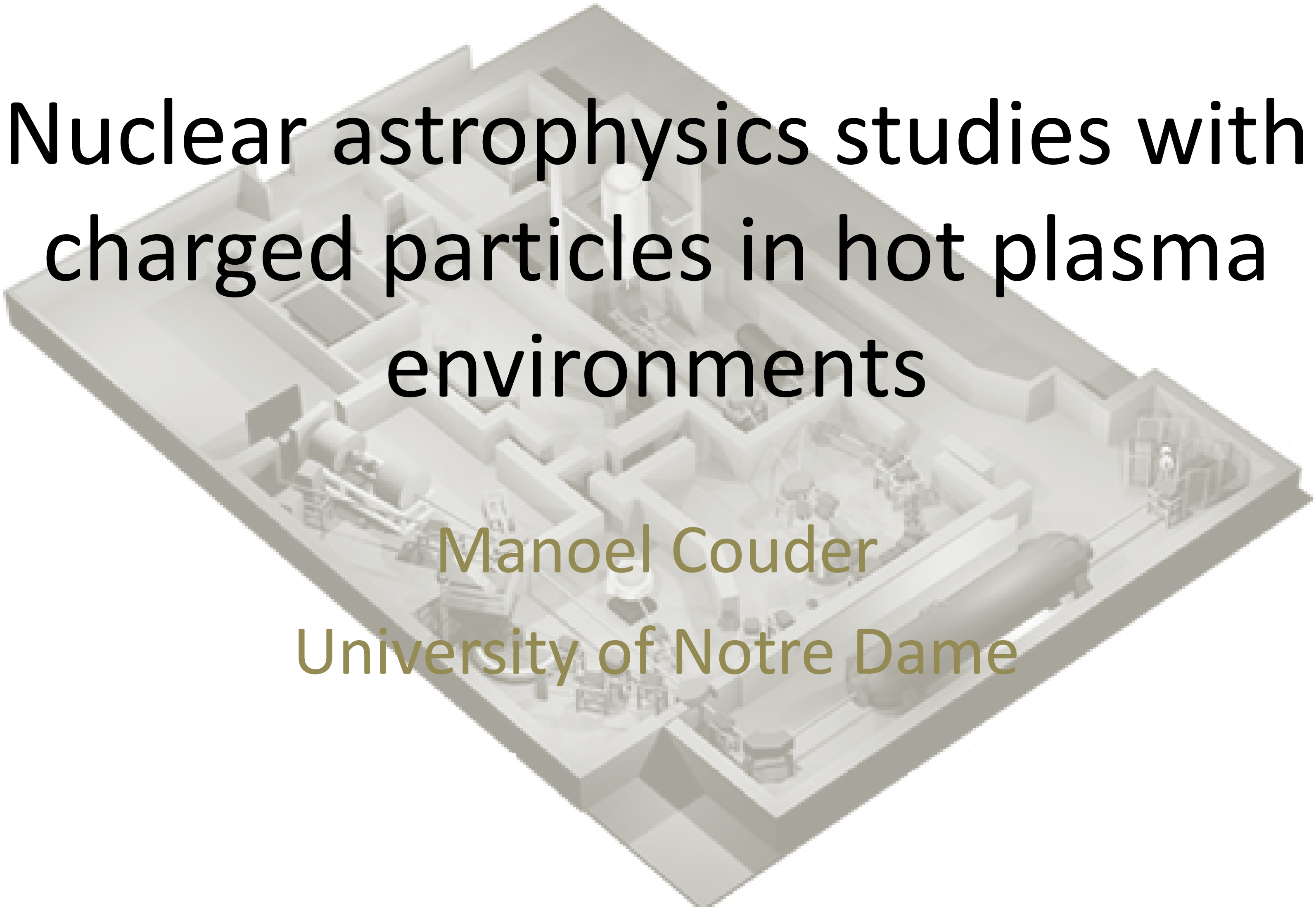
Nuclear astrophysics studies with charged particles in hot plasma environments



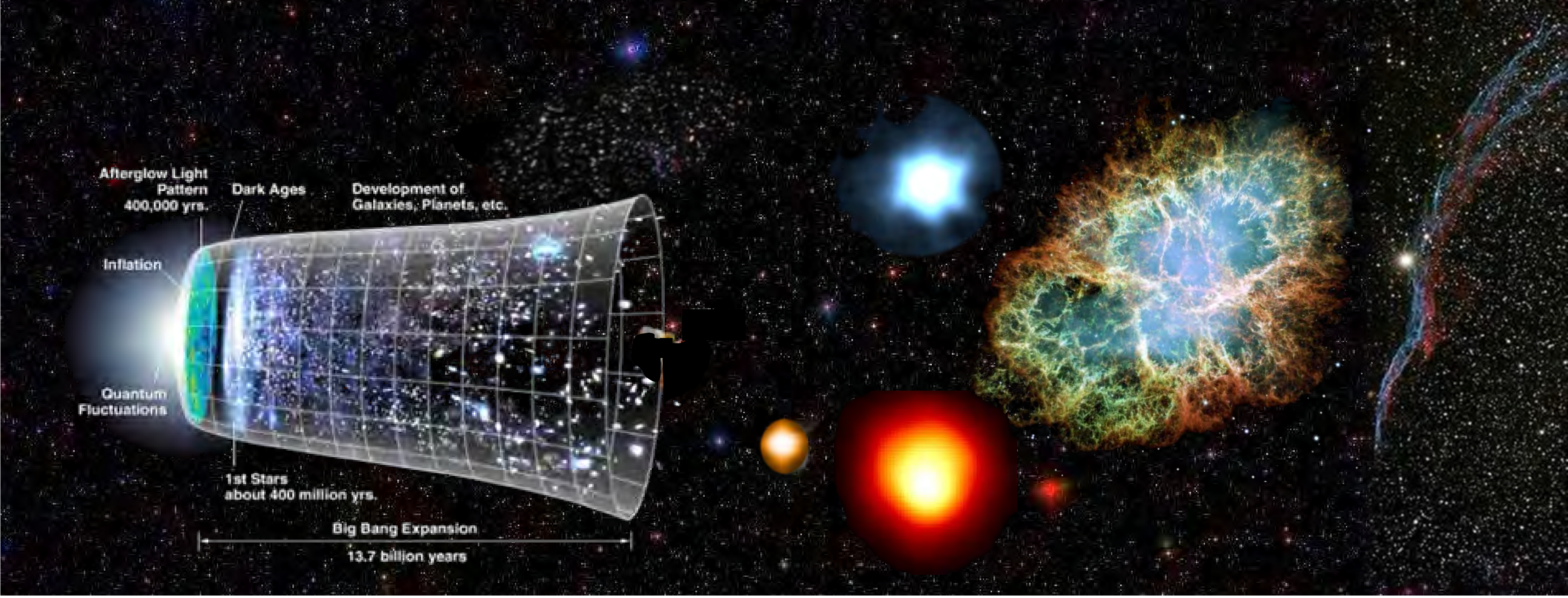
Manoel Couder

University of Notre Dame

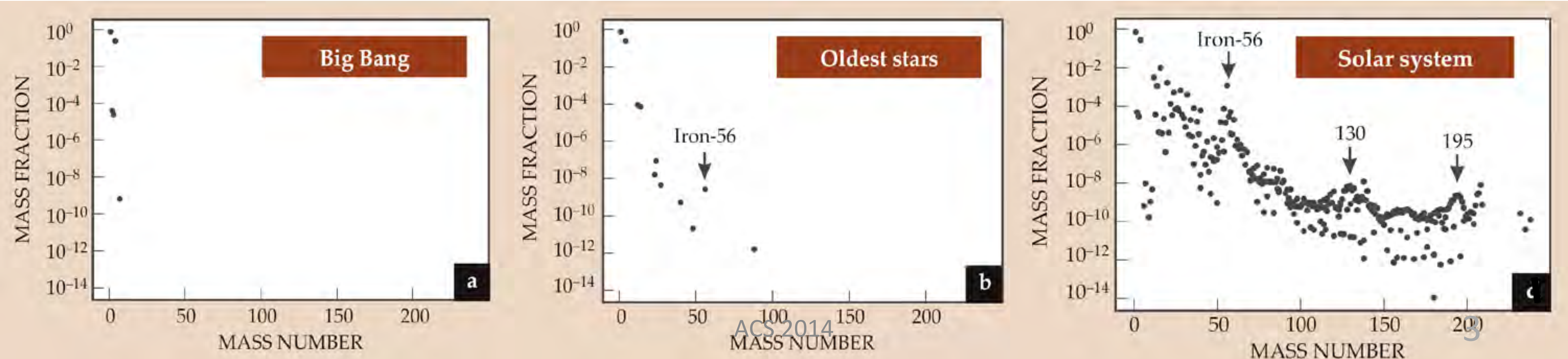
Summary

- Accelerator based nuclear astrophysics reaches yield and background limits at very low energy
- Electron screening in accelerator based measurement are not fully understood
- Inertial fusion experiments provide thermonuclear plasma environments similar to those in stellar core
- NIF provides the opportunity to study effects relevant to nuclear astrophysics
- Recent work have demonstrated the possibility to perform experiments that present new/unique challenges D. Sayre
- Reaction $^{10}B(p,\alpha)^{7}Be$ is proposed to demonstrate feasibility

