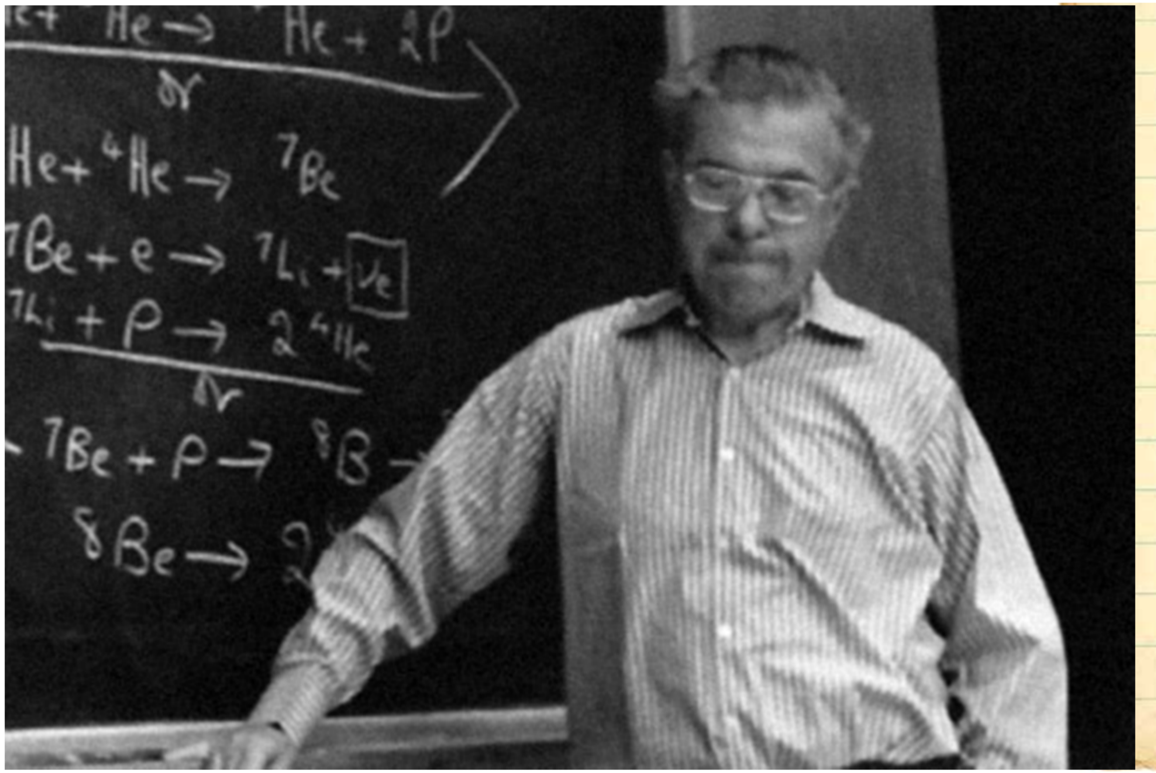
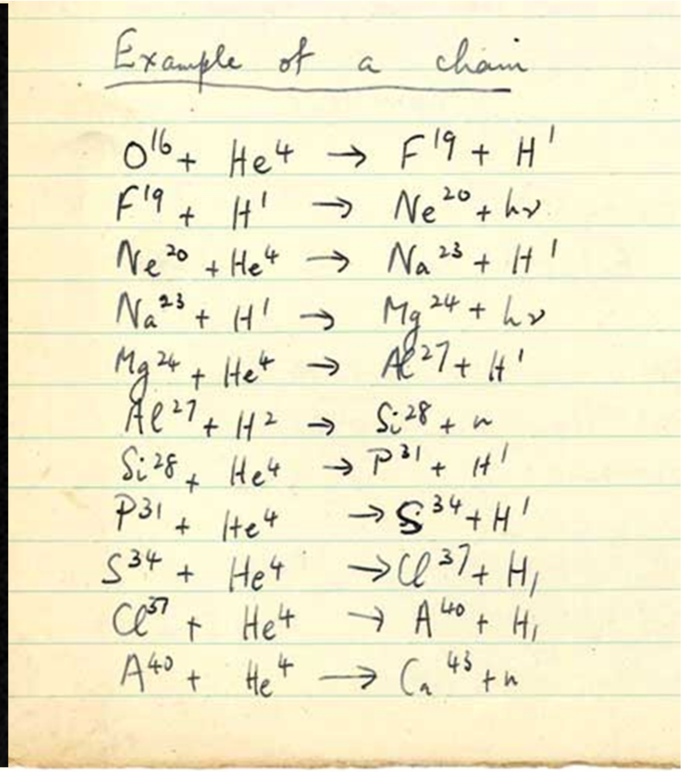
The Physics of Underground Accelerators

Michael Wiescher
Joint Institute for Nuclear Astrophysics JINA
University of Notre Dame

- Background and presents efforts
- The physics questions and issues
- Status of US initiatives

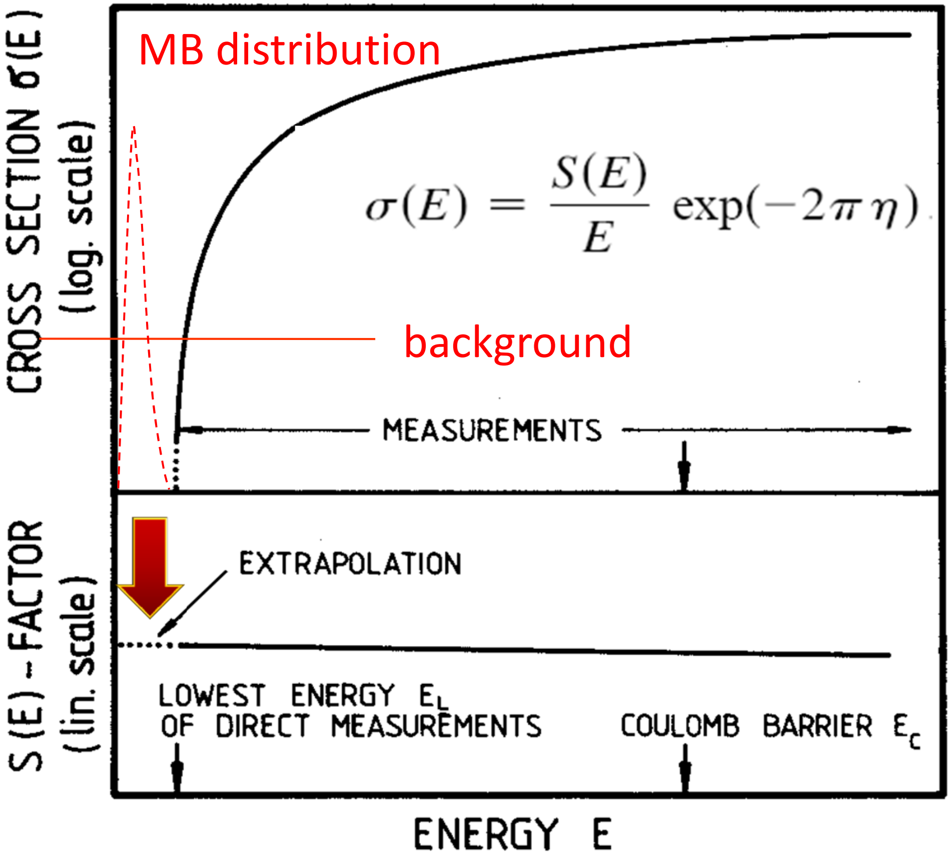
Nuclear reactions in stars

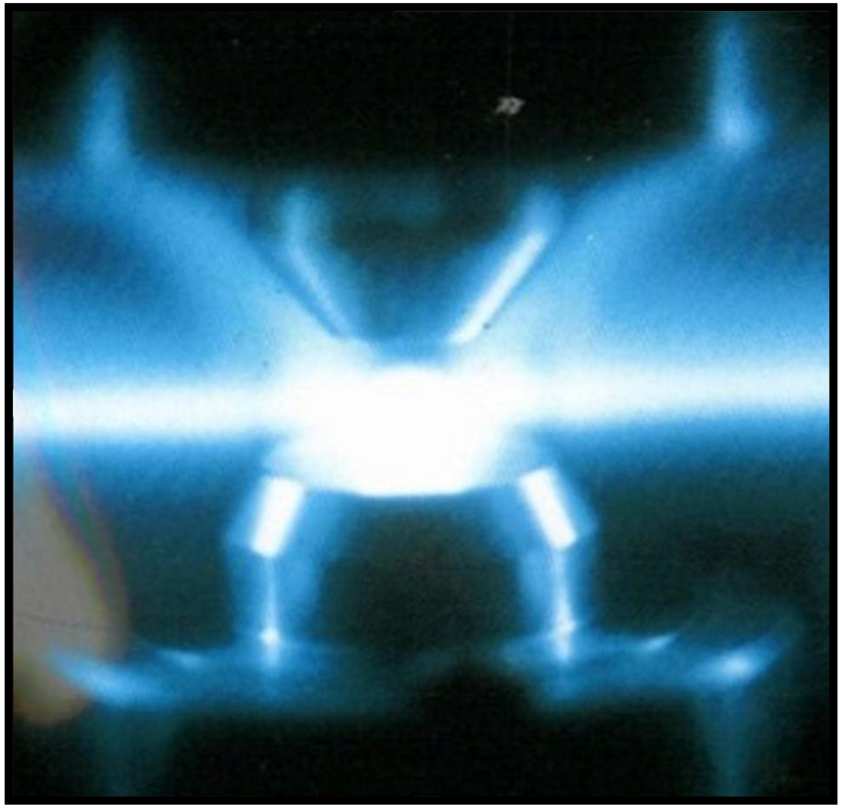




Nuclear reaction processes in stars determine the energy production and the lifetime of stars; they provide new signatures (e.g. neutrinos) for probing the stellar burning mechanisms. Nuclear reactions govern the formation of new elements through complex nucleosynthesis processes driven by nuclear fuel conditions and provide the seed for subsequent explosive burning processes.

