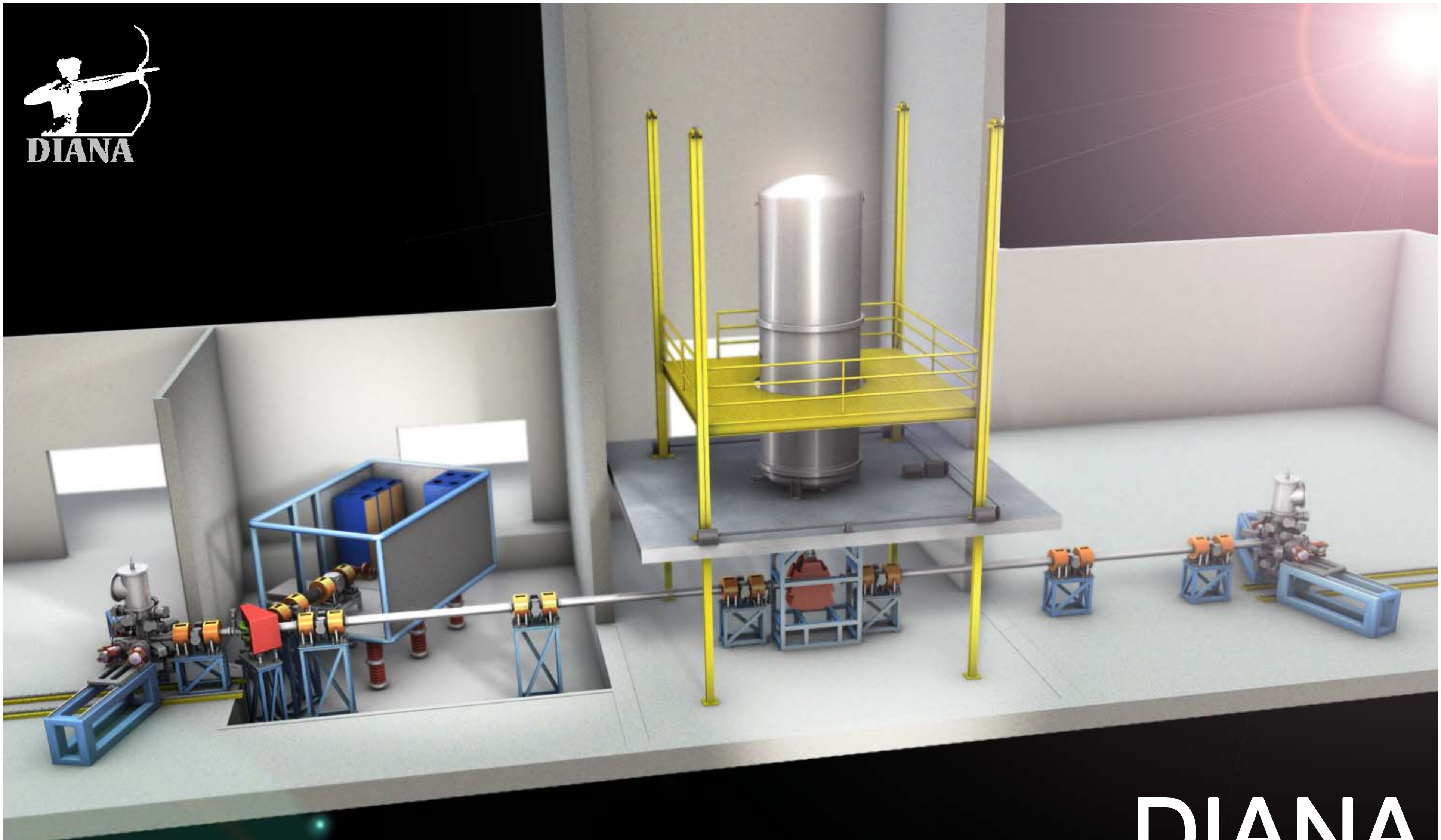

DIANA

A NOVEL NUCLEAR ASTROPHYSICS UNDERGROUND ACCELERATOR FACILITY

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Lawrence Berkeley National Laboratory

RPM

March 23rd 2009

DUSEL S-4 Proposal for DIANA

- Submitted S-4 January 2009 in response to NSF 09-500: "Development of Technical Designs for Potential Candidates for the DUSEL Suite of Experiments"

- Physics program proposal:
  1. Solar neutrino sources and solar metallicity (Std. Solar Model)
  2. Carbon-based stellar nucleosynthesis
  3. Neutron sources for heavy element production (beyond Fe)

- Very broad range of nuclear astrophysics topics can be addressed in future with this infrastructure

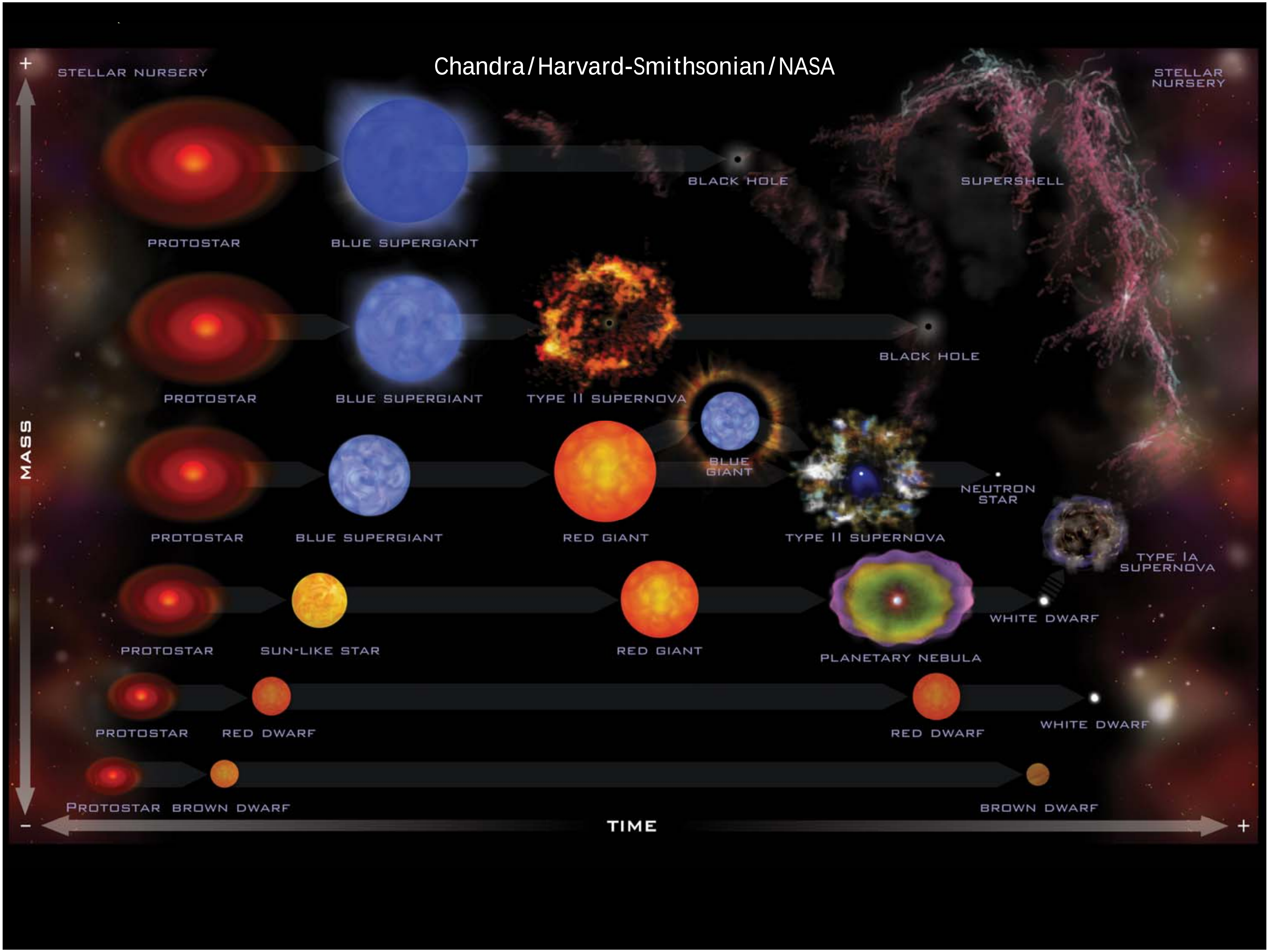
DIANA physics program studies stellar evolution

- The NSAC long range plan identifies this physics:

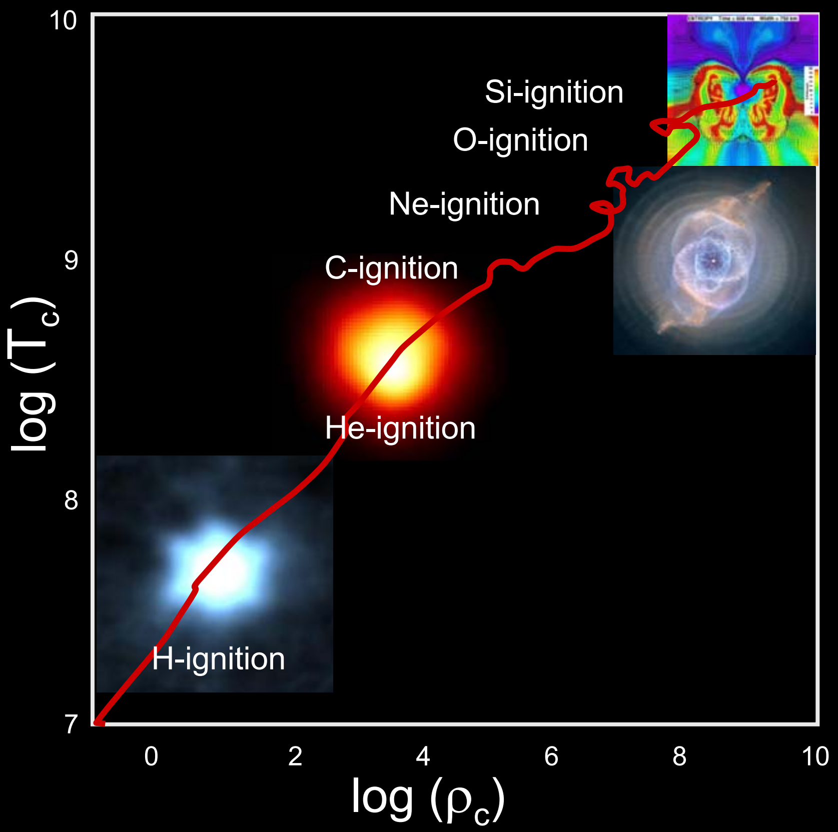
  "What are the nuclear reactions that drive stars and stellar explosions?"

  "… The extremely small cross sections of the stellar reaction rates result in the long liftimes of stars, but represent the main challenge to a direct experimental study. … Stellar models still suffer from large uncertainties in key nuclear reactions such as 12C(a,g) that then also affect the modelling of core collapes and Type 1a supernovae. … The largest handicap is the small cross section coupled with large natural background, which prohibits the detection of the characteristic reaction signals. The use of underground-based low-energy accelerator facilities [such as LUNA] reduces background by orders of magnitude. DUSEL will provide an opportunity for the development of such a facility in the United States."

  The Frontiers Nuclear Science: A Long Range Plan **(December 2007)**


Chandra/Harvard-Smithsonian/NASA
STELLAR NURSERY
STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
SUPERSHELL
PROTOSTAR
BLUE SUPERGIANT
TYPE II SUPERNOVA
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
BLUE GIANT
TYPE II SUPERNOVA
NEUTRON STAR
TYPE IA SUPERNOVA
PROTOSTAR
SUN-LIKE STAR
RED GIANT
PLANETARY NEBULA
WHITE DWARF
PROTOSTAR
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF
MASS
TIME

Nuclear burning & stellar evolution



Each phase of stellar evolution consists of different nuclear fuel cycles, determined by available nuclear reactions, characterized by:

Energy generation
Time scale
Nucleosynthesis cycles and outputs

New Solar Neutrino Experiments

Solar neutrino detection is poised to assume its initial conception as a probe of the deep solar interior and the SSM

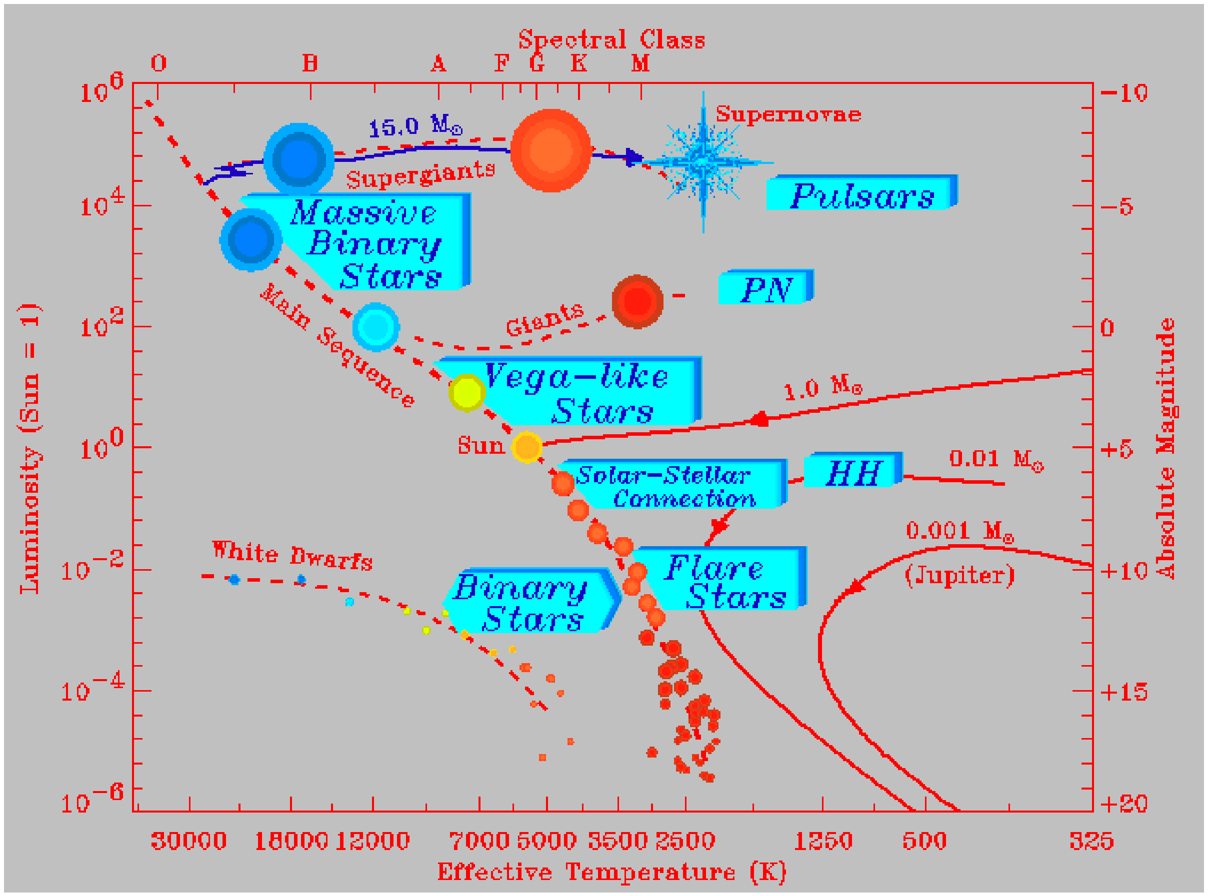
(see W. Haxton's talk: re-assuming Ray Davis' motivation for solar ν's)

- Borexino has detected MSW effect at low energy from disappearance of ^{7}Be (1.8 sigma) -- needs verification
- KamLAND aims for direct detection of ^{7}Be solar neutrinos
- KamLAND could detect CNO cycle neutrinos, which would constrain CNO energy contribution to the Standard Solar Model, currently rather unknown.

Do Nuclear Reactions Power the Stars?

Helioseismology results and solar photosphere abundance data suggest that:

- The sun is homogeneous
- The sun is young
- The sun is not powered by nuclear reactions



Teach the controversy!

http://www.creationdiscovery.org/cdp/articles/shrsun.html

Physics questions

Solar neutrino sources and solar metallicity (Std. Solar Model)

- What is the absolute flux of neutrinos from the sun?
- What is the solar core temperature?
- What is the abundance of non-hydrogen nuclei?

Carbon-based stellar nucleosynthesis

- What is the composition of stellar material after proton and helium burning (depending on the stellar mass)?
- What is the progenitor material for supernova explosive nucleosynthesis?
- What is the time scale for later stellar burning (carbon and oxygen phases) -- as a function of stellar mass?

Neutron sources for heavy element production (beyond Fe)

- How large is the neutron production in RG stellar burning? How significant is the slow neutron capture process for nucleosynthesis?

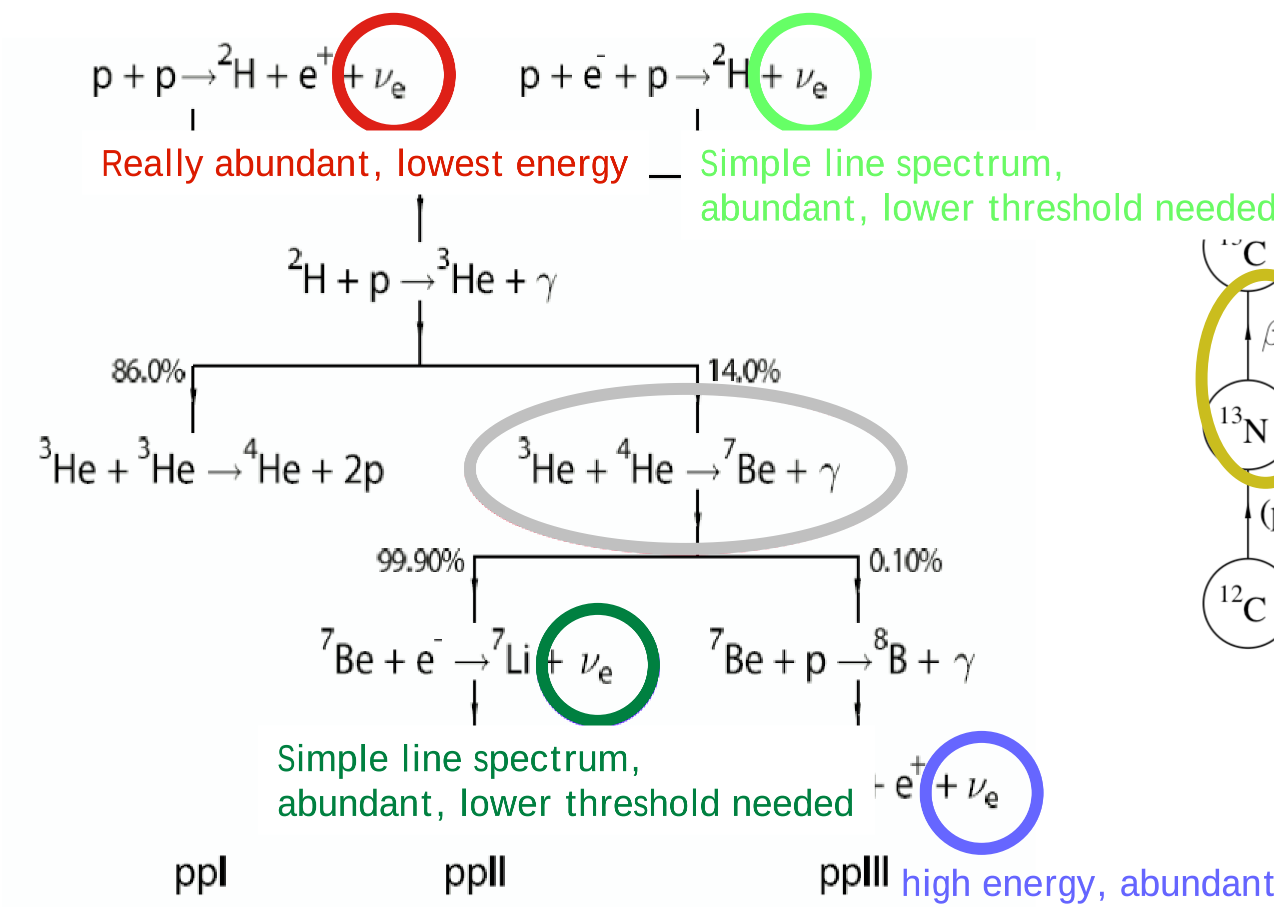
Solar neutrino sources and solar metallicity

Recent meeting at Institute for Nuclear Theory, UW Seattle:

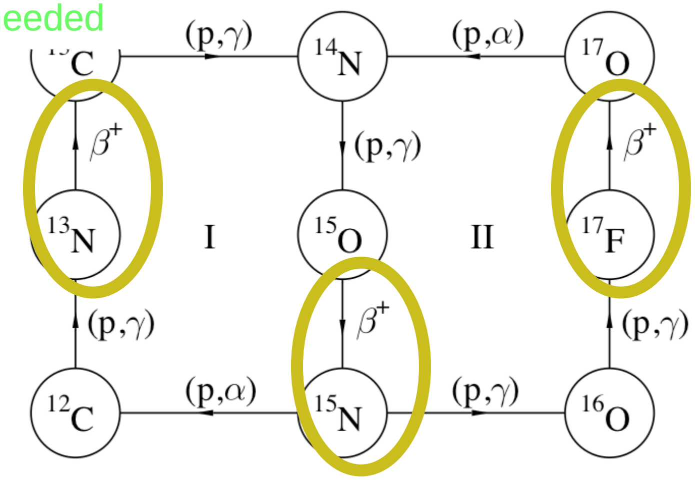
Solar Fusion Cross Sections for the pp chain and CNO cycle

Q: What are the data needs for next generation of solar neutrino studies?