Galactic Chemical Evolution



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



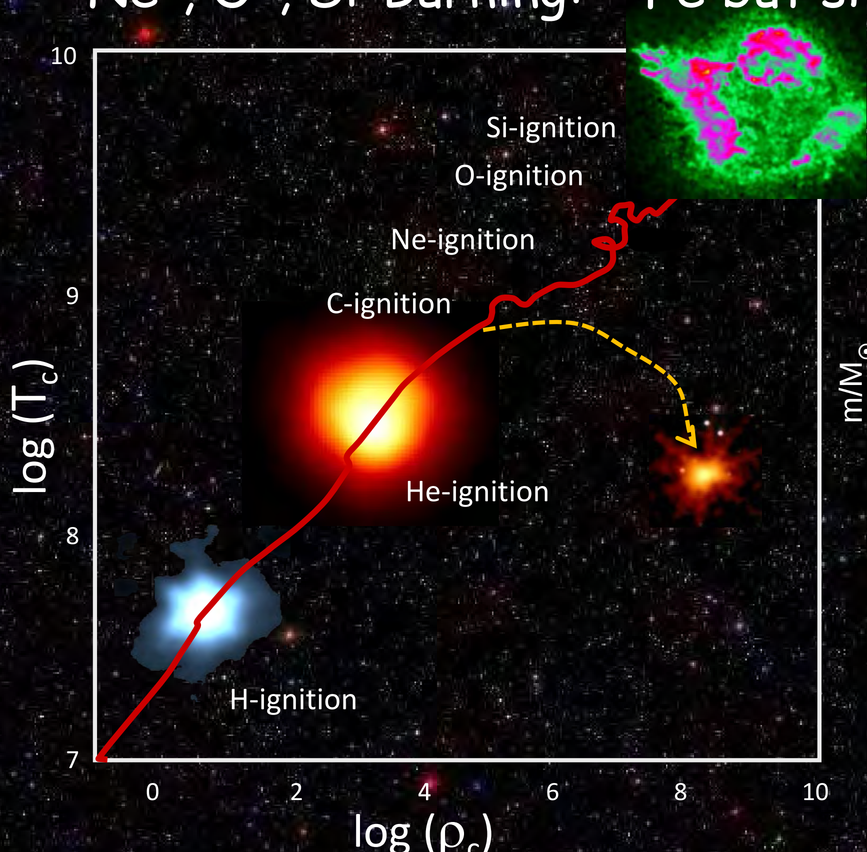
Nucleosynthesis in Stars

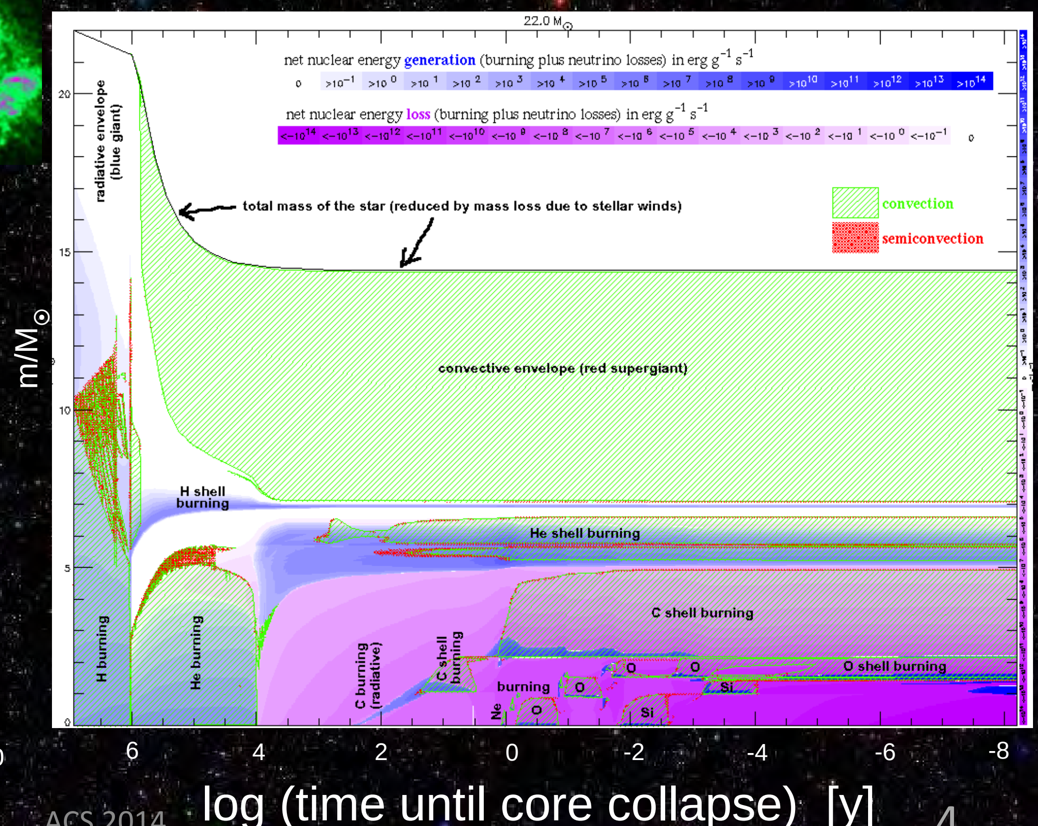
Hydrogen Burning: ^{4}He, ^{14}N

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

Carbon Burning: ^{16}O, ^{20}Ne, ^{24}Mg ... s-nuclei

Ne-, O-, Si-Burning: ^{56}Fe but shell distributions



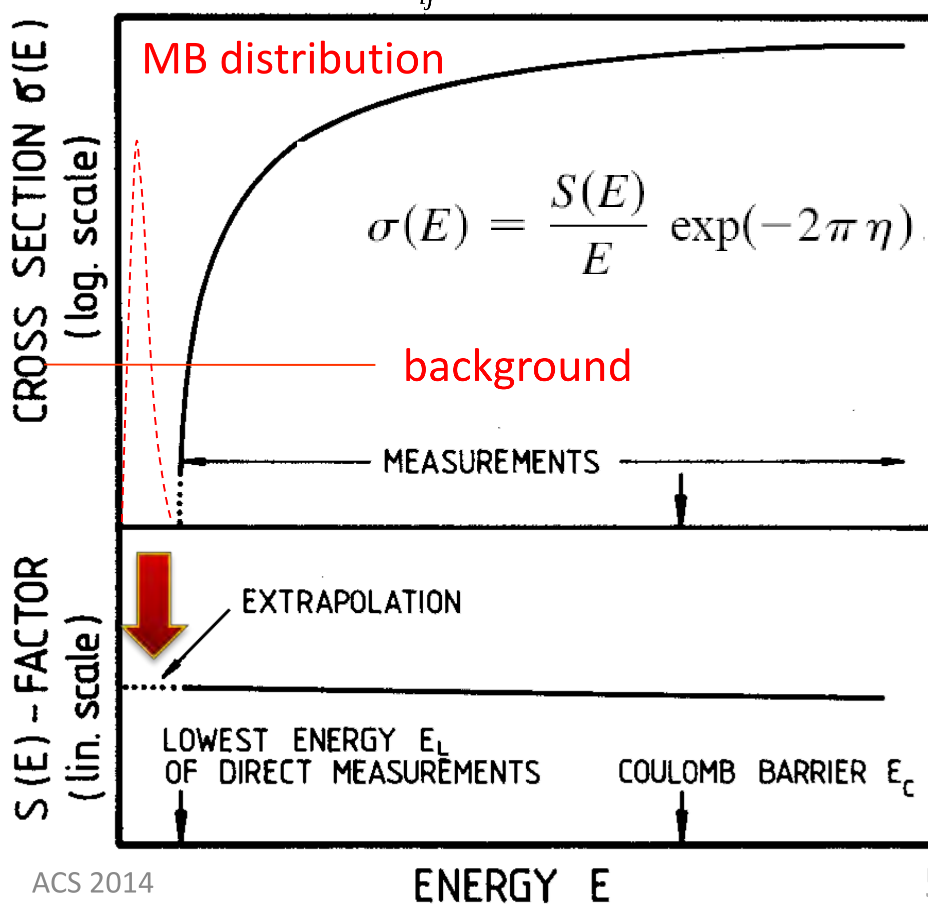


1: Thermonuclear Reaction Rates

Characterize the engine of stars; determine the energy production, define the time scale of burning, set its seed production, and provide new signatures for observations!