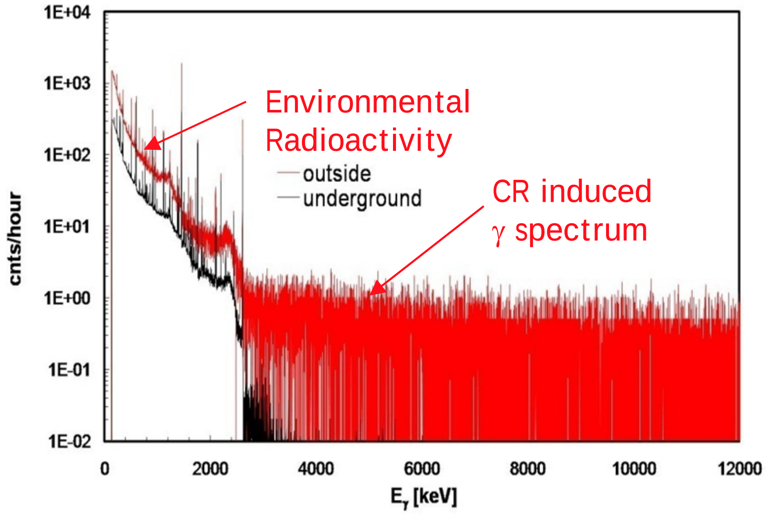
The challenge of reaction rates

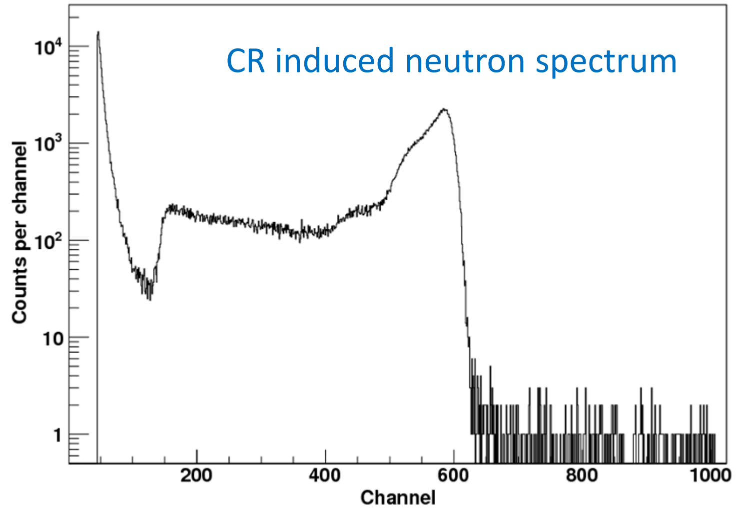


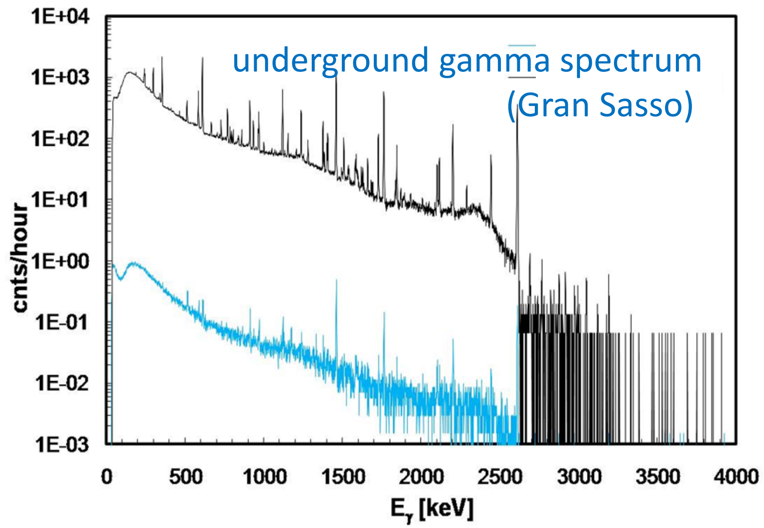


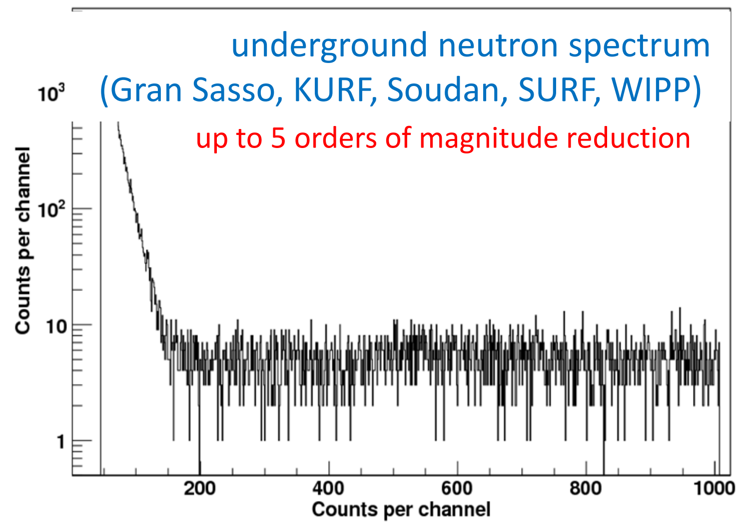
$$N_A\langle\sigma v\rangle = \sqrt{\frac{8}{\pi\cdot\mu}}\cdot(kT)^{-3/2}\cdot\int_0^\infty E\cdot f(E)\cdot\sigma(E)\cdot\exp\left(-\frac{E}{kT}\right)dE$$