Solar pp chain neutrinos



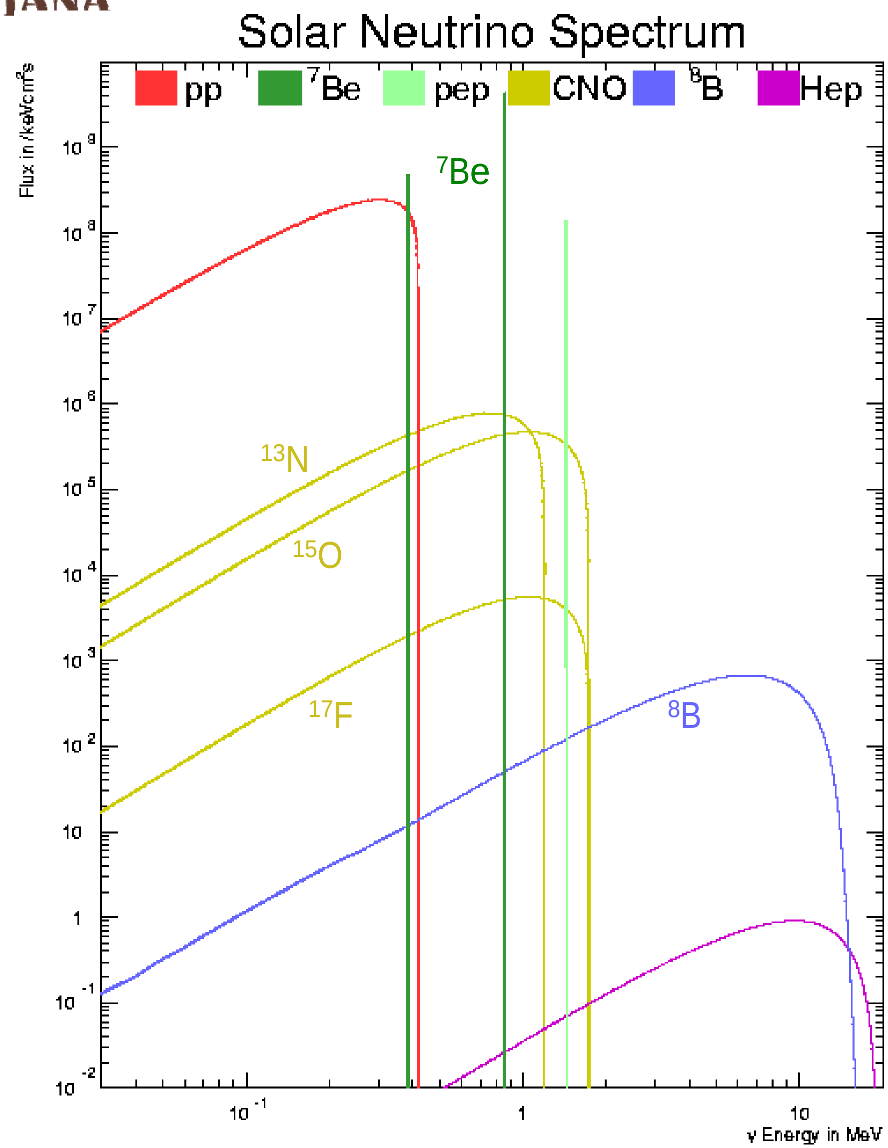
Solar CNO cycle neutrinos



high energy, less abundant

Informative for CNO energy

Solar neutrino sources and solar metallicity



Predicted solar neutrino fluxes (generated from the SSM)

Depend on

- T -- solar core temperature
- Z/X -- metallicity (non-H abundance)

^{8}B neutrino flux varies as ~ T^{22}, strongly with (Z/X)

Both $\Phi(^8B)$ and $\Phi(^7Be)$ depend sensitively on S_{34}

Experiments to measure neutrino oscillation parameters, matter effects need confirmation of SSM for more precise flux and spectrum predictions.

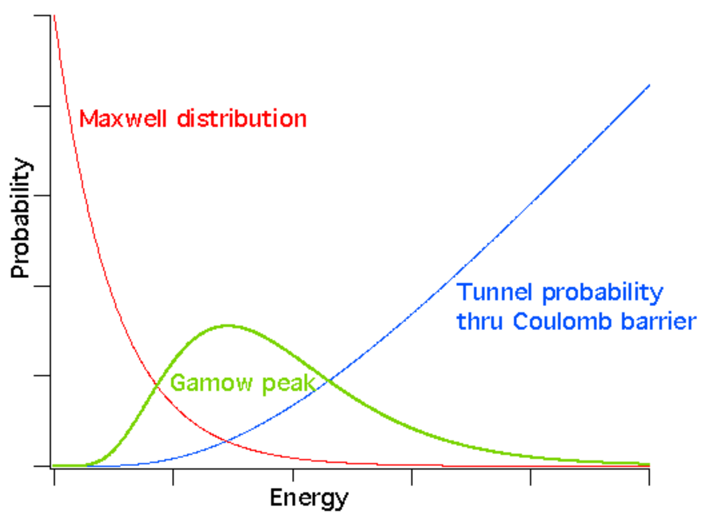
Stellar Reaction Cross Sections

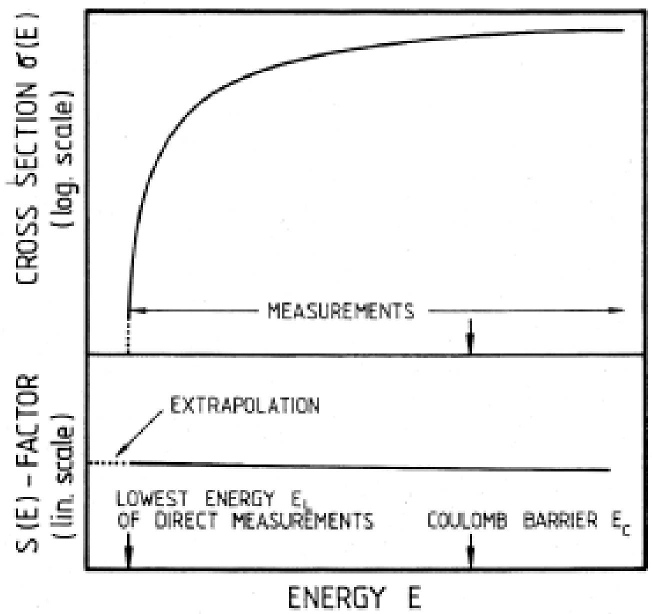
X + Y ⟶ P + Q

$$R = N_x N_y \langle \sigma v \rangle = N_x N_y \sqrt{\frac{8}{\pi \mu}} \frac{1}{(k_b T)^{3/2}} \int_0^\infty E \cdot \sigma(E) \exp\left(\frac{E}{k_b T}\right) dE$$

Simplify by factoring into the thermal distribution with Coulomb barrier and the nuclear structure dependent portion:

$$\sigma(E) = \frac{S(E)}{E} \exp(-2\pi\eta)$$

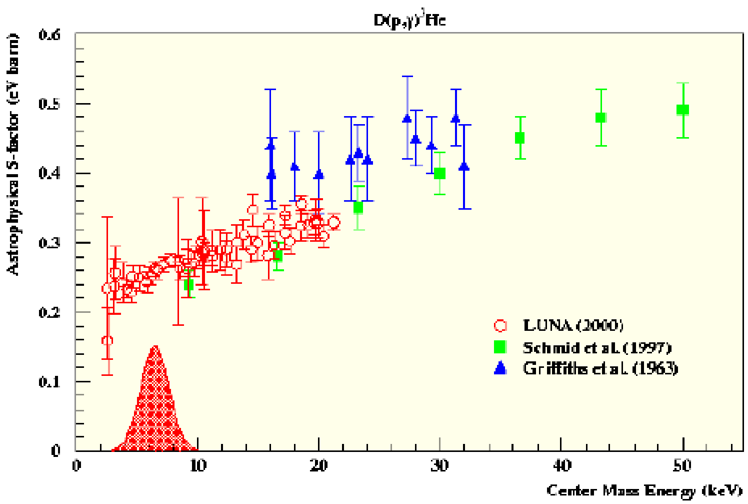


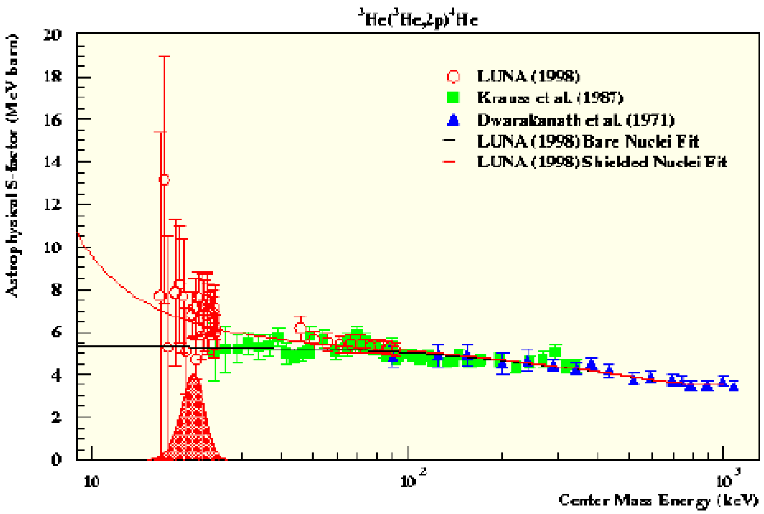


Stellar Reaction Cross Sections

Reactions have been reliably measured through the Gamow peak …

underground (LUNA)



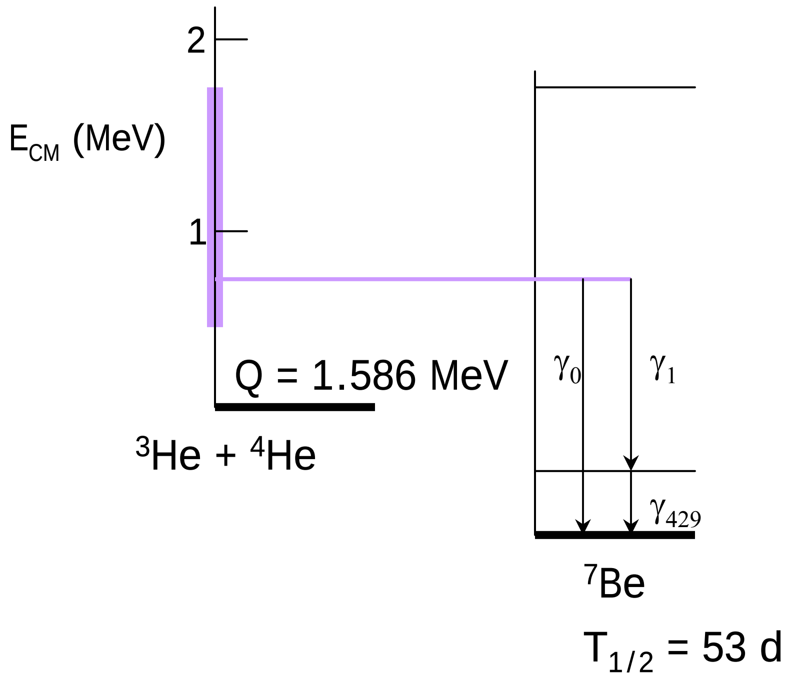


$d(p,\gamma)^3He$

$^3He(^3He,2p)^4He$

Solar neutrino sources and solar metallicity

$^{3}He(\alpha,\gamma)^{7}Be$



Long history -- lots of data, lots of theory

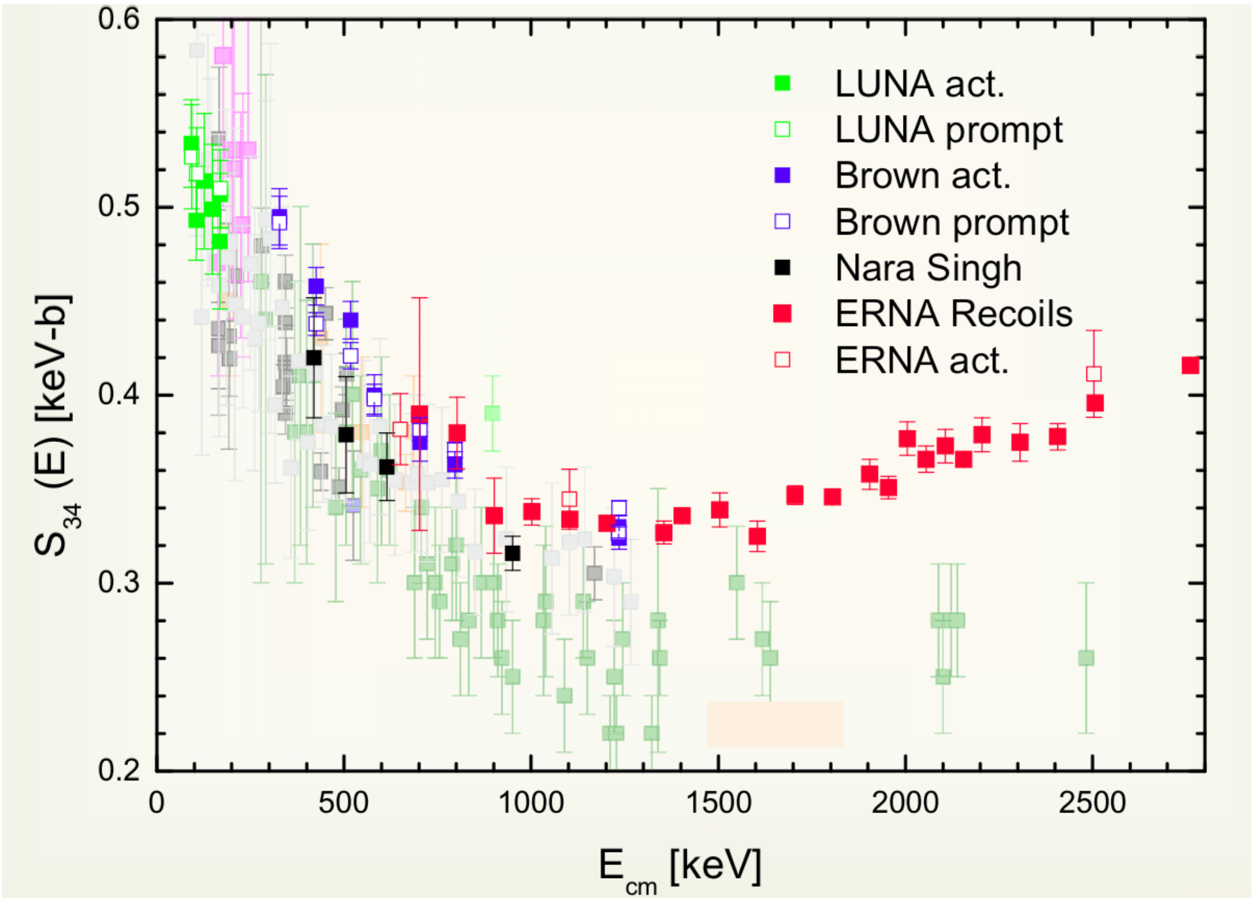
Measurement techniques:
Direct capture gamma rays
Activation -- ^{7}Be activity off-line

Closed gas cell
Implanted target
Gas jet target

DIANA approach:
High-intensity, cleanest geometry possible
Prompt, high-resolution gamma detection

Solar neutrino sources and solar metallicity

- Data on SSM inputs (including S_{34}) recently reviewed at INT meeting
http://www.int.washington.edu/PROGRAMS/solar_fusion.html