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

$$R_{i,j} = \frac{n_i\cdot n_j}{1+\delta_{ij}}\cdot\langle\sigma v\rangle_{i,j}$$



Solar Nuclear Reaction Network

pp-chain

$p + p \Rightarrow {}^2H + e^+ + \nu_e$ (pp)

$p + p + e^- \Rightarrow {}^2H + \nu_e$ (pep)

99.75% | 0.25%

${}^2H + p \Rightarrow {}^3He + \gamma$ — 0.00005% — ${}^3He + p \Rightarrow {}^4He + e^+ + \nu_e$ (hep)

86% | 14%

${}^3He + {}^3He \Rightarrow {}^4He + 2p$

${}^3He + {}^4He \Rightarrow {}^7Be + \gamma$

99.89% | 0.11%

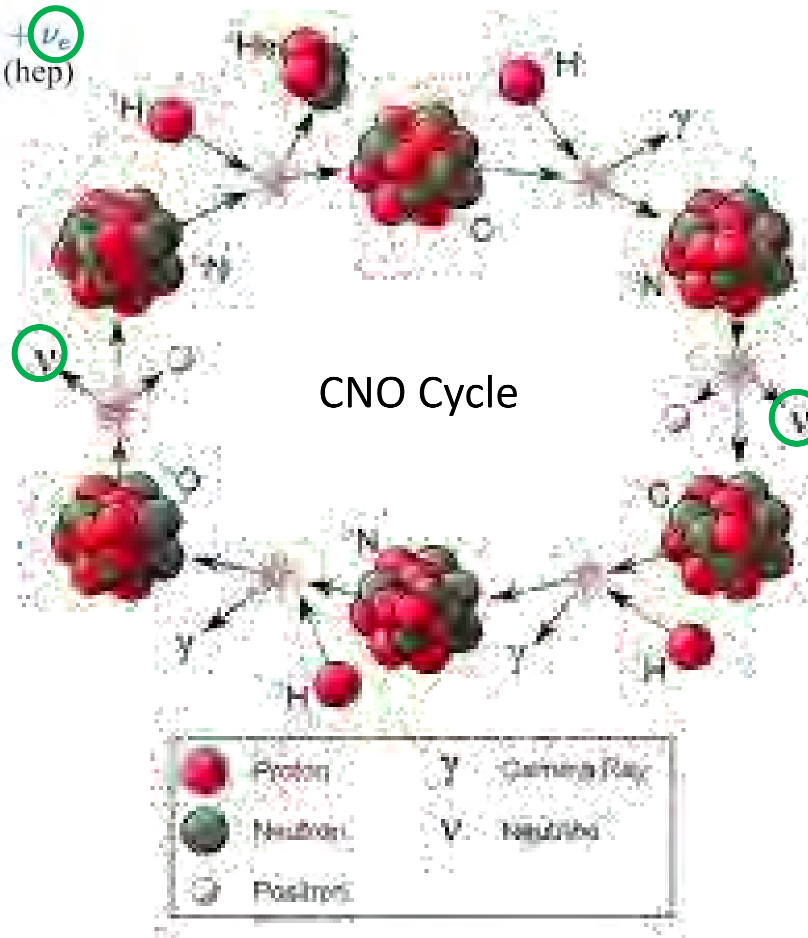
${}^7Be + e^- \Rightarrow {}^7Li + \nu_e$

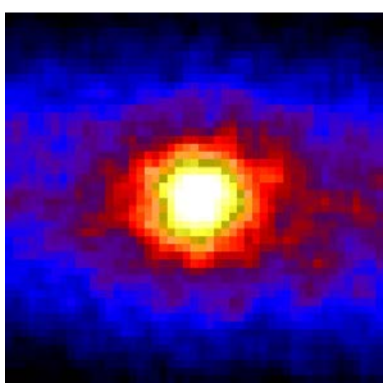
${}^7Li + p \Rightarrow 2\ {}^4He$

${}^7Be + p \Rightarrow {}^8B + \gamma$

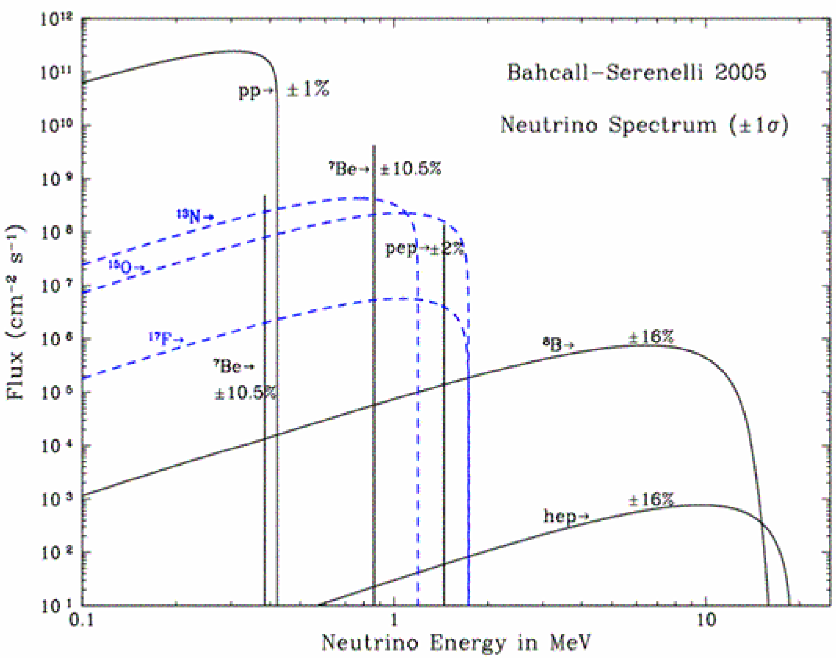
${}^8B \Rightarrow {}^8Be^* + e^+ + \nu_e$