Background reduction





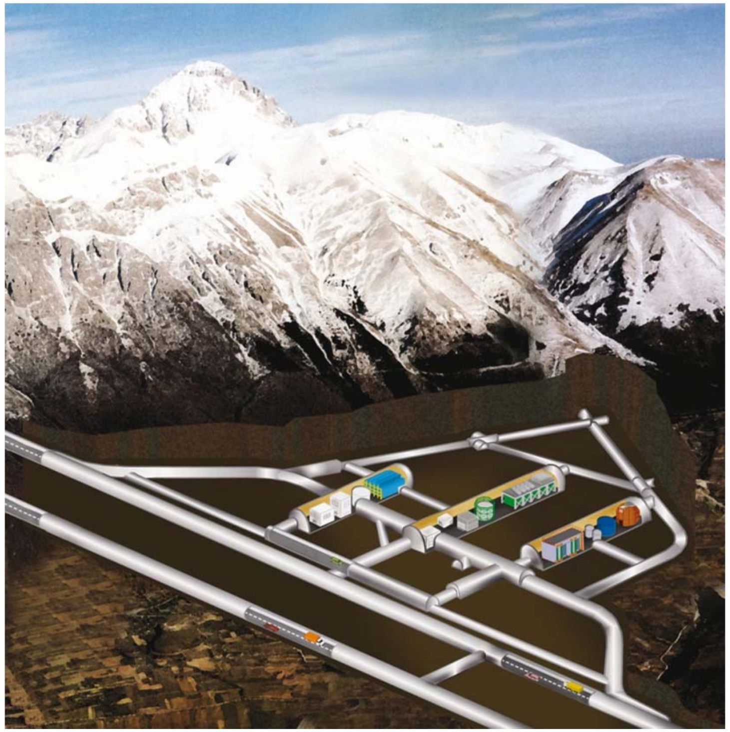


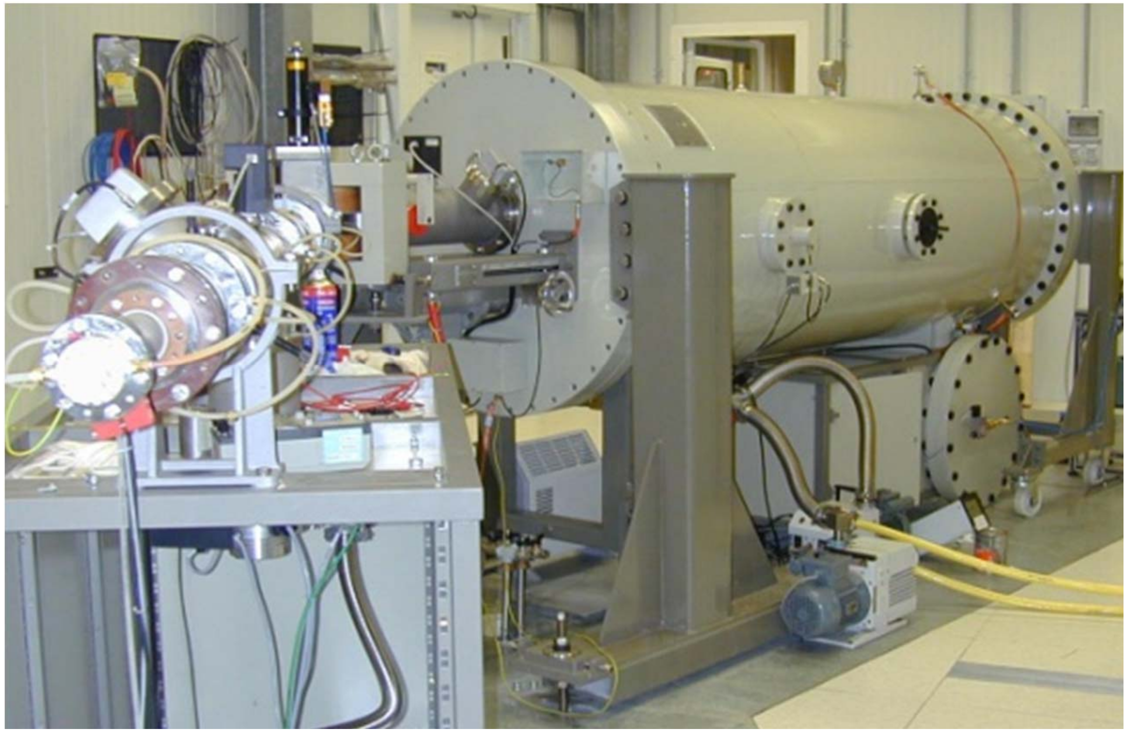


High luminosity, low background experiments

The LUNA underground accelerator laboratory

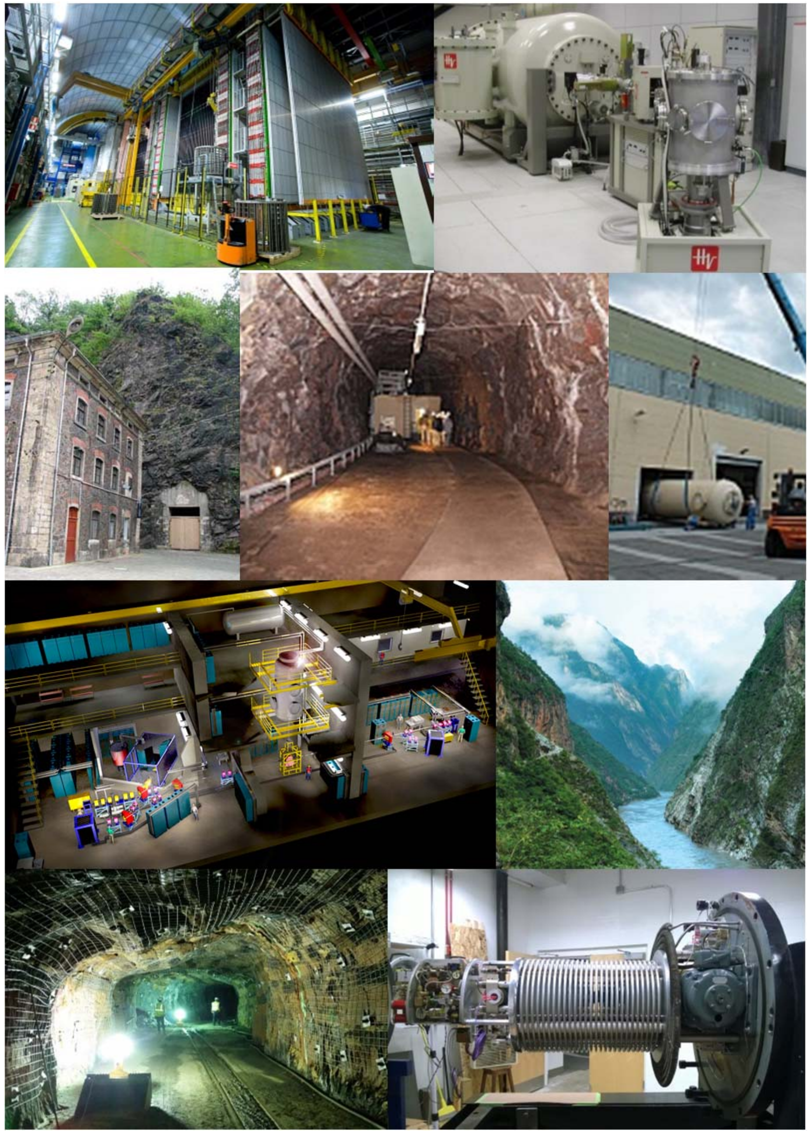
Light ion on heavy target with measurement of light reaction products, limited by solid angle and detection efficiency. The program has concentrated on measuring reactions of relevance for stellar hydrogen burning, e.g. in the pp-chains & CNO cycles.





Present initiatives to expand the physics case

- LUNA-MV, Gran Sasso
- Felsenkeller, Dresden
- DIANA, SURF
- DIANA, Jinping
- CASPAR, SURF

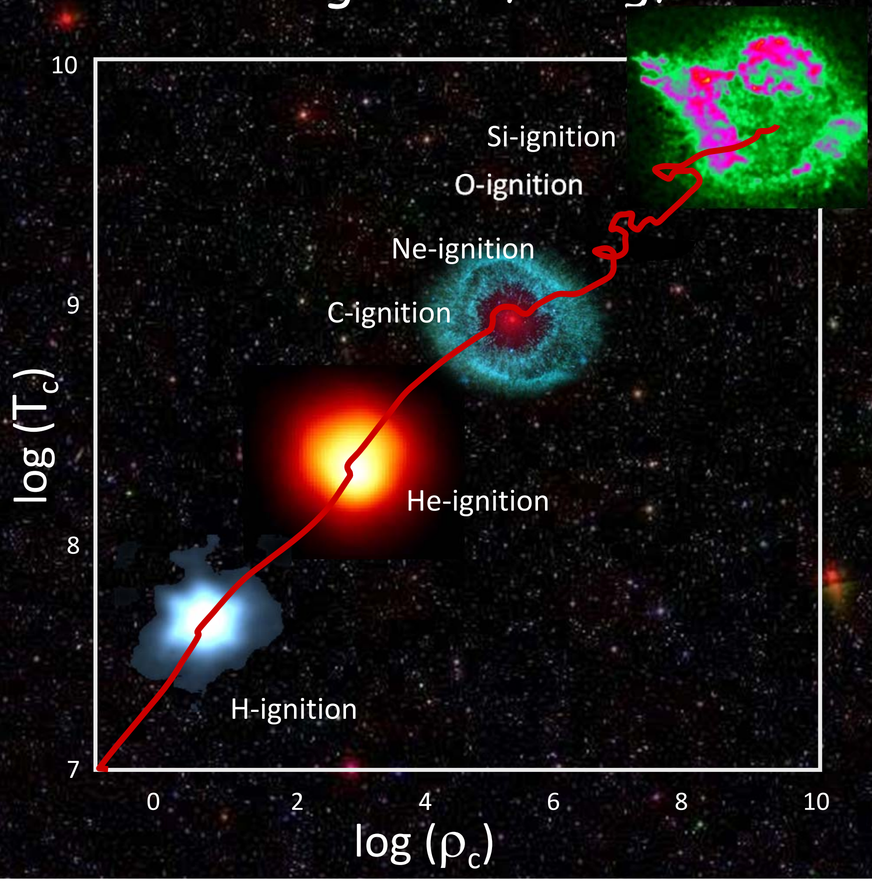


The physics case: Nuclear Burning in Stars

Hydrogen Burning: ^{4}He, ^{14}N

Helium Burning: ^{12}C, ^{16}O, ^{22}Ne, n, s-nuclei

Carbon Burning: ^{20}Ne, ^{24}Mg,



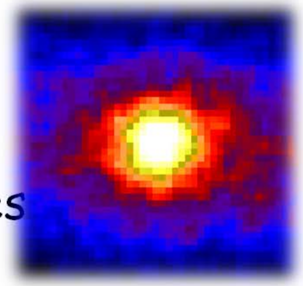
is characterized by low energy reaction sequences:

- pp-chains,
- CNO cycles
- He-burning
- Carbon fusion

What are the specific goals for underground reaction measurements?

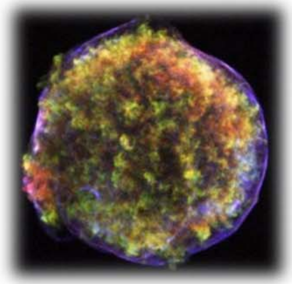
The specific physics goals

- **Solar neutrino sources and solar metallicity**
  Key reactions for neutrino production in pp-chains & CNO cycles



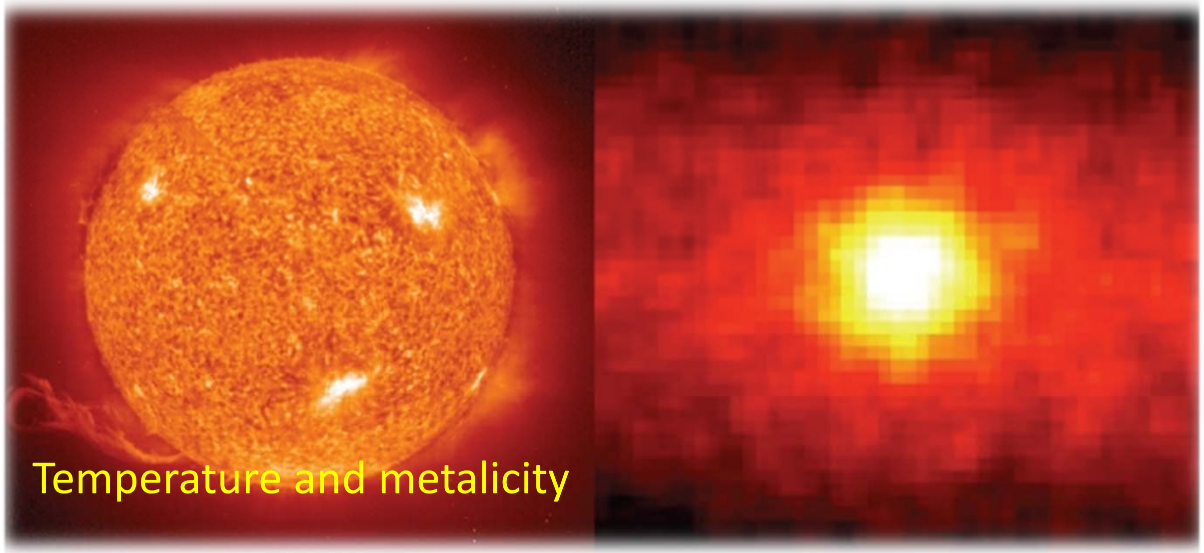
- **Stellar neutron sources and s-process abundances**
  $^{13}C(\alpha,n)$, $^{22}Ne(\alpha,n)$ and other possible neutron sources that affect the synthesis of light isotopes and s-process synthesis

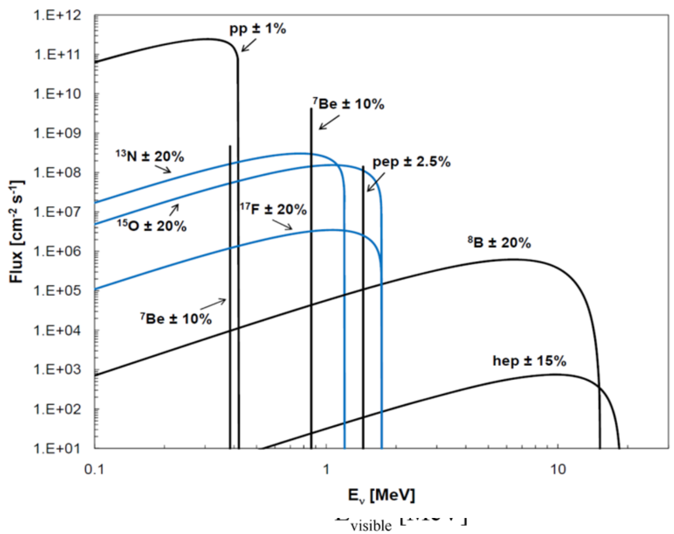
- **Carbon reactions, late stellar evolution, and type Ia SN explosion**
  $^{12}C(\alpha,\gamma)$ and $^{12}C+^{12}C$ fusion that determine $^{12}C/^{16}O$ budget and affect the fate of stars after the red giant phase

