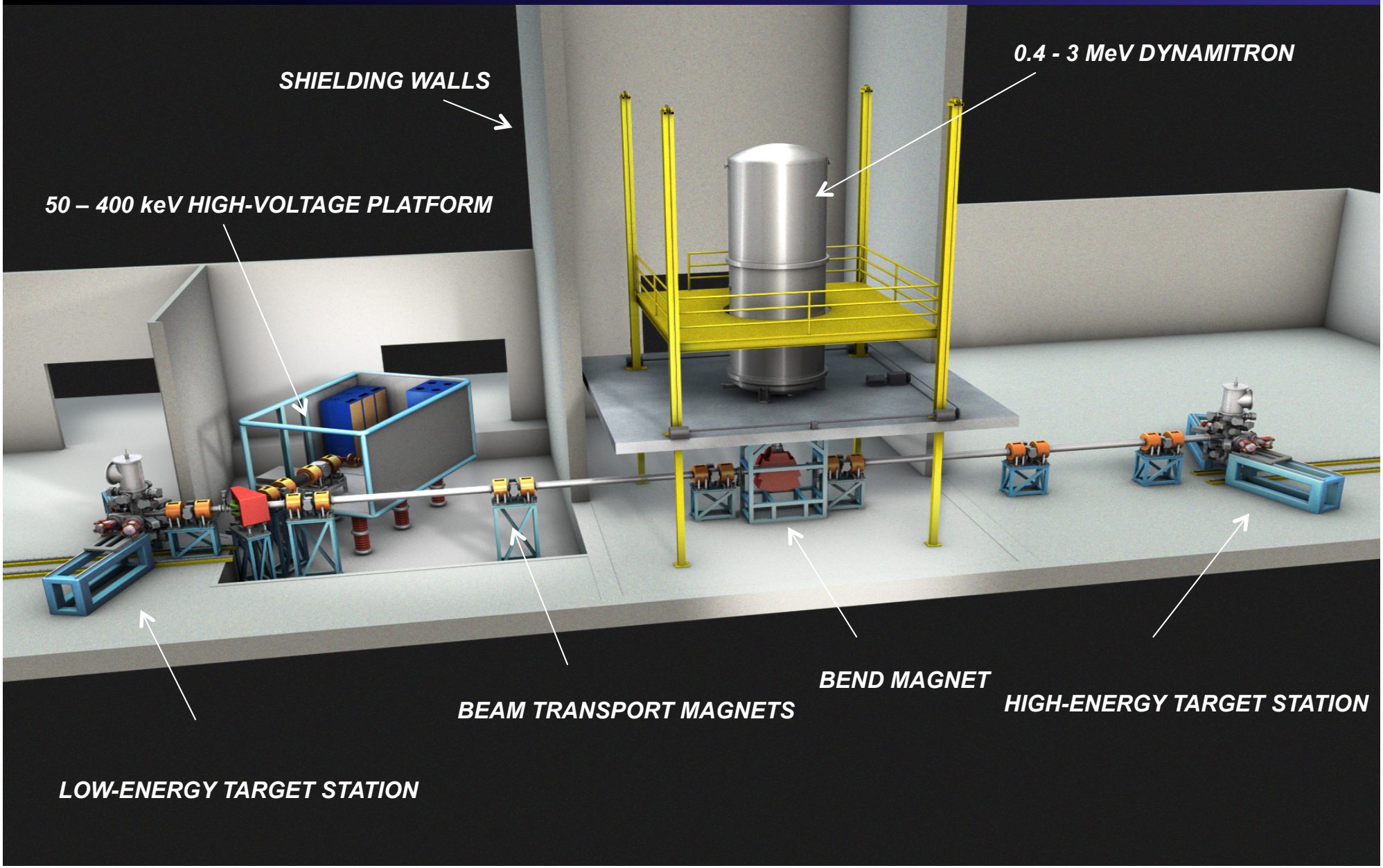
DIANA @ 4850 DUSEL Lab Level

Dakota Ion Accelerators for Nuclear Astrophysics



Courtesy Dave Plate, DUSEL Project Office

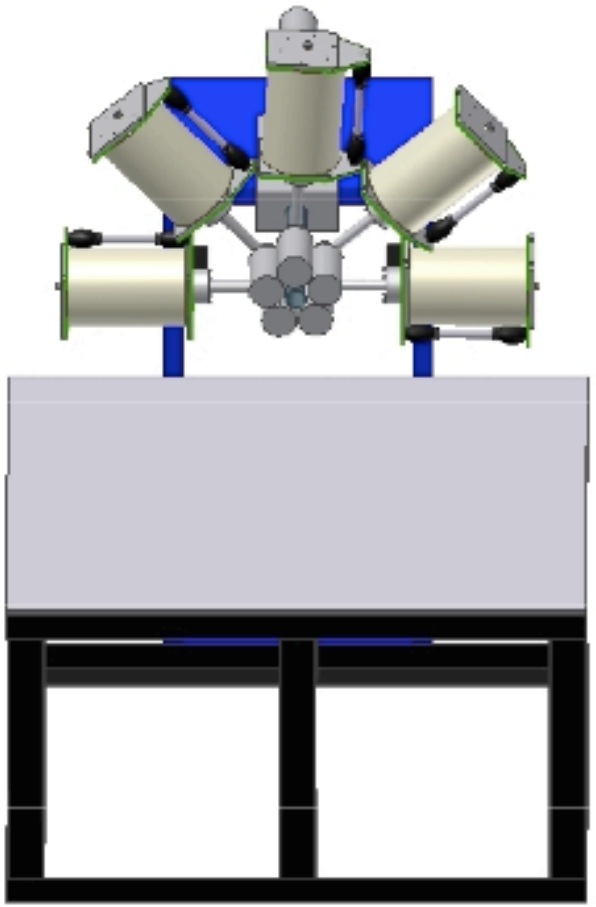