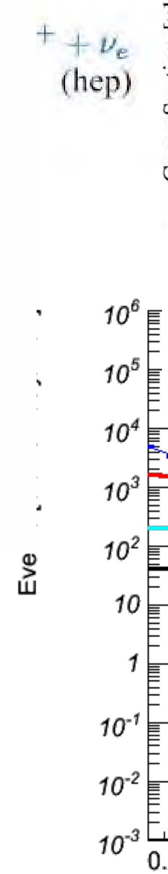
ppI | ppII | ppIII

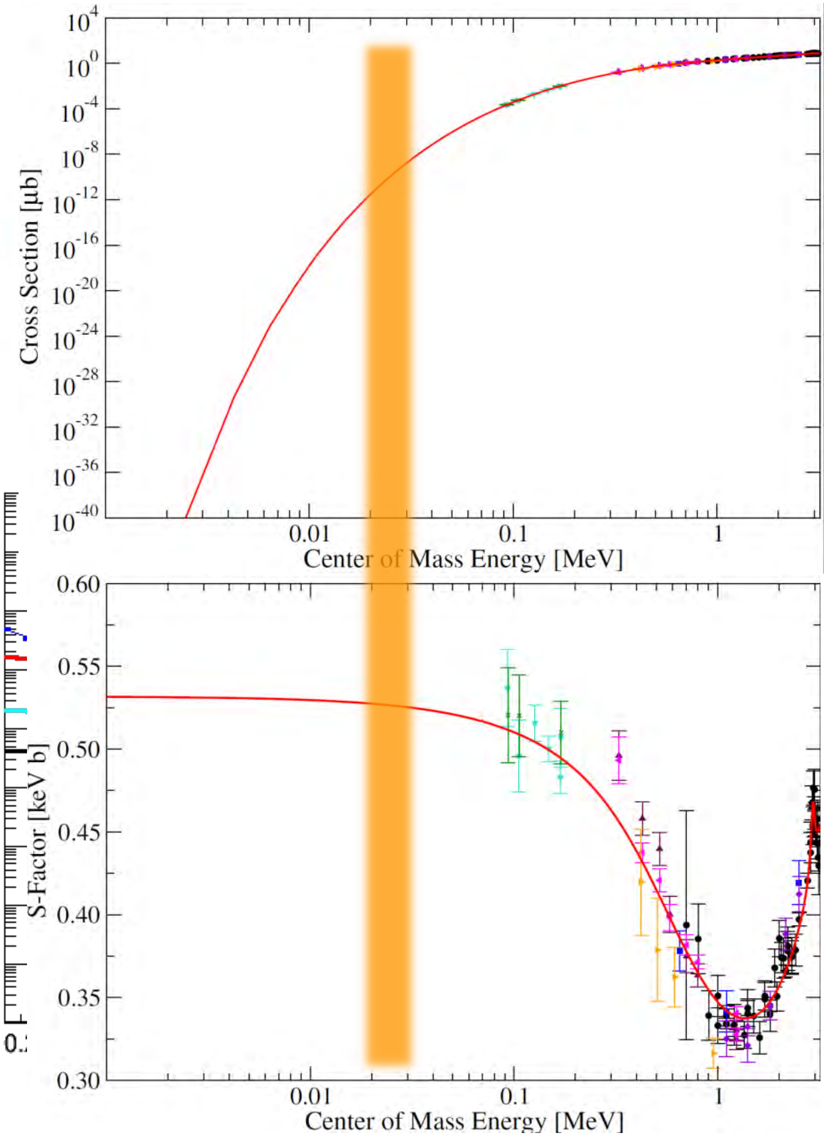




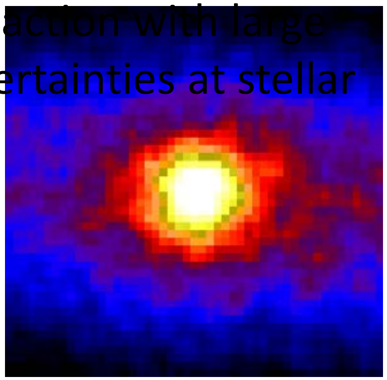
Solar Neutrino Sources







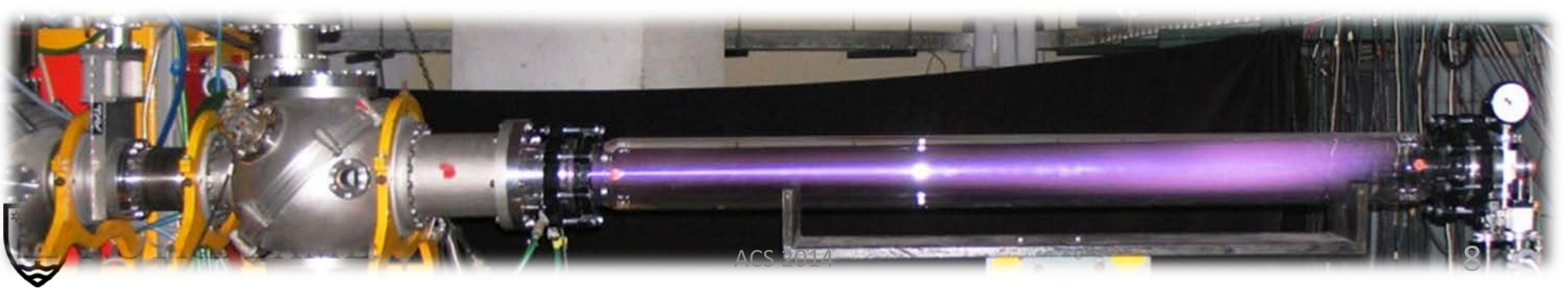
Critical nuclear reaction with large cross section uncertainties at stellar temperature



Low energy accelerator studies with high beam intensity

At low energy, yield is decreasing and the signal is eventually overwhelmed by the background (Cosmic rays, environmental, beam induced)

Yield measurements with particle and/or gamma detector arrangements



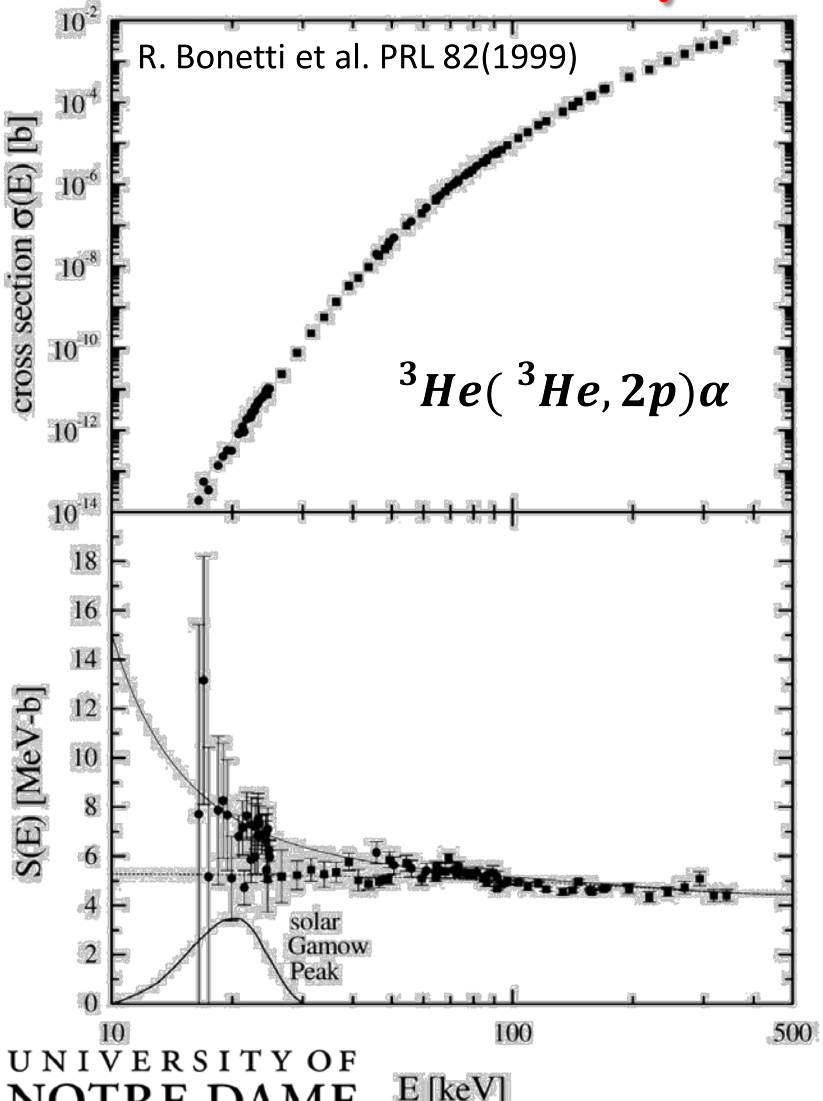
Compact Accelerator System to Perform Astrophysics Research

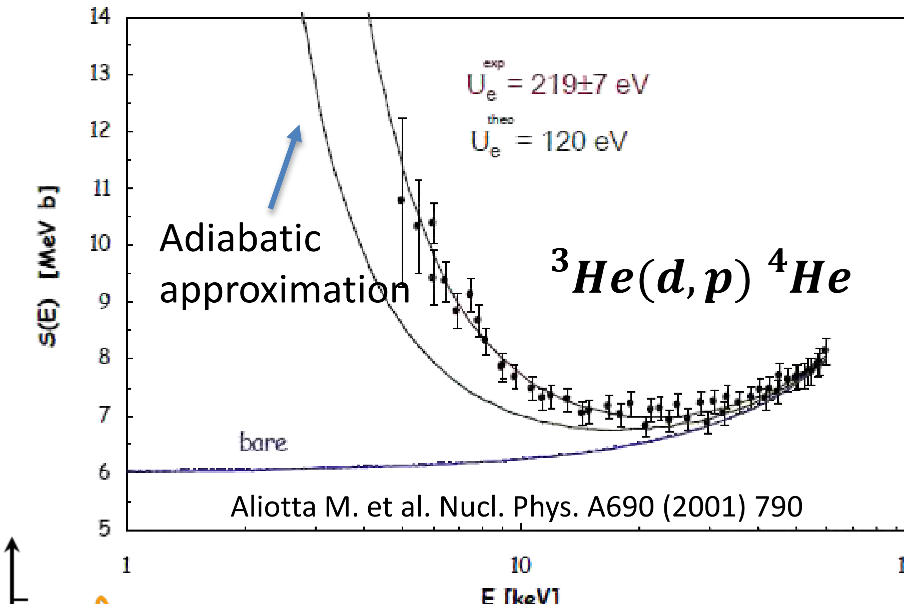
Highly reduced comic rays

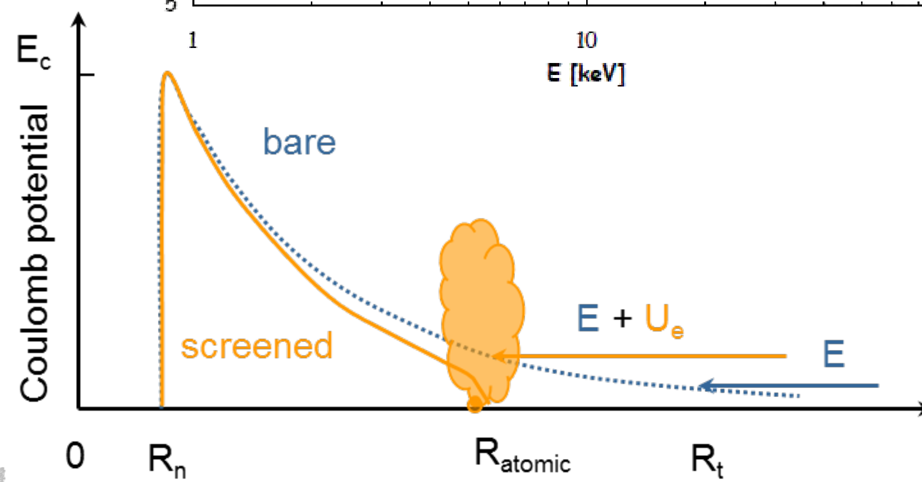
Sanford Underground Research Facility
4850 ft underground in
Homestake Mine, South Dakota