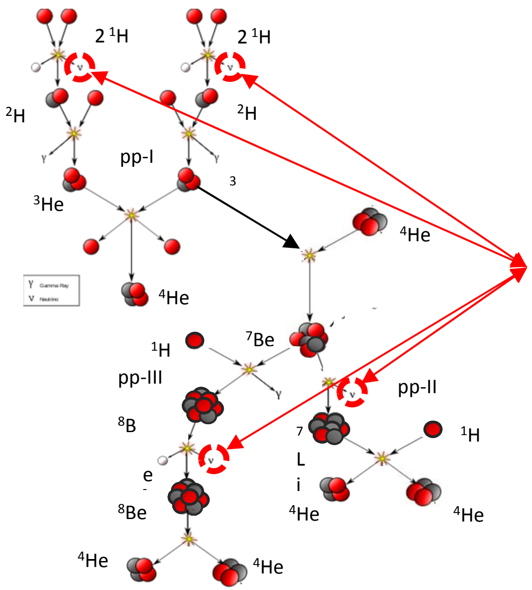


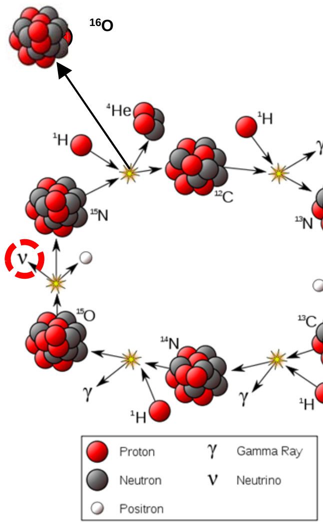
- **Nuclear plasma physics**
  Screening effects in stellar plasmas, light ion fusion reactions that can be mapped directly at NIF