Solar neutrino sources and solar metallicity

Need calculations to extrapolate the cross section to “zero” energy

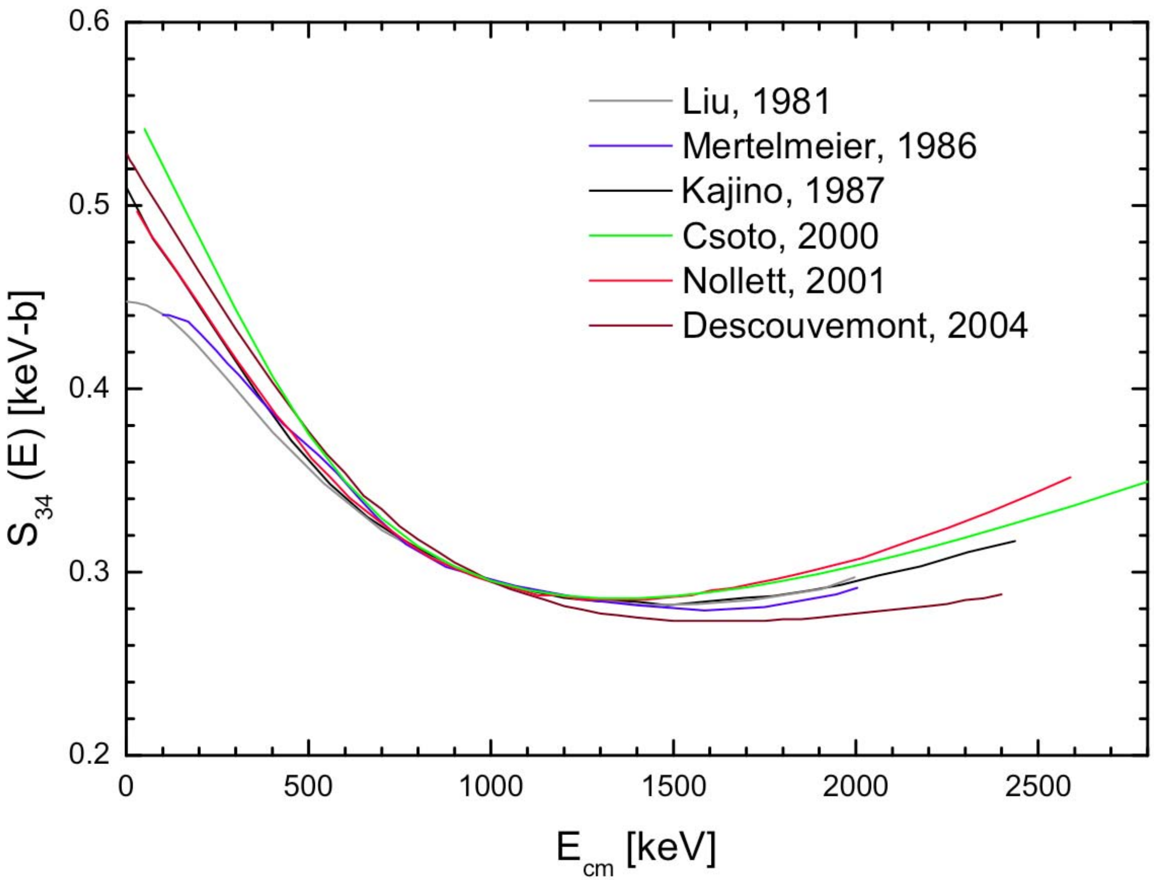
Substantial model dependence

Re

R.I

$S_{34}(0)$ is still not known to +/- 5%

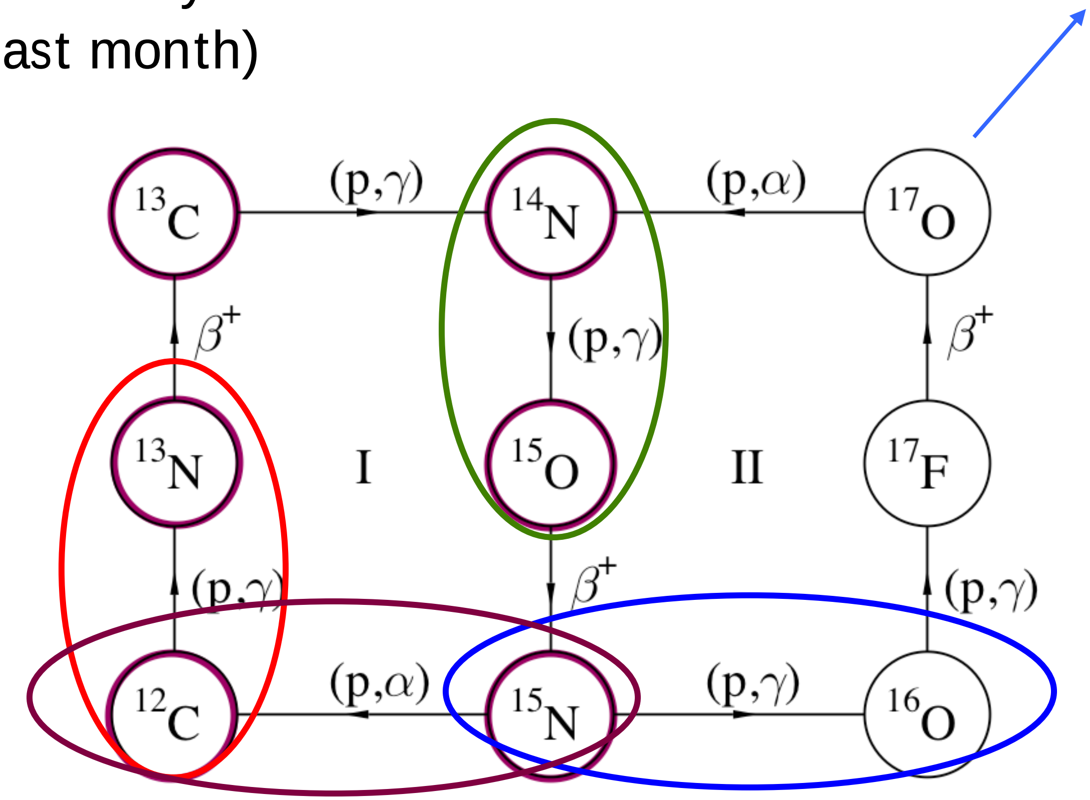
Need careful measurements at a wide range of energies



Solar neutrino sources and solar metallicity

CNO reactions determine metallicity of the sun (Z/X)
New initiatives in solar neutrino detectors seek CNO ν's
Solar metallicity is otherwise very difficult to constrain
(q.v. Wick Haxton's talk last month)

Reaction candidates:
12C(p,g)13N
15N(p,g)16O
17O(p,g)18F
15N(p,a)12C
14N(p,g)15O



Low energy CNO cycle reactions

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

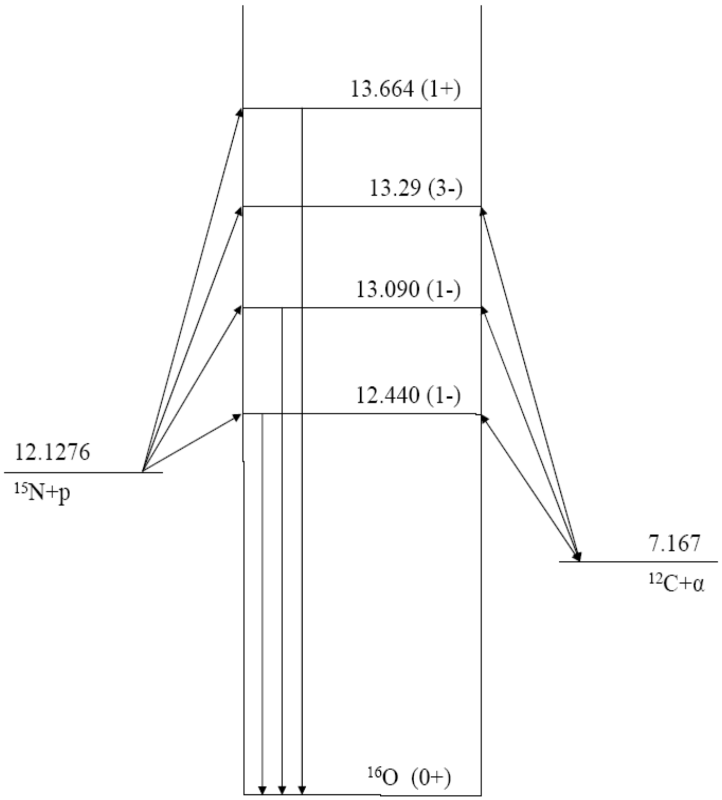
Substantial uncertainty in extrapolation

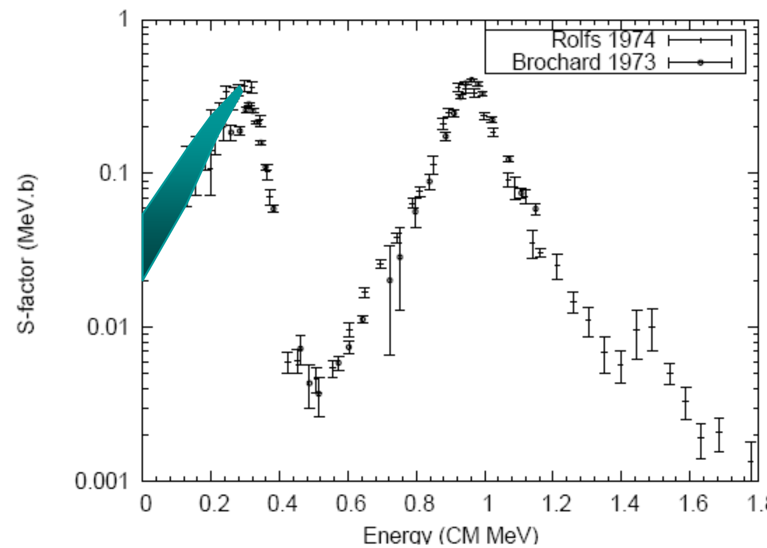
- Near threshold contributions

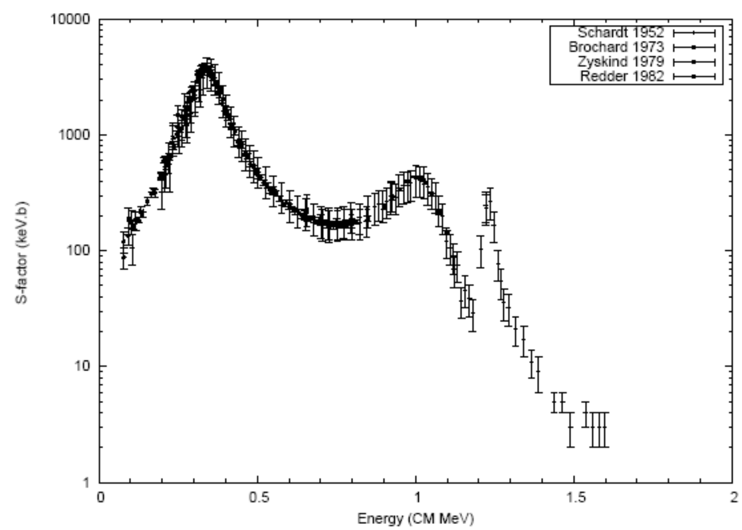
Broad energy range is necessary

- connect low and high energy data sets
- determine resonant contributions

High-resolution gamma-ray detection







Carbon-based Nucleosynthesis

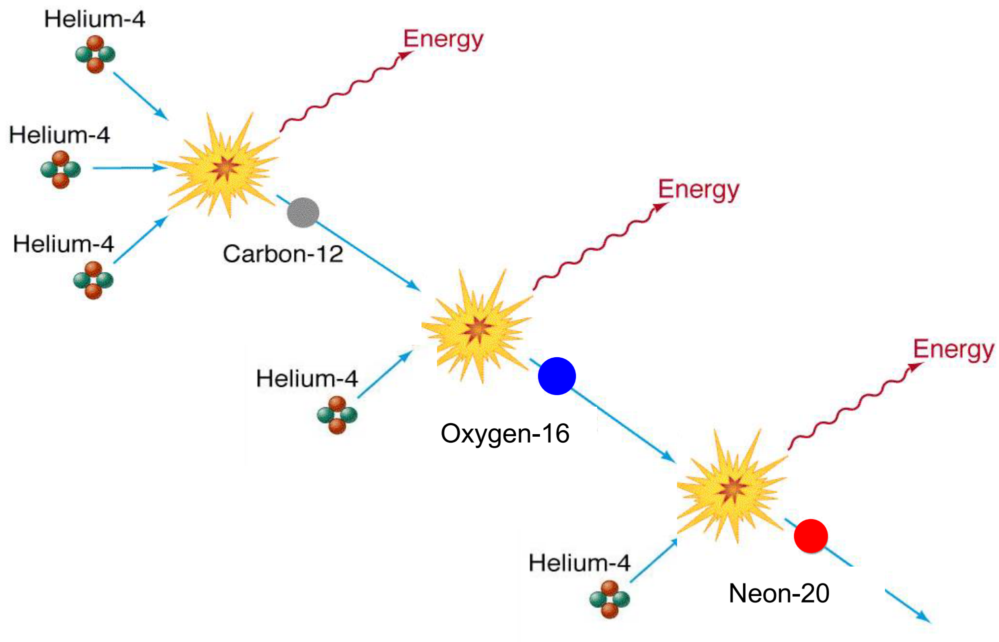
$^{12}C(\alpha,\gamma)^{16}O$

How much energy is produced in helium burning

How long does it last?

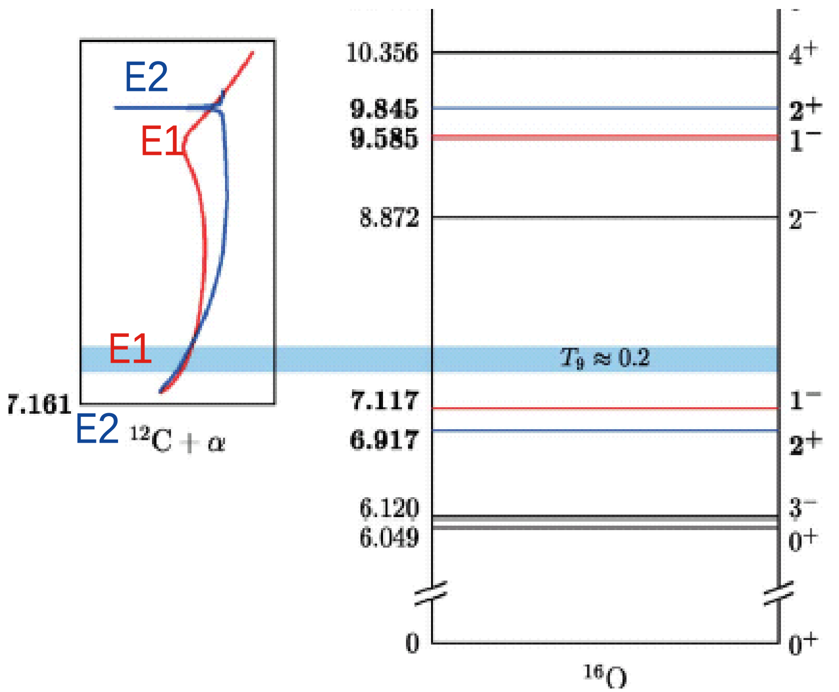
$^{4}He(2\alpha,\gamma)^{12}C(\alpha,\gamma)^{16}O(\alpha,\gamma)^{20}Ne$

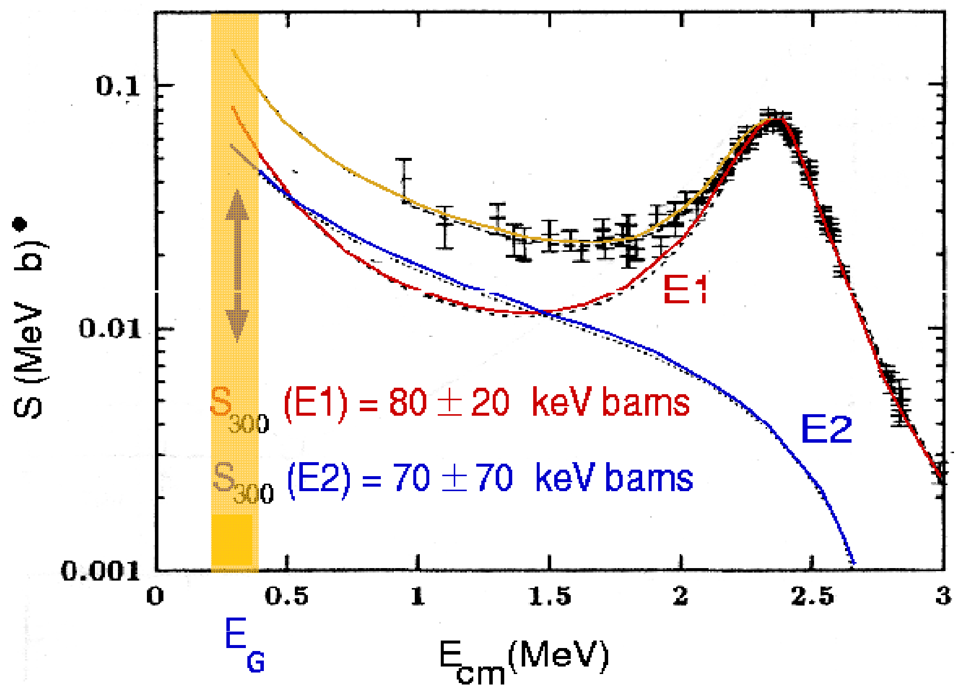
- Late Stellar Evolution
  determines Carbon
  and/or Oxygen phase
  significant effect on s-process
- Type Ia Supernova
  central carbon burning
  of C/O white dwarf
- Type II Supernova
  shock-front nucleosynthesis
  in C and He shells of
  pre-supernova star



Carbon-based Nucleosynthesis

Level structure gives strong interference between resonant components for E1 and E2 capture transitions





Gamow window ~ 300 keV, T_9 ~0.2

Surface measurements end at 0.9 MeV

DIANA design goal: measure at < 0.7 MeV

Neutron Sources for Heavy Element Production

S-process nucleosynthesis

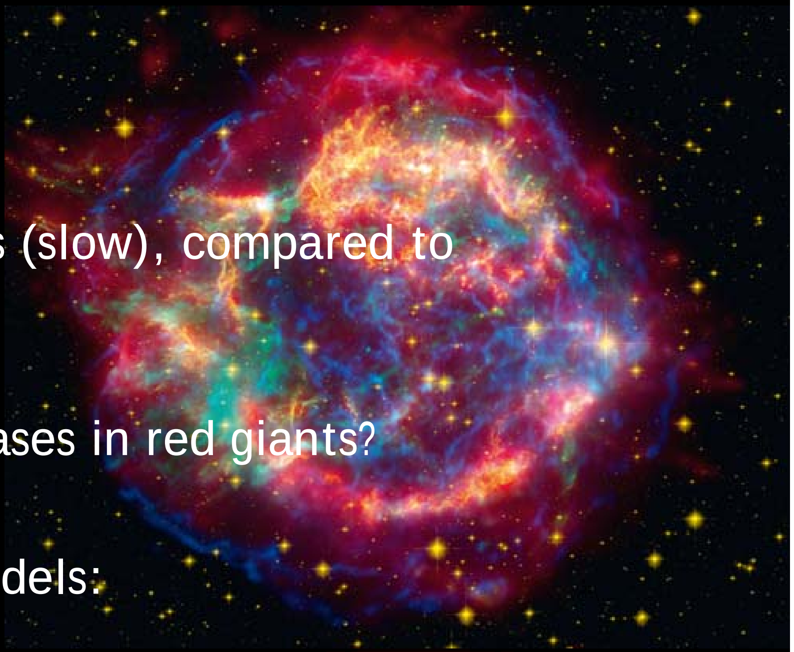
- What is the neutron production rate in stars (slow), compared to explosive phases (rapid)?

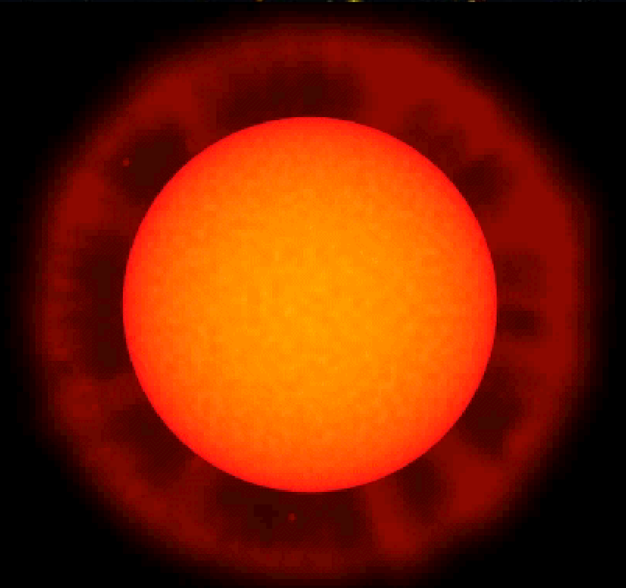
What are the active rates in stellar burning phases in red giants?