UNIVERSITY OF NOTRE DAME

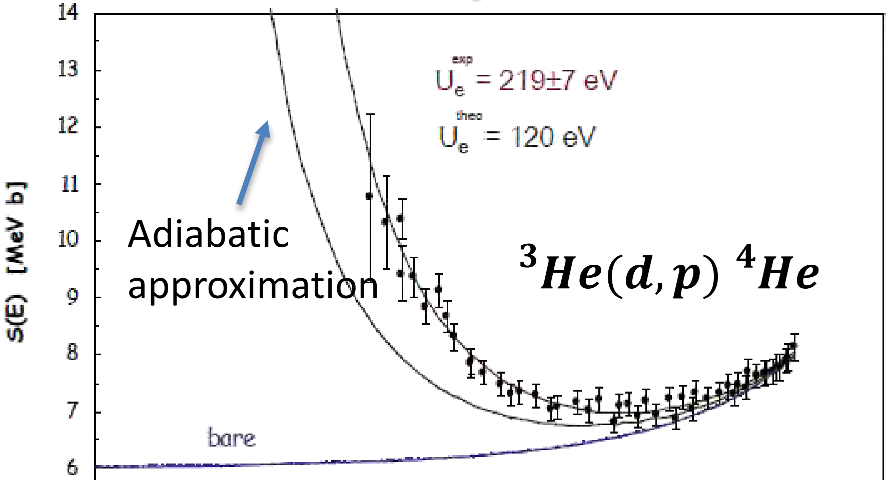
2: Laboratory electron screening

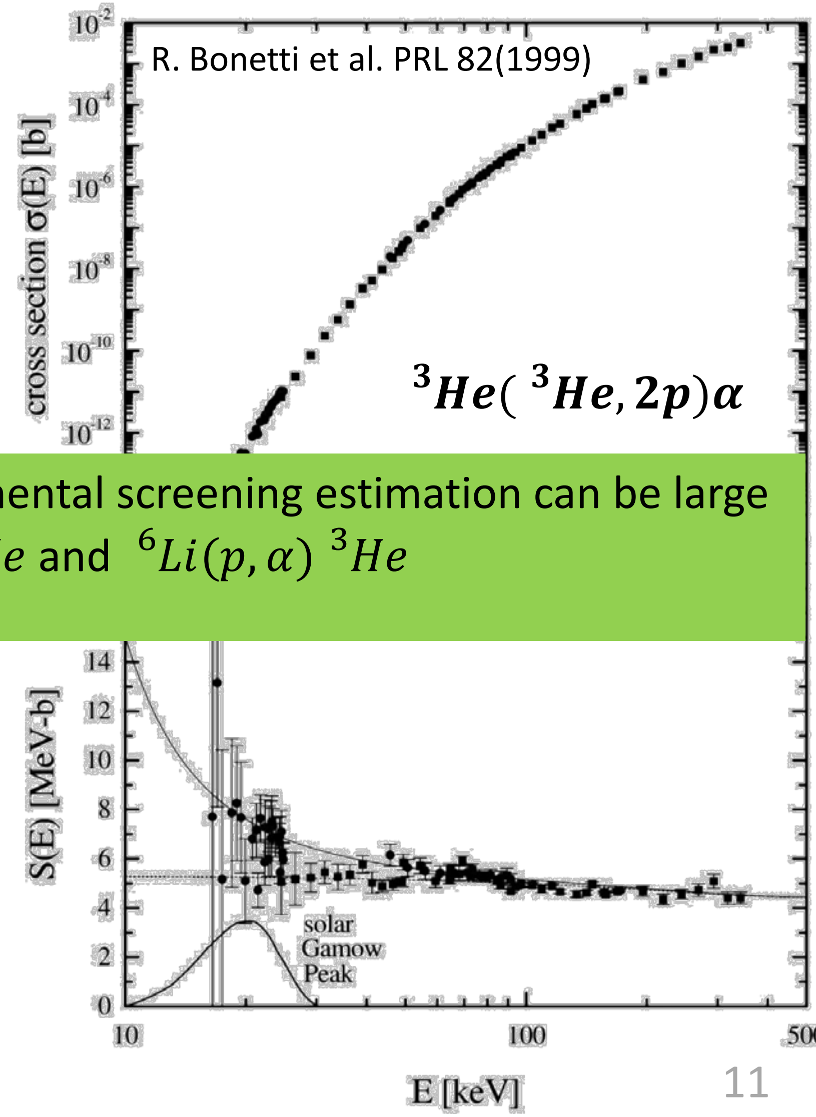




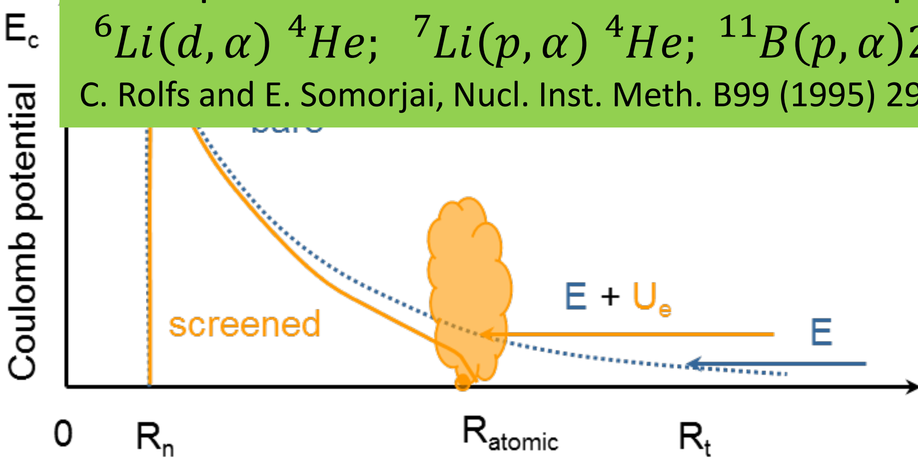


Laboratory electron screening

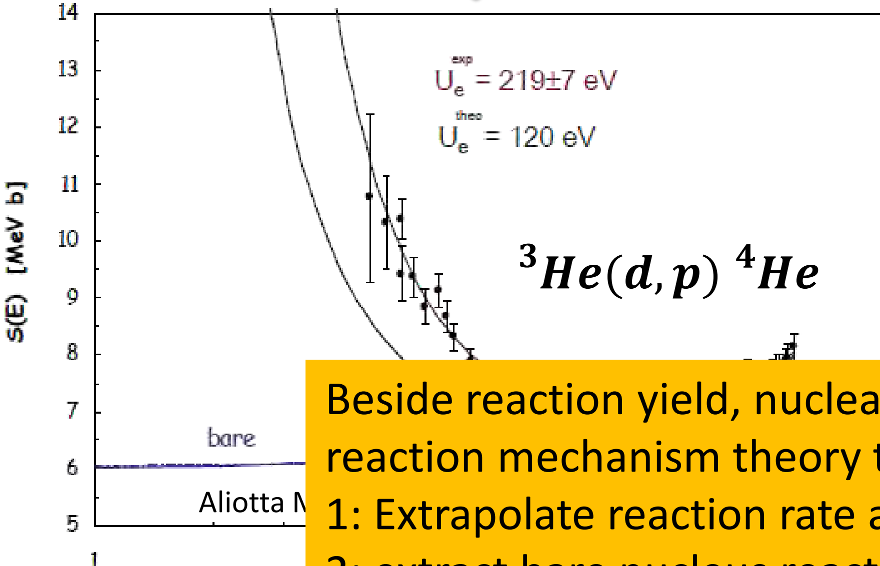


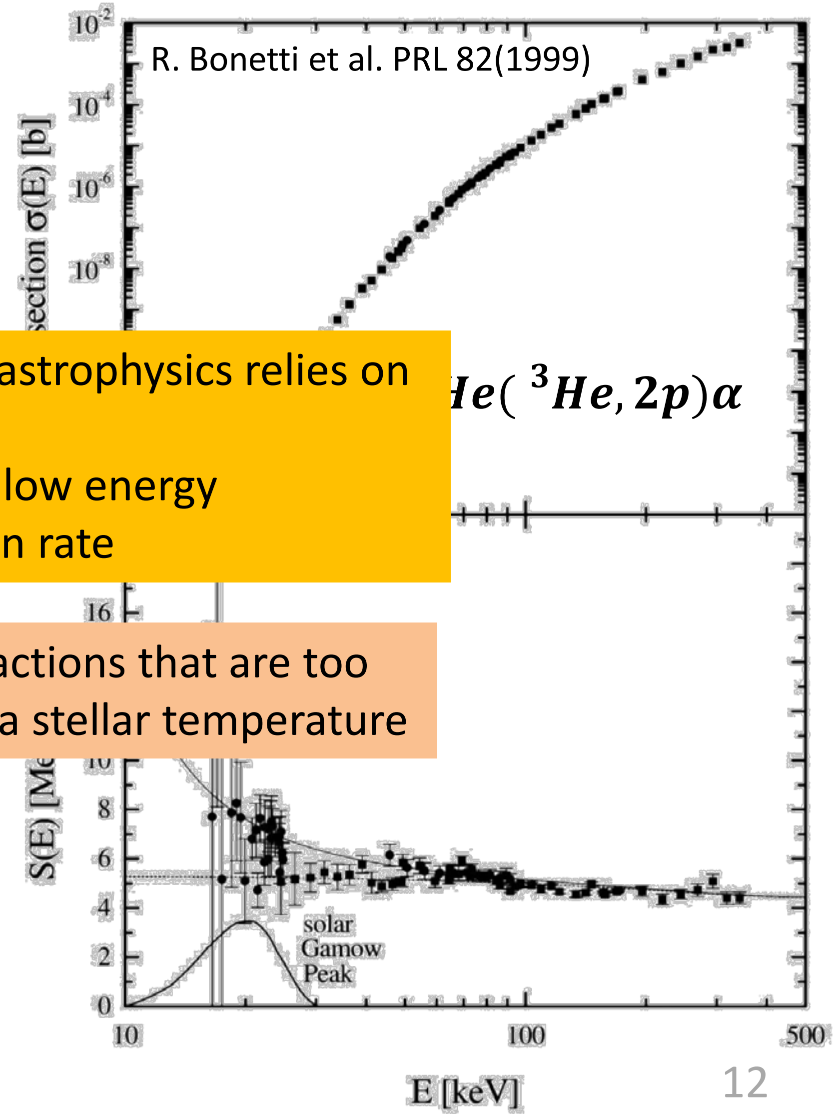


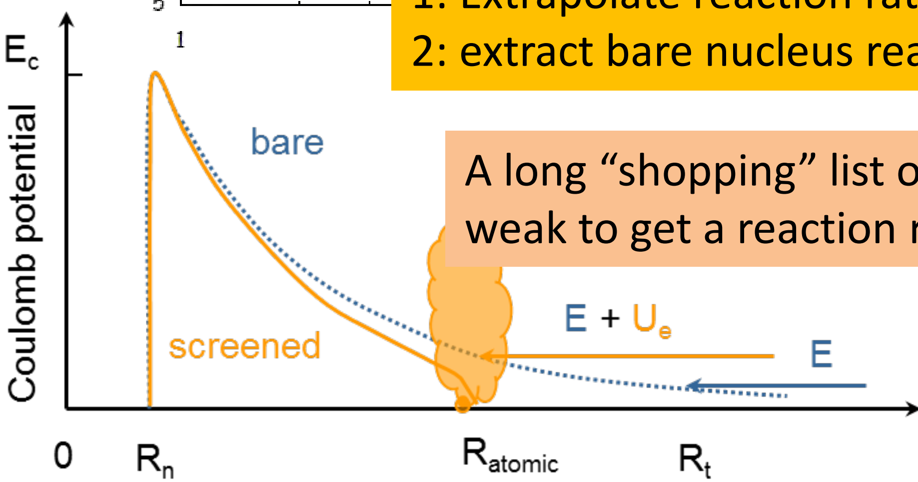
Discrepancies between theoretical and experimental screening estimation can be large
$^{6}Li(d,\alpha)\ ^{4}He$; $^{7}Li(p,\alpha)\ ^{4}He$; $^{11}B(p,\alpha)2\ ^{4}He$ and $^{6}Li(p,\alpha)\ ^{3}He$
C. Rolfs and E. Somorjai, Nucl. Inst. Meth. B99 (1995) 297



Laboratory electron screening





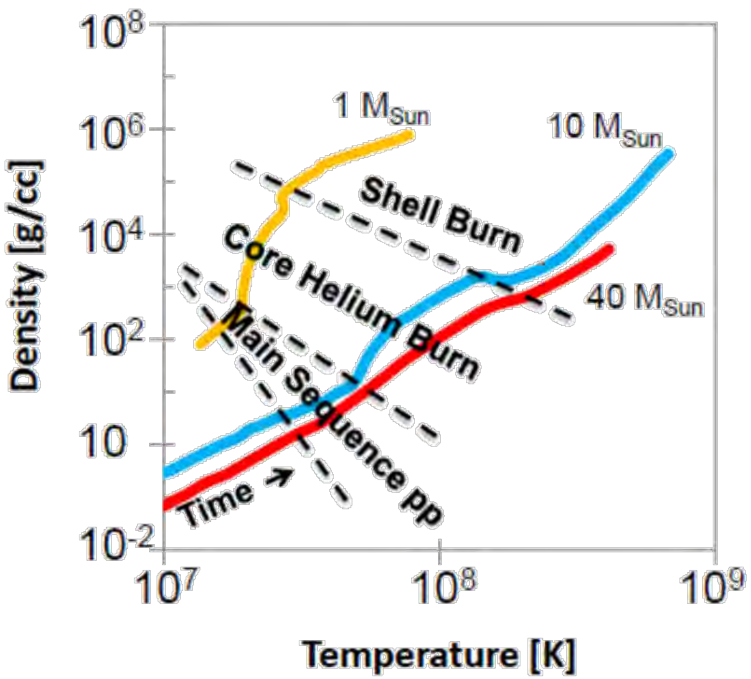


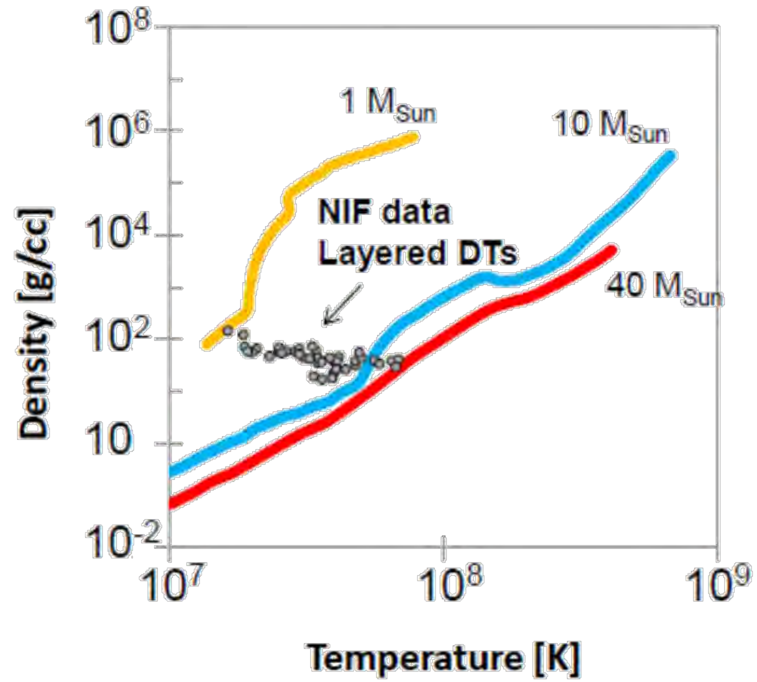
Beside reaction yield, nuclear astrophysics relies on reaction mechanism theory to