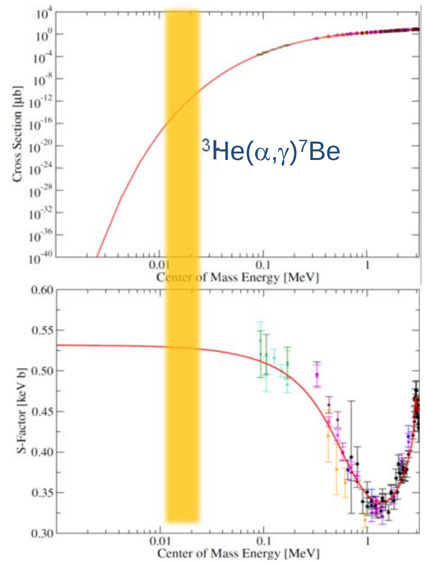
Solar neutrino sources

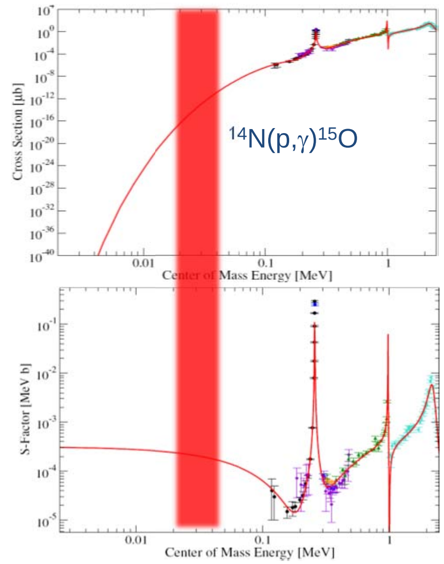




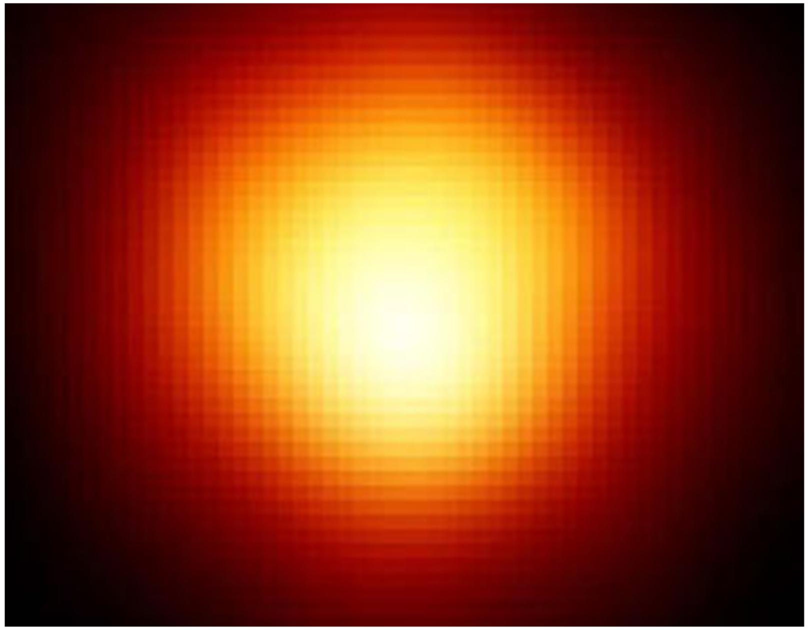


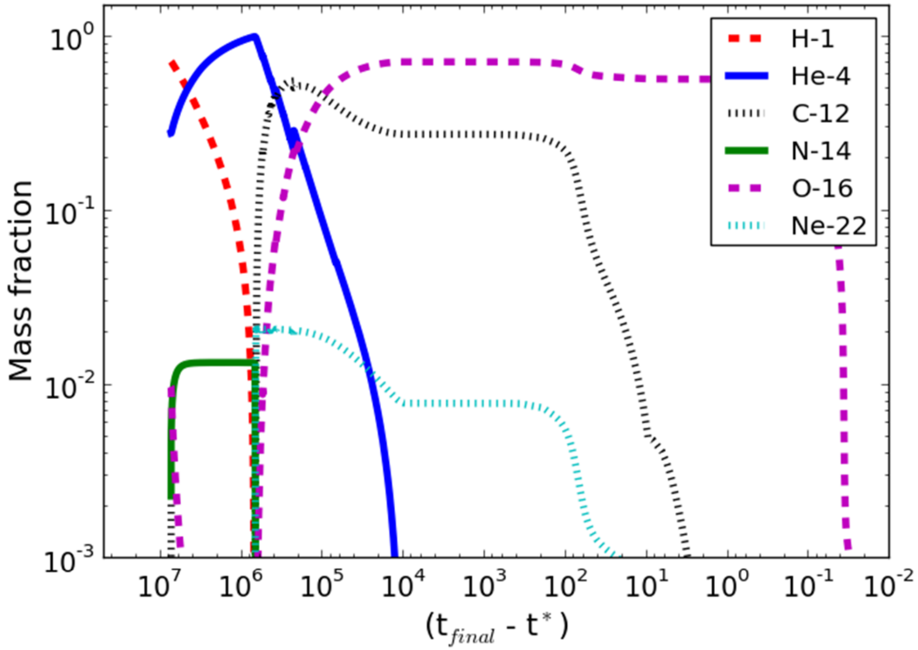


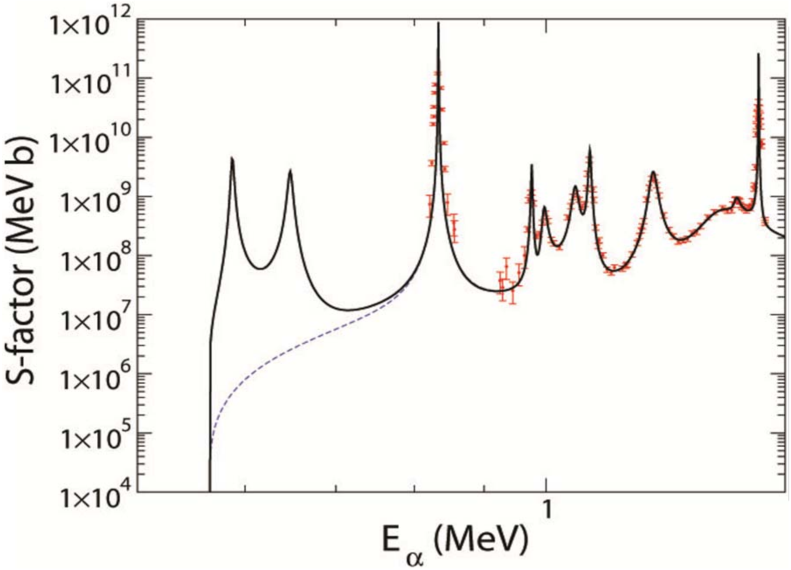


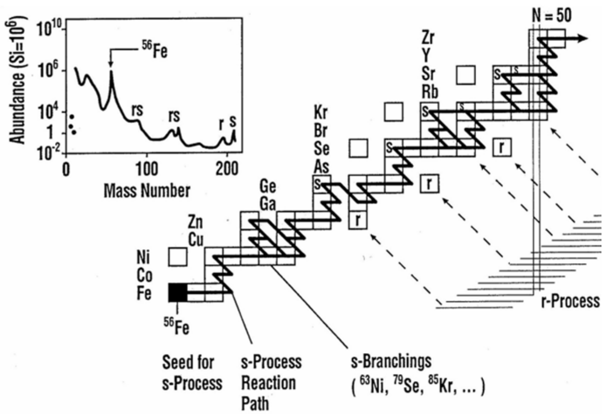


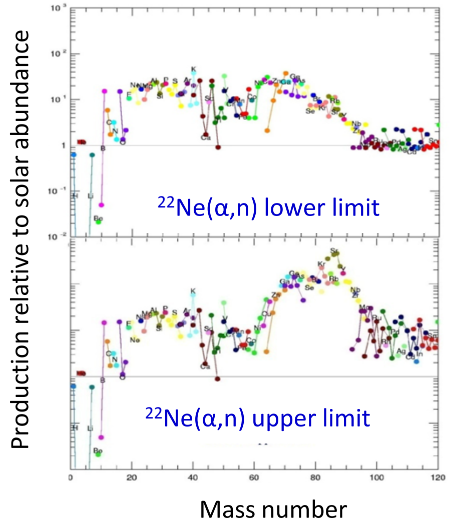
Neutron sources in helium burning



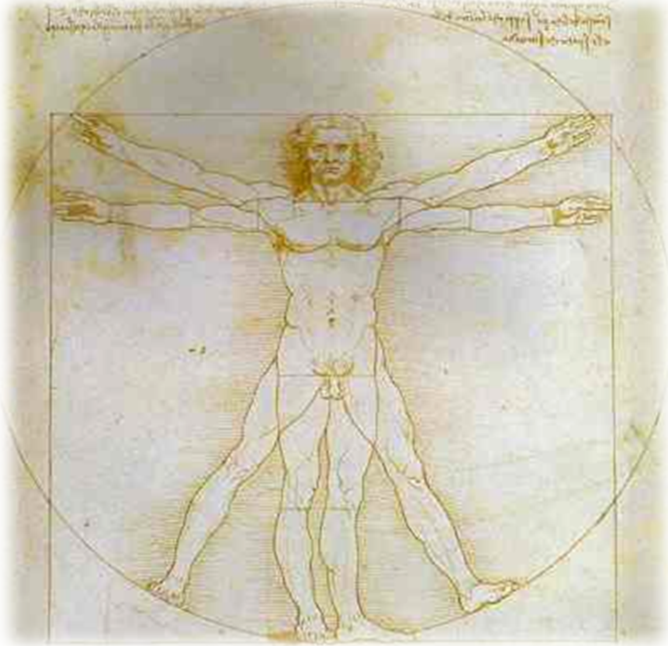


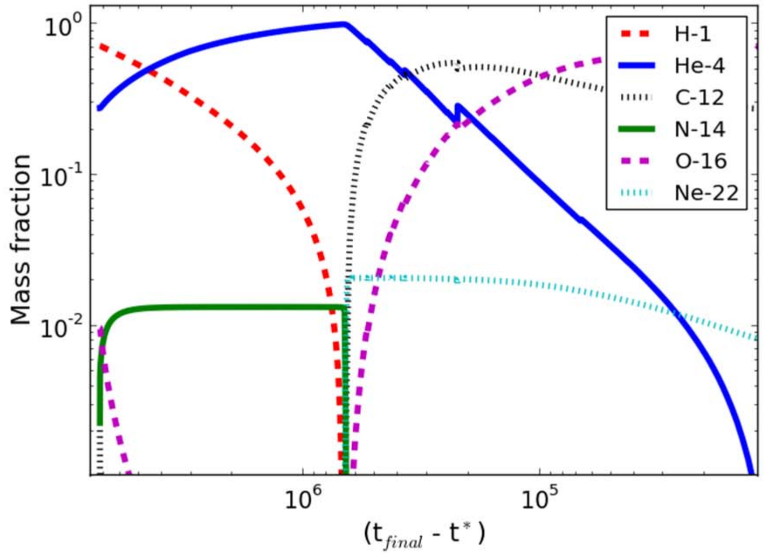


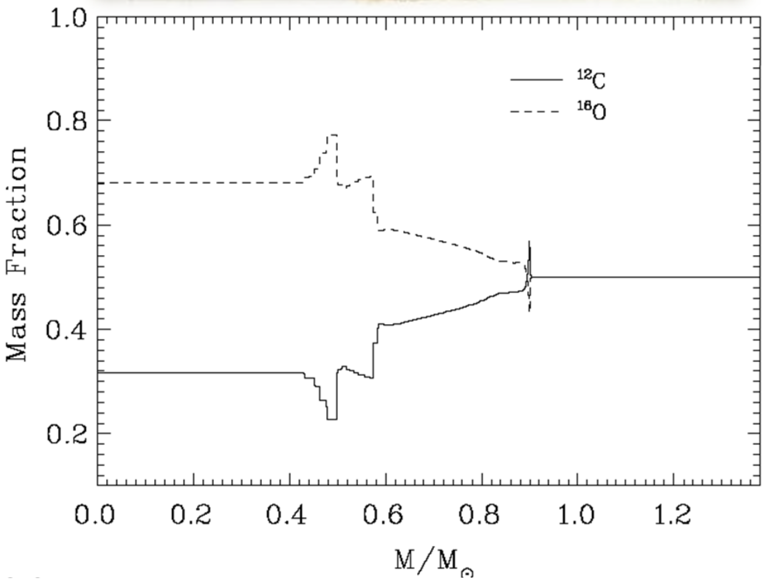


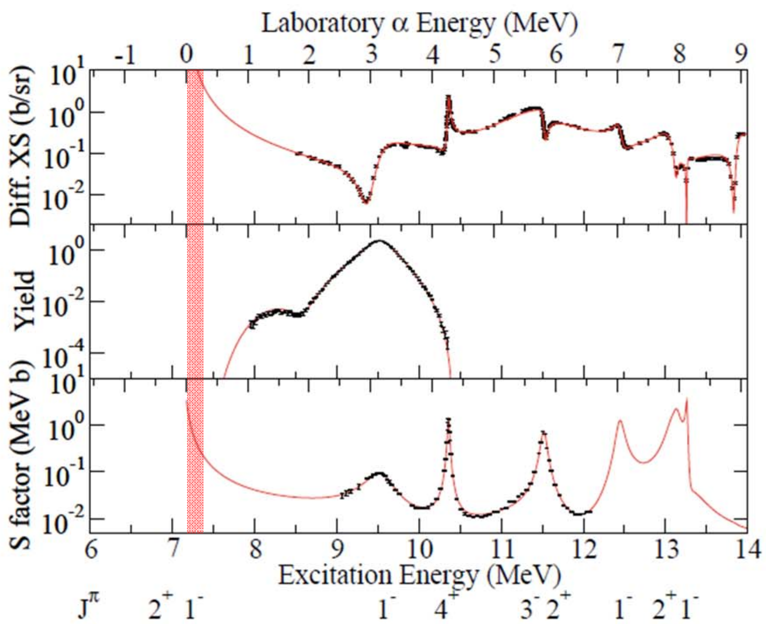


The $^{12}C/^{16}O$ ratio in our universe

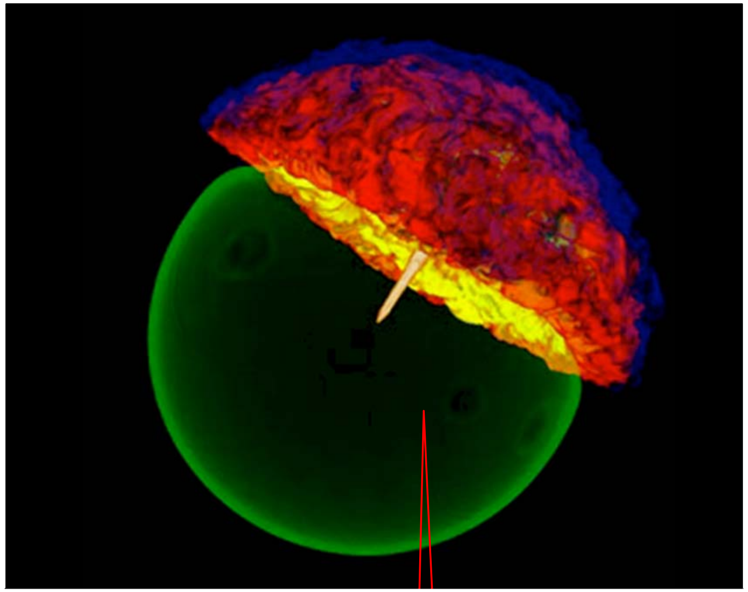


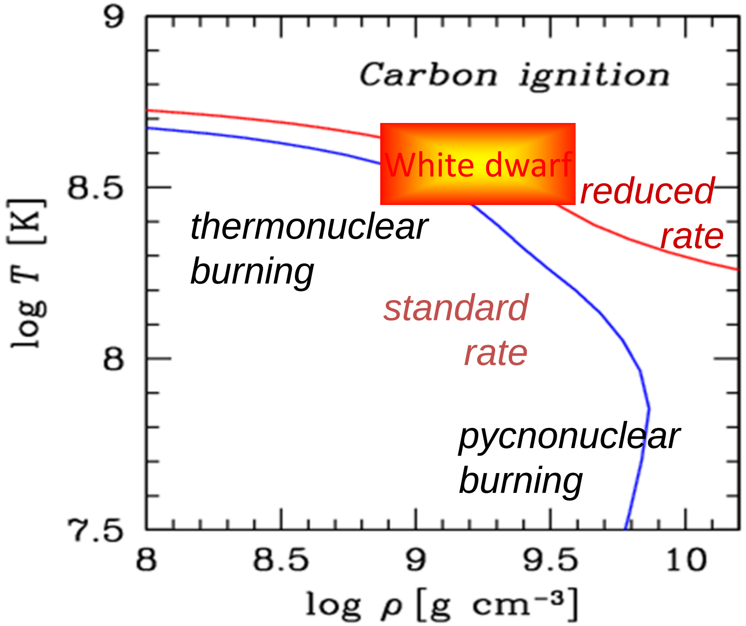


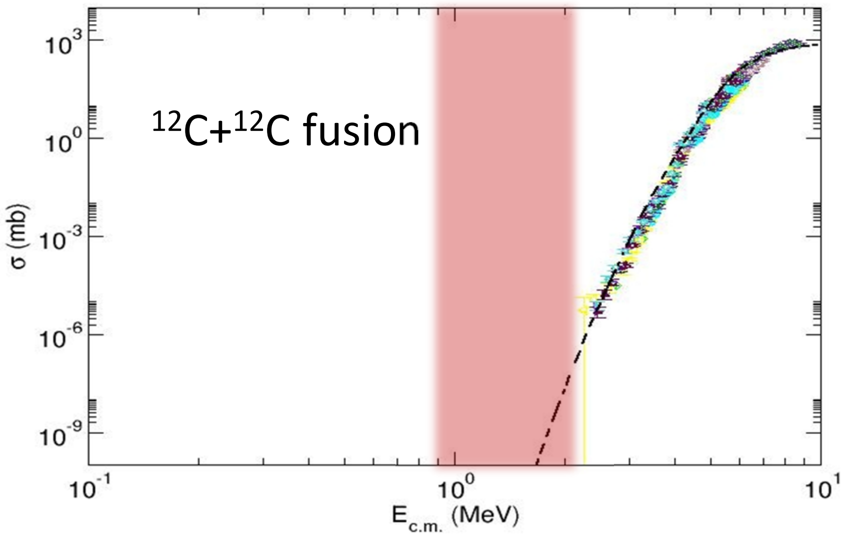


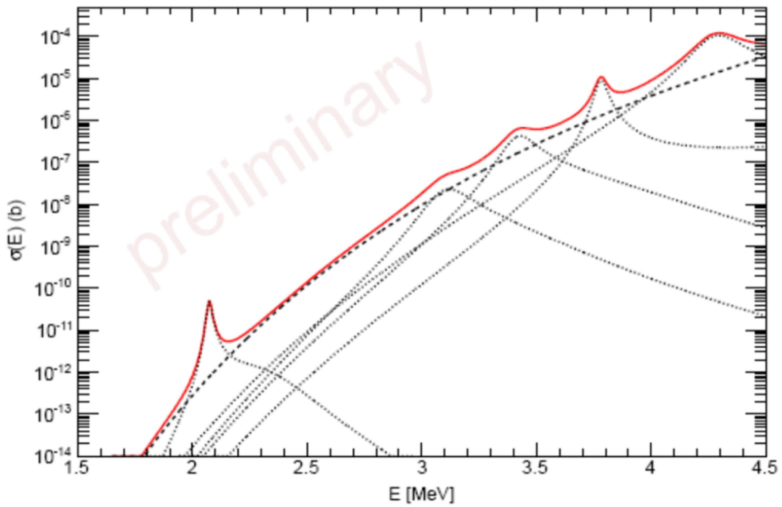


Carbon burning & type Ia supernovae

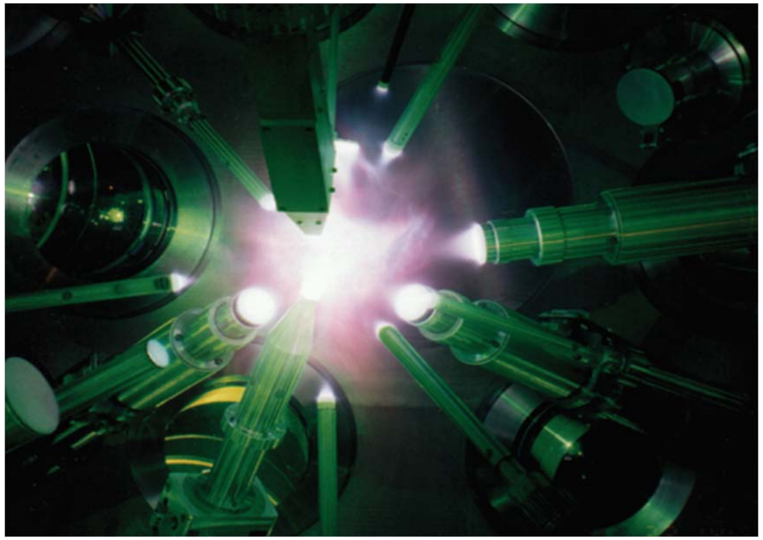


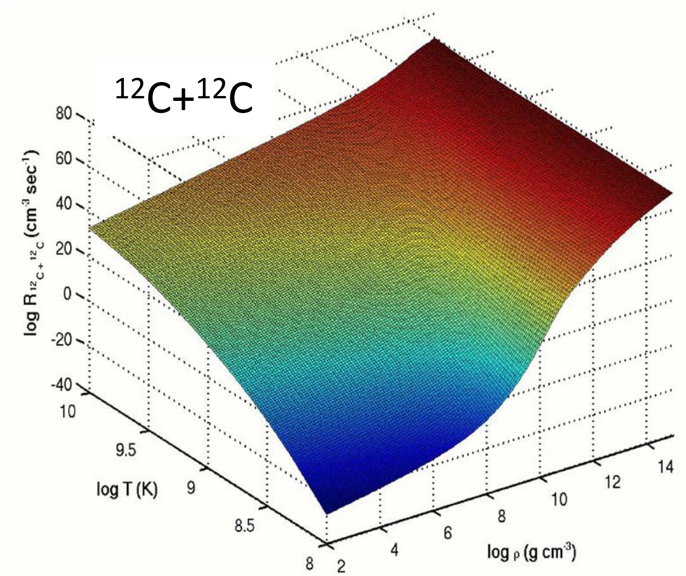






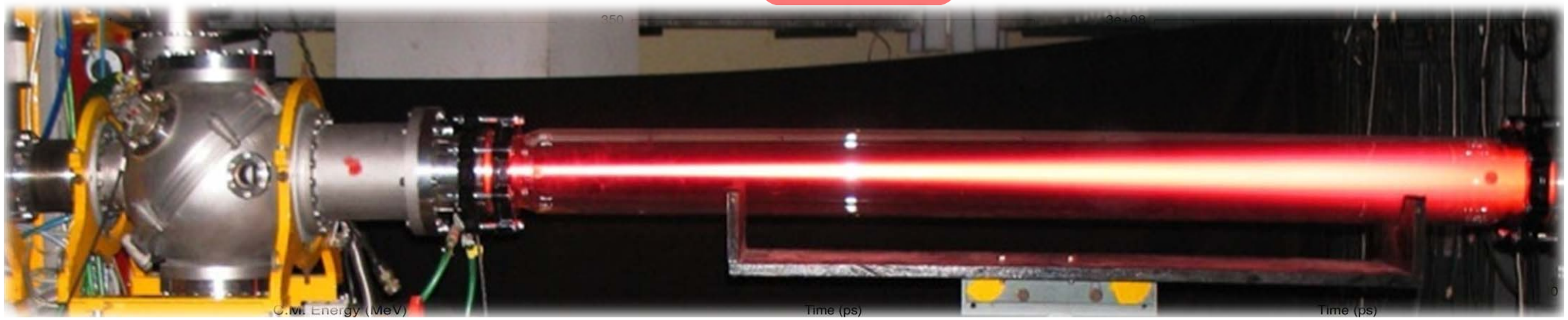
Nuclear Plasma Physics





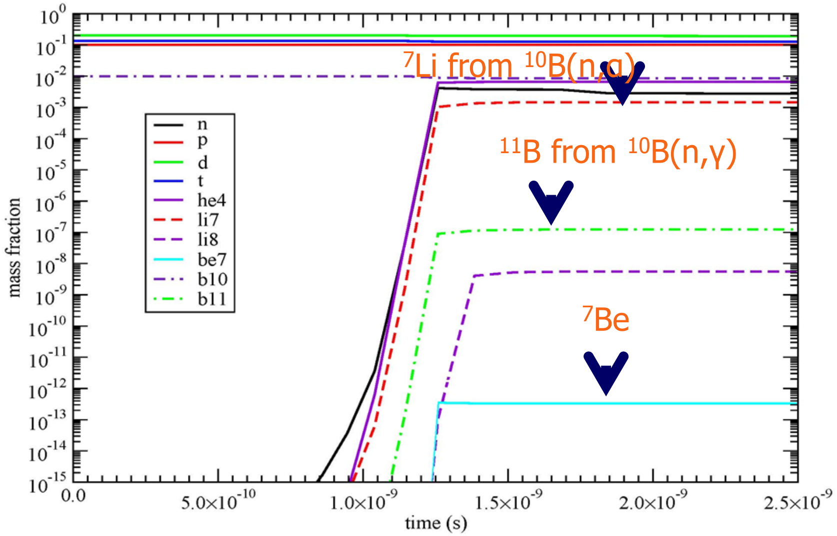
Exploring the screening of low energy reactions

$$N_A\langle\sigma v\rangle=\sqrt{\frac{8}{\pi\cdot\mu}}\cdot(kT)^{-3/2}\cdot\int_0^\infty E\cdot\exp\left(\frac{U(z)}{kT}\right)\cdot\sigma(E)\cdot\exp\left(-\frac{E}{kT}\right)dE$$

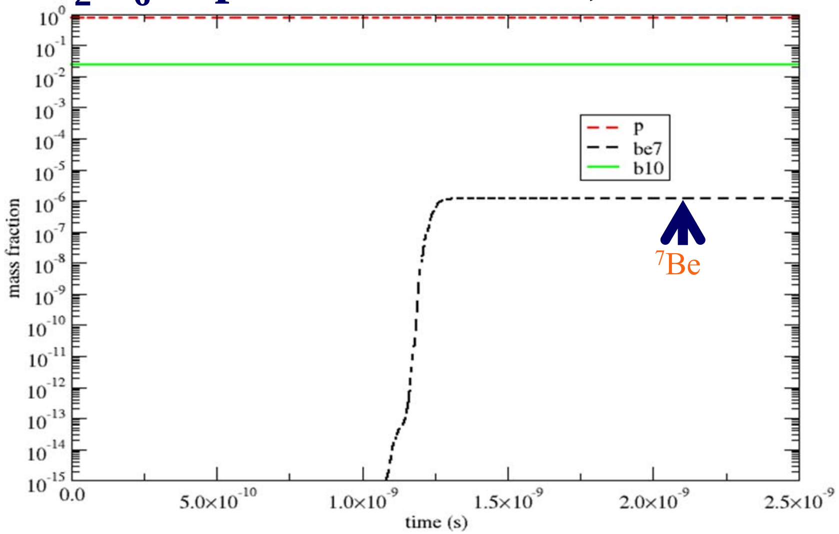


$^{10}B(p,\alpha)^{7}Be$ reaction as signature with post-shot collection of radioactive ^{7}Be