Two main reactions dominate the s-process models:

$^{13}C(\alpha,n)^{16}O$

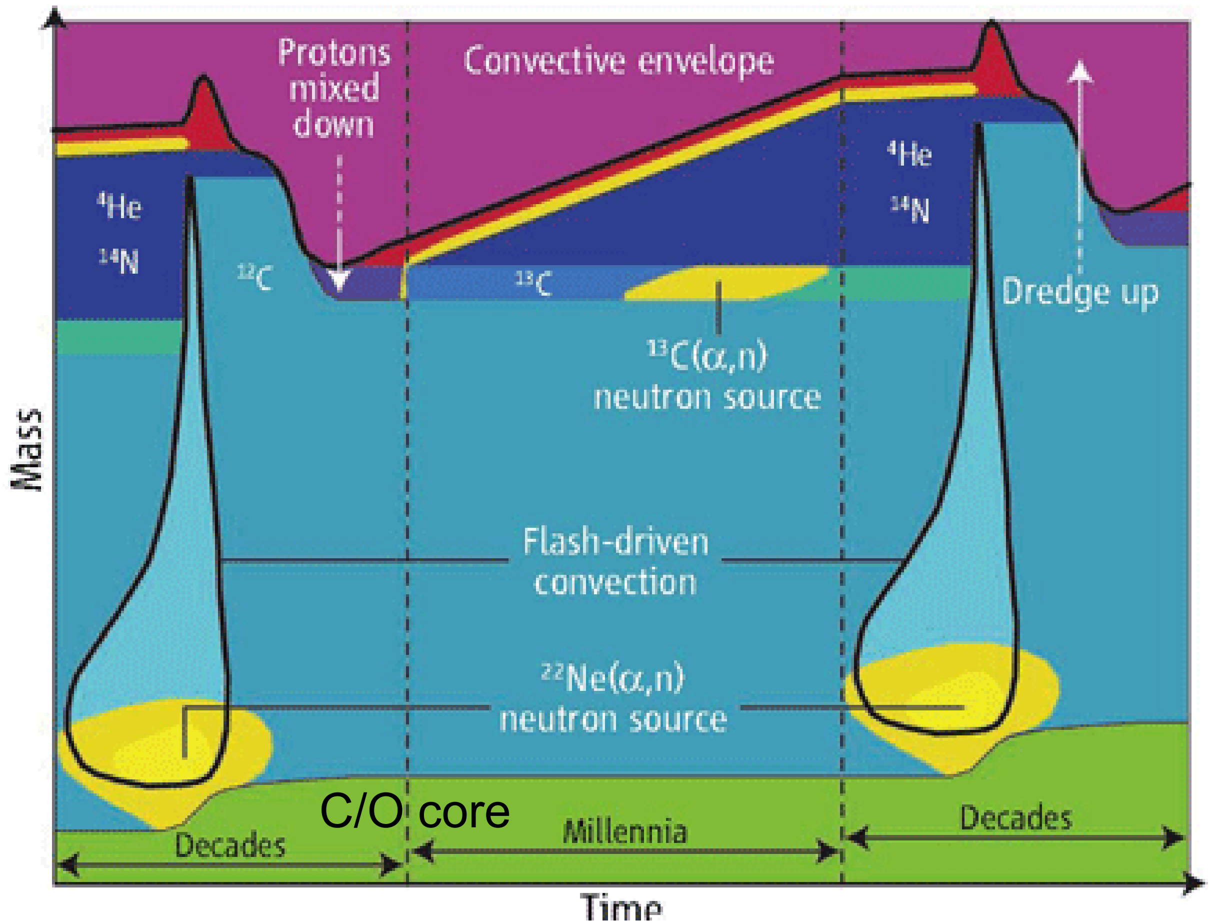
$^{22}Ne(\alpha,n)^{25}Mg$





S-Process site

Intershell helium burning in AGB star as mass loss provides convection

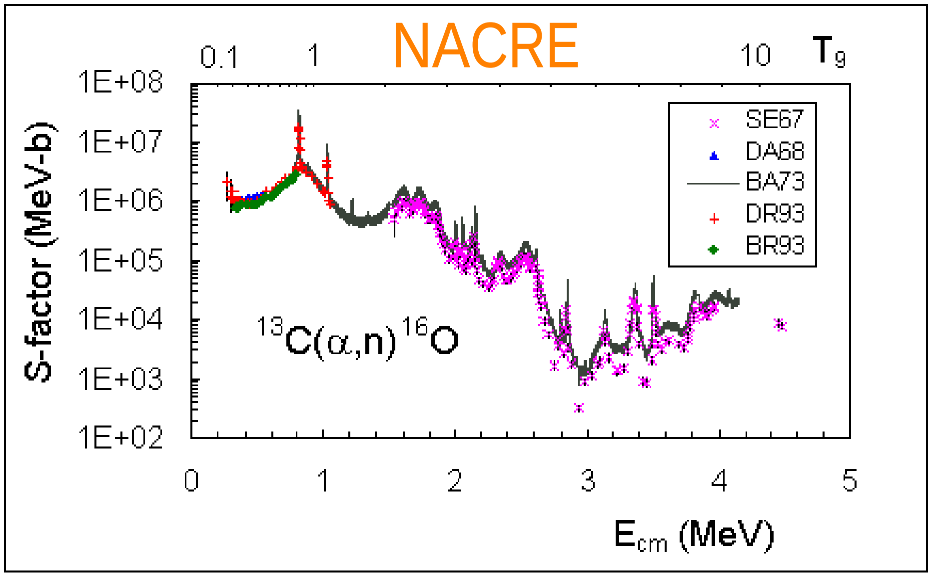


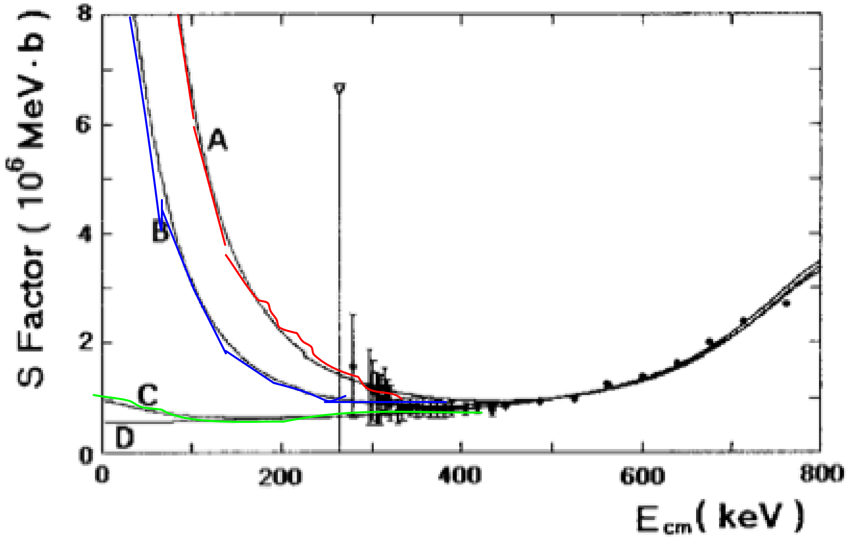
Boothroyd, Science (2006)

Neutron Sources for Heavy Element Production

$^{13}C(\alpha,n)^{16}O$ ~ 95% of neutron production in low-mass stars

main Red Giant phase neutron source at T_9 ~ 0.1





S. Kato et al. Nucl. Phys. A 718 189 (2003)

Low-energy measurements:

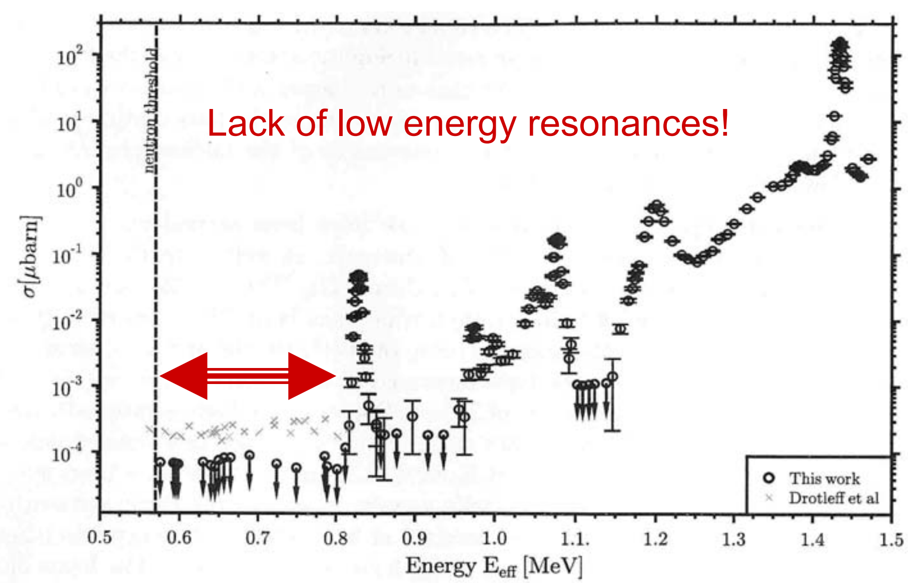
Seek sub-threshold part (E = -3 keV) suggested by R-matrix fit
Higher energy measurements for resonant contributions

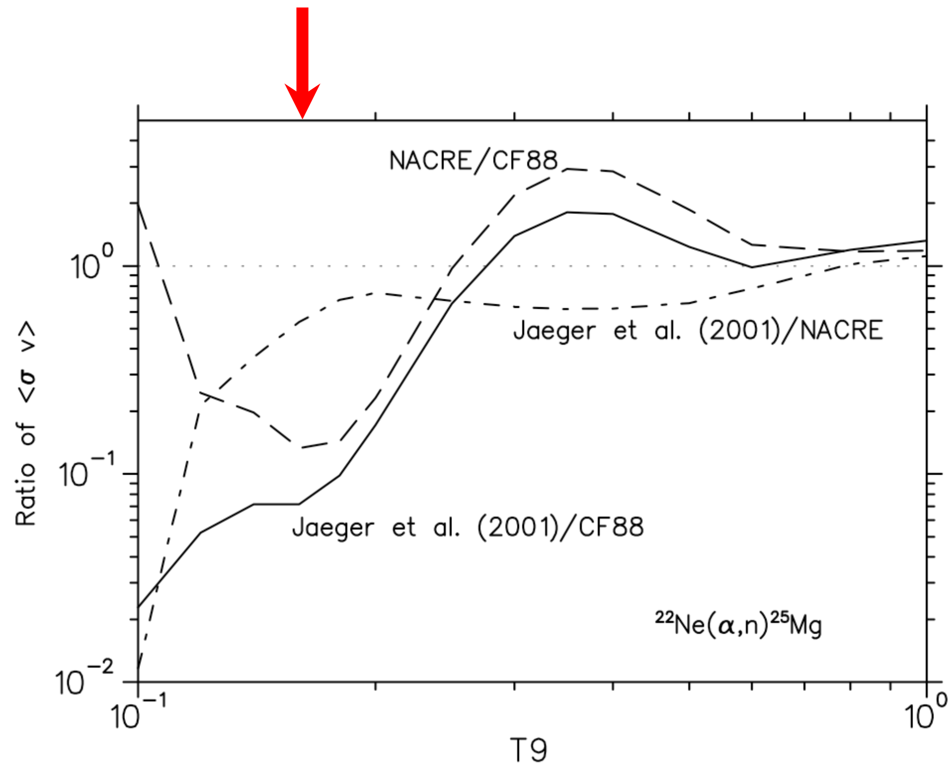
Low-energy, background suppressed, underground

Neutron Sources for Heavy Element Production

$^{22}Ne(a,n)^{25}Mg$

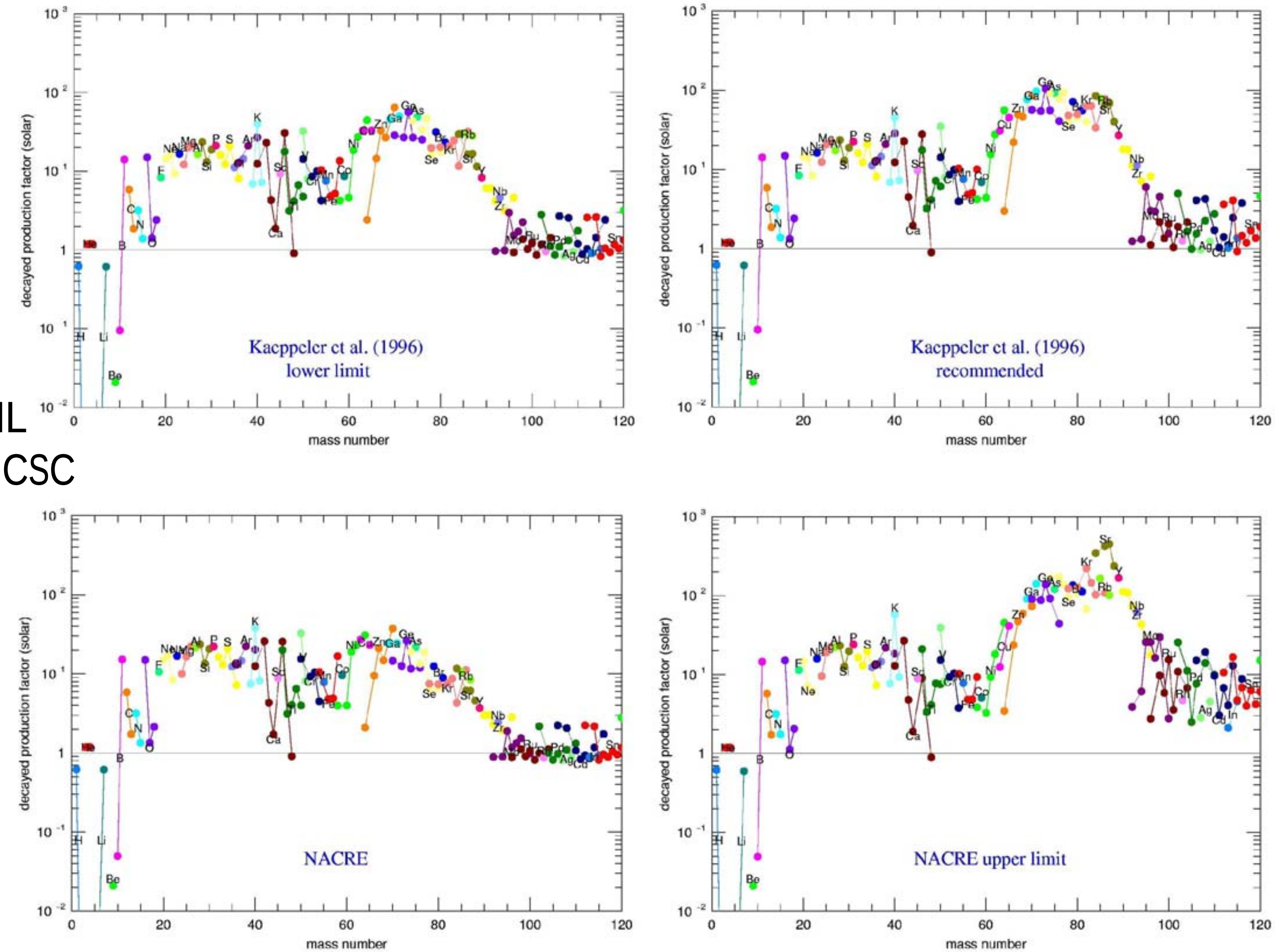
Similar problem with near-threshold resonances -- expected resonances don’t show up in available data, complicating extrapolation to low energy





Neutron Sources for Heavy Element Production

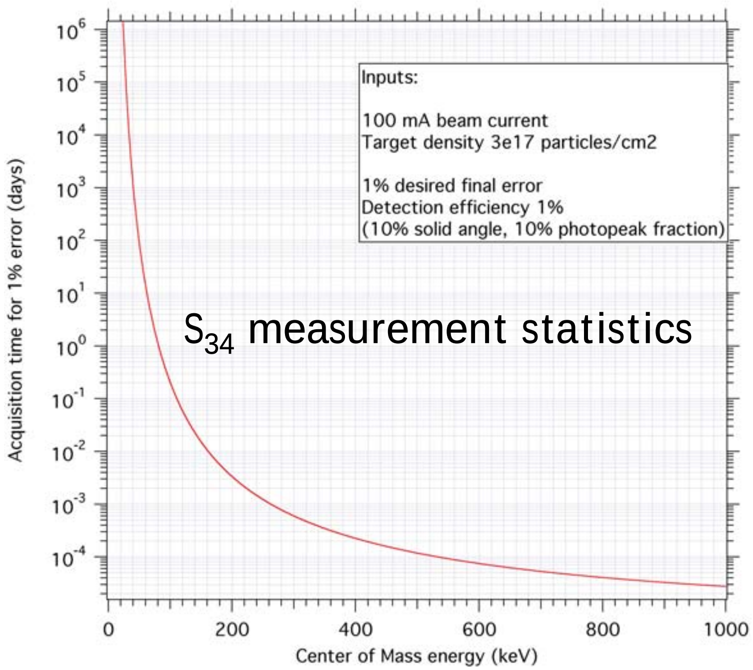
Heger, LANL
Woosley, UCSC



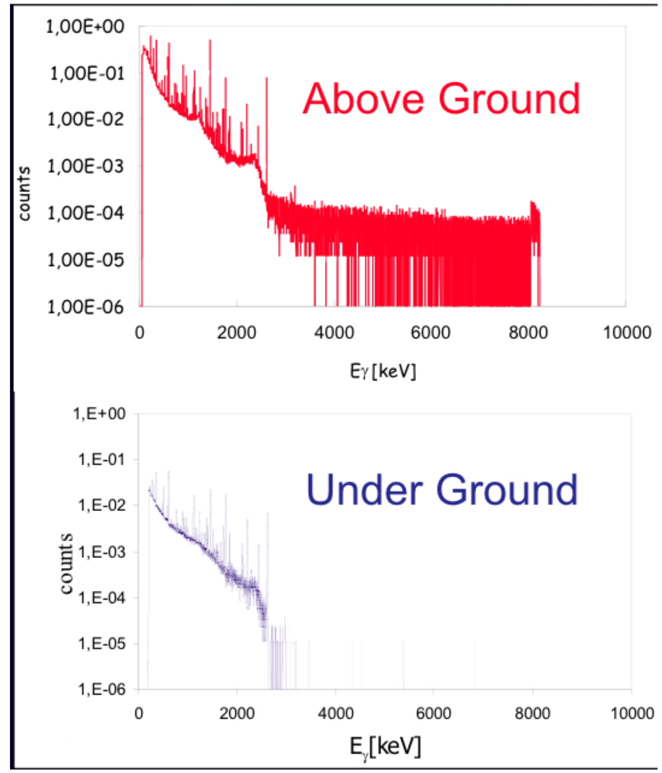
Variation between limits suggests large effect on weak s-process abundance distribution large consequences for p-process predictions

Why underground?