DIANA Overview

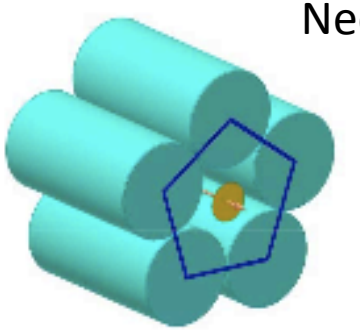


Detectors

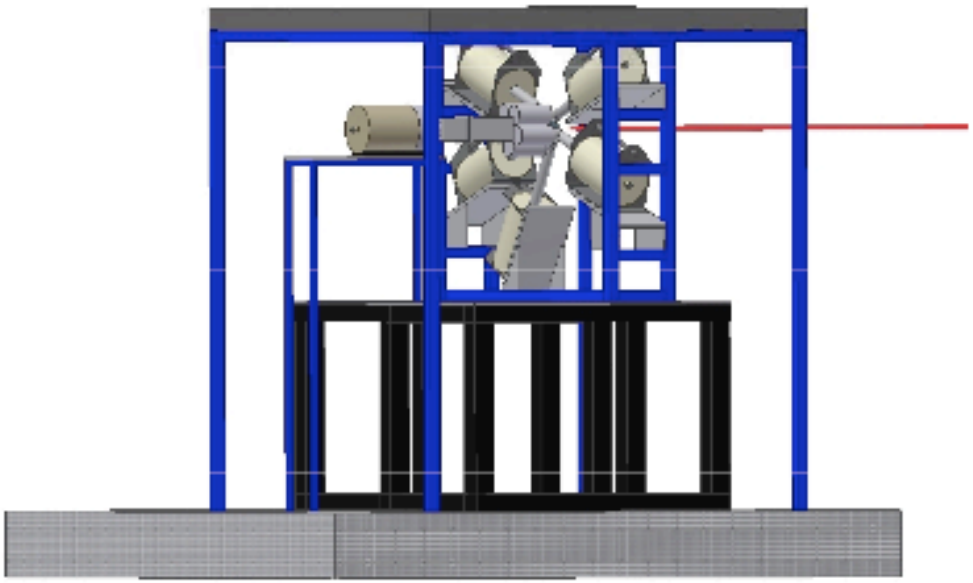
HPGe Are Ideal (Un-enriched MAJORANA Look Very appealing!)