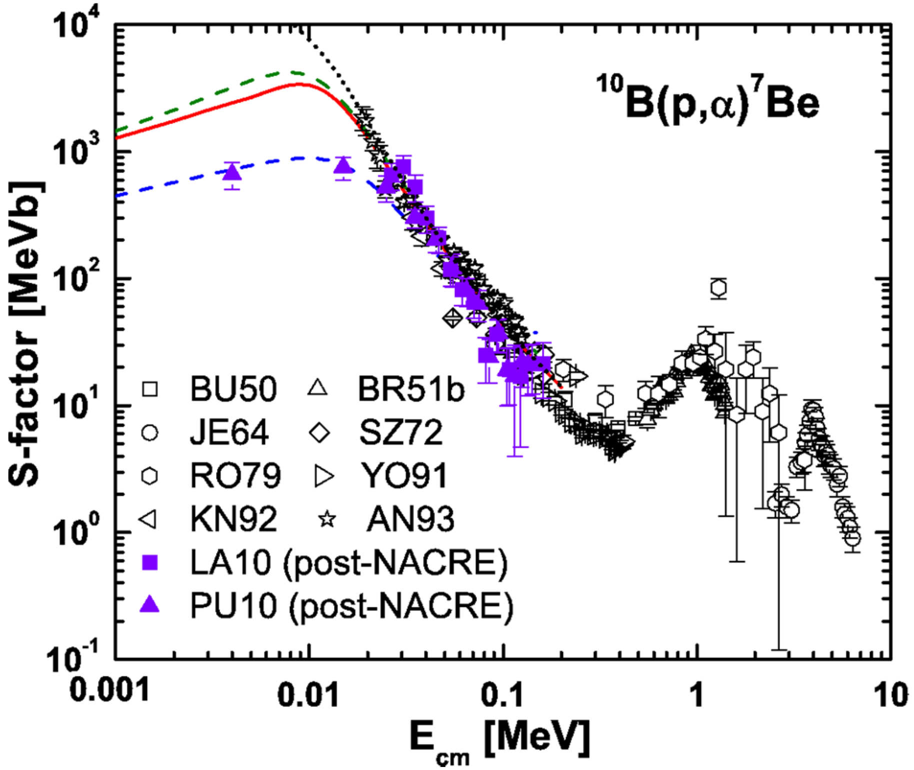
D-T capsule: 10% ^{10}B, 10% H



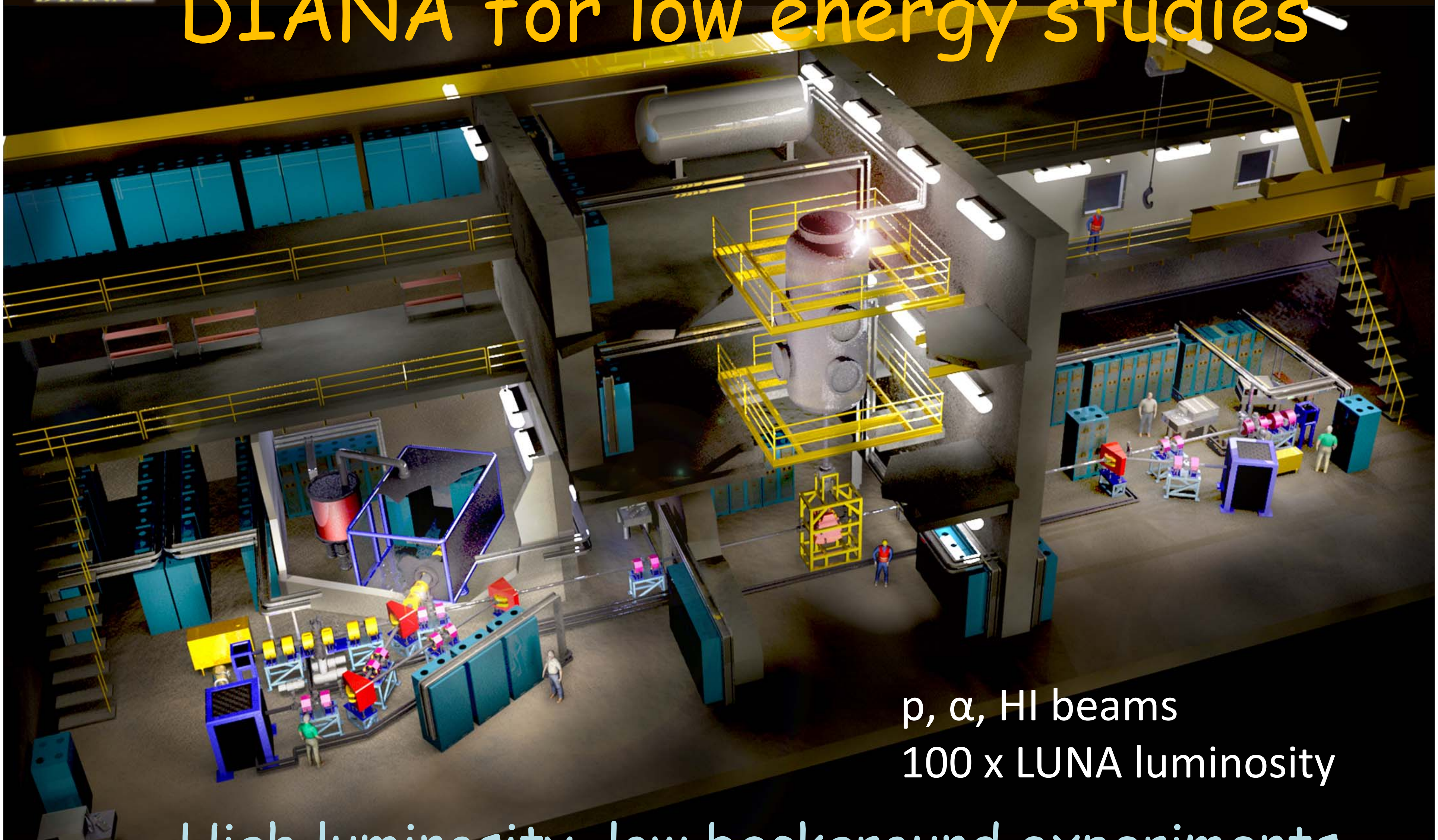
B_2H_6 capsule: 2×10^{16} ^{10}B, 6×10^{16} H



Y. Xu et al, Nucl. Phys. A 918 (2013)



Underground accelerator project DIANA for low energy studies

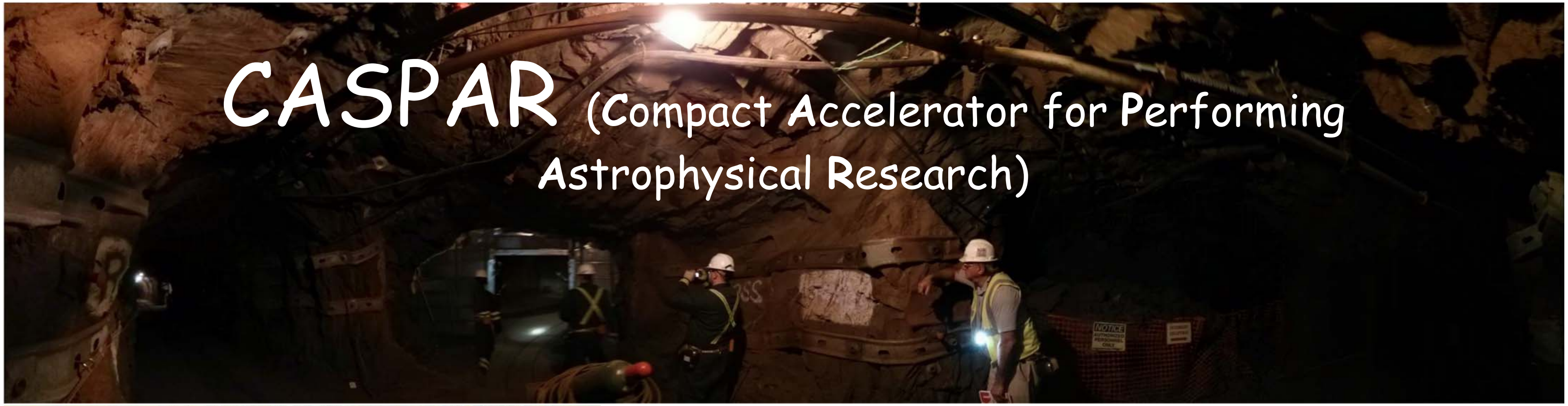


p, α, HI beams

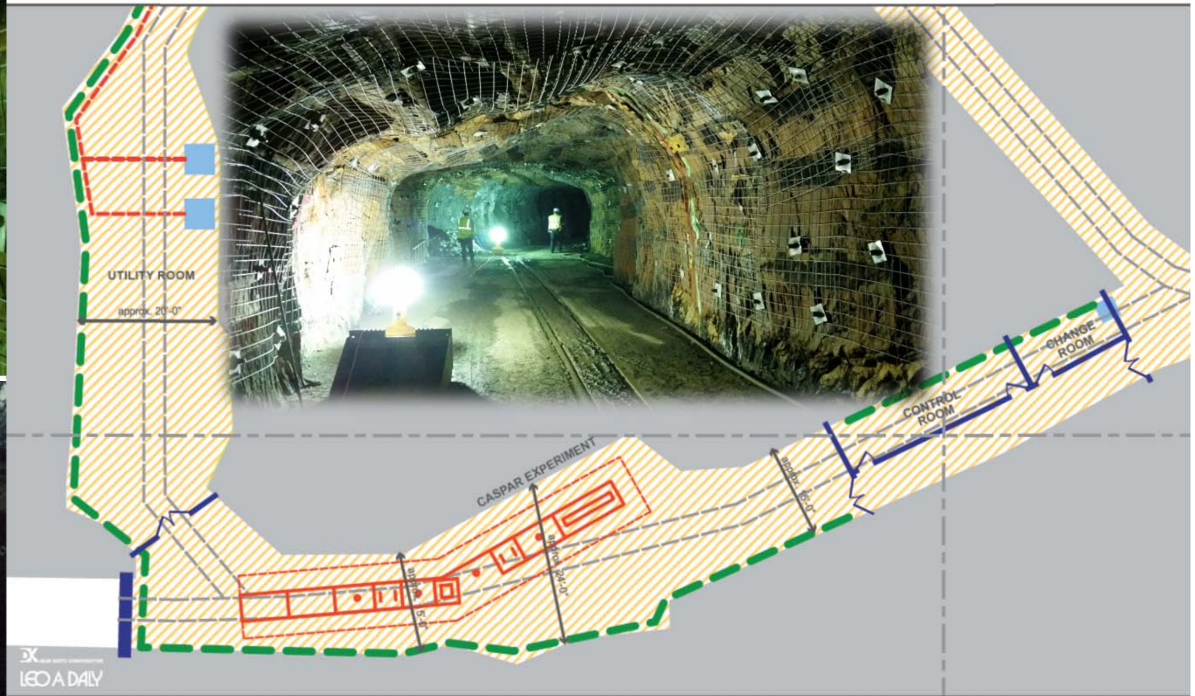
100 x LUNA luminosity

High luminosity, low background experiments

CASPAR (Compact Accelerator for Performing Astrophysical Research)