Very low reaction yields: events/day



Surface background rates: events/second



Background issues:

Source	Solution
Cosmic ray induced background	Passive shielding
Natural radioactivity	Active shielding: veto, radon flush, local rock surveys
Beam induced background	careful material choice, low activation good target geometries, ion optics, beam purity Q-value gating, event ID

Detector Systems

- ^{3}He thermalized neutron counter (UNC group)
- Underground neutron background
- should be much lower than surface rate

- High efficiency, segmented, multi-ring NaI scintillation counter

- Segmented, high resolution Ge detectors

- Overhead muon veto

- External neutron veto system

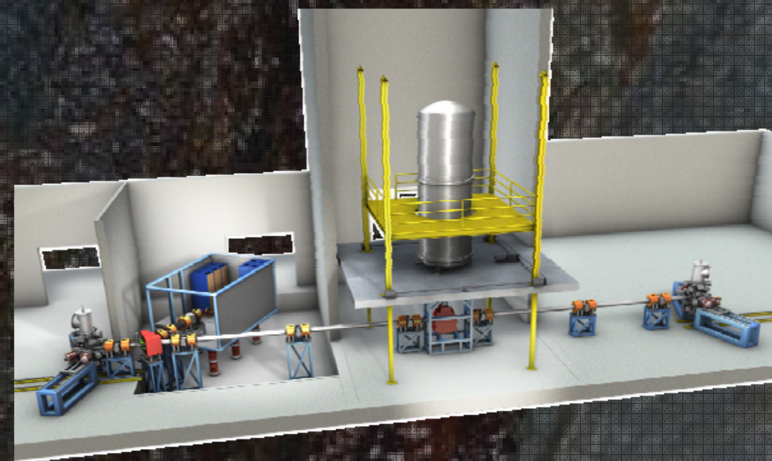
Passive elements

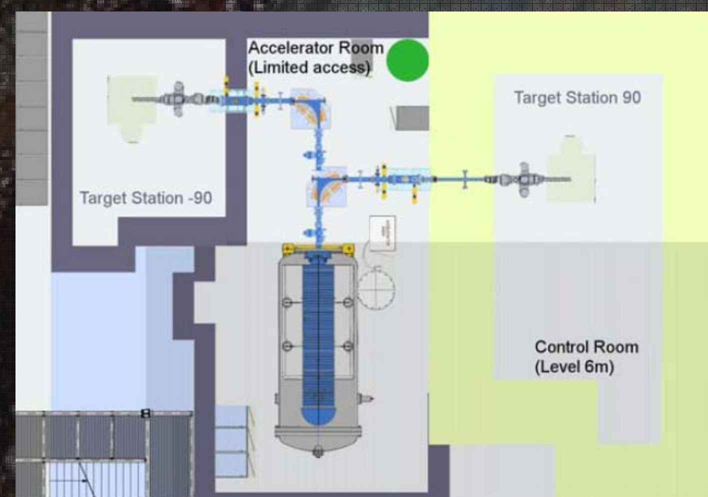
- Radon gas flush system to encapsulate main Gamma detector elements

- Water shielding at walls

International Context for Nuclear Astrophysics
(**INT Workshop Solar Fusion Cross Sections for the pp chain and CNO cycle 2009)**

- Europe
  - LUNA MV
  - ELENA, Boulby, Potash Mine
- US
  - DIANA (DUSEL)
- India
  - FRENA
- Additional Efforts
  - WIPP (US), Canfranc (Spain), Rumania

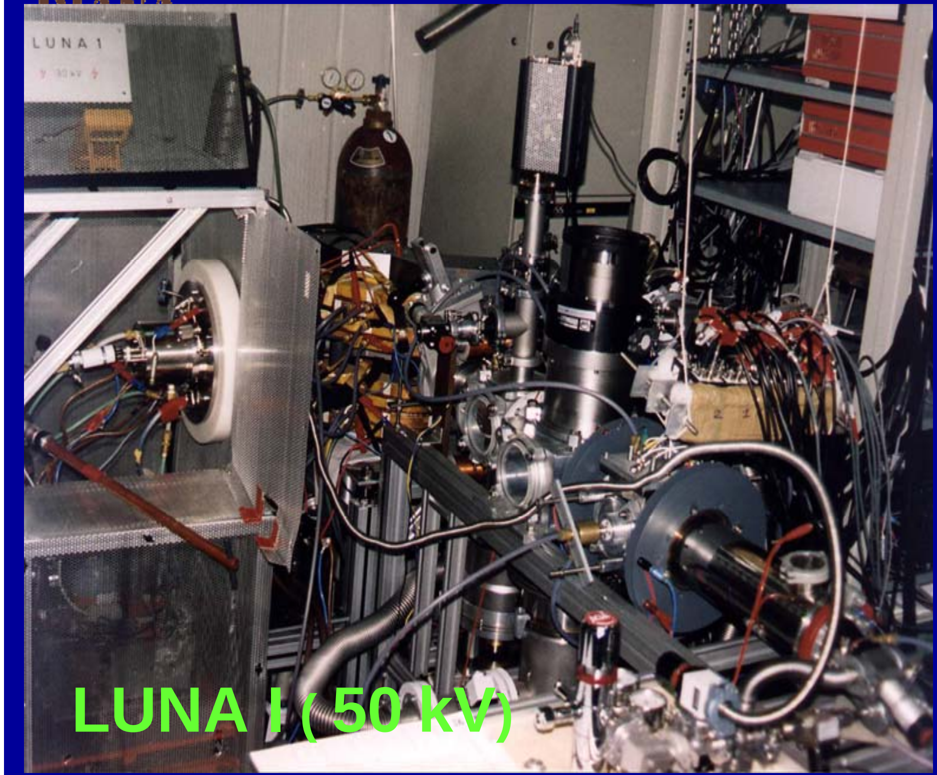


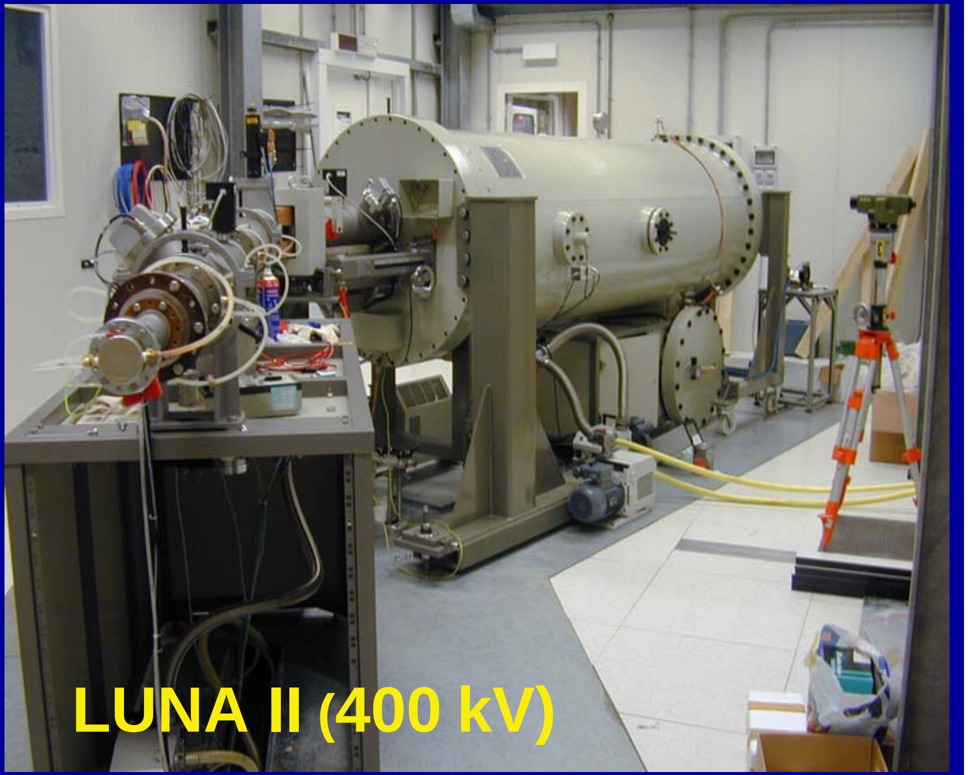


Conclusion from the INT Workshop

- Clear need for an advanced low energy facility
  - Complement and extend the physics reach of the LUNA 400kV in Gran Sasso
- Clear need for higher energy
  - Provide consistent data over a wider energy range
  - Extend the experimental program beyond Solar Fusion Cross Section into Carbon-based Nucleosynthesis, Neutron Sources…

LUNA in Gran Sasso has pioneered underground accelerator facilities



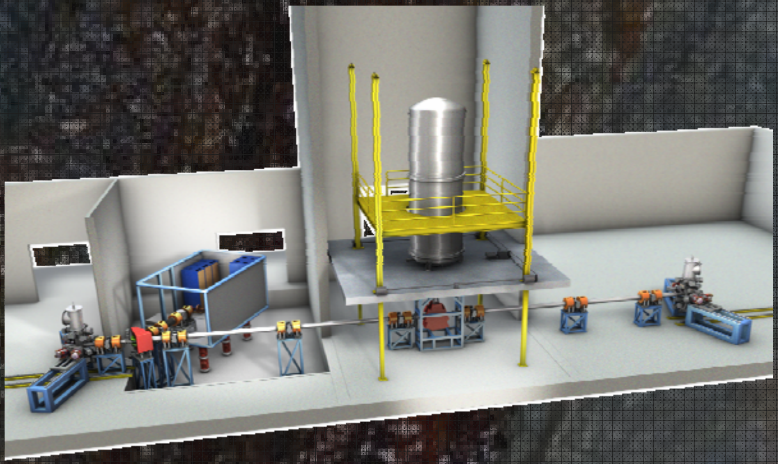


Voltage Range :1 - 50 kV
Output Current:1 mA
Beam energy spread:20 eV
Long term stability (8 h): 10^{-4}
Terminal Voltage ripple: 5 10^{-5}

Voltage Range :50-400 kV
Output Current: 1 mA (@ 400 kV)
Absolute Energy error: ±300 eV
Beam energy spread: <100 eV
Long term stability (1 h): 5 eV
Terminal Voltage ripple:5 Vpp

Courtesy of Pietro Corvisiero INFN-Genova

International Context for Nuclear Astrophysics
(INT Workshop Solar Fusion Cross Sections for the pp chain and CNO cycle 2009)



- Europe
  - LUNA MV
  - ELENA, Boulby, Potash Mine
- US
  - DIANA (DUSEL)
- India
  - FRENA
- Additional Efforts
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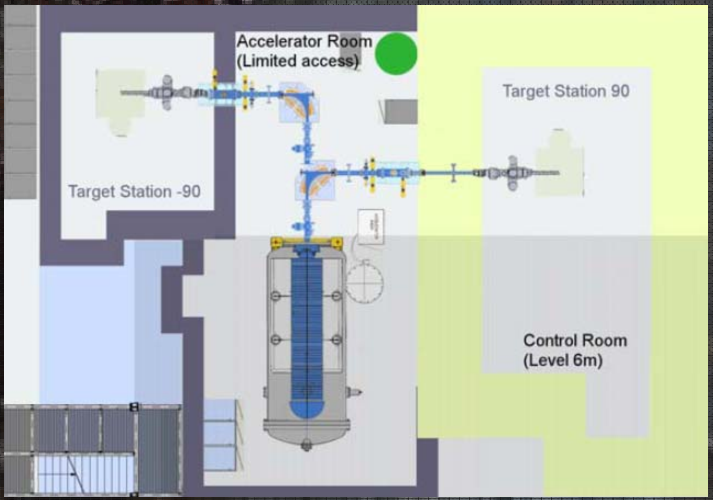

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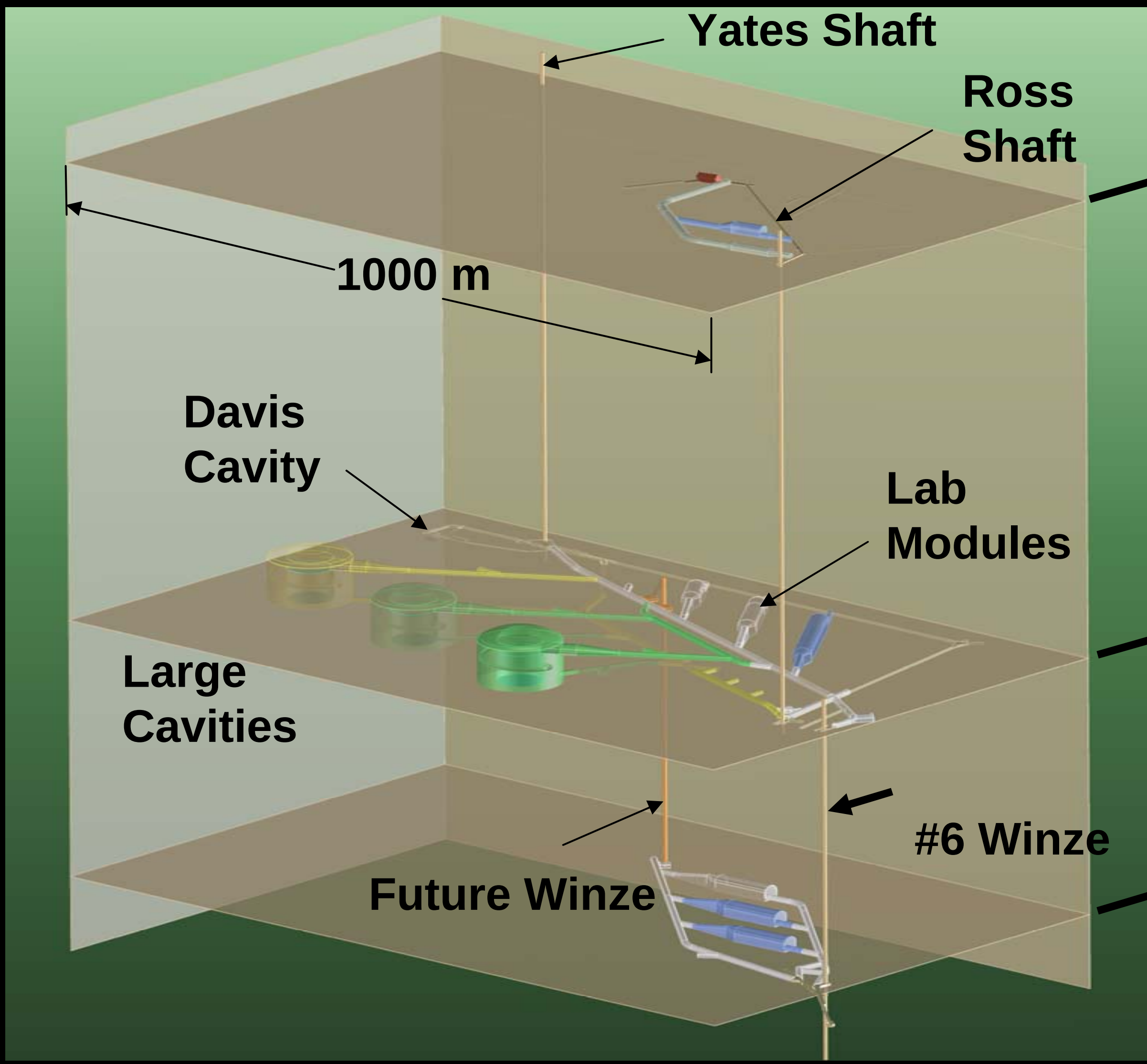
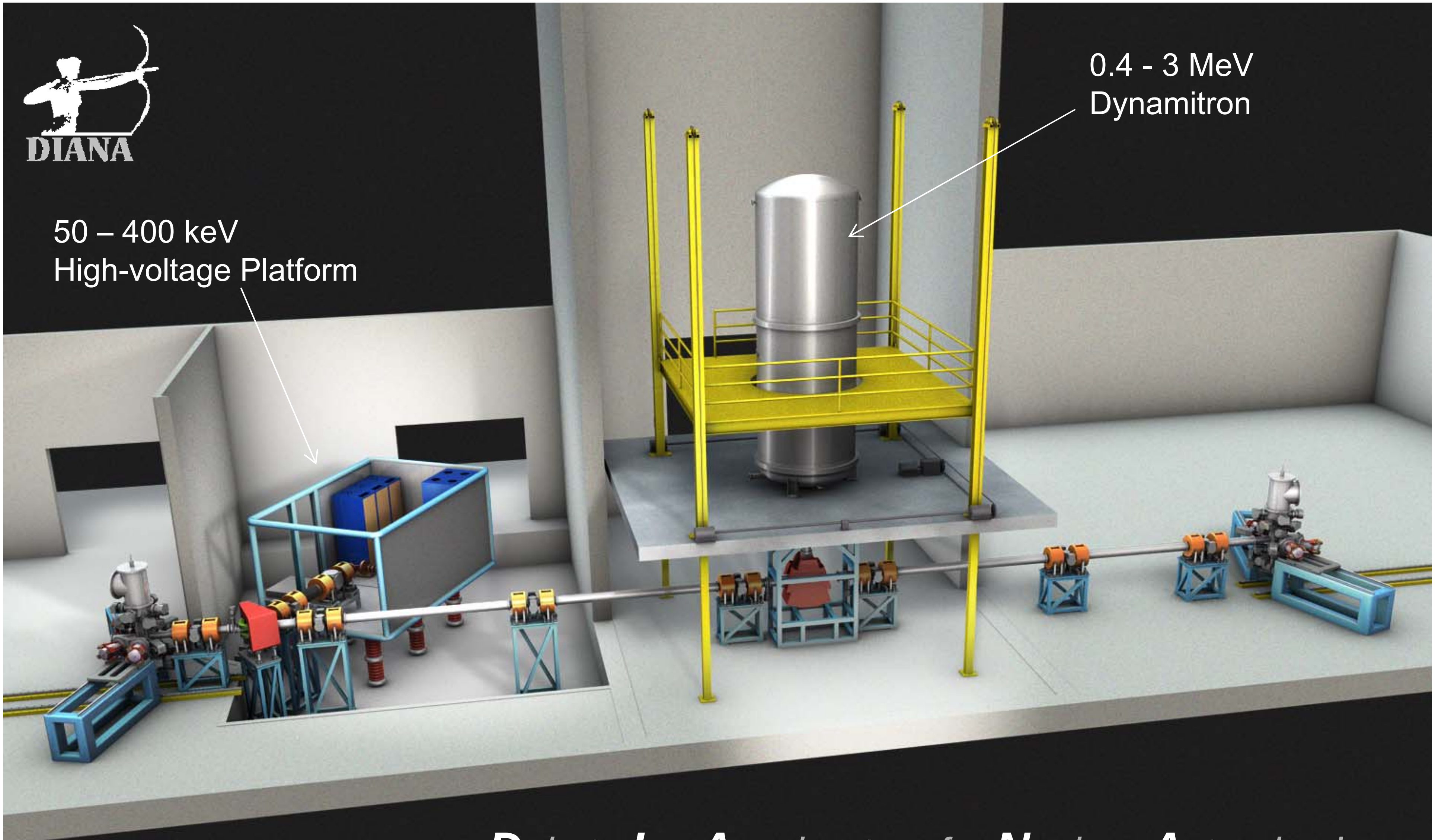
THE DUSEL HOMESTAKE SITE

All hardware has to be brought through the existing main shafts.