Need to Fit Supersonic Jet Target Geometry



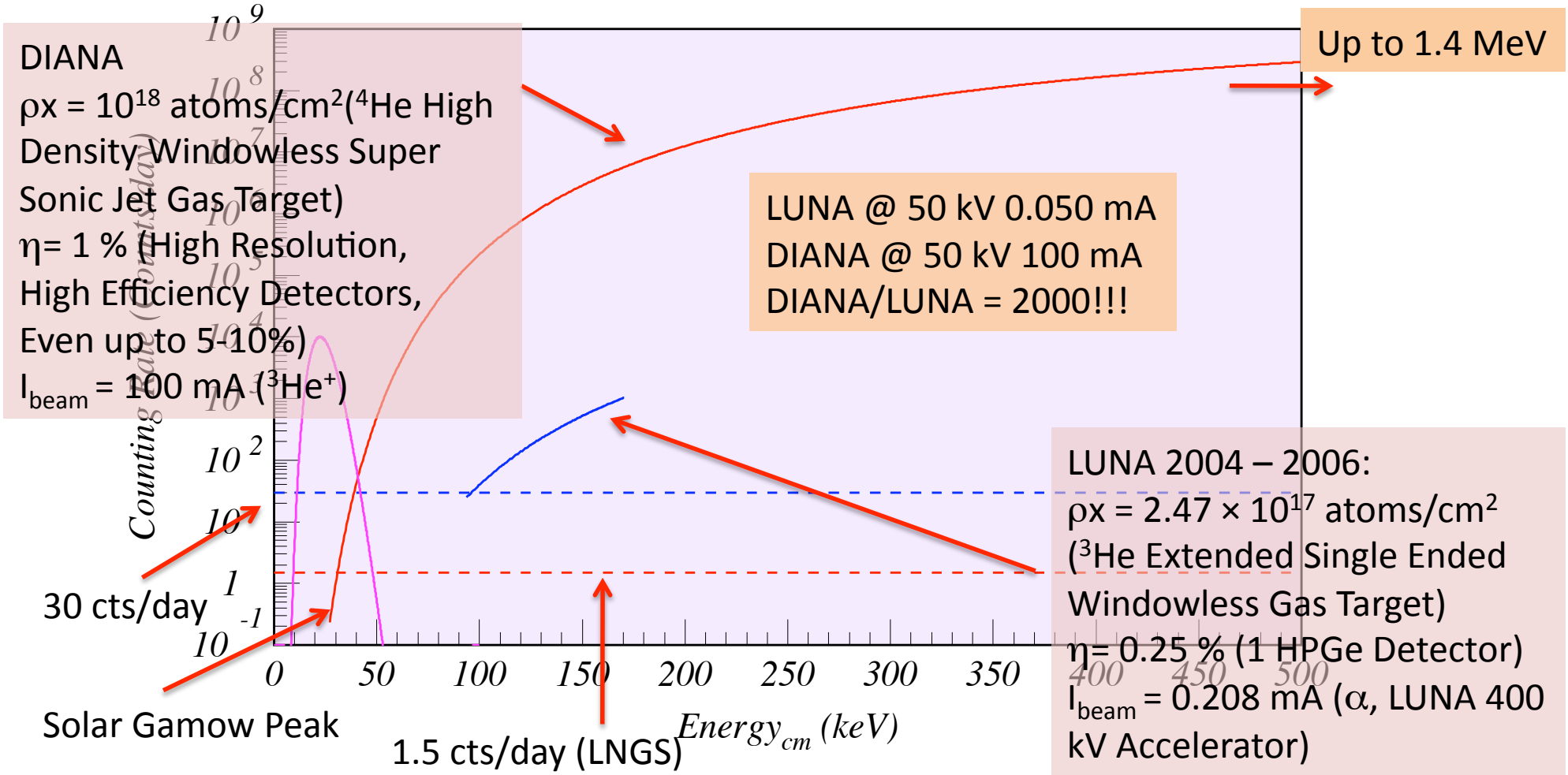


MC simulations of design for optimizing the segmentation of Ge crystals



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

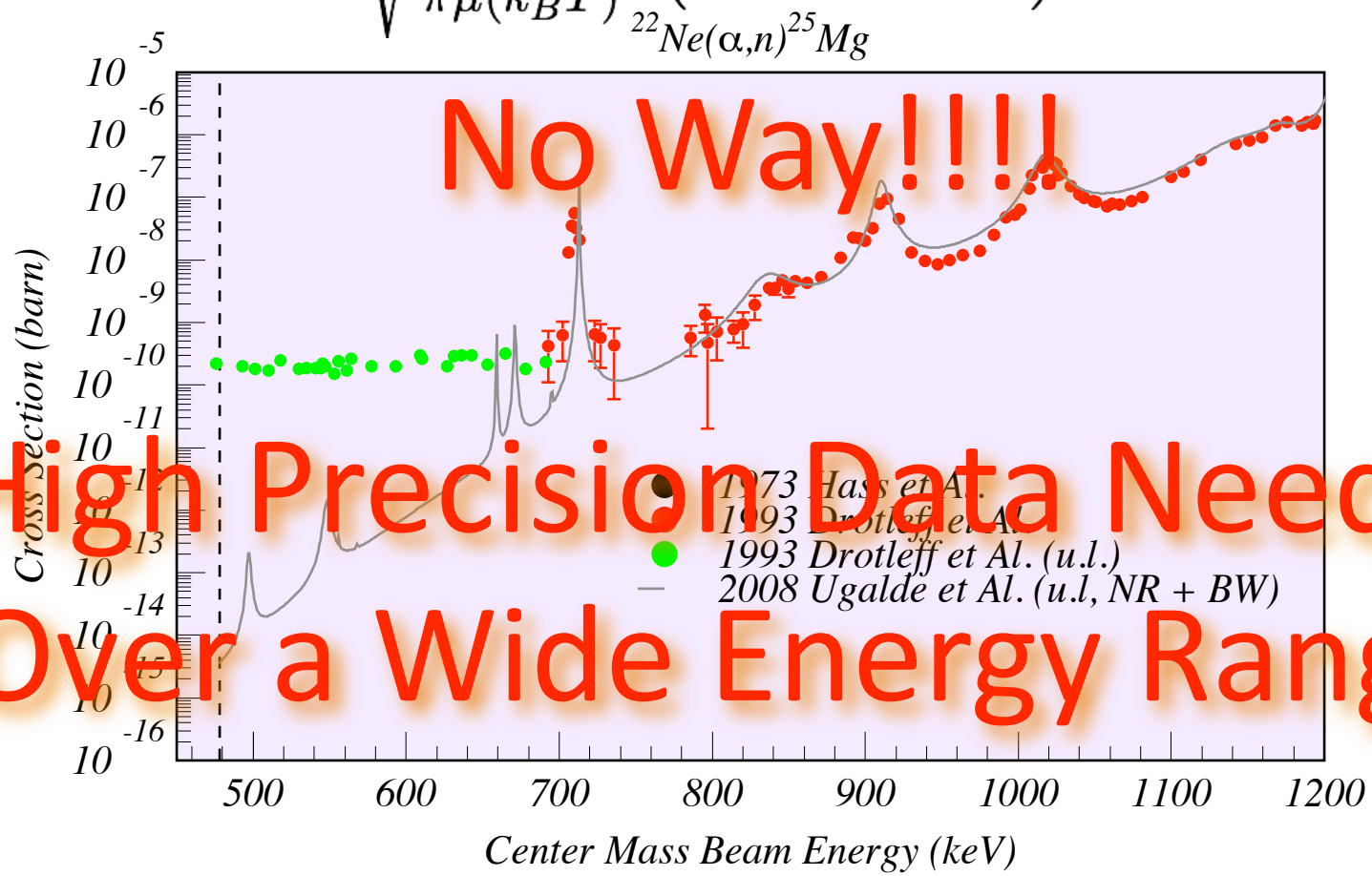
Berkeley Lab Has a High Experience in High Beam Intensity Ion Sources Design!



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

Narrow Breit-Wigner Single Level Resonance:

$$< \sigma v > (T) = \sqrt{\frac{8}{\pi \mu (k_B T)^3}} \left(E_{res} e^{-E_{res}/k_B T} \right) 2\pi^2 \lambda^2 (E_{res}) \omega \gamma_{res}$$



No Way!!!!

High Precision Data Needed Over a Wide Energy Range!

E_α Threshold = 478.3 kev (cm) = 565 keV (lab)

Summary

✧The underground approach for measuring nuclear reaction of astrophysical interest has been proved to be successful.

✧Many nuclear reaction of astrophysical interest could receive benefits from being measured in an underground laboratory.

✧ DIANA's goal will be to improve current accelerator, detectors and target technologies presently used in underground nuclear physics, towards (hopefully) outstanding results.