1: Extrapolate reaction rate at low energy
2: extract bare nucleus reaction rate

A long “shopping” list of reactions that are too weak to get a reaction rate a stellar temperature

Inertial confinement facilities Conditions

Advantage: Star like environment (temperature and density)





Plot from Daniel CASEY, LLNL
Data analysis from Prav Patel
Stellar evolution simulations by Dave Dearborn

Inertial confinement facilities Conditions

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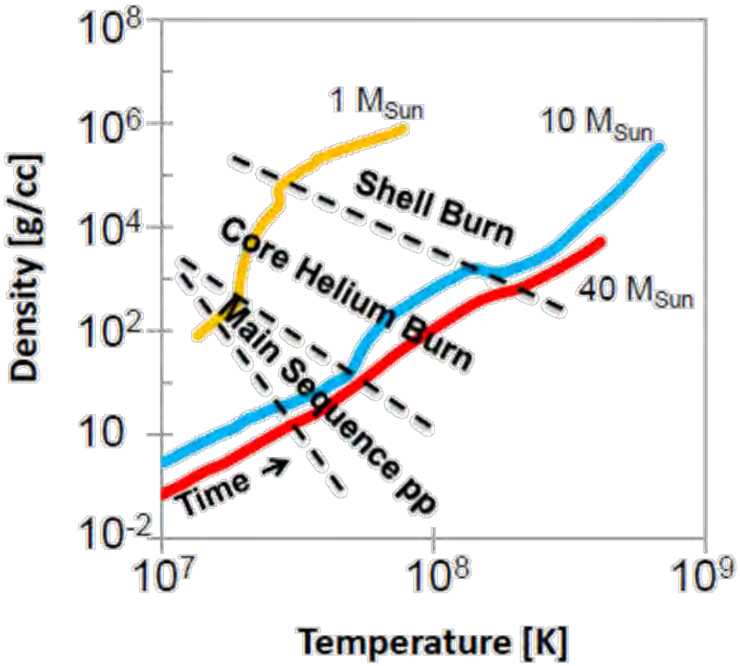
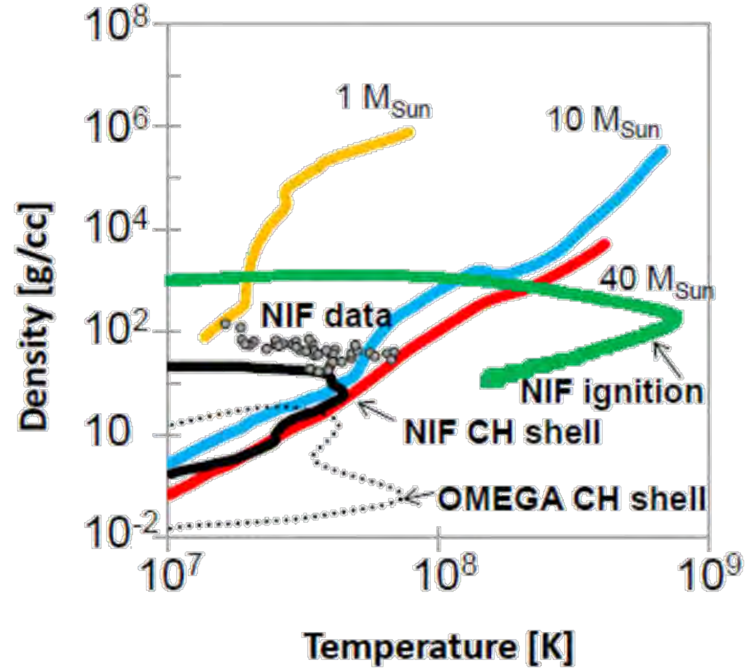




Plot from Daniel CASEY, LLNL
Data analysis from Prav Patel
Stellar evolution simulations by Dave Dearborn
NIF Simulations Harry Robey and Bob Tipton
OMEGA Simulation P. B. Radha

Using NIF to study reaction rate?