PICTURE OF THE DUSEL HOMESTAKE SITE



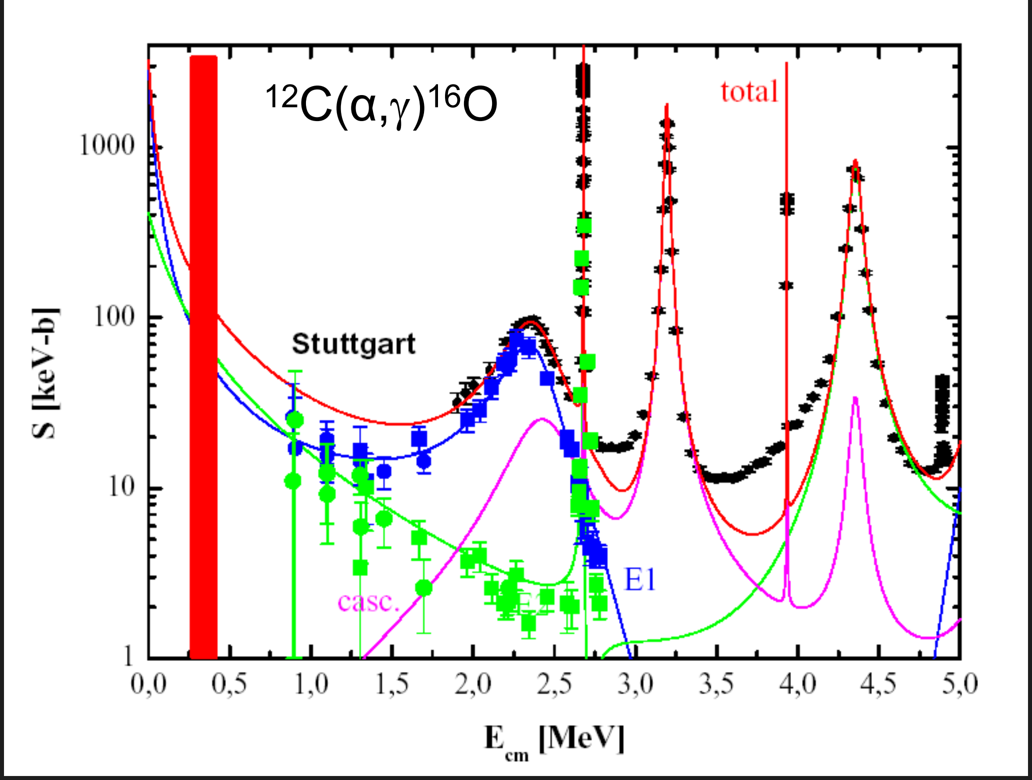


Dakota Ion Accelerators for Nuclear Astrophysics
is a collaboration between the following institutions

University of Notre Dame
The University of North Carolina at Chapel Hill
Colorado School of Mines — Earth • Energy • Environment
Western Michigan University
Berkeley Lab — Ernest Orlando Lawrence Berkeley National Laboratory

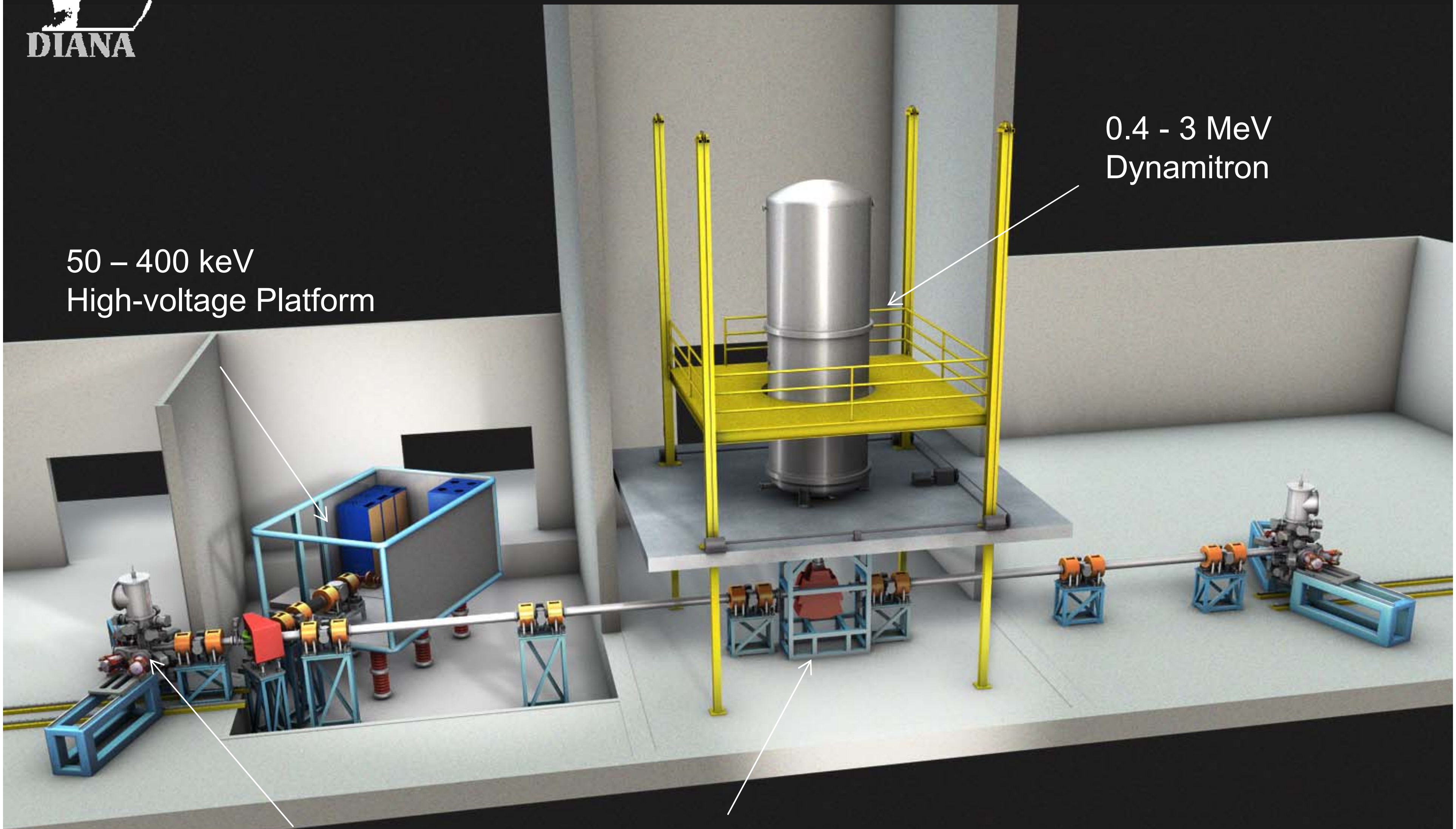
Unique Features of the DIANA Facility

- Consist of two coupled accelerators
  - cover a wide range of ion beam energies and intensities
  - Target can be fed from both accelerator (This will allow a particular reaction to be measured at both accelerators in complementary energy ranges with identical target and detector set-ups.)
  - Provides overlap to connect the results to measurements above ground.



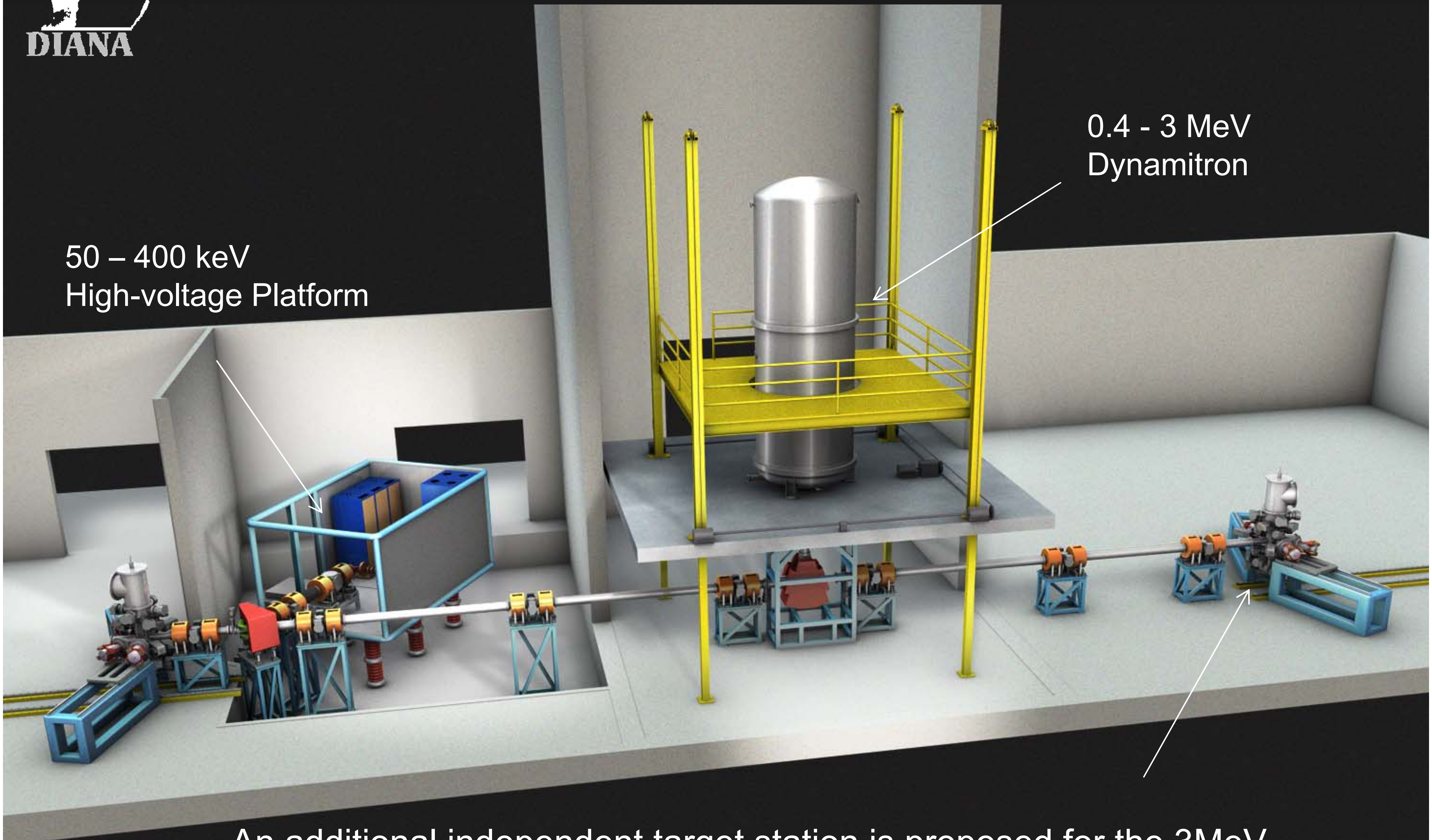
Wide energy range with the same target is necessary to provide consistent data for a high quality extrapolation to low energies

Unique Features of the DIANA Facility



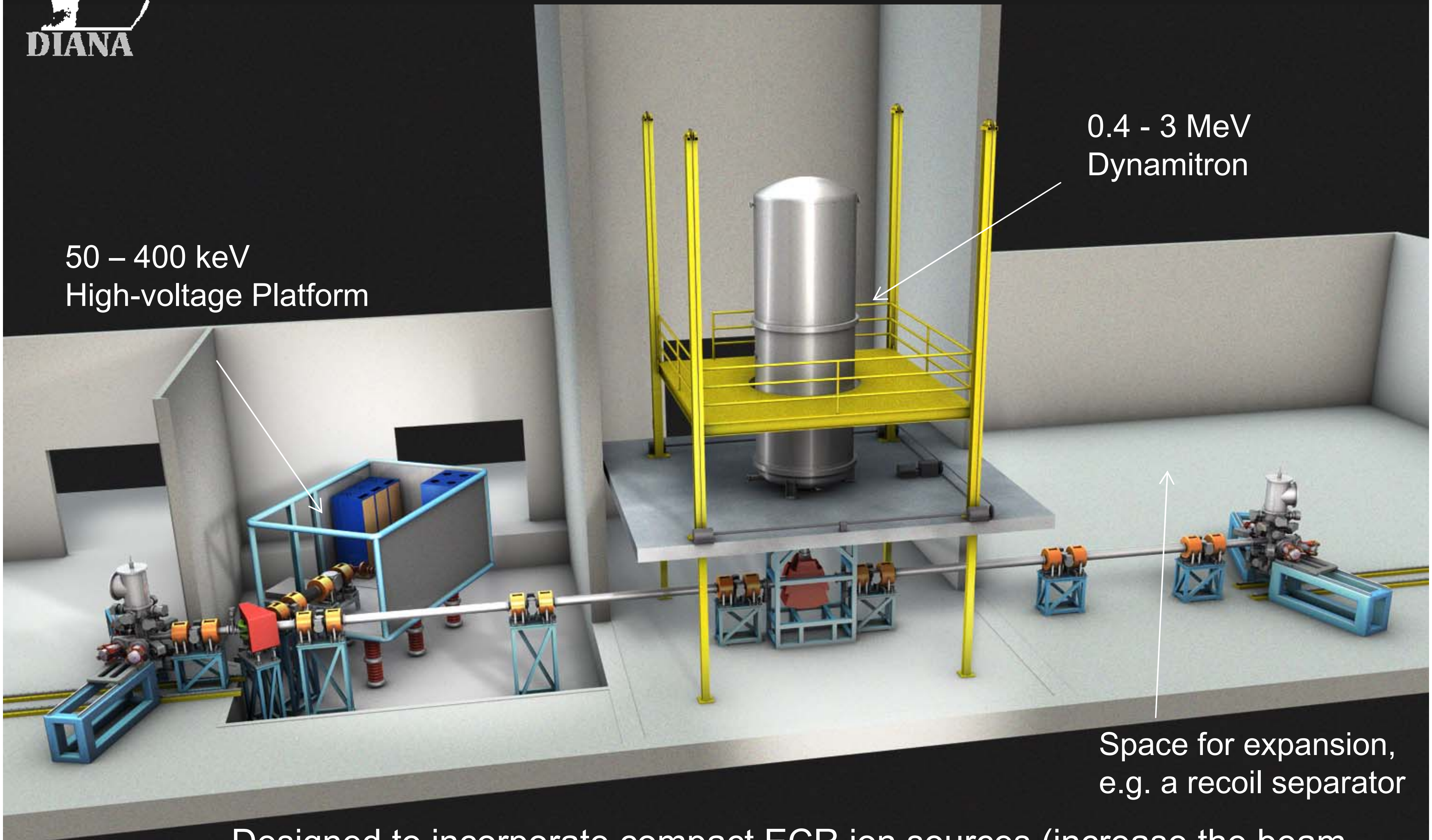
The two coupled accelerators cover a wide range of ion beam energies and intensities for consistent cross section measurements with identical target and detector set-up.

Unique Features of the DIANA Facility



An additional independent target station is proposed for the 3MeV accelerator for conducting two experimental campaigns simultaneously or preparing the next experimental campaign.

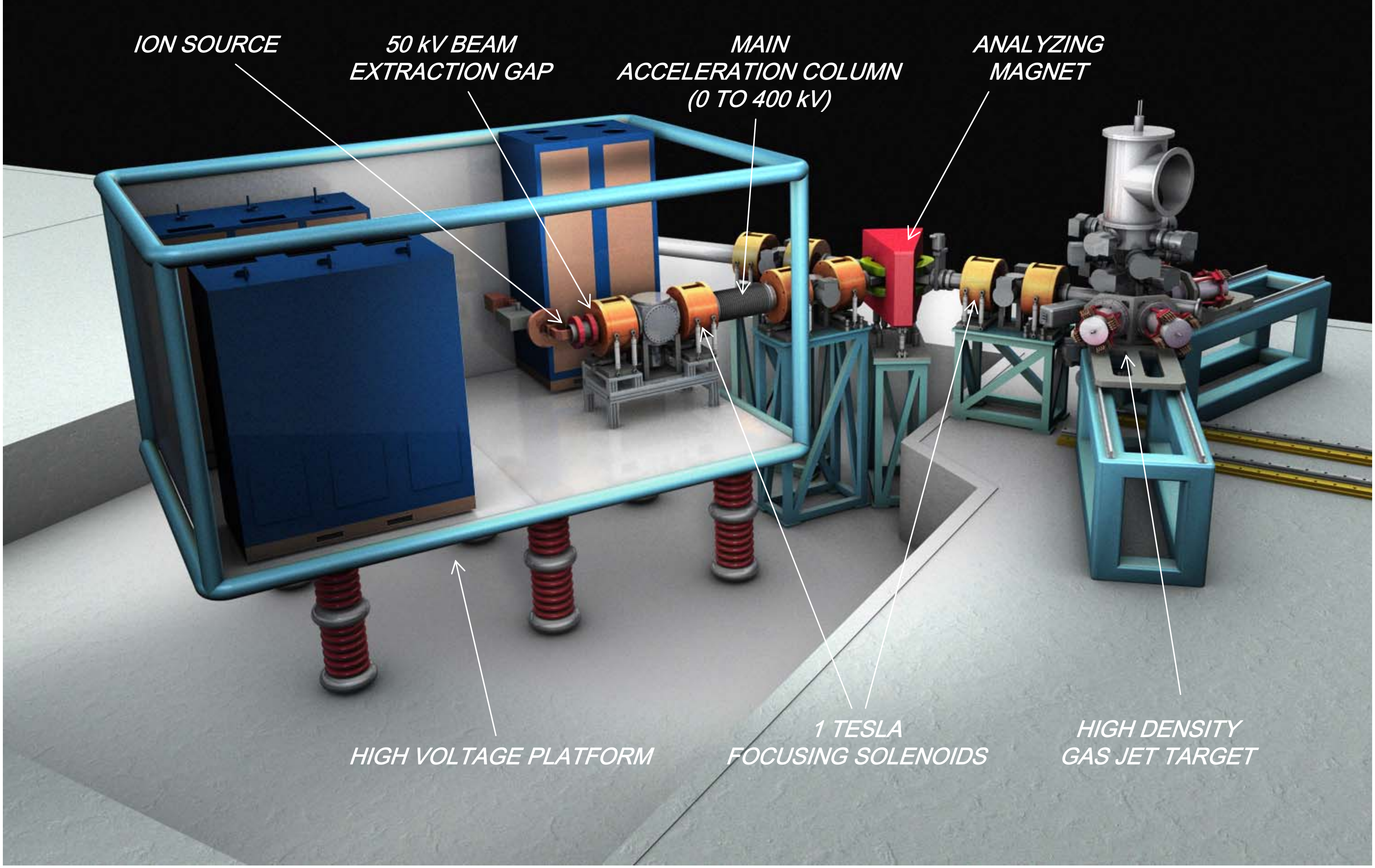
Unique Features of the DIANA Facility



Designed to incorporate compact ECR ion sources (increase the beam energy or vary the accelerated ions (from light to heavier). This feature will allow expansion of the scientific goals in the future.

Unique Features of the DIANA Facility

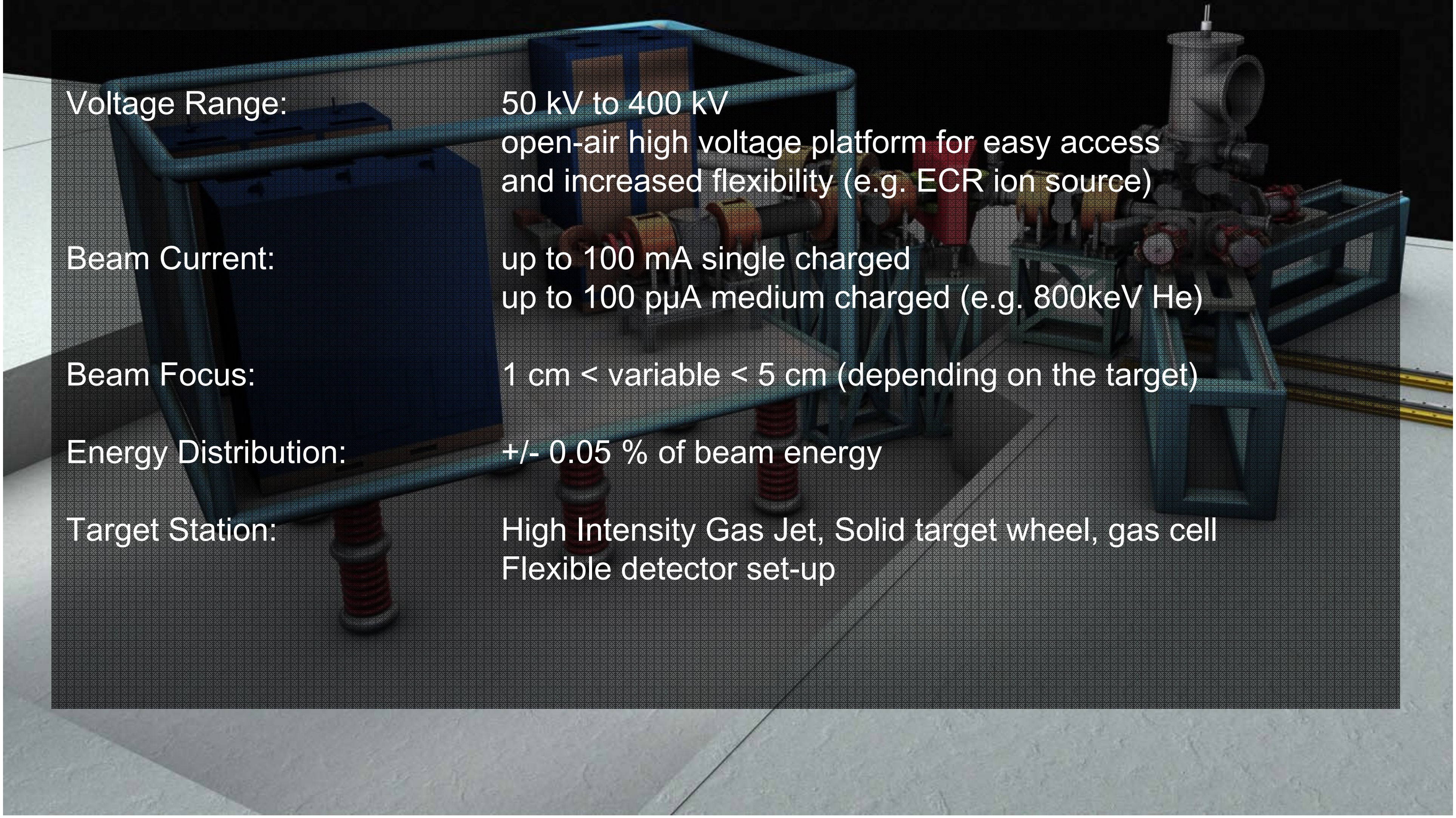
Low Energy Accelerator and Target Station



Unique Features of the DIANA Facility

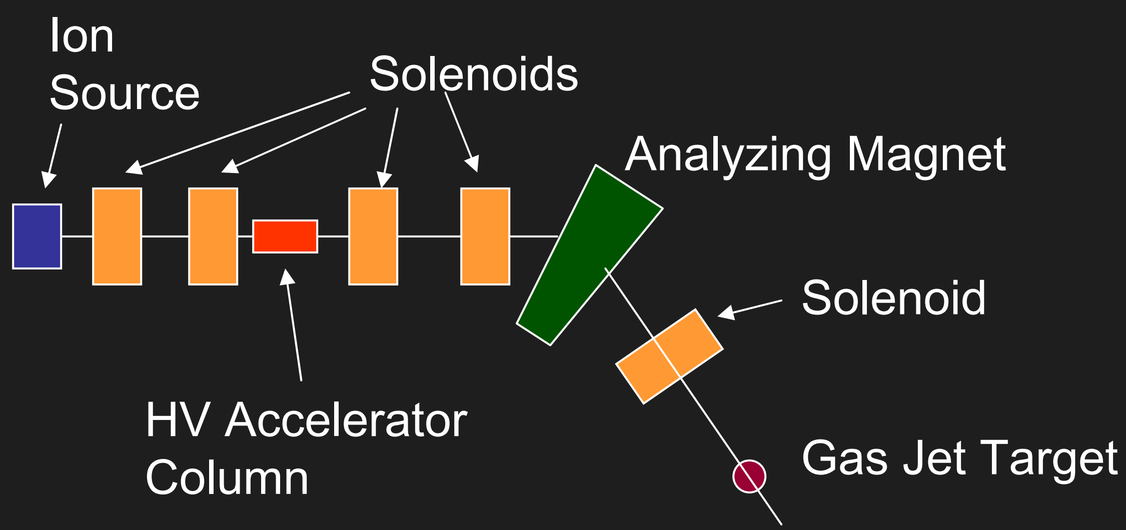
Low Energy Accelerator and Target Station

One to two orders of magnitude higher ion beam intensity on target in order to address the low count rates close to the Gamow window energies.