The DIANA Team

@ DUSEL Workshop

Thursday, October 1st 2009, Lead SD

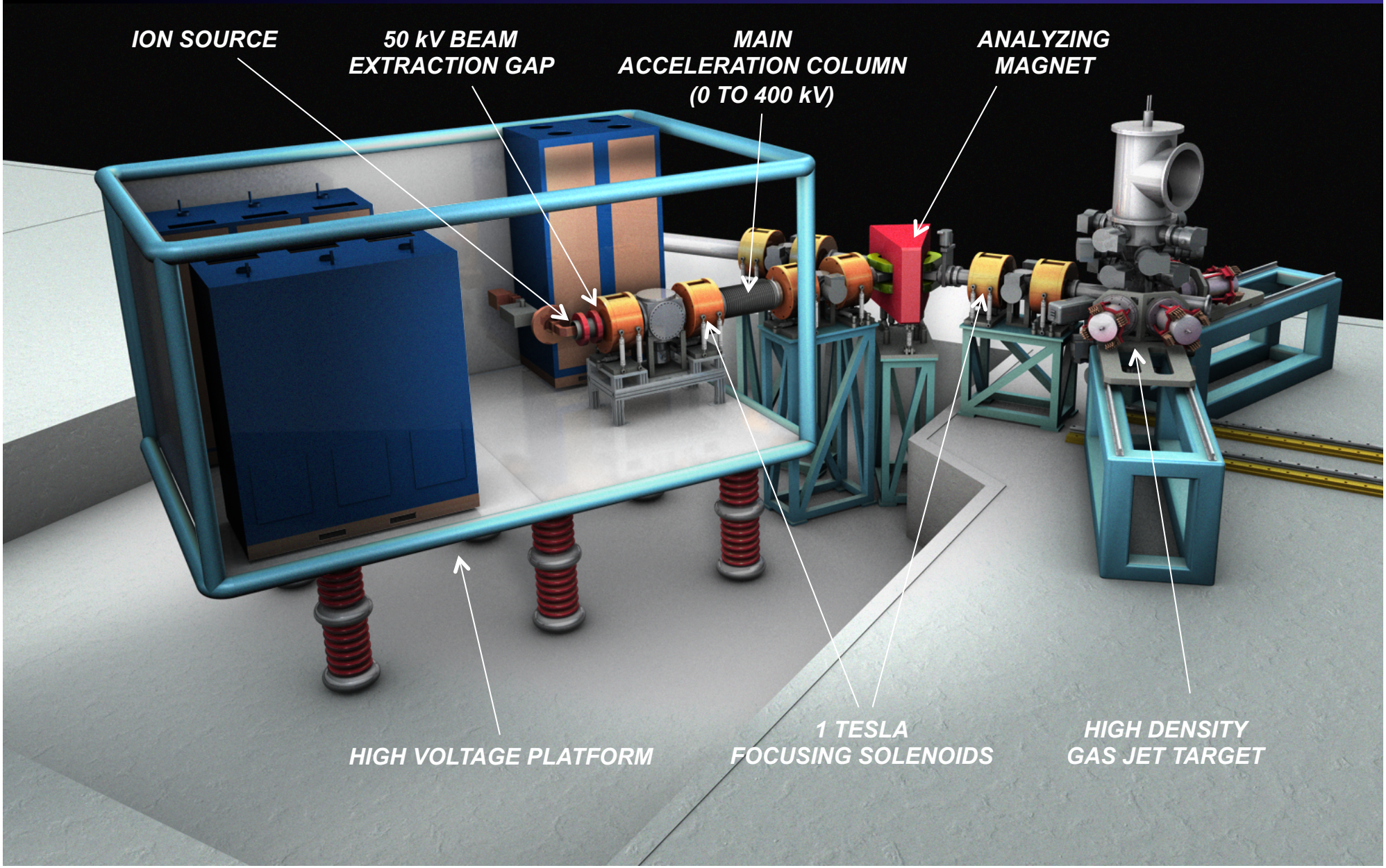
UNIVERSITY OF NOTRE DAME

COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

BERKELEY LAB
ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY

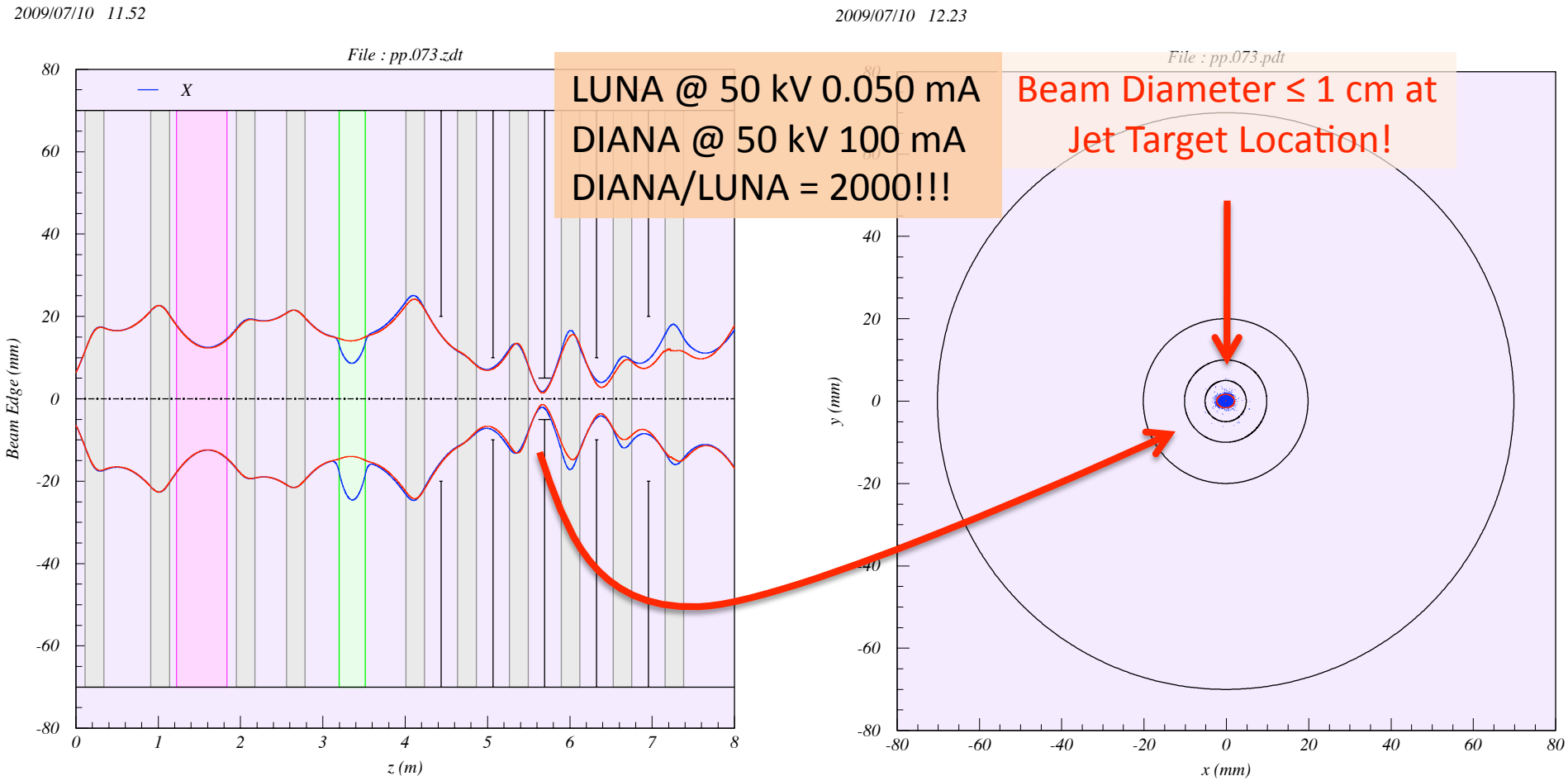
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