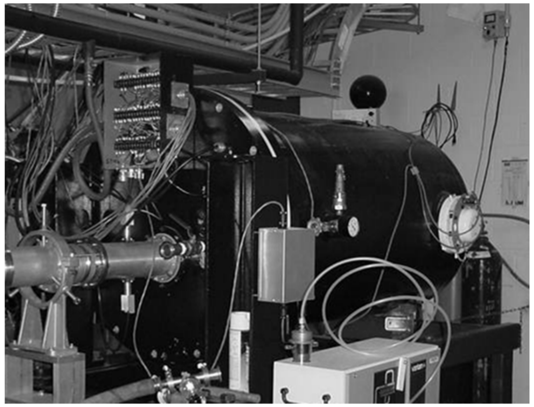
ACCELERATOR CAVERN

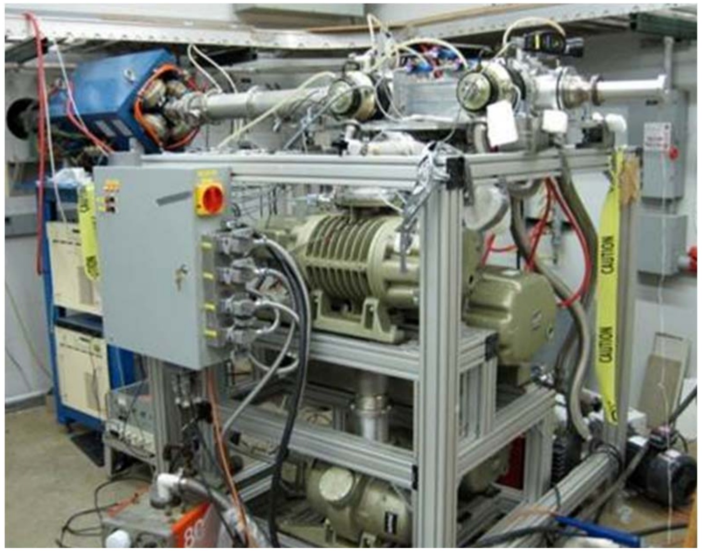
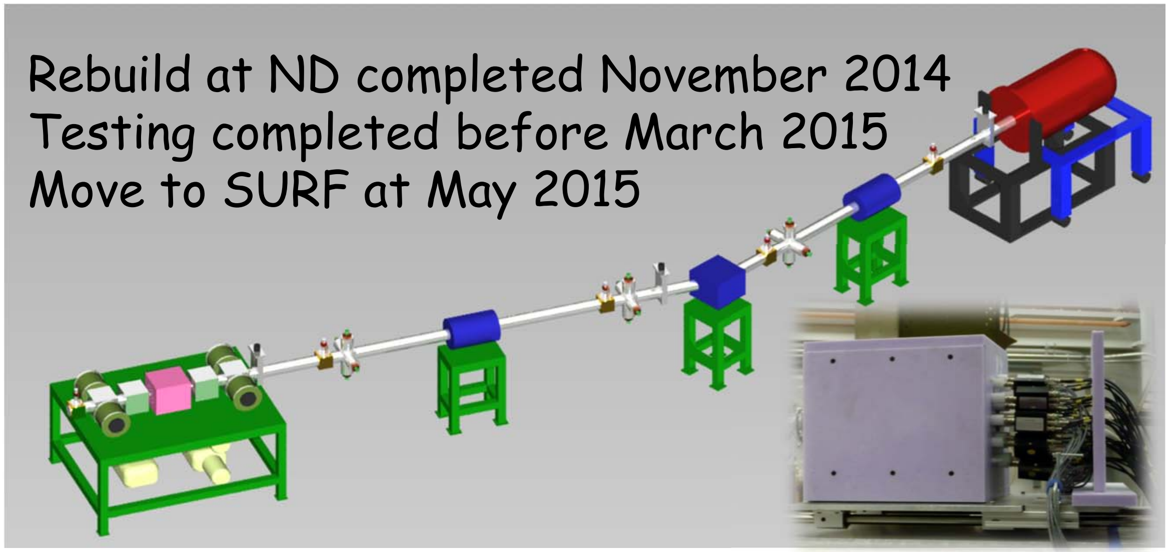


Sanford Underground Facility
in Homestake Mine, South Dakota

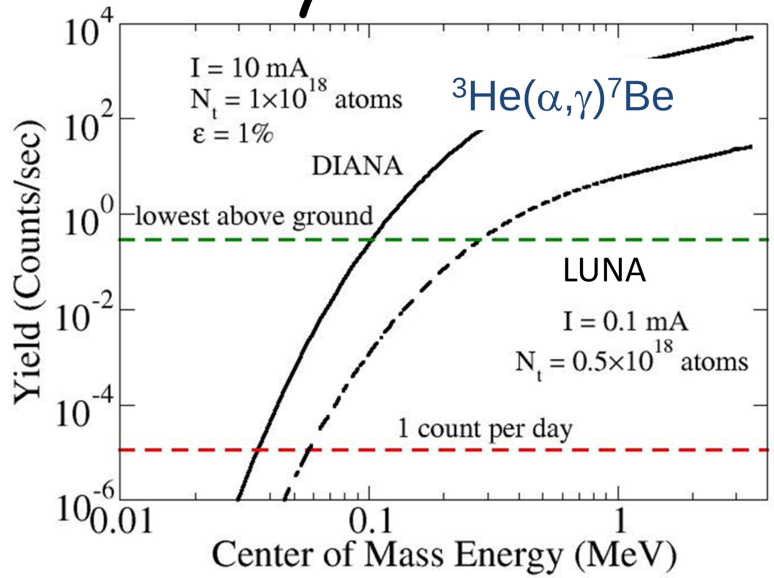
The Caspar Plan

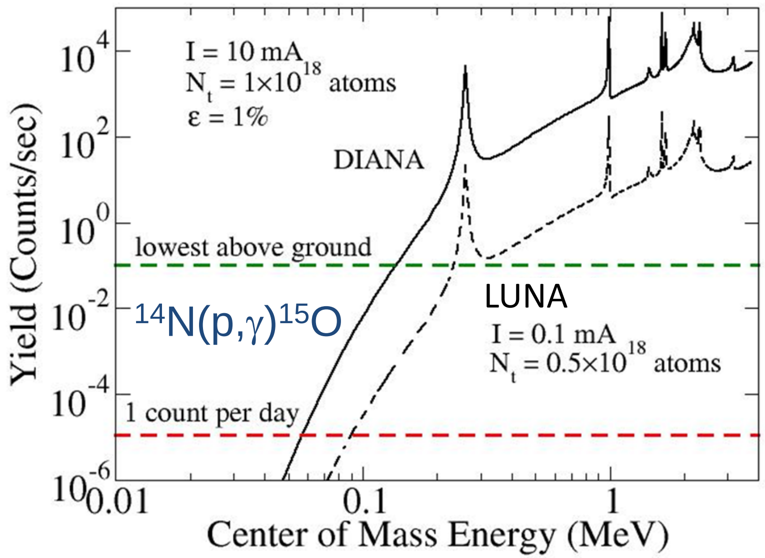
The accelerator is being rebuilt and tested, gas target system is being built from existent components!



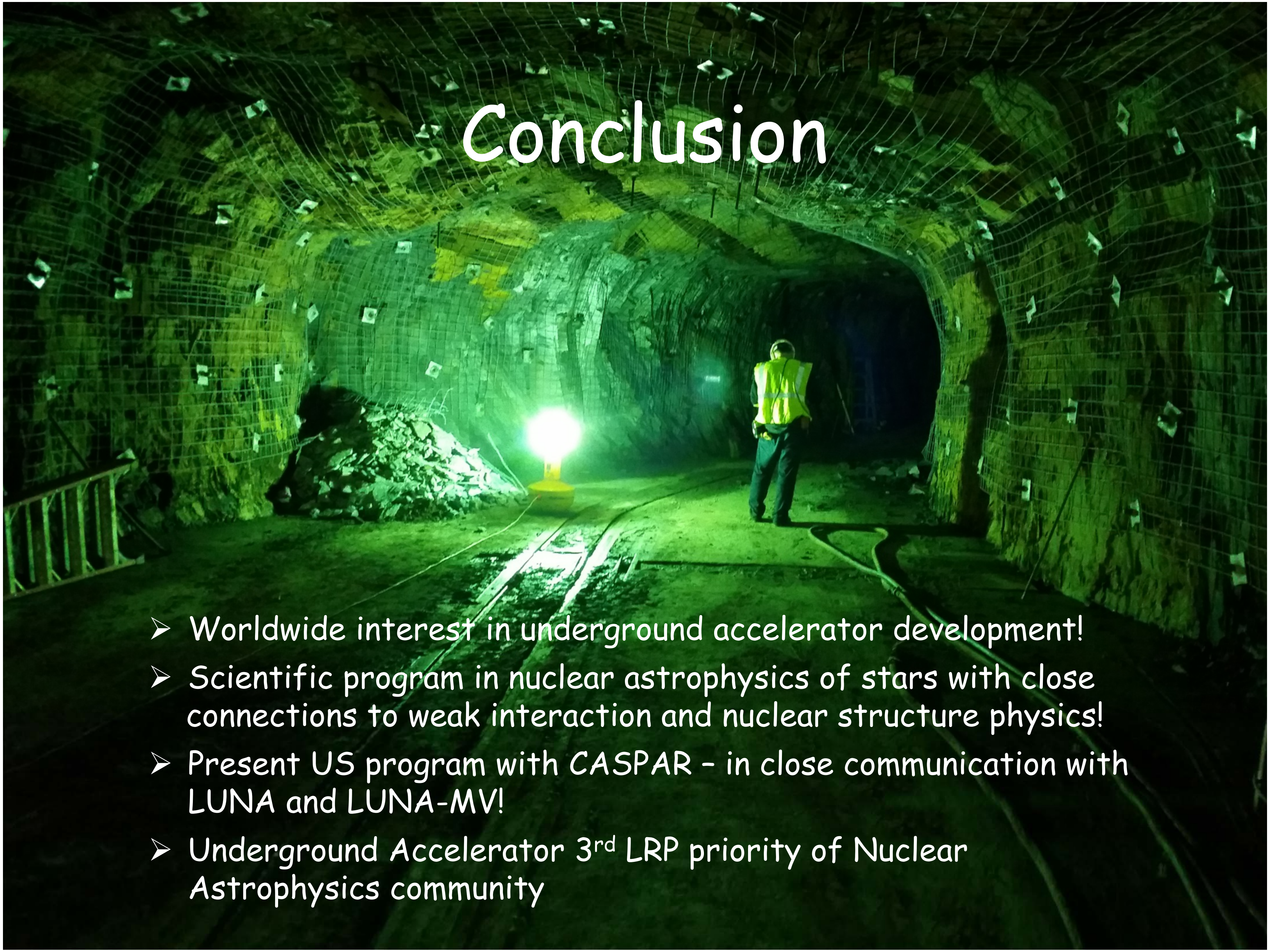




Underground Accelerator
with high beam intensity





Potential first upgrade: LENA style high intensity ECR source mounted on a 200kV platform at underground site.



Conclusion

- Worldwide interest in underground accelerator development!
- Scientific program in nuclear astrophysics of stars with close connections to weak interaction and nuclear structure physics!
- Present US program with CASPAR – in close communication with LUNA and LUNA-MV!
- Underground Accelerator 3rd LRP priority of Nuclear Astrophysics community