Advantage: Star like environment (temperature and density)

Question:
- Are the plasma condition sufficiently well understood to extract reaction rate?
- Is the plasma at thermodynamic equilibrium at its temperature and density peak ?
- What can we measure?
- Can we use a known nuclear reaction to demonstrate we understand the plasma?

Success: $\mathrm{T(T,2n)}\ {}^{4}He$

D. Sayre

Producing and detecting ${}^{7}Be$ a perfect proof and useful proof of concept

$T_{\frac{1}{2}} \approx 53$ days makes it an interesting particle to use as a reaction rate diagnostic.

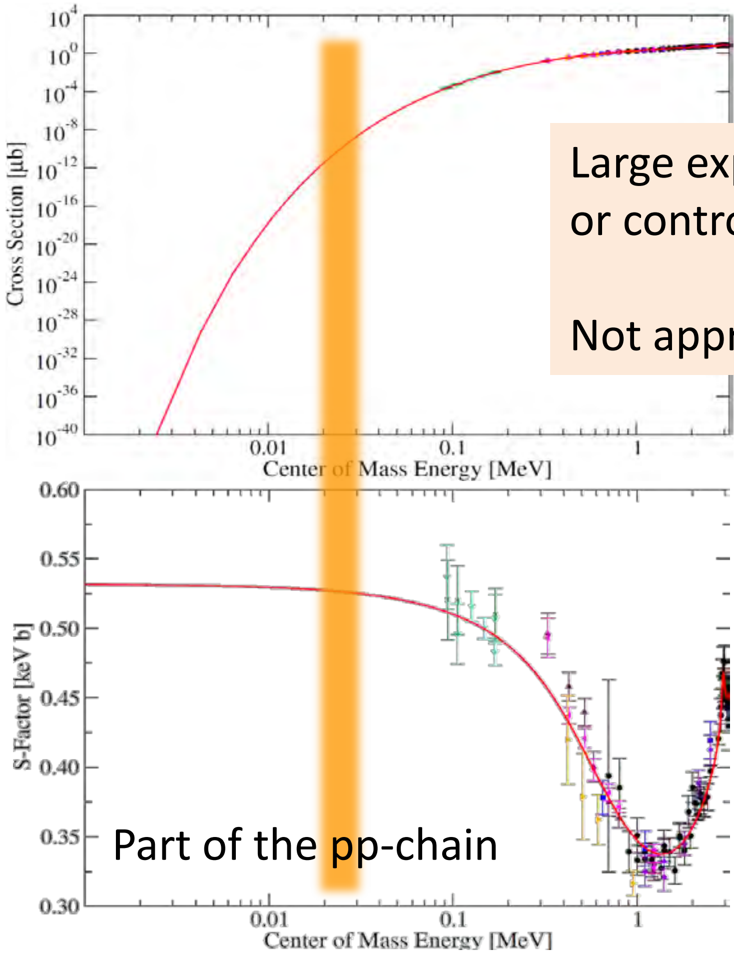
Produced in the pp-chain by reactions between low-Z element, i.e. low(er) coulomb barrier.

Can be captured with RAGS (Radiochemical Analysis of Gaseous Samples) using Xe carrier gas injected in the NIF chamber before the shot.

C. Velsko & D. Shaughnessy

^{7}Be production channels

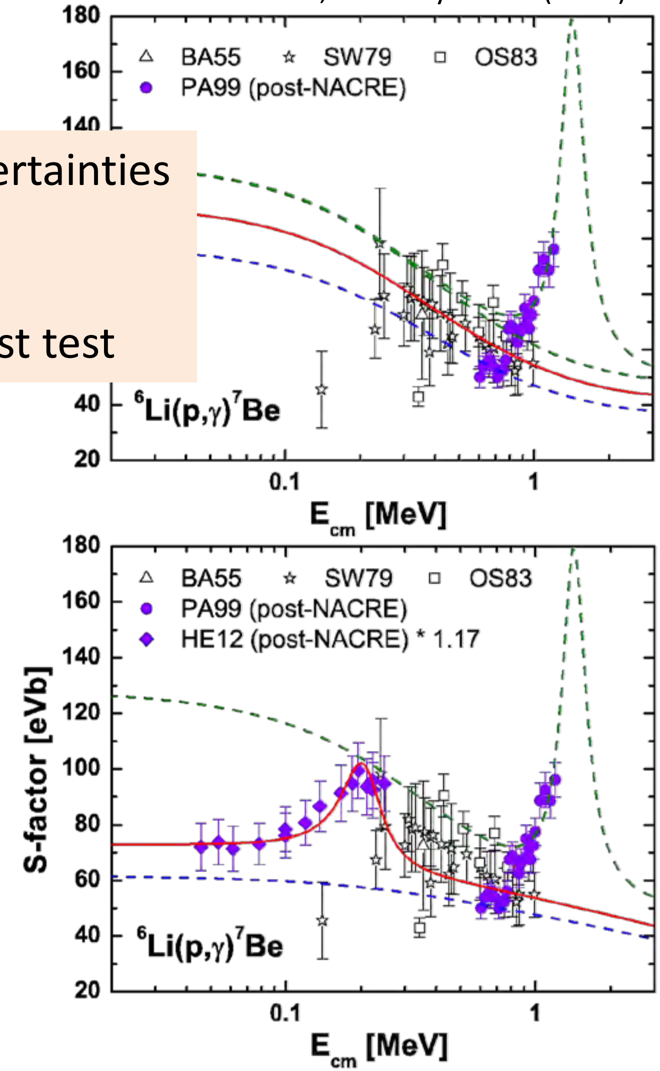
$^{4}He + {}^{3}He \rightarrow {}^{7}Be + \gamma$



Part of the pp-chain

$^{6}Li + p \rightarrow {}^{7}Be + \gamma$

Y. Xu et al, Nucl Phys A918 (2013)



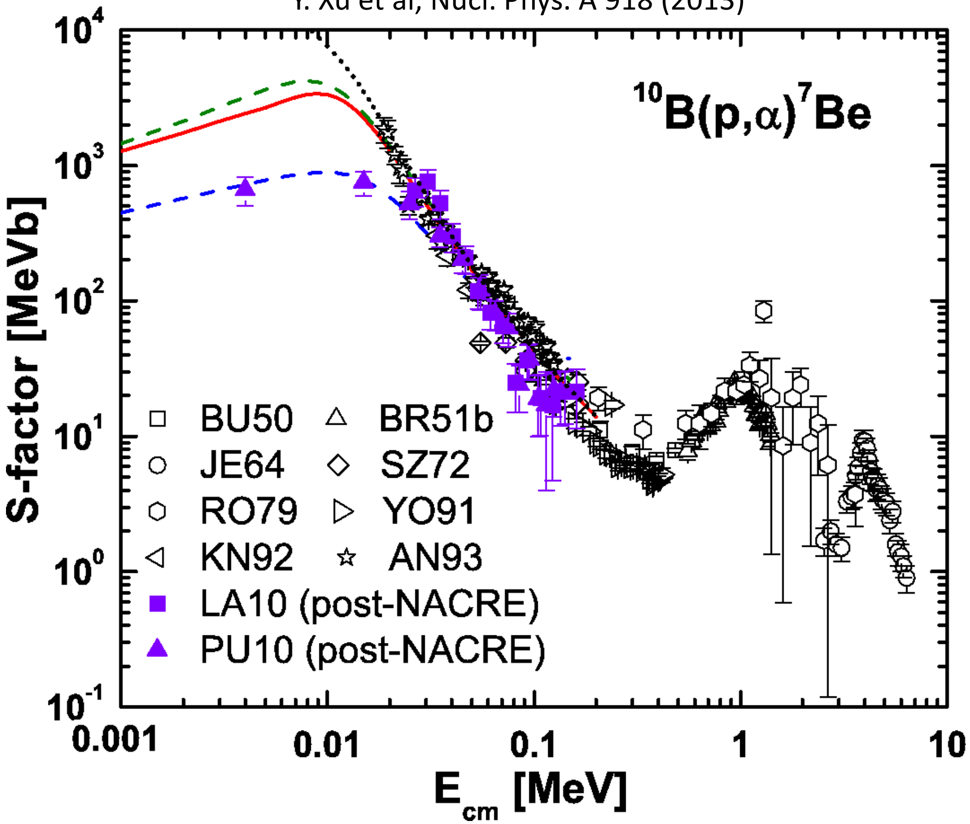
Large experimental uncertainties or controversial data