DIANA Low Energy



DIANA Low Energy Simulations

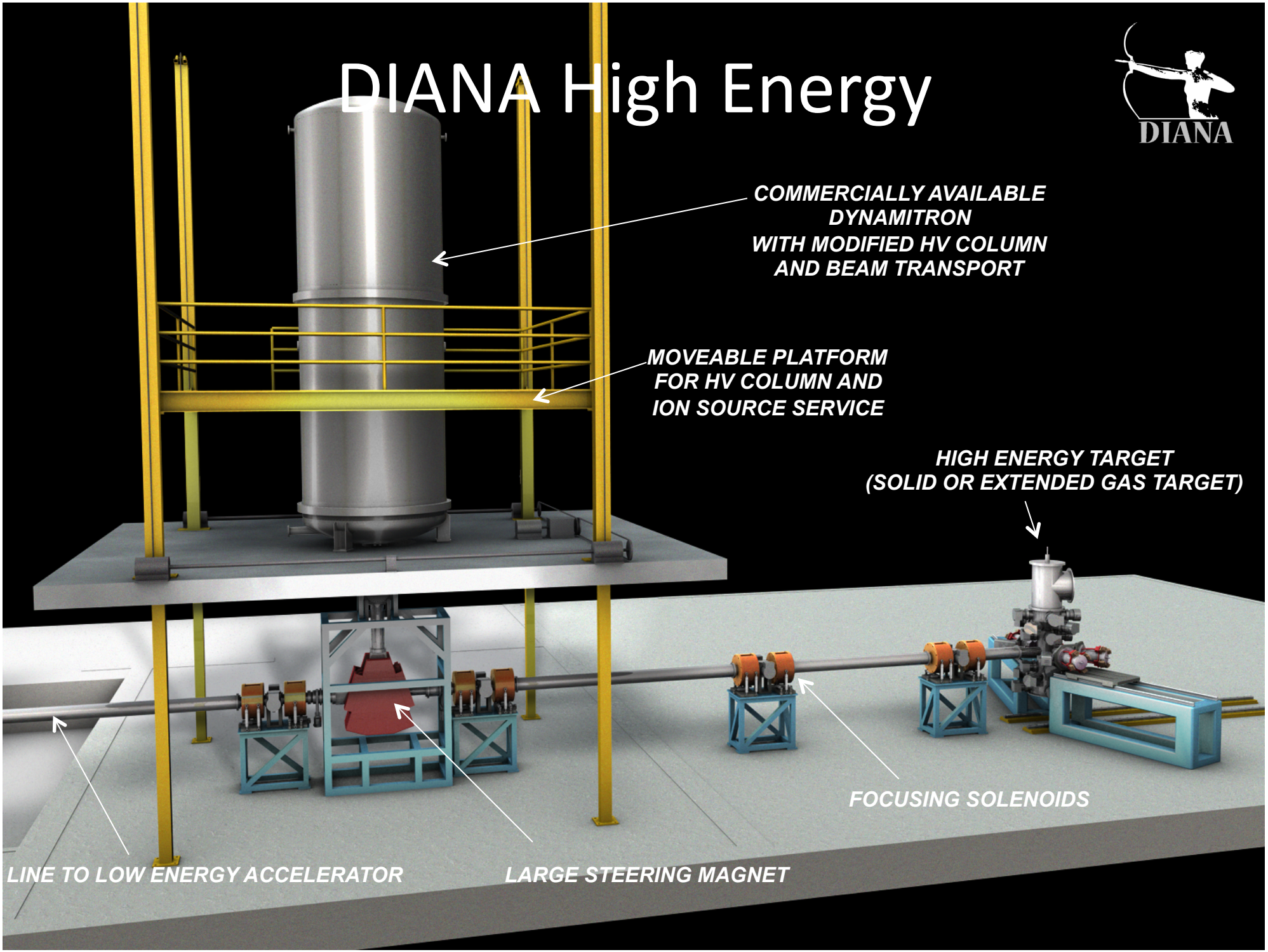
100 mA $^3He^+$ Beam at 50 kV



LUNA @ 50 kV 0.050 mA
DIANA @ 50 kV 100 mA
DIANA/LUNA = 2000!!!

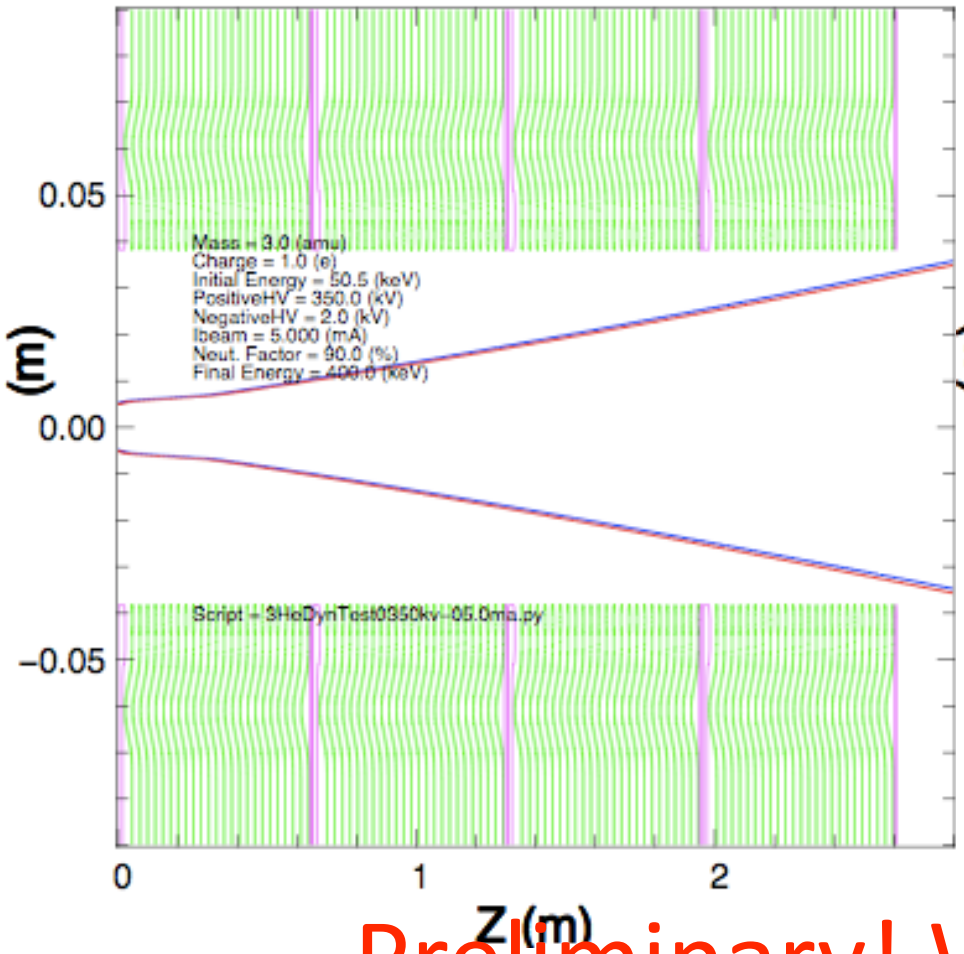
Beam Diameter ≤ 1 cm at Jet Target Location!

DIANA High Energy

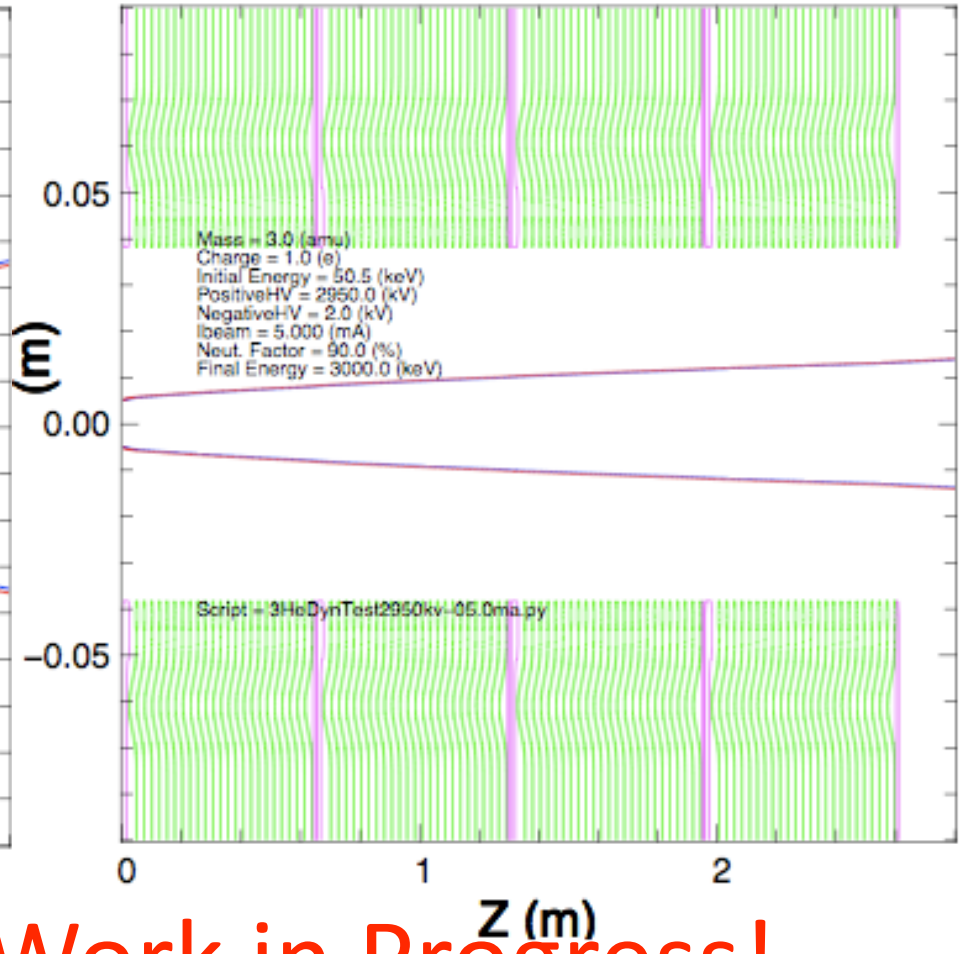


DIANA High Energy Simulations

5 mA $^3He^+$ Beam at 400 kV



5 mA $^3He^+$ Beam at 3 MV



Preliminary! Work in Progress!