Voltage Range:	50 kV to 400 kV open-air high voltage platform for easy access and increased flexibility (e.g. ECR ion source)
Beam Current:	up to 100 mA single charged up to 100 pμA medium charged (e.g. 800keV He)
Beam Focus:	1 cm < variable < 5 cm (depending on the target)
Energy Distribution:	+/- 0.05 % of beam energy
Target Station:	High Intensity Gas Jet, Solid target wheel, gas cell Flexible detector set-up

COMPACT LOW ENERGY ACCELERATOR LAYOUT FOR HIGH SPACE-CHARGE BEAM TRANSPORT



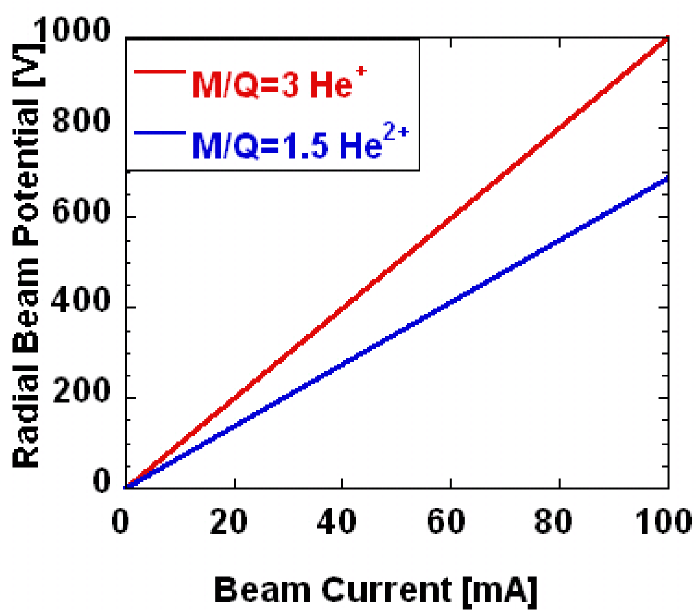
- Distance from extraction to gas jet: 6.62 m
- Solenoids of VENUS design (32 cm length, 26 cm radius)
- Acceleration gap based on high current injector at GSI, Darmstadt
- Design was supported through LDRD

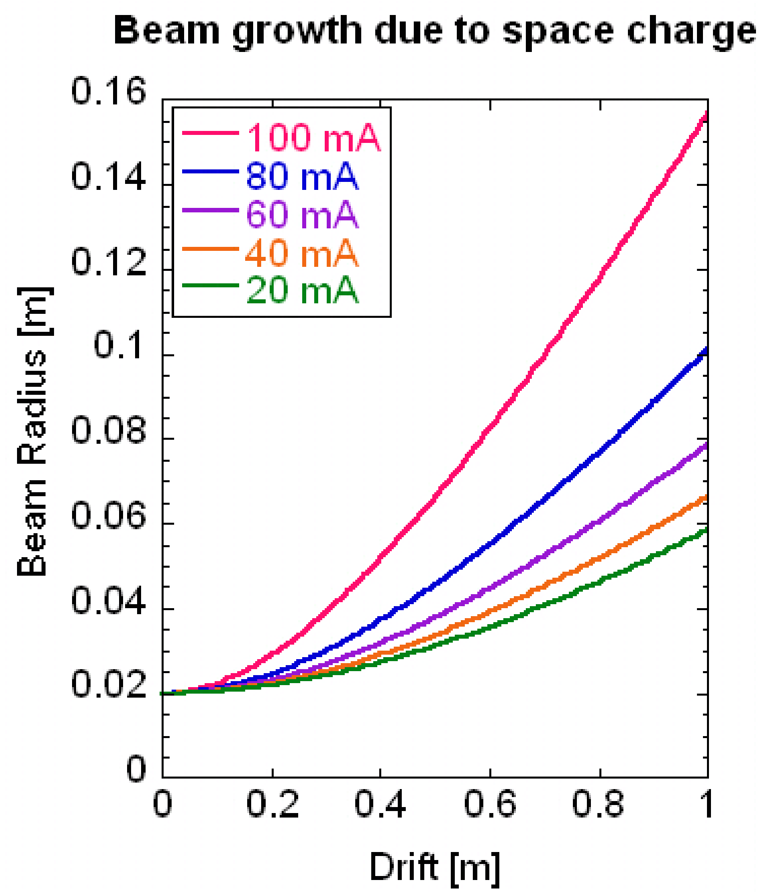
Challenges of the Design, Consequences of the high current requirement

- Space charge at low acceleration voltage
- Space Charge Neutralization
- Beam induced back ground
- Target interface
- Target power/ Beam dump
- Ion optics changes over the wide energy range

Challenges of the Design,
Consequences of the high current requirement

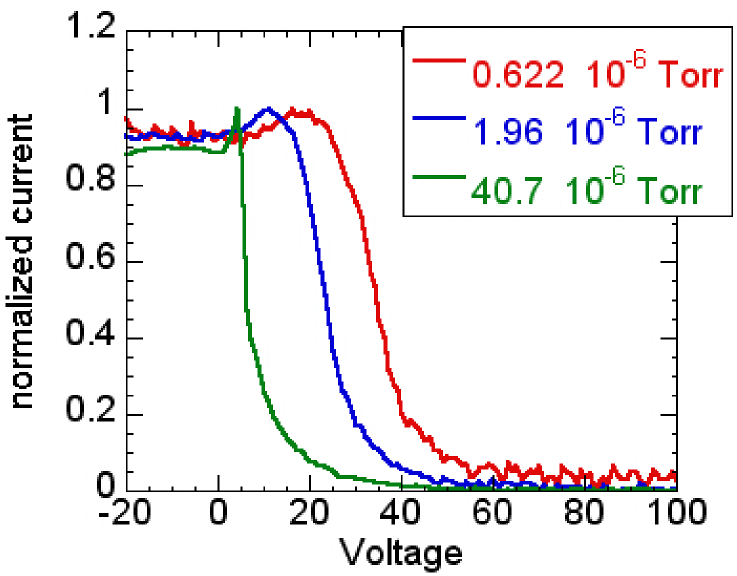
- Space charge at low acceleration voltage
  - Without some degree of neutralization a 100mA beam can't be transported at 50kV
  - Space charge can introduce an unacceptable energy spread





Challenges of the Design, Consequences of the high current requirement

- Space Charge Neutralization
  - When the beam passes through residual gas, it gets partially ionized, positive ions are expelled by the beam potential, electrons are trapped in the beam potential and neutralize it (quasi neutralized plasma)
  - Degree of neutralization is depended
    - on the time structure of the beam
    - the pressure in the beam line
    - the presence of electric fields – beam transport is mainly magnetic focusing elements
  - Simulation of the DIANA beam line assumes 90% neutralization



Measurement of the beam potential due to space charge in the VENUS beam line

The beam potential decreases with increasing pressure

Challenges of the Design, Consequences of the high current requirement

- Space Charge Neutralization
  - When the beam passes through residual gas, it gets partially ionized, positive ions are expelled by the beam potential, electrons are trapped in the beam potential and neutralize it (quasi neutralized plasma)
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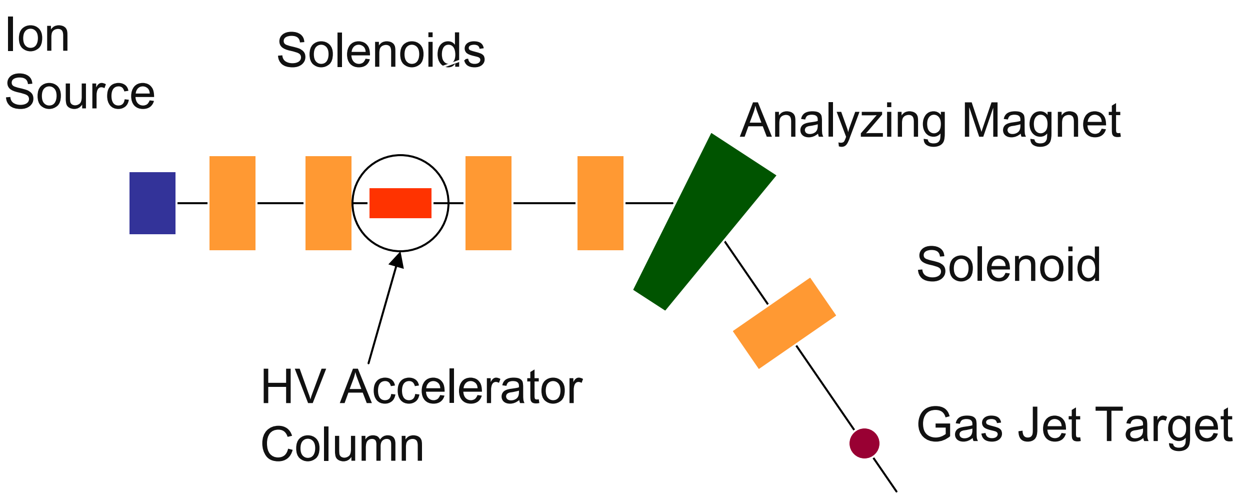
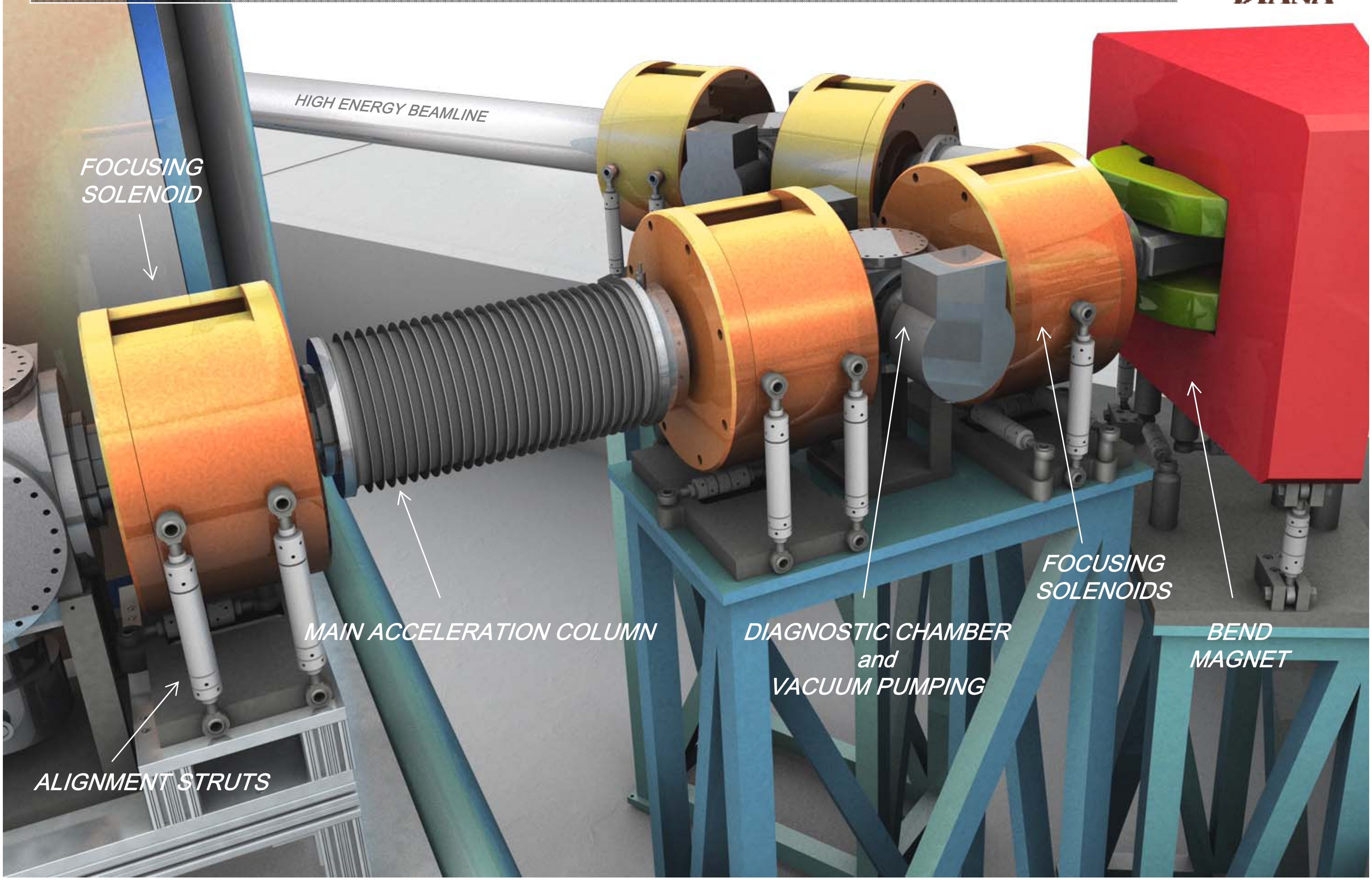


- HV acceleration gap is an issue for the lower beam energies
- Neutralization in analyzing magnet unknown (R&D item)

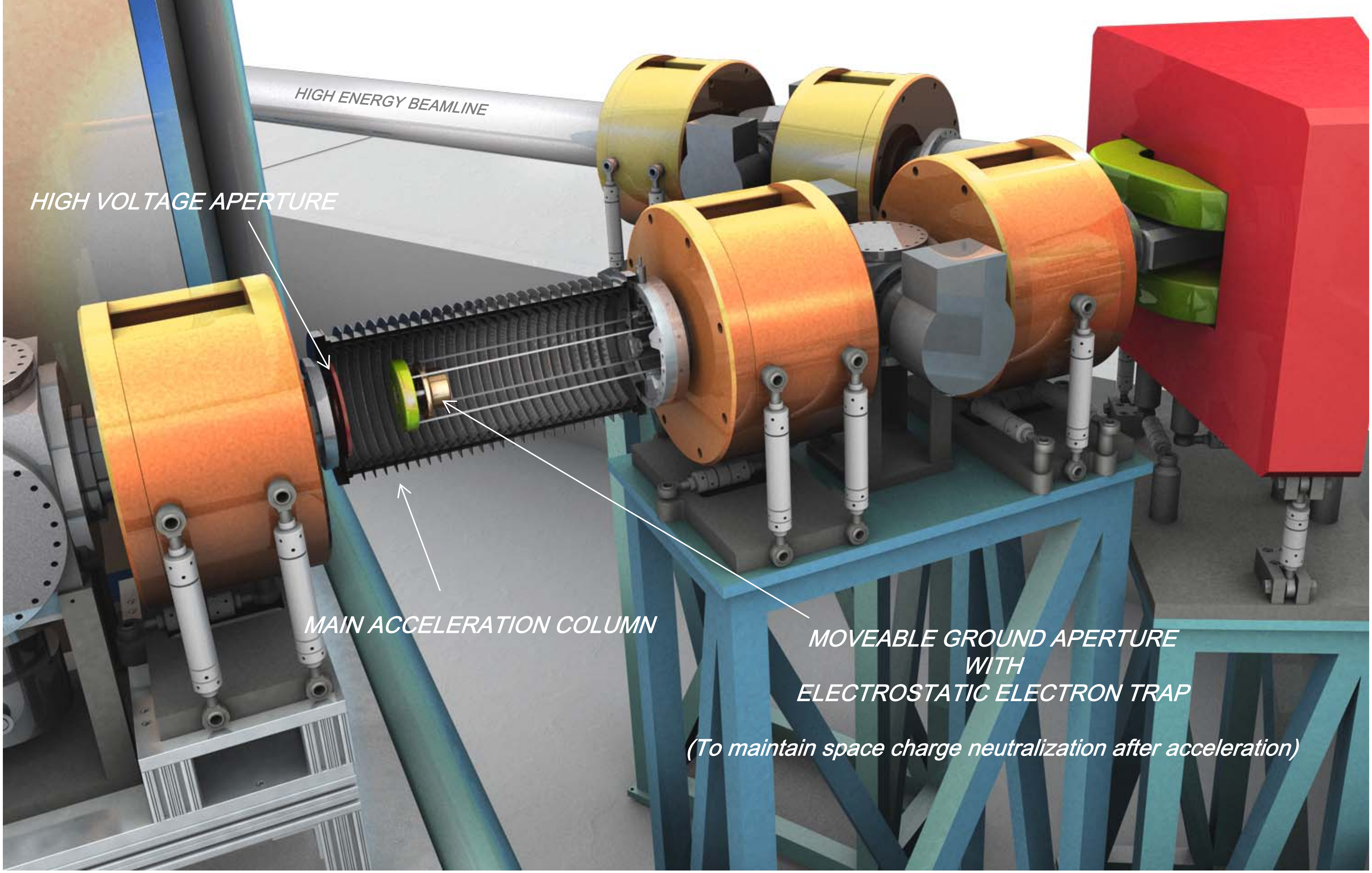
ADJUSTABLE ACCELERATION GAP WILL BE
A MAIN FEATURE OF DIANA LOW ENERGY ACCELERATOR