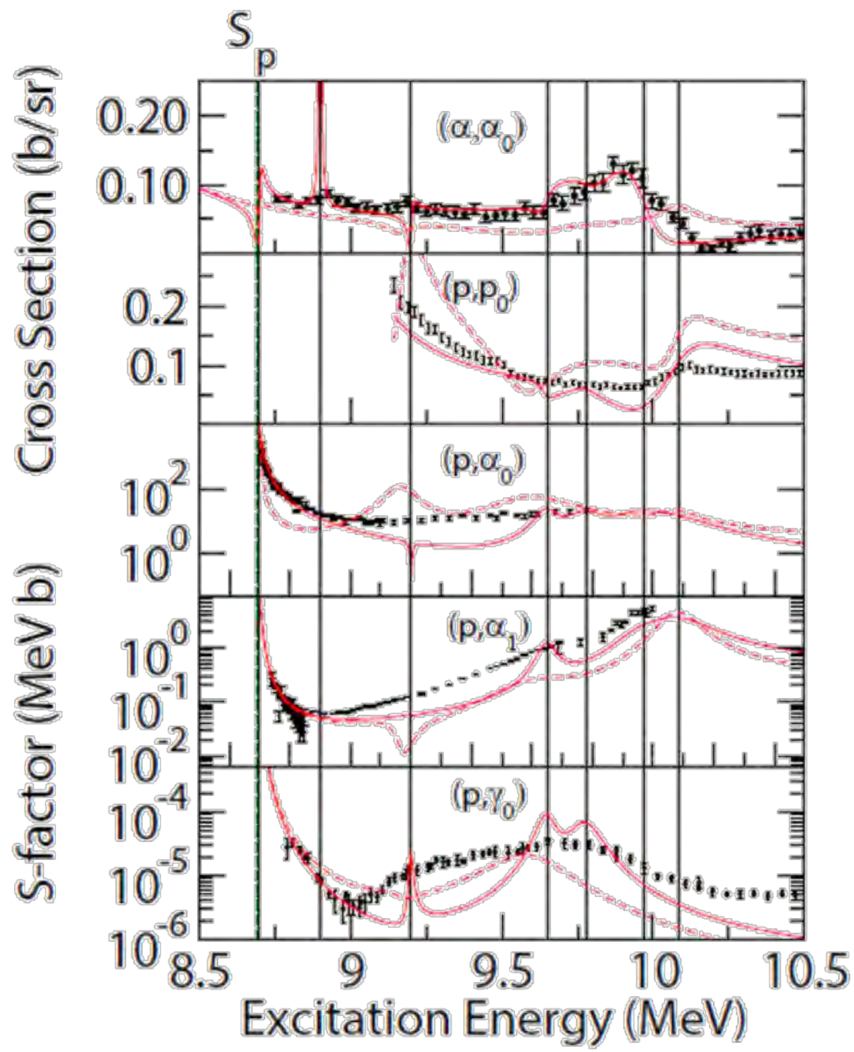
Not appropriate for a first test

^{7}Be production channel

$$^{10}B + p \rightarrow \ ^{7}Be + \alpha$$

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





^{7}Be production channel

$$^{10}\boldsymbol{B} + \boldsymbol{p} \rightarrow {}^{7}\boldsymbol{Be} + \boldsymbol{\alpha}$$

Responsible for the destruction of ^{10}B in stellar environment

Experimental reaction rate has been investigated

Proposal at NIF for a BH_3 filled capsule in a direct drive pusher shot

- The ^{7}Be collection efficiency needs to be estimated
- The reaction rate uncertainty at NIF temperatures need to be improved to provide energy/density distribution
- High energy shot to compensate for radiative (bremsstrahlung) loss
- Plasma electron screening not present in this type of shot (low density, high temperature)

How much ^{7}Be could one get?

$$^{10}\boldsymbol{B} + \boldsymbol{p} \rightarrow {}^{7}\boldsymbol{Be} + \boldsymbol{\alpha}$$

Assuming a plasma temperature of 20keV and 10^{16} molecules of BH_3

A density at maximum compression of 200 g/cm^3 of 2×10^{16} Borane molecules

A total of ~10^{10} ^{7}Be will take place BUT … too optimistic according to my NIF friends

Total reactants should be lower, and density exaggerated
10^6 seems to be a more realistic number

Signature of reaction will depend on:
Collection efficiency
Gamma detector efficiency at 478 keV

~500 counts seems reasonable

Reaction producing shorter lifetime isotopes

$^{17}O(p,\gamma)^{18}F$ (110 min. half life) 15-20% uncertainty in reaction rate at nova temperature
$^{12}C(p,\gamma)^{13}N$ (10 min. half life) 30% uncertainty in reaction rate at stellar energies introducing a large uncertainty to the contribution of CNO reactions to the solar neutrinos

The slowest reaction of the CNO cycle $^{14}N(p,\gamma)^{15}O$ could be another candidate on the long term but the 122 sec. half life of ^{15}O may be pushing the limit of the method

And one day, collection of stable product and analysis of the collected gas with AMS ☺

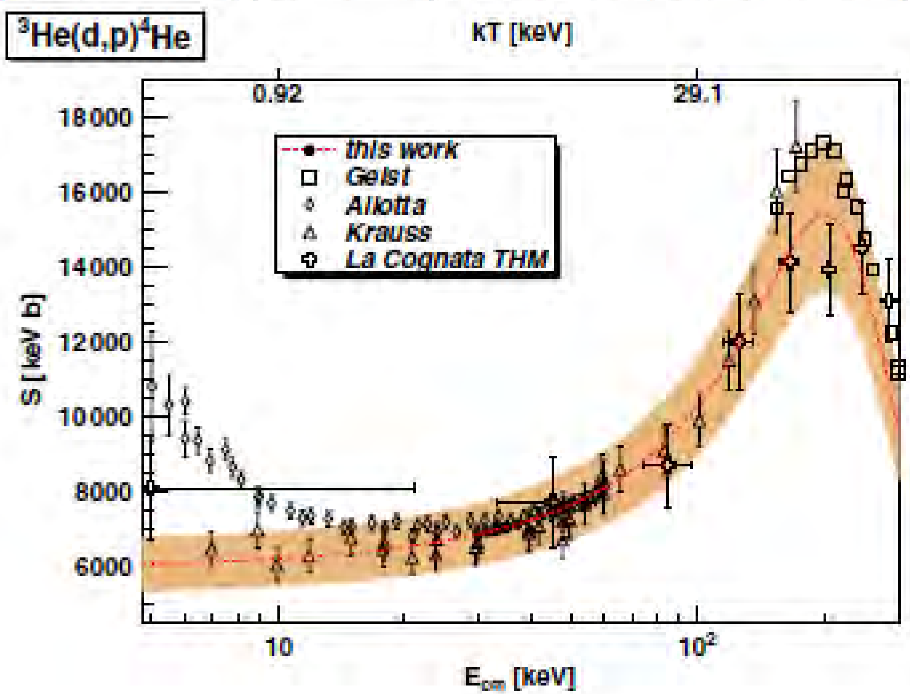
Usage of ^{7}Be producing reaction in other plasmas based measurements

Recently two petawatt laser facilities measured reaction rates:

PRL 111, 082502 (2013) PHYSICAL REVIEW LETTERS week ending 23 AUGUST 2013

Measurement of the Plasma Astrophysical *S* Factor for the ^{3}He(d, p)^{4}He Reaction in Exploding Molecular Clusters

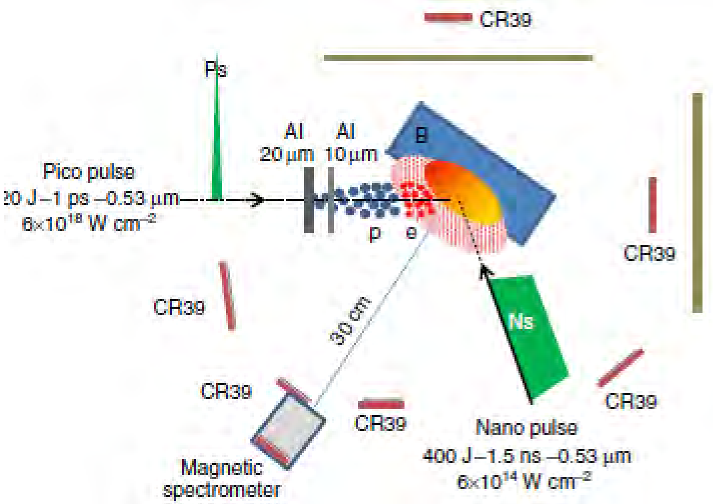
M. Barbui,[1,*] W. Bang,[2] R. Burch,[1] G. Giuliani,[1]
M. Barbarino,[1] H. Zheng . Donovan,[2] S. Kimura,[4]
M. Ma itmire[2]



Received 24 Jan 2013 | Accepted 27 Aug 2013 | Published 8 Oct 2013 DOI: 10.1038/ncomms3506

Fusion reactions initiated by laser-accelerated particle beams in a laser-produced plasma

C. Labaune[1], C. Baccou[1], S. Depierreux[2], C. Goyon[2], G. Loisel[1], V. Yahia[1] & J. Rafelski[3]



$^{11}B(p,\alpha)2\ ^{4}He$

We report proton-boron reaction rates that are orders of magnitude higher than those reported previously.

Summary

- The conditions in the core of a NIF shot make it a ideal place to study nuclear reaction between charged particles
- An experimental program to study such reaction requires a proof of concept: $^{10}B + p \rightarrow \alpha + {}^{7}Be$
  - The rate of this reaction will be studied with accelerator based techniques to reduce the rate uncertainty at NIF energies
- It is proposed to study at NIF key reactions associated with the understanding of the solar neutrino flux
  - The appropriate diagnostics are “already in place” (RAGS)
- Using reactions producing ^{7}Be as a diagnostic in other plasma based experiments is suggested.