DIANA



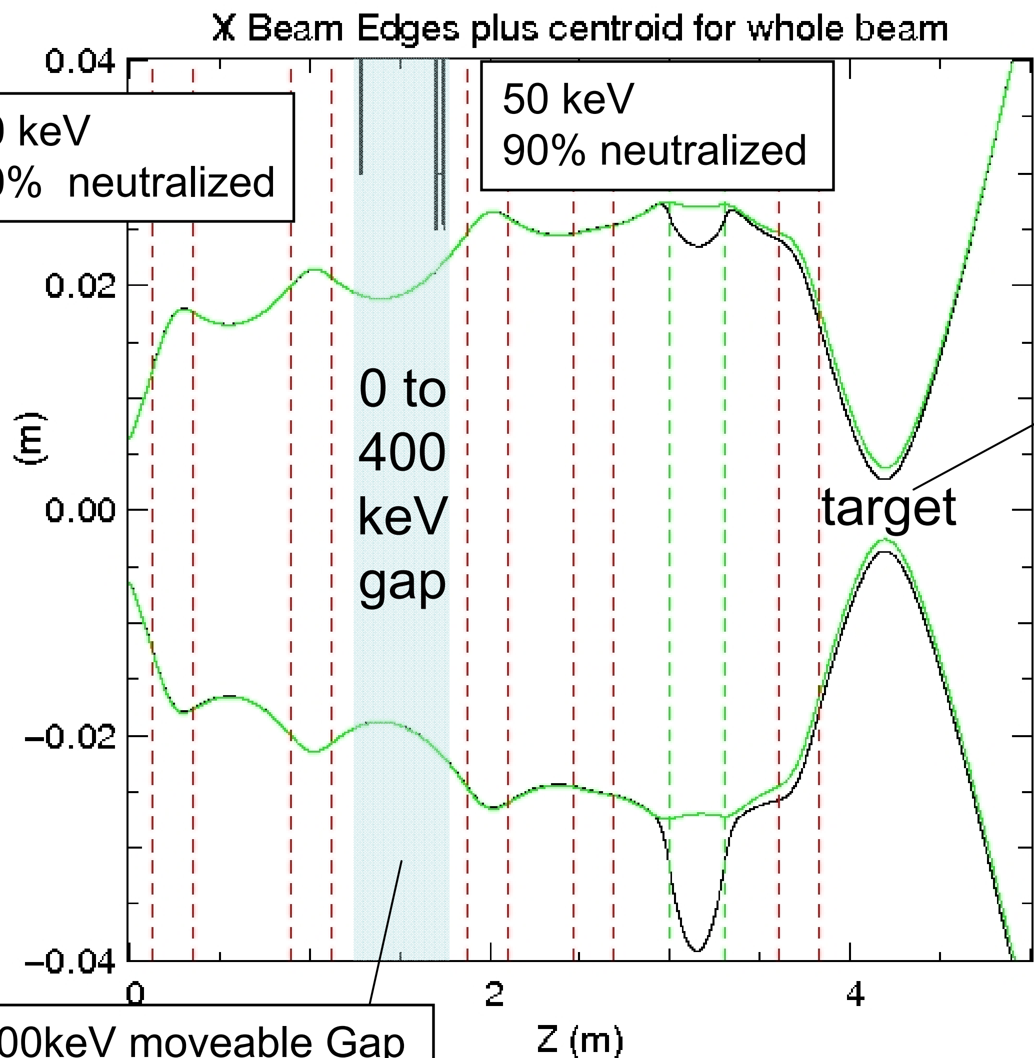
ADJUSTABLE ACCELERATION GAP WILL BE A MAIN FEATURE OF DIANA LOW ENERGY ACCELERATOR

DIANA

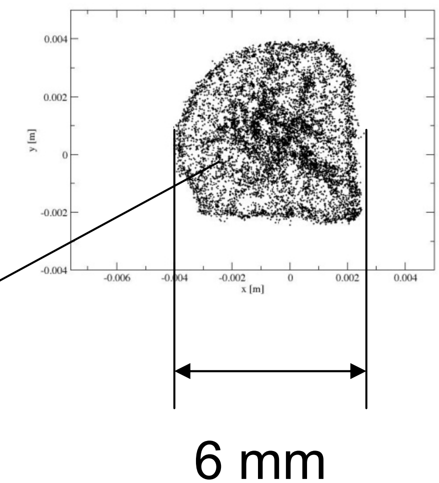


WARP BEAM ENVELOPE FOR 50 keV

Beam from ion source

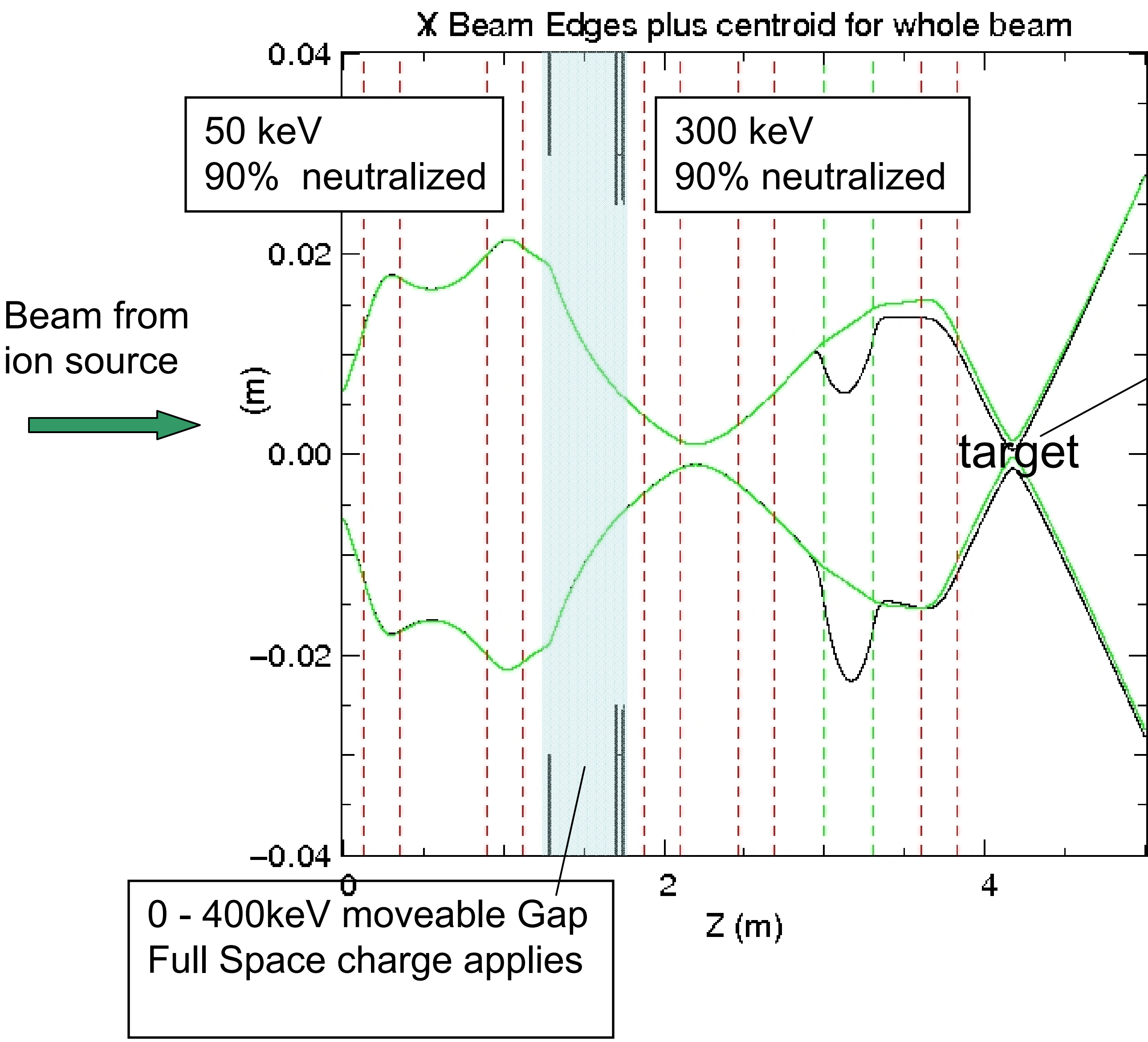


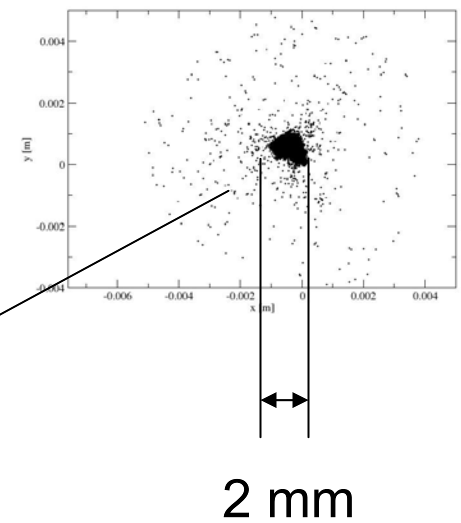
0 - 400keV moveable Gap
Full Space charge applies



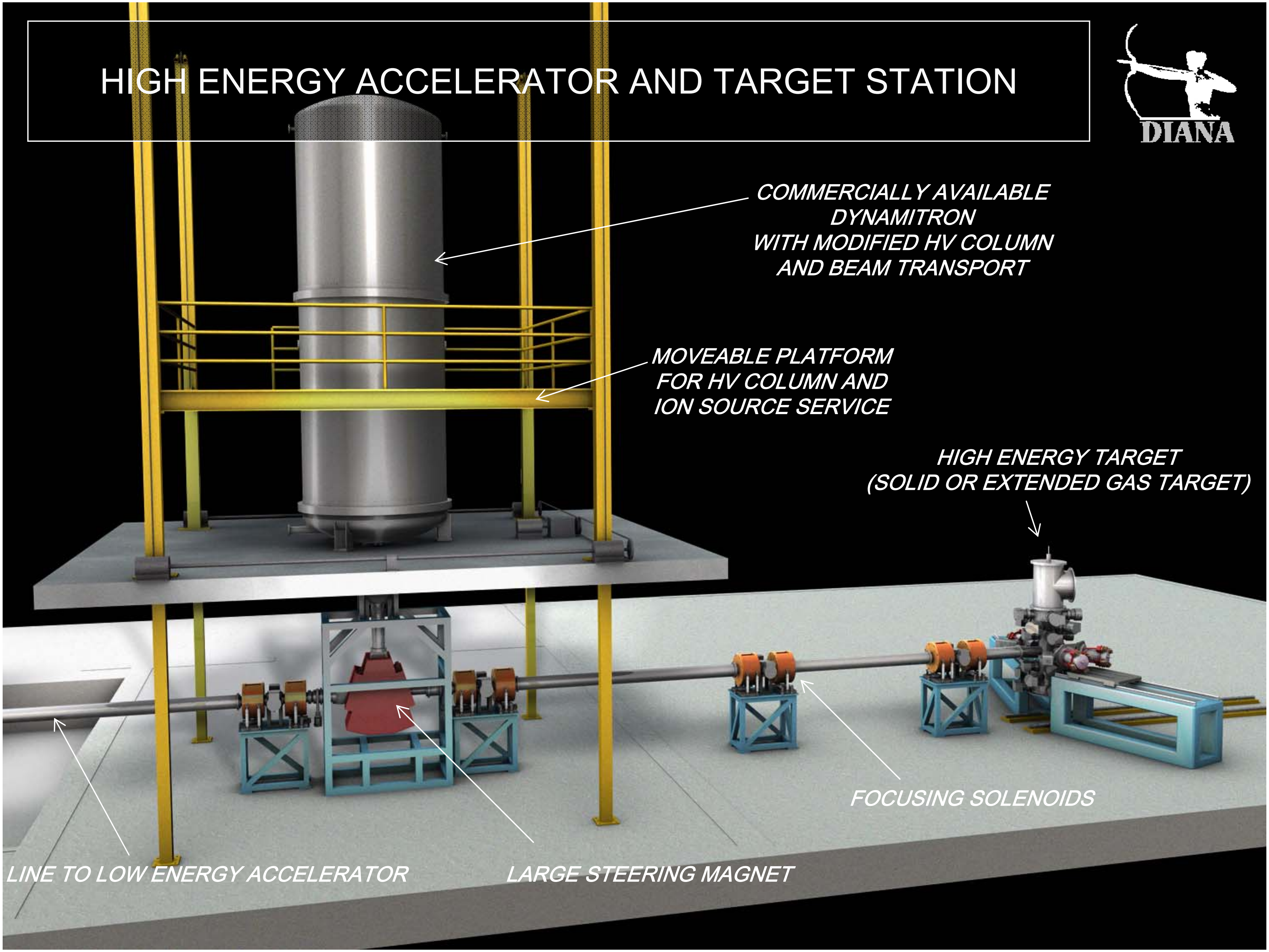
Needs interfacing with the gas jet target geometry

WARP BEAM ENVELOPE FOR 300 keV





needs interfacing with the gas jet target geometry


HIGH ENERGY ACCELERATOR AND TARGET STATION
DIANA
COMMERCIALLY AVAILABLE DYNAMITRON WITH MODIFIED HV COLUMN AND BEAM TRANSPORT
MOVEABLE PLATFORM FOR HV COLUMN AND ION SOURCE SERVICE
HIGH ENERGY TARGET (SOLID OR EXTENDED GAS TARGET)
FOCUSING SOLENOIDS
LINE TO LOW ENERGY ACCELERATOR
LARGE STEERING MAGNET

HIGH ENERGY ACCELERATOR AND TARGET STATION

DIANA

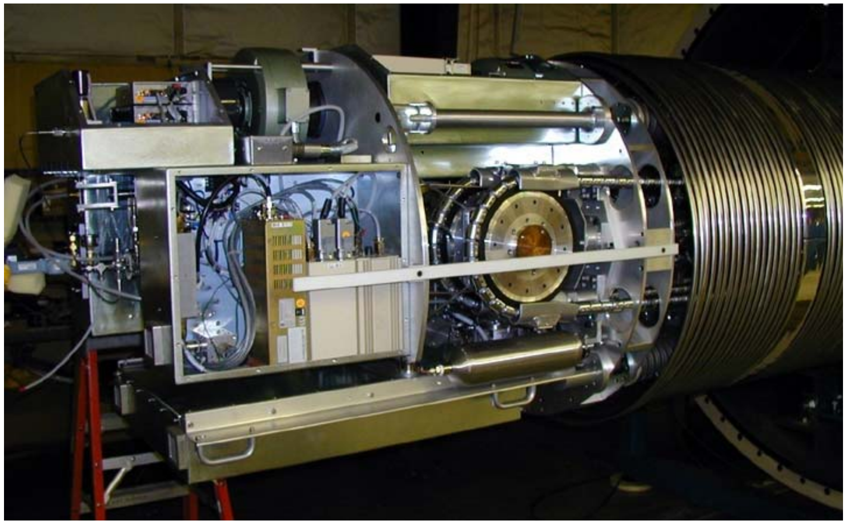
Maximum Energy:	6 MeV for Oxygen or Neon (charge state 2^{+})
Maximum Beam Current:	< 10 mA
Vacuum Pressure in HV Column:	10^{-6} mTorr
Energy Stability:	+/- 0.05% (Goal)
Energy Resolution:	+/- 0.05% (Goal)
Ion Sources:	permanent-magnet microwave source (several mA of singly charged ions) small, permanent-magnet ECR source for multiply charged ions ~30 pμA low-charged ions total extracted beam current 1-2 mA
Maximum Magnet Bending Power:	6 MeV ^{20}Ne

LINEAR DC ACCELERATORS ARE THE CLASSIC APPROACH FOR ASTROPHYSICS STUDIES

DIANA

NEC 3UH-HC Pelletron

5.5 MeV Van De Graaf Injector
Hahn-Meitner Institute, Berlin
(ECR ion source at the terminal)

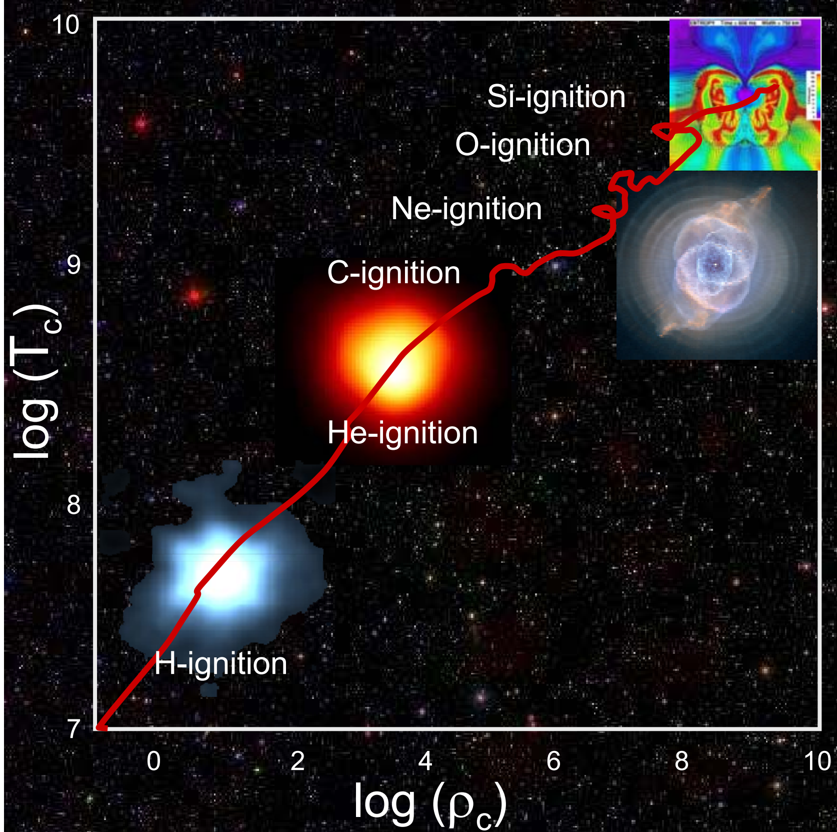


Picture of a NEC Pelletron Platform

ECR ion source on Dynamitron platform will be most challenging development item

Challenges:
Vacuum Pumping, Extraction, Mass Analysis

DIANA will be a unique astrophysics accelerator that will address a wide range of stable ion nuclear astrophysics questions



Physics Program

- Solar neutrino sources and the metallicity of the sun
- Carbon-based nucleosynthesis
- Neutron sources for the production of trans Fe elements

Unique Features

- Wide and overlapping range of energies
- Significantly higher beam currents than currently achievable
- Target stations can be operated with overlapping beam energies
- State of the art facility with challenging technical requirements

Flexibility and wide energy range would make it a unique facility world wide and enable a long experimental program (10+ years)

Nuclear Astrophysics
Underground Accelerator Working Group

Thank you

DIANA S-4 PROJECT

Project Director
Michael Wiescher
Institute for Structure and Nuclear Astrophysics
University of Notre Dame

Project Management
Matthaeus Leitner
Engineering Division
Lawrence Berkeley National Laboratory

TARGET STATION DESIGN

Principal Investigator
Michael Wiescher
Institute for Structure and Nuclear Astrophysics
University of Notre Dame

Gas Jet Development
Target Station Physics Design
Magnet Optics and Design
Neutron Detectors

1 Post Doc
1 Staff Scientist

DIAGNOSTICS DEVELOPMENT

Principal Investigator
Christian Iliadis
Nuclear Astrophysics Group
University of North Carolina

Detector Development

1 Post Doc

ACCELERATOR AND FACILITY DESIGN

Principal Investigator
Daniela Leitner
Nuclear Science Division
Lawrence Berkeley National Laboratory

Low-Energy Accelerator Design
High-Energy Accelerator Design
Ion Optics
Facility Integration
Target Station Mechanical Design
Project Management

1 Post Doc
0.2 FTE Staff Scientist
0.8 FTE Mechanical Engineer
0.5 FTE Electrical Engineer
0.1 FTE Project Management
0.05 FTE Cost Estimator

SHIELDING DEVELOPMENT

Principal Investigator
Michael Famiano
Physics Department
Western Michigan University

Shielding Development

0.15 Scientist

Dakota Ion Accelerators for Nuclear Astrophysics is a collaboration between the following institutions:

UNIVERSITY OF NOTRE DAME
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL
ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY