Understanding the Universe: From Nuclei to the Stars

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Biographical Sketch *(L. Adriana Banu)*

Professional Preparation

B.S. in Physics *(summa cum laude, top of the class)*, July 2000, University of Bucharest, Romania
Ph.D. in Nuclear Physics *(magna cum laude)*, July 2005, Mainz University, Germany
Postdoctoral Research Associate in Nuclear Astrophysics, 10/2005 – 08/2010, Cyclotron Institute, Texas A&M University, College Station, Texas, USA

Appointments

08/2010 – present: Assistant Professor, Department of Physics and Astronomy, James Madison University, Harrisonburg, Virginia 22807, USA

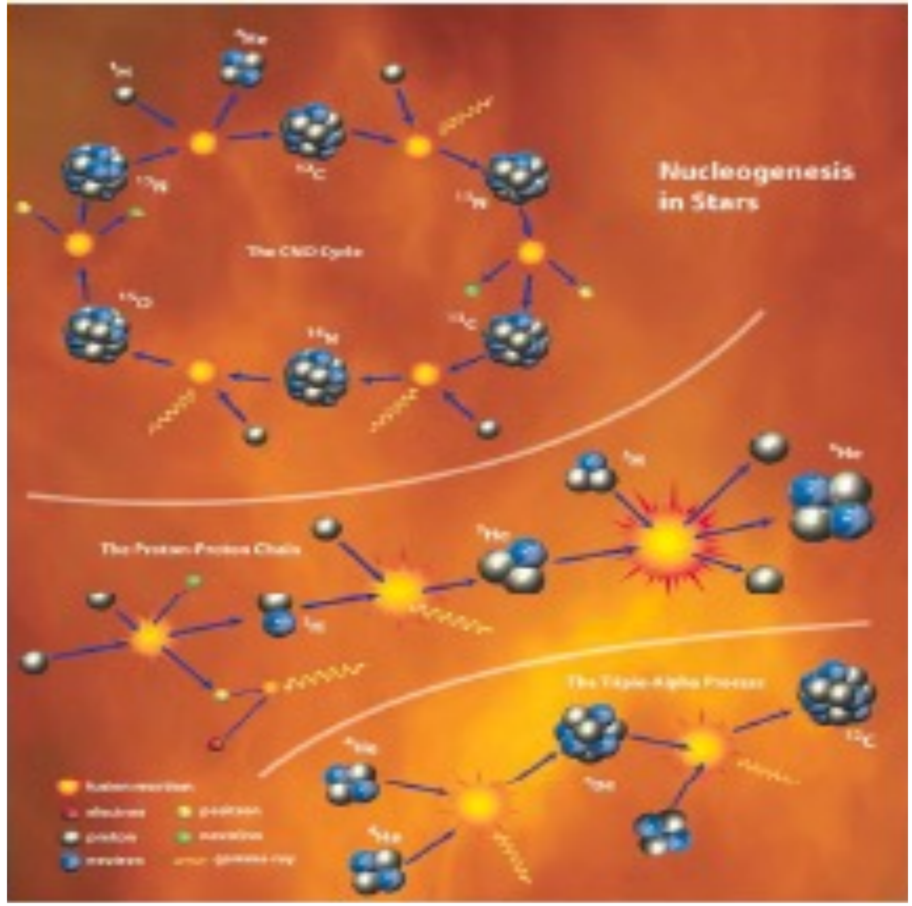
Honors, Awards, Grants

- Grant award by the Research Corporation for Science Advancement for the proposal "Determination of key astrophysical photonuclear reaction cross sections towards understanding the origin of p-nuclei" (2014-2016)
- Member of the CEU14 Review Committee for the 7th annual Conference Experience for Undergraduates held jointly with the DNP/JPS Fall Meeting, Waikoloa, HI (2014)
- Member of the International Scientific Committee of the Russbach School on Nuclear Astrophysics (2014-present)
- Invited lecture at "10th Russbach School on Nuclear Astrophysics", Russbach, Austria (2013)
- Grant award by the Jeffress Memorial Trust for the proposal "Studying the (α,p)-process in X-ray bursts using rare isotope ion beams" to be executed at the Cyclotron Institute at Texas A&M (2012-2015)
- Invited seminar at Triangle University Nuclear Laboratories (TUNL), Durham, NC (2009).
- Invited talk at "Gordon Research Conferences: Frontiers of Nuclear Structure through Spectroscopy and Reactions", Colby-Sawyer College, New London, NH (2009).
- Selected for oral communication at the "10th Symposium on Nuclei in the Cosmos", Mackinac Island, MI (2008).
- Over 100 citations in refereed publications.
- Scholarship at Padua University granted to outstanding European students through the European Cultural Exchange Programme ERASMUS, Padua, Italy (1999-2000)
- Fellowship at the GSI Summer Student School, Darmstadt, Germany (1999).

"The most incomprehensible thing about the universe is that it is comprehensible."

—Albert Einstein

From nuclei…



to stars…

Nuclear Physics is basic to two major themes is astrophysics:

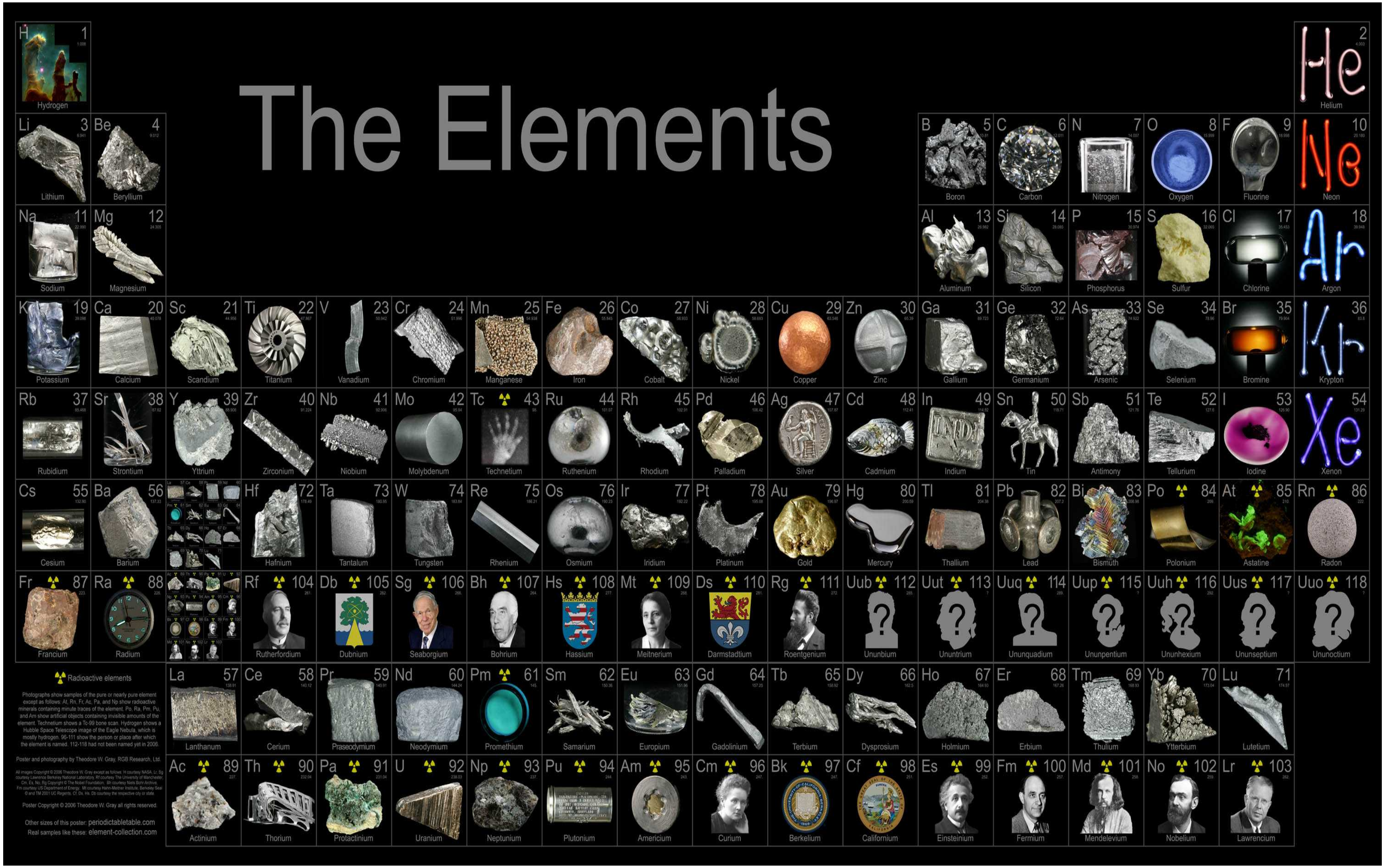
- the (nucleo)synthesis of all chemical elements
- the energy generation in stars and stellar environments

The Big Questions

1. **Where do the chemical building blocks of humankind come from?**

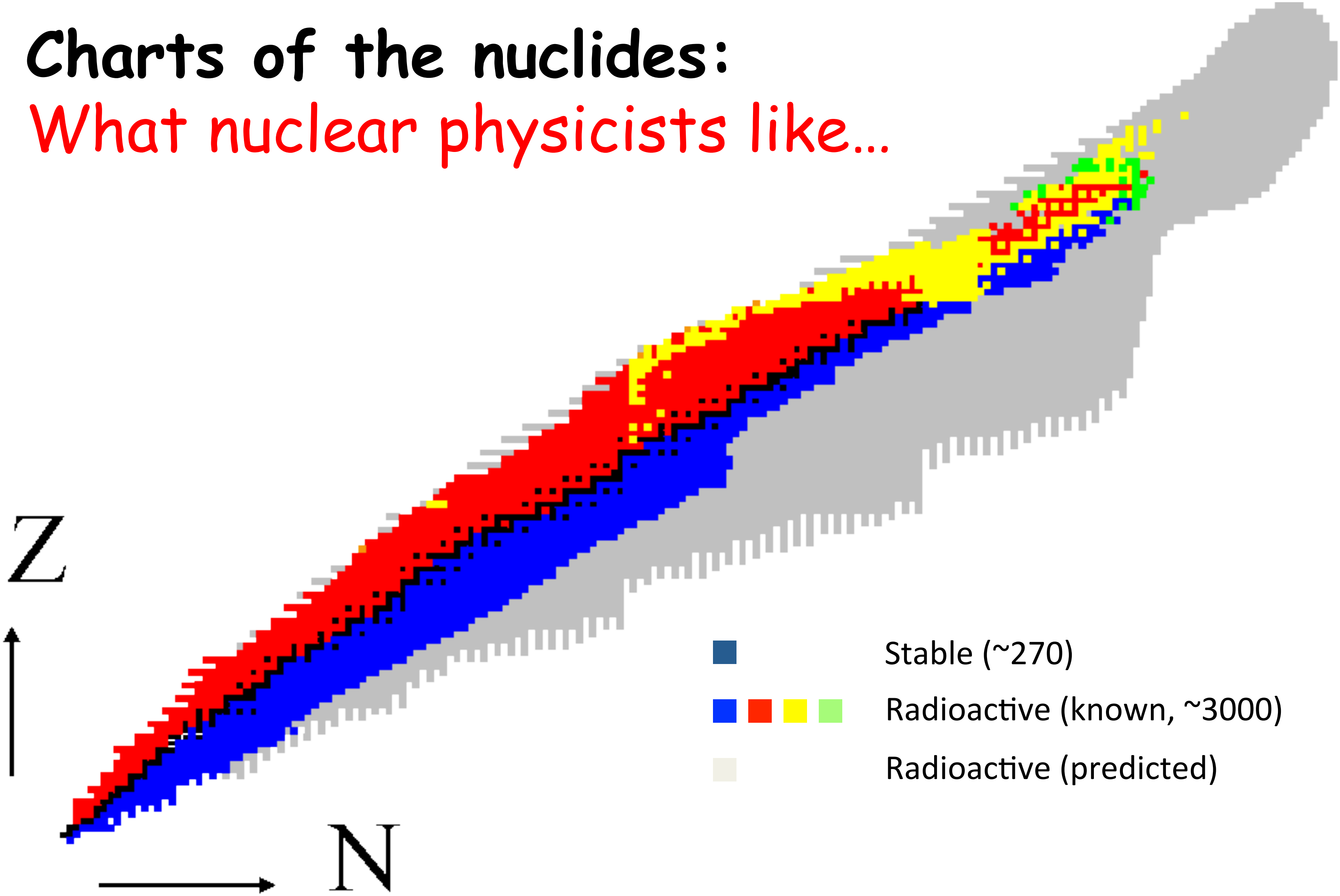
2. **What makes the stars shine?**

In search of the building blocks of the Universe…



Charts of the nuclides:

What nuclear physicists like…



$^{A}_{Z}X_{N}$

A chemical element (X) is uniquely identified by the atomic number *Z* ! Mass number: A = N + Z

- Nucleosynthesis: the synthesis of *Elements* through *Nuclear Reactions*

Two original proposals:

(full) Big-Bang nucleosynthesis

all elements formed from protons and neutrons
sequence of n-captures and β decays
soon after the Big Bang

Stellar nucleosynthesis

elements synthesised inside the stars
nuclear processes
well defined stages of stellar evolution

Alphe

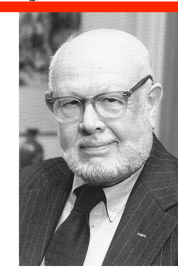
Pl

B²FH)

HINT: Investigate nuclear properties!







The Nobel Prize in Physics 1967

The Nobel Prize in Physics 1983

Which one is correct?

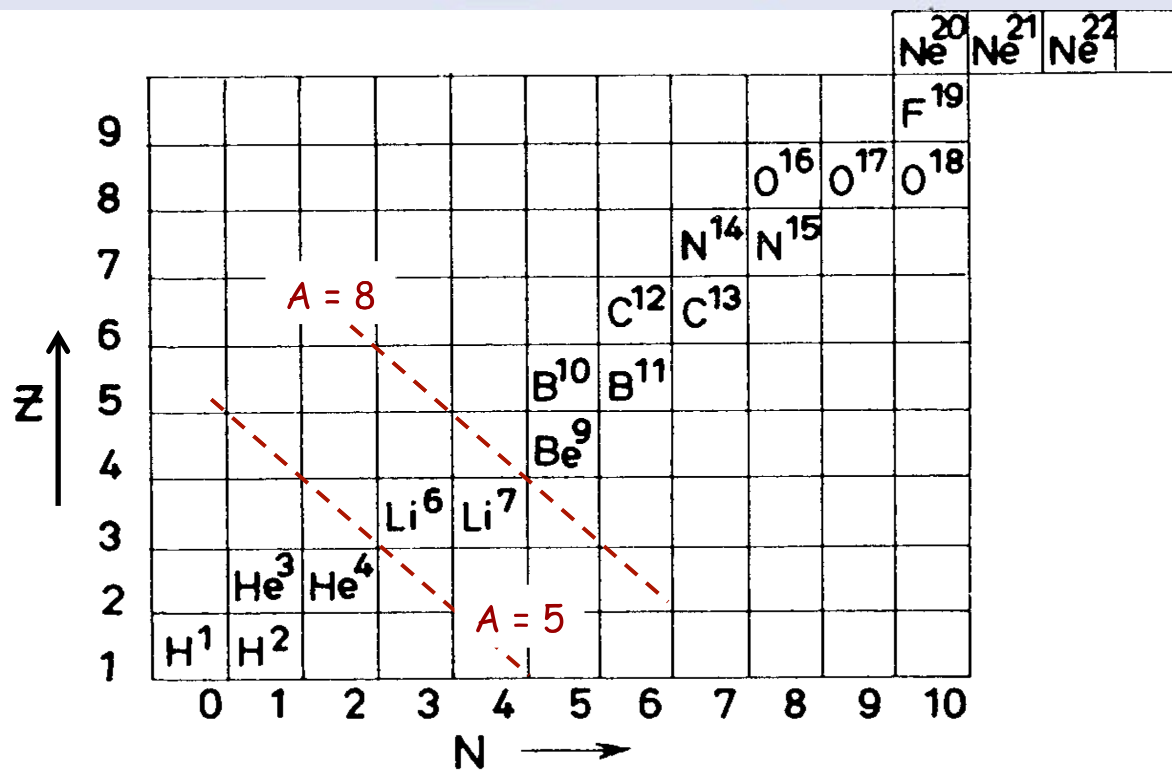
• Big Bang Nucleosynthesis

- occurred within the first 3 minutes of the Universe after the primordial quark-gluon plasma froze out to form neutrons and protons
- BBN stopped by further expansion and cooling (temperature and density fell below those required for nuclear fusion)
- BBN explains correctly the observed mass abundances of ^{1}H (75%), ^{4}He (23%), ^{2}H (0.003%), ^{3}He (0.004%), trace amounts (10^{-10}%) of Li and Be, and no other heavy elements

Mass stability gap at **A=5** and **A=8** !!!

BBN 

No way to bridge the gap through sequence of neutron captures during BB …



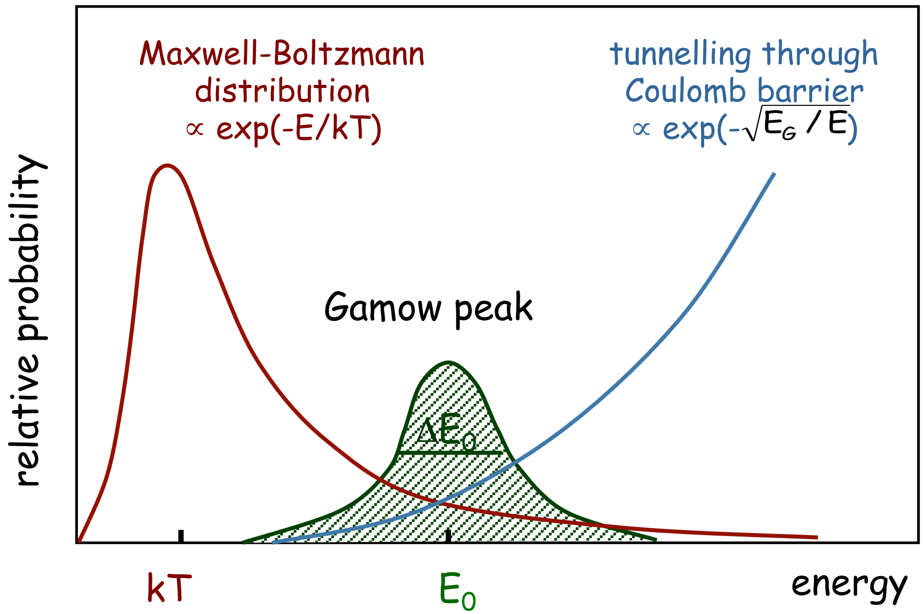
After that, very little happened in nucleosynthesis for a long time.

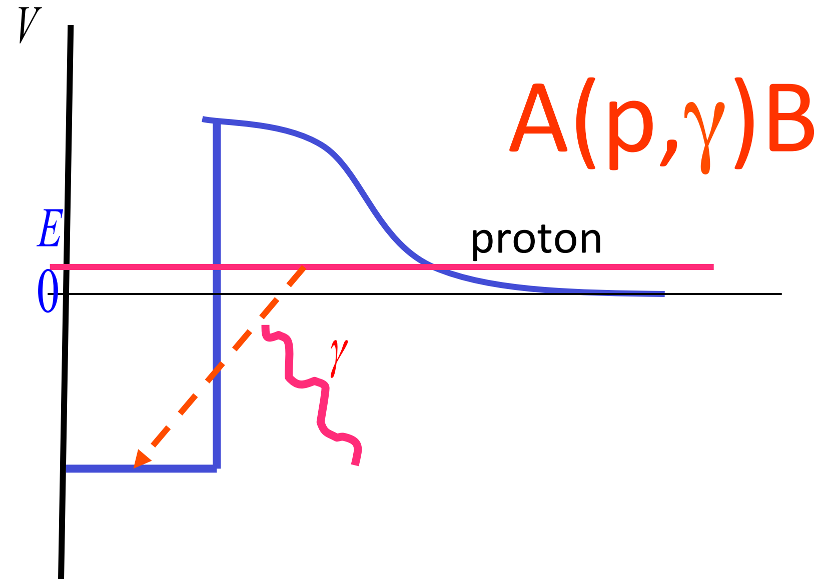
temperature and density too small !!!

It required galaxy and star formation via gravitation to advance the synthesis of heavier elements.

matter coalesces to higher temperature and density…

Because in stars the reactions involve mainly charged particles, stellar nucleosynthesis is a slow process.





charged particles → Coulomb barrier

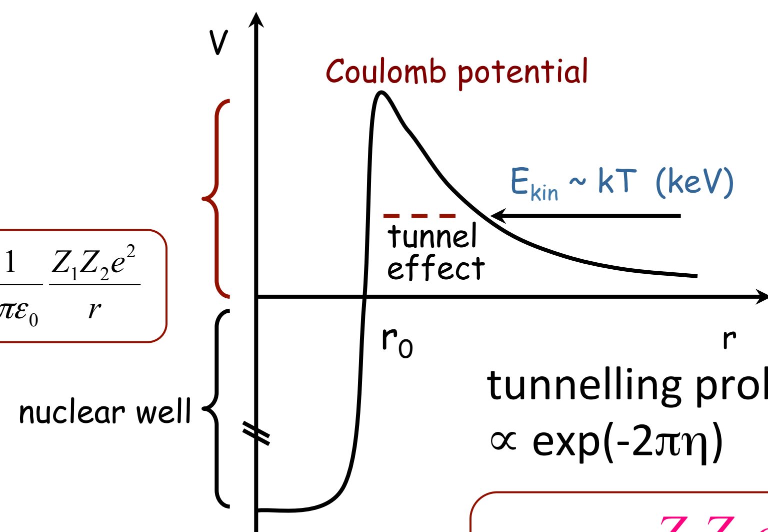
energy available: from thermal motion

$kT \sim 8.6 \times 10^{-8}\ T[K]\ \text{keV}$

T ~ 10^7 K (our Sun) ⇒ kT ~ 1 keV

T ~ 10^9 K (supernovae) ⇒ kT ~ 100 keV

$$\frac{1}{4\pi\varepsilon_0}\frac{Z_1 Z_2 e^2}{r}$$

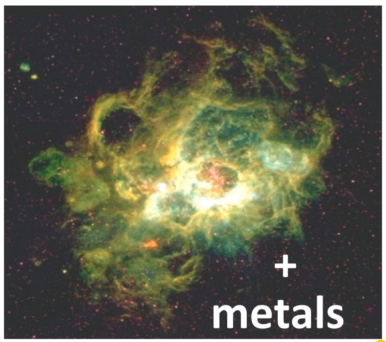


tunnelling probability:
∝ exp(-2πη)

$$\eta(E) = \frac{Z_1 Z_2 e^2}{\hbar v}$$

- Stellar life cycle

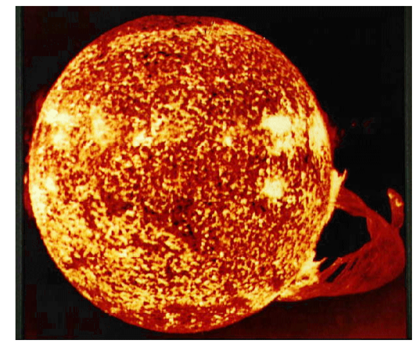
Interstellar gas



BIRTH
gravitational contraction

DEATH
explosion

Stars

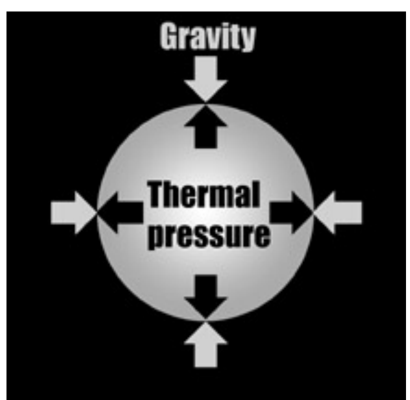


element mixing

thermonuclear reactions

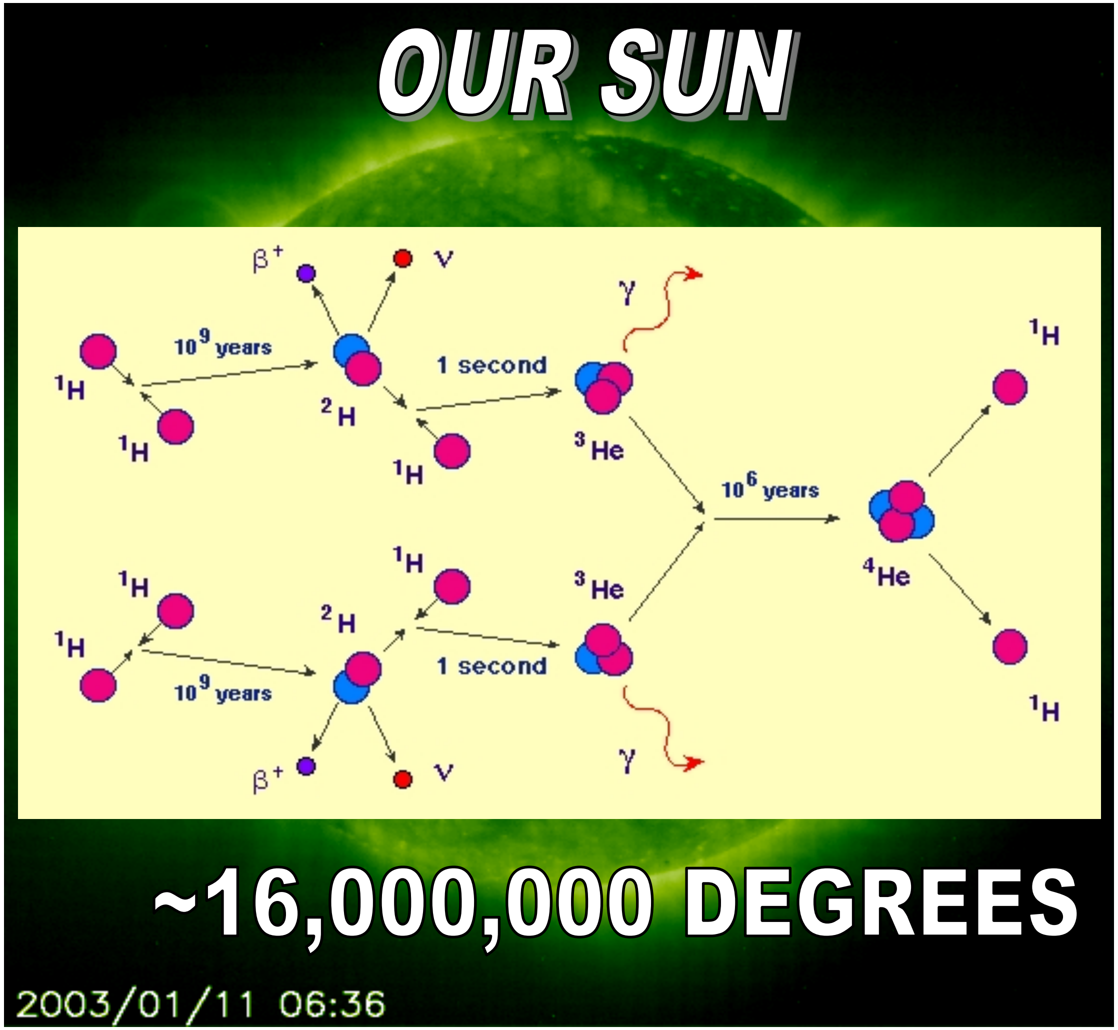
⇕

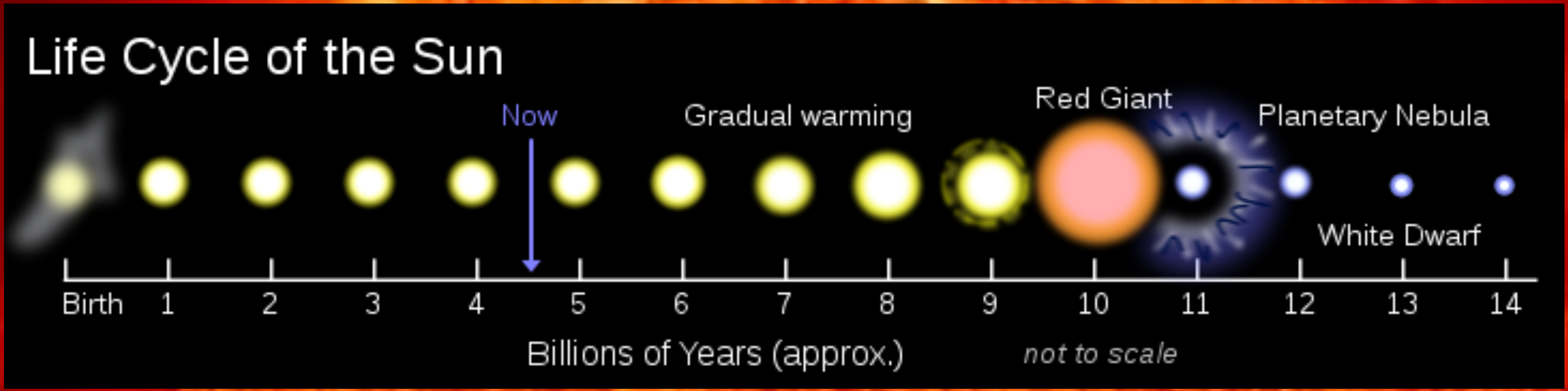
- ➢ energy production
- ➢ stability against collapse
- ➢ synthesis of "metals"



• Hydrogen Burning

- slow or fast (explosive) H-burning
- almost 95% of all stars spend their lives burning the H in their core (including our Sun). Our Sun is a slow nuclear reactor (a fusion reactor we could not make!)





until hydrogen fuel is depleted $\Rightarrow$ the life time of our sun depends on the nuclear reaction rates

life time of stars depends on their mass: at larger masses burn faster! We are lucky!

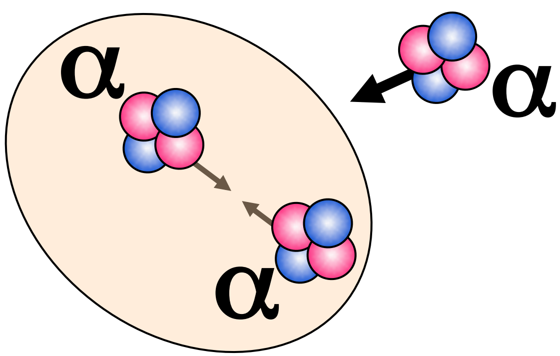
• Helium Burning: **Carbon formation**

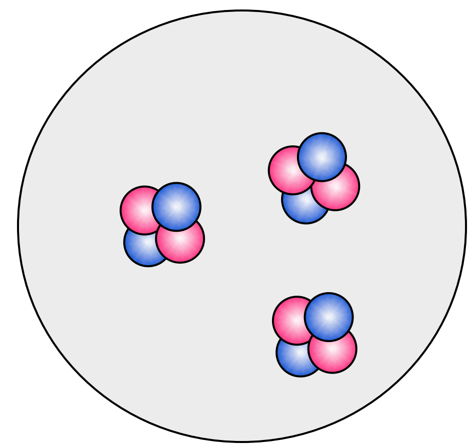
- *BBN produced <u>no elements heavier than Li</u> due to the absence of a stable nucleus with 8 nucleons*

- *in stars ^{12}C formation set the stage for the entire nucleosynthesis of heavy elements*

<u>How is Carbon synthesized in stars?</u>

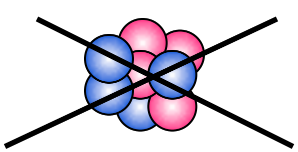
T ~ $6*10^8$ K and ρ ~ $2*10^5$ gcm^{-3}





$^4He + ^4He \leftrightarrow ^8Be$

$^8Be + ^4He \leftrightarrow ^{12}C$



^{8}Be unstable

(τ ~ 10^{-16} s)

- Helium Burning: **Oxygen formation**

  - *Oxygen production from carbon:*

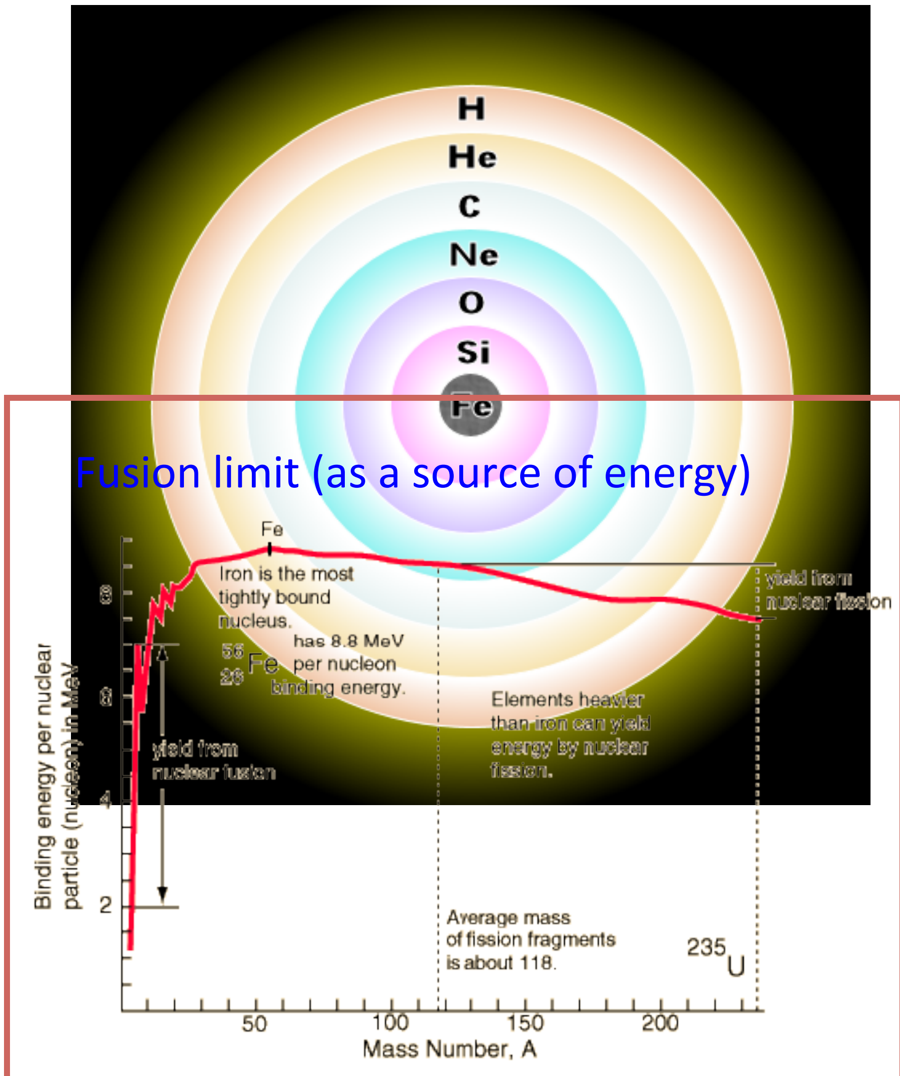
$$^{12}C + {}^{4}He \rightarrow {}^{16}O + \gamma$$

Carbon consumption !

Reaction rate is very small ⇒ not all C is burned, but Oxygen production is possible and Carbon-based life became possible…

• Nucleosynthesis up to Iron

<u>***A massive star near the end of its lifetime has "onion ring" structure***</u>



Carbon burning $\Rightarrow$ $T \sim 6*10^8$ K, $\rho \sim 2*10^5$ gcm^{-3}

^{12}C + ^{12}C -> ^{20}Ne + ^{4}He + 4.6 MeV

^{23}Na + ^{1}H + 2.2 MeV

Neon burning $\Rightarrow$ $T \sim 1.2*10^9$ K, $\rho \sim 4*10^6$ gcm^{-3}

^{20}Ne + γ -> ^{16}O + ^{4}He

^{20}Ne + ^{4}He -> ^{24}Mg + γ

Oxygen burning $\Rightarrow$ $T \sim 1.5*10^9$ K, $\rho \sim 10^7$ gcm^{-3}

^{16}O + ^{16}O -> ^{28}Si + ^{4}He + 10 MeV

^{31}P + ^{1}H + 7.7 MeV

Silicon burning $\Rightarrow$ $T \sim 3*10^9$ K, $\rho \sim 10^8$ gcm^{-3}

major ash: Fe

stars can no longer convert mass into energy via nuclear fusion !

- Nucleosynthesis beyond Iron

WE BELIEVE THAT

HALF of THE ELEMENTS BEYOND IRON ARE PRODUCED

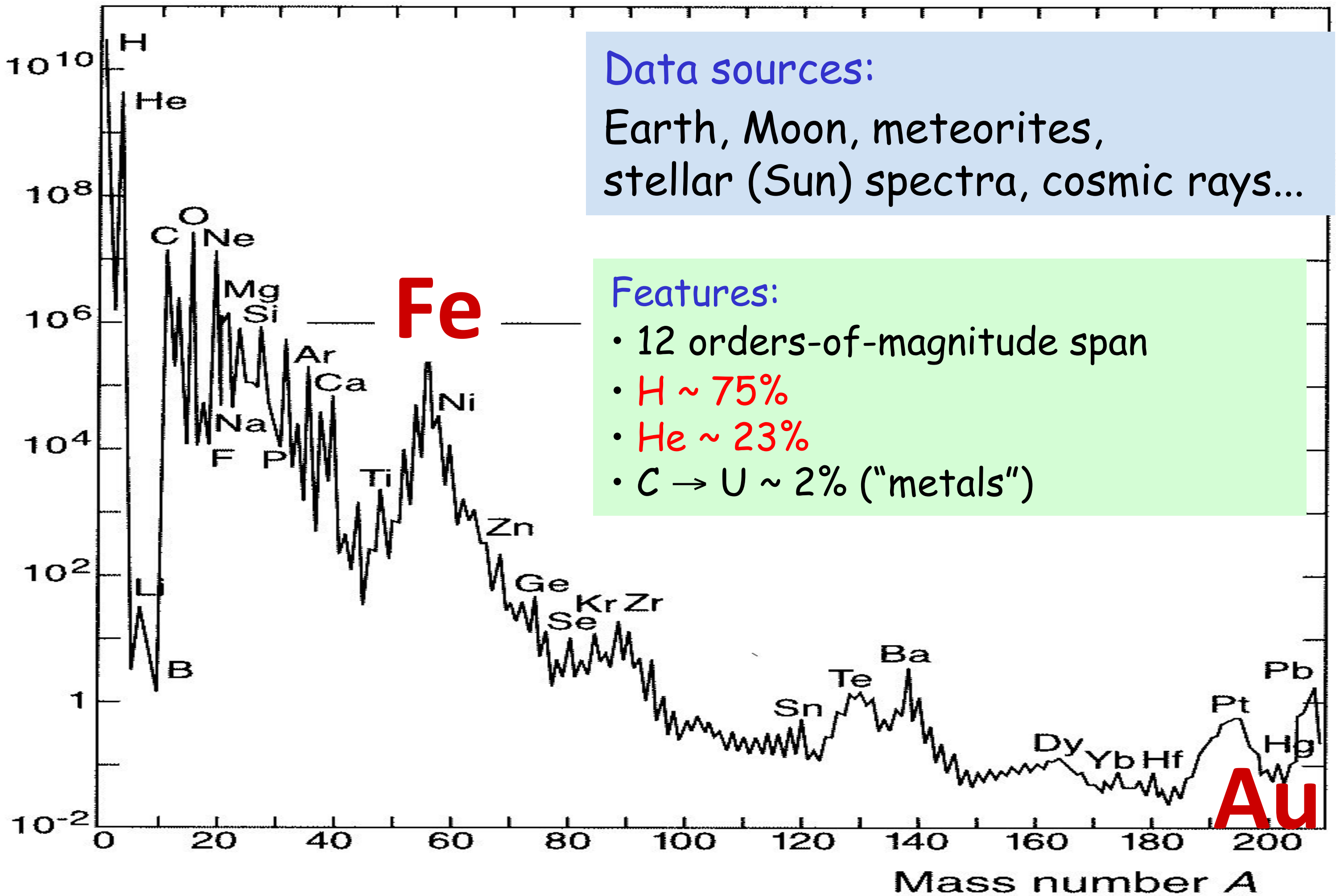
IN EXPLOSIONS of SUCH STARS

SUPERNOVAE

Almost 5 billion years ago, our solar system began the journey with its gravitation collapse…

If we look around us today, we can see what elements were in our interstellar cloud…

• Abundance of the Elements



Data sources:

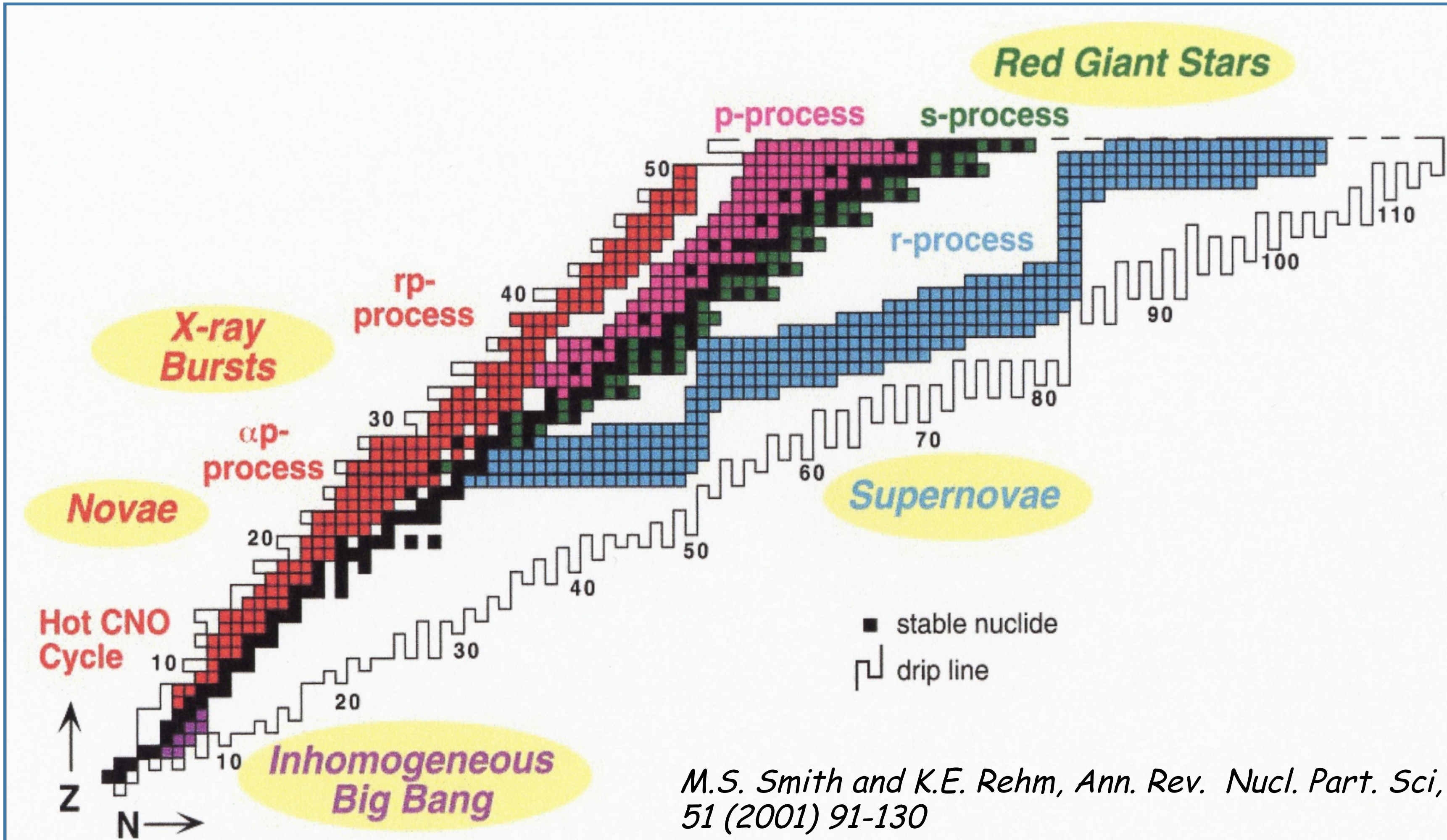
Earth, Moon, meteorites, stellar (Sun) spectra, cosmic rays...

Features:

- 12 orders-of-magnitude span
- H ~ 75%
- He ~ 23%
- C → U ~ 2% ("metals")

Abundance of elements and isotopes are UNIQUE finger prints of various cosmic processes. To interpret and understand them, diverse and vast nuclear physics knowledge is needed!!! Not fully solved!

Overview of main astrophysical processes



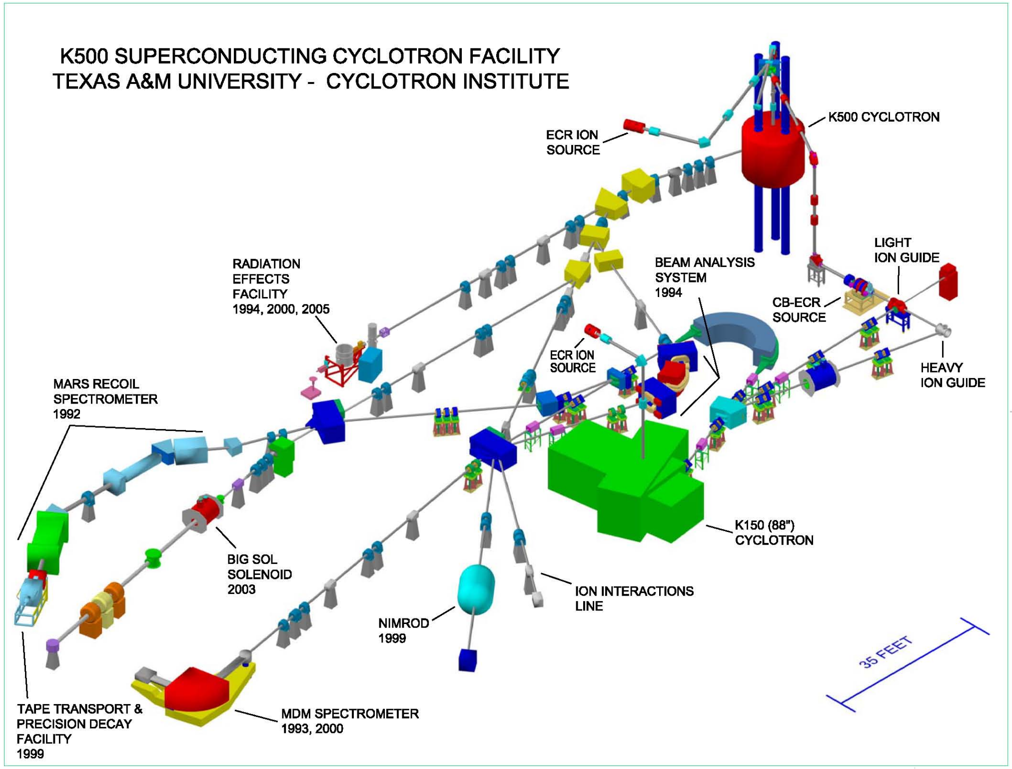
M.S. Smith and K.E. Rehm, Ann. Rev. Nucl. Part. Sci, 51 (2001) 91-130

Two big problems:

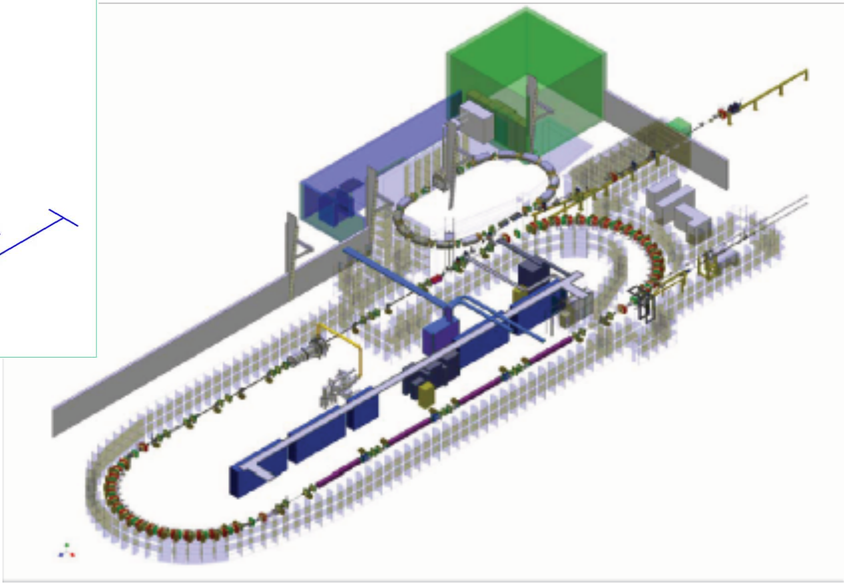
1. - reactions in stars involve(d) radioactive nuclei ⇒ use RNB
2. - very small energies and very small cross sections ⇒indirect methods

RESOURCES:

Accelerator-based facilities for my current research in Nuclear Astrophysics



HIγS @ Duke University

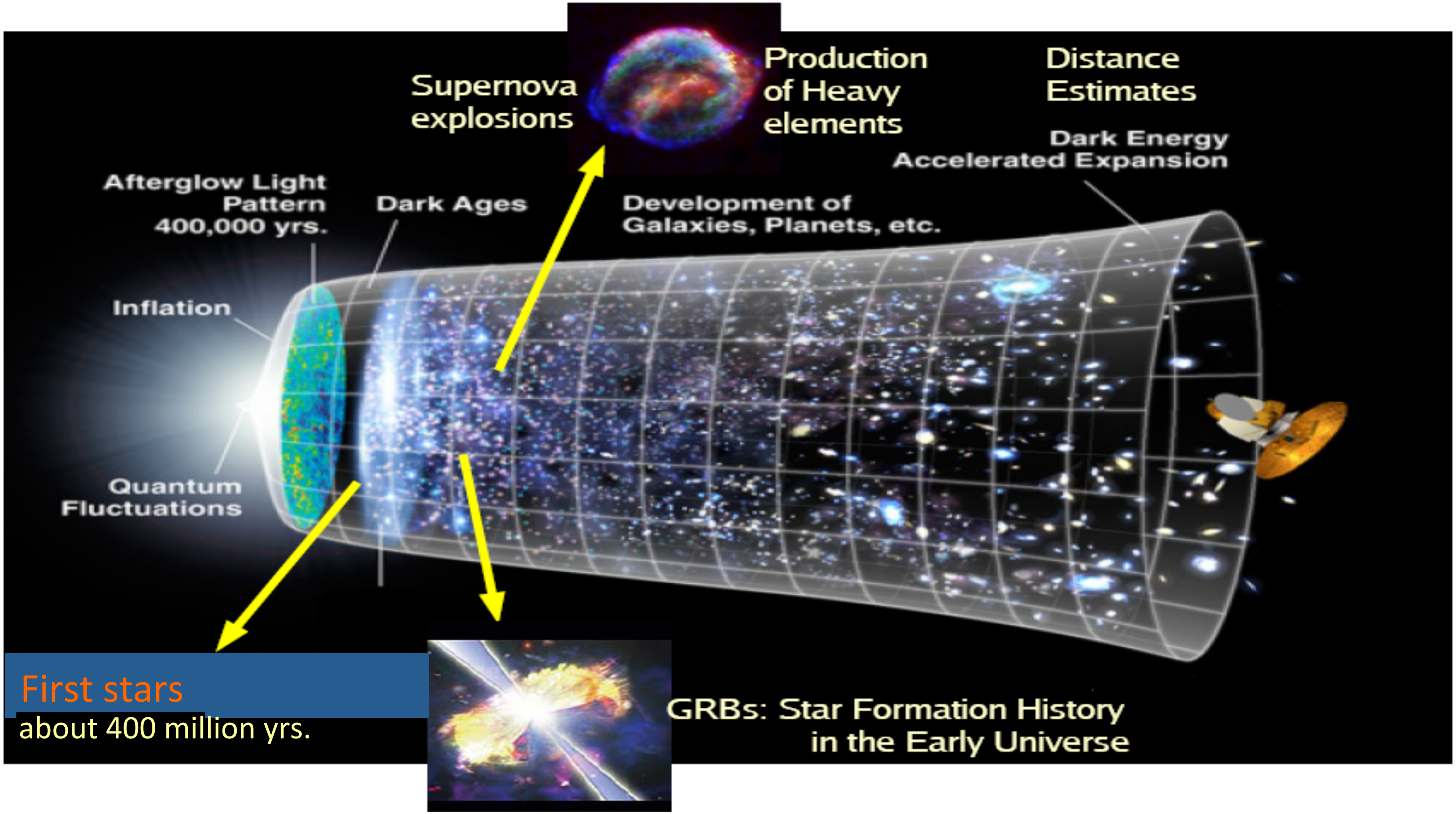


The most intense accelerator-driven γ-ray source in the world

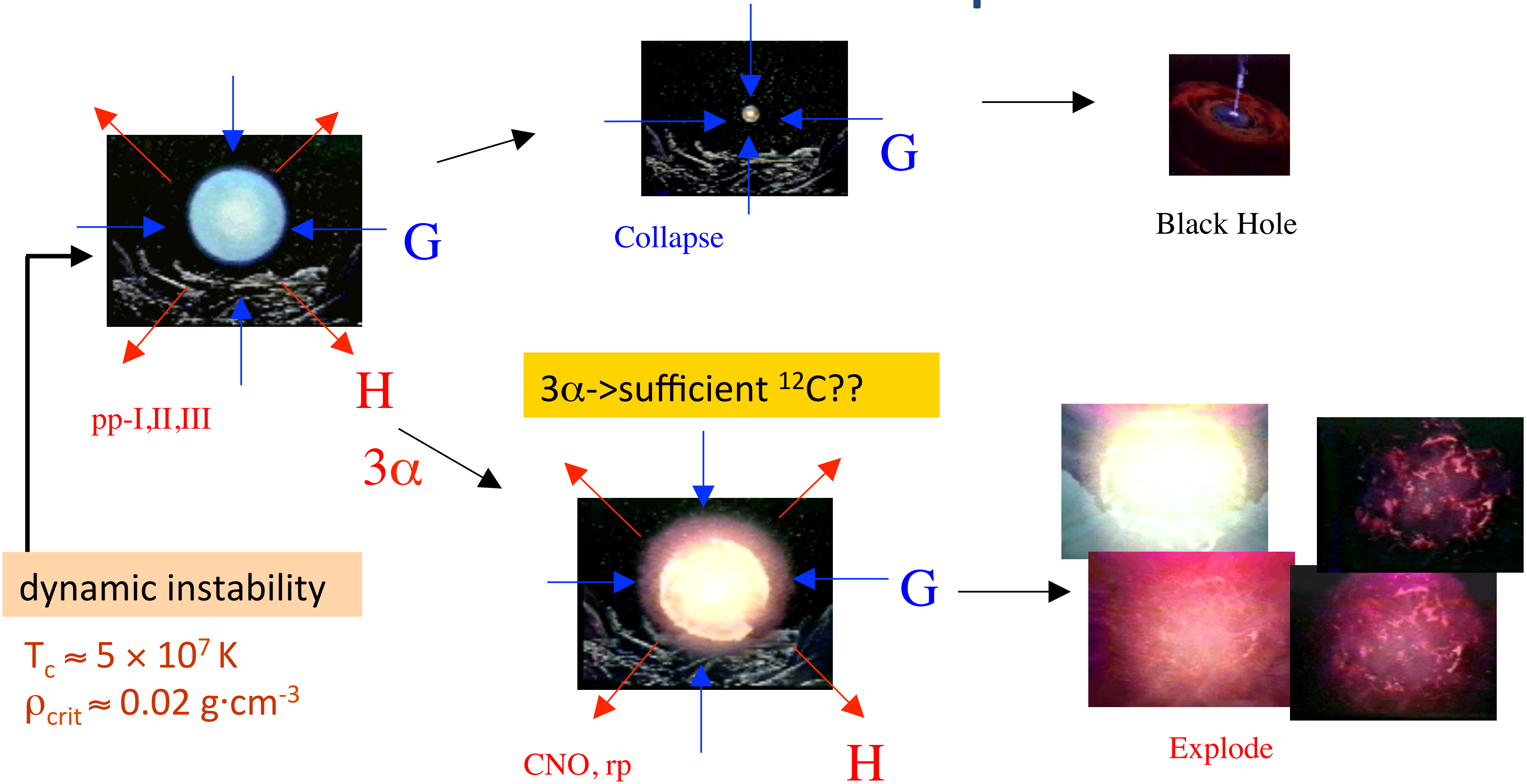
Astrophysical motivation

The first sources of light:

Population III stars



Fate of Massive Pop III Stars



Critical metallicity of CNO material for explosion:

- $Z \geq 10^{-8}$, 250-300 $M_\odot$ryer et al., APJ 2000)
- $Z \sim 10^{-9}$, 120-1000 $M_\odot$leger et al., APJ 2001)

Interest in $^{12}N(p,\gamma)^{13}O$

M. Wiescher et al., 1989, Ap.J., 343 :

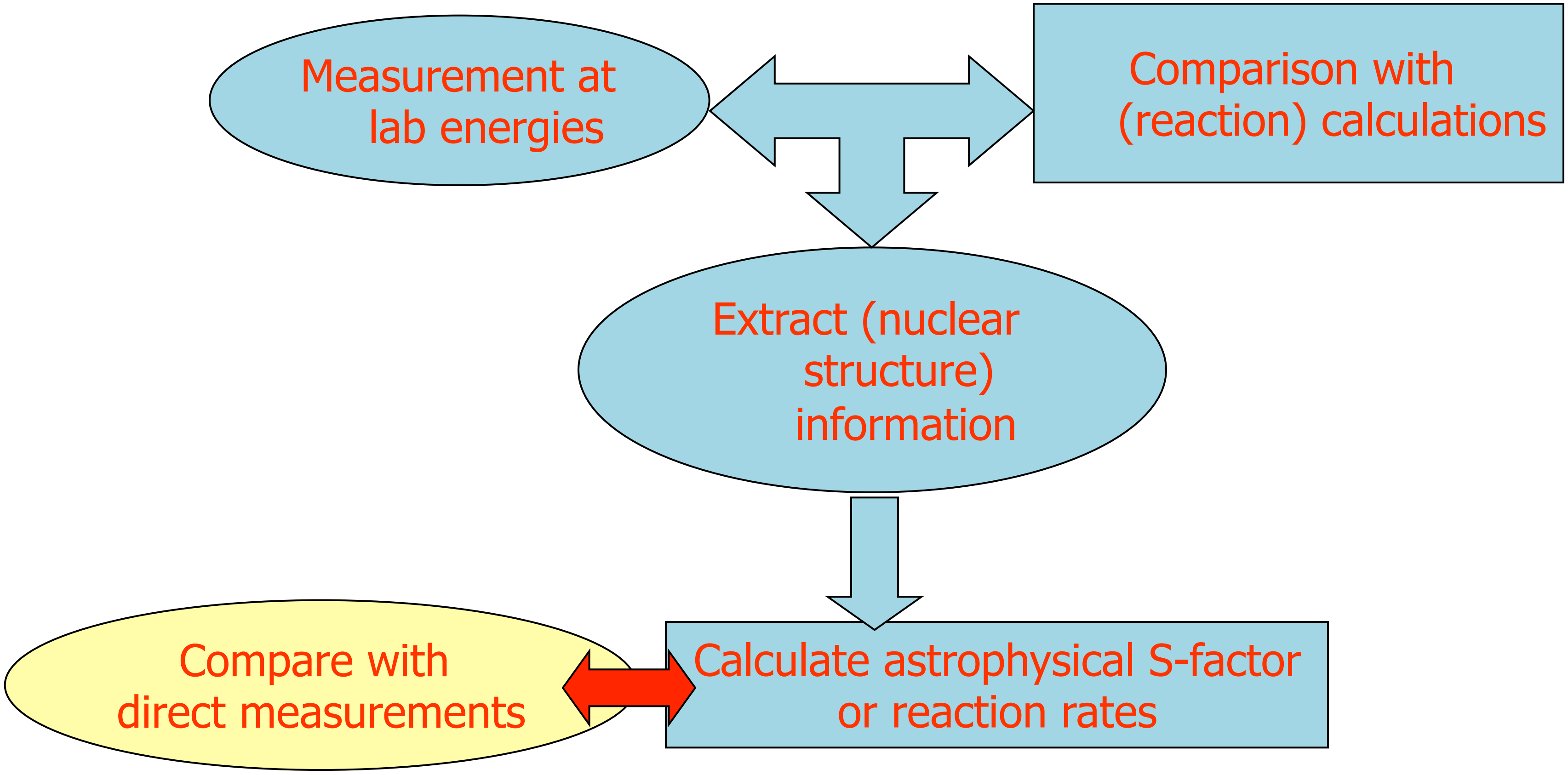
Hot pp chains and rap-process chains in low-metallicity objects

pp-I: $p(p,e^{+}\nu)d(p,\gamma)^{3}He(^{3}He,2p)^{4}He$
pp-II: $^{7}Be(e^{-},\nu)^{7}Li(p,\alpha)^{4}He$
pp-III: $^{7}Be(p,\gamma)^{8}B(\beta^{+}\nu)^{8}Be(\alpha)^{4}He$

• process material from pp cycles into CNO nuclei

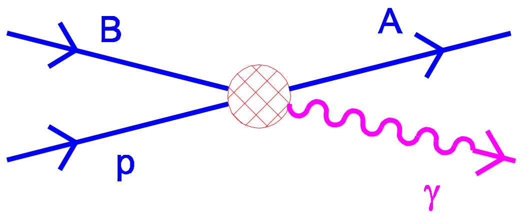
pp-IV: $^{7}Be(p,\gamma)^{8}B(p,\gamma)^{9}C(\beta^{+}\nu)^{9}B(p)^{8}Be(\alpha)^{4}He$
pp-V: $^{7}Be(\alpha,\gamma)^{11}C(\beta^{+}\nu)^{11}B(p,2\alpha)^{4}He$
rap-I: $^{7}Be(p,\gamma)^{8}B(p,\gamma)^{9}C(\alpha,p)^{12}N(p,\gamma)^{13}O(\beta^{+}\nu)^{13}N(p,\gamma)^{14}O$
rap-II: $^{7}Be(\alpha,\gamma)^{11}C(p,\gamma)^{12}N(p,\gamma)^{13}O(\beta^{+}\nu)^{13}N)p,\gamma)^{14}O$
rap-III: $^{7}Be(\alpha,\gamma)^{11}C(p,\gamma)^{12}N(\beta^{+}\nu)^{12}C(p,\gamma)^{13}N(p,\gamma)^{14}O$
rap-IV: $^{7}Be(\alpha,\gamma)^{11}C(\alpha,p)^{14}N(p,\gamma)^{15}O$

- Indirect Methods: *basic approach*



Asymptotic Normalization Coefficient Method

Radiative proton capture in stars: B + p → A + γ [B(p,γ)A]



$$\sigma \propto |M|^2$$

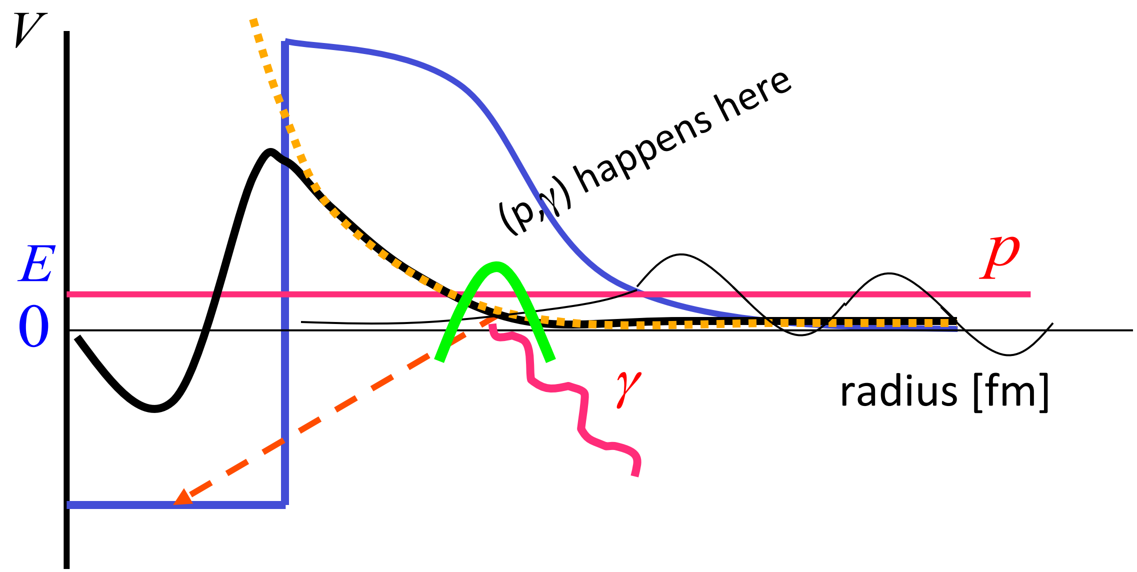
Reaction matrix element:

$$M = \left\langle I^{A}_{Bp}(r_{Bp}) \middle| \hat{O}(r_{Bp}) \middle| \psi_i^{(+)}(r_{Bp}) \right\rangle$$

At large radii:

$$I^{A}_{Bp}(r) \approx C_{nlj} \frac{W_{-\eta, l+1/2}(2\kappa r)}{r}$$

- Classical barrier penetration problem:
- low energies ⇒ capture at large radii

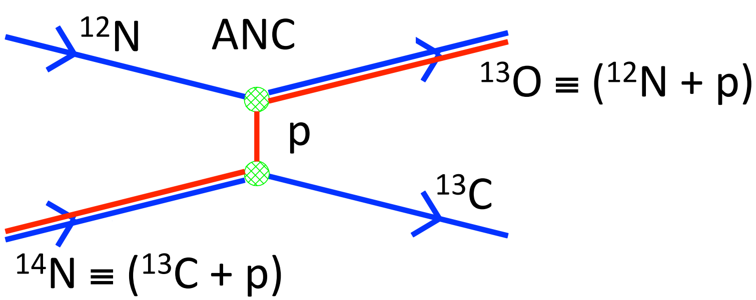


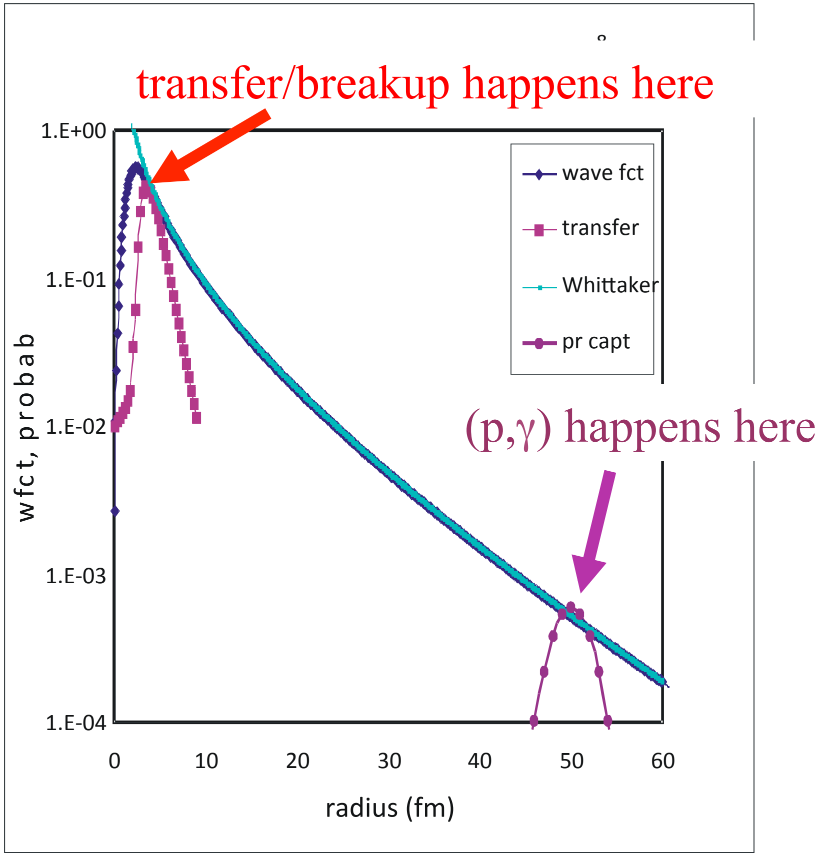
$$\sigma_{capture} \propto \left(C^{A}_{Bp}\right)^2$$

Measuring ANC in the laboratory

- e. g. $^{12}N + p \rightarrow {}^{13}O + \gamma$ (astrophysical reaction of interest)

- *peripheral* proton transfer at lab. energy (~ 10 AMeV): $^{12}N + {}^{14}N \rightarrow {}^{13}O + {}^{13}C$

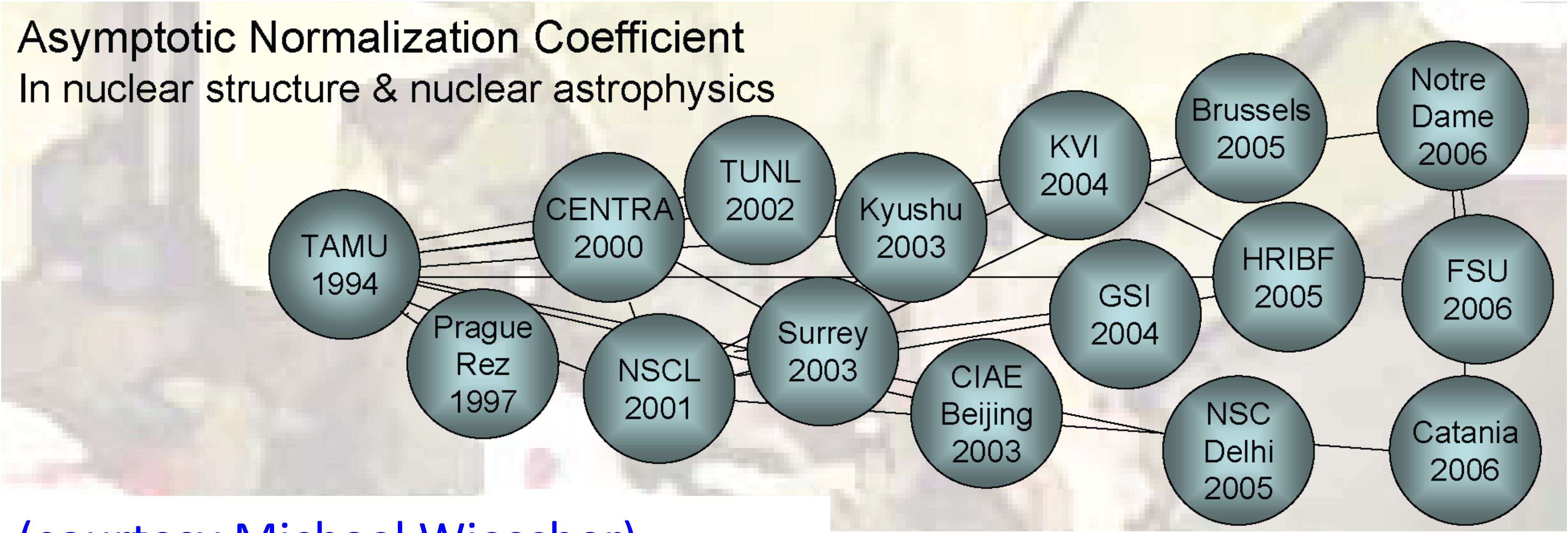




Outside nuclear potential:

$$I^A_{Bp}(r) \approx C_{nlj} \frac{W_{-\eta,l+1/2}(2\kappa r)}{r}$$

ANC family tree

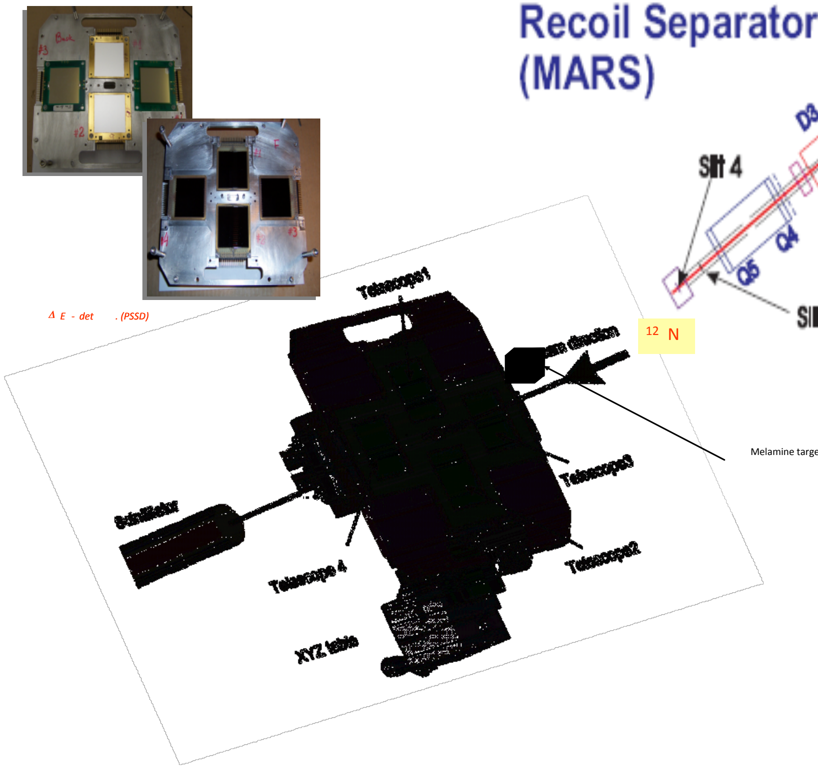


(courtesy Michael Wiescher)

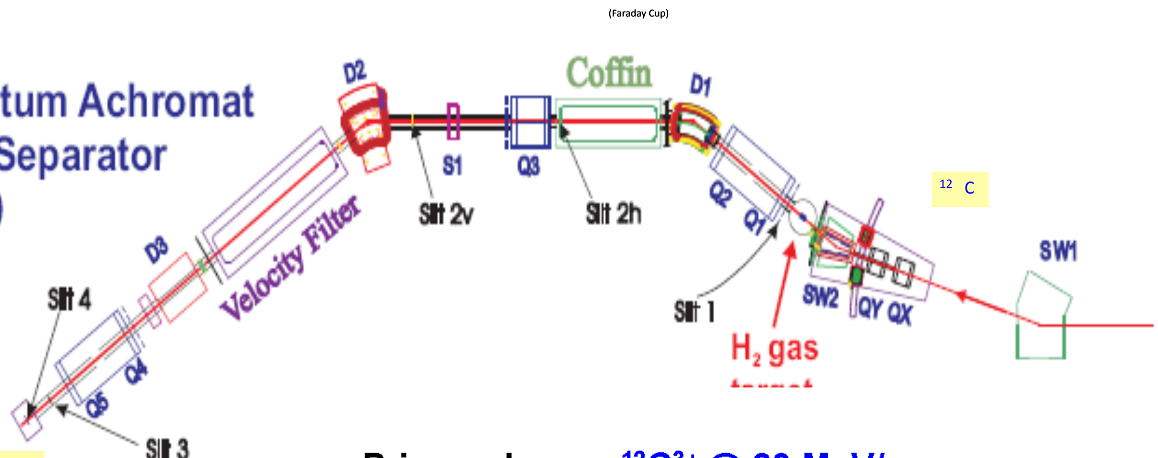
ANC method (references):

- Xu, Gagliardi, Tribble, Mukhadmedzhanov, Timofeyuk, PRL 73, 2027 (1994)
- A.M. Mukhadmedzhanov et al., PRC 56, 1302 (1997)
- C.A. Gagliardi et al., PRC 59, 1149 (1999)
- L. Trache, F. Carstoiu, C.A. Gagliardi, R.E. Tribble, PRL 87, 271102 (2001)

Experimental Setup for $^{12}N(p,\gamma)^{13}O$ study via (^{12}N,^{13}O) proton transfer reaction



Momentum Achromat Recoil Separator (MARS)



Primary beam: $^{12}C^{3+}$ @ 23 MeV/u

Primary reaction: p(^{12}C,^{12}N)n

Secondary beam: $^{12}N^{7+}$ @ 12 MeV/u, ~ 200 kHz

Purity: ~ 99.8%

Secondary reaction: ^{14}N(^{12}N,^{13}O)^{13}C

Secondary target: melamine ($C_3N_6H_6$), 1.6 mg/cm^2

Beam spot size: 3.8 $\times$ 4.3 mm (FWHM)

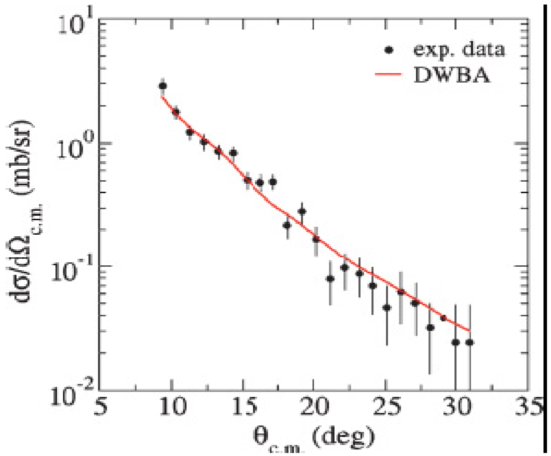
^{12}N is radioactive!

$T_{1/2}$ = 11 ms

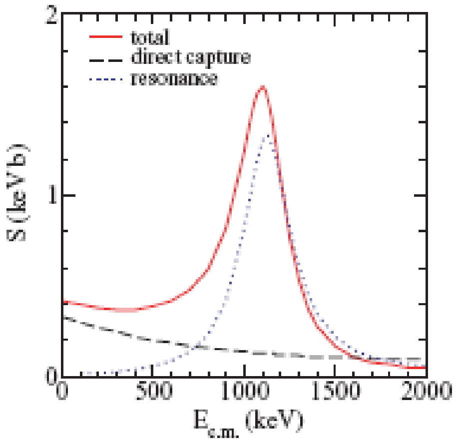
Flight time in MARS < 0.5 μs

Detection system: 4 dE-E Silicon detectors (dE-detectors are position sensitive)

$^{14}N(^{12}N,^{13}O)$ proton-transfer react ⇒ $^{12}N(p,\gamma)^{13}O$ (rap proc)

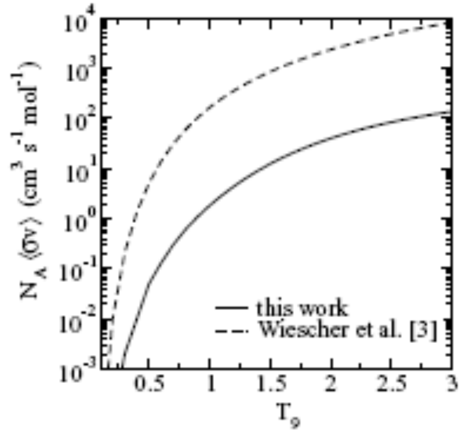


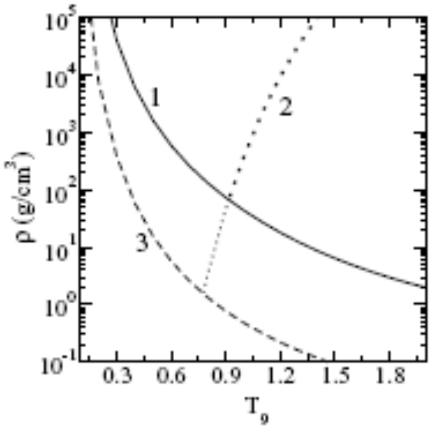
ANC, S-factor,
Reaction rate



$$C^2\left({}^{13}O\right) = \frac{\sigma_{\exp}^{diff}(\vartheta)}{\sigma^{DWBA}(\vartheta)/b^2}$$

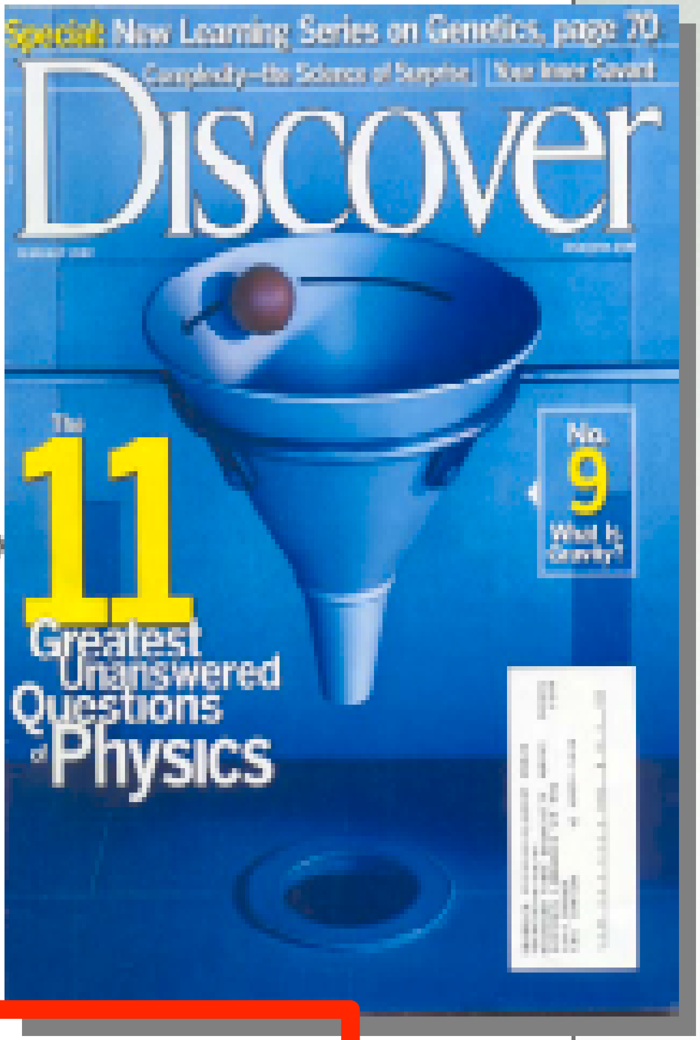
$$C^2_{p_{1/2}}({}^{13}O) = 2.53 \pm 0.30\ \mathrm{fm}^{-1}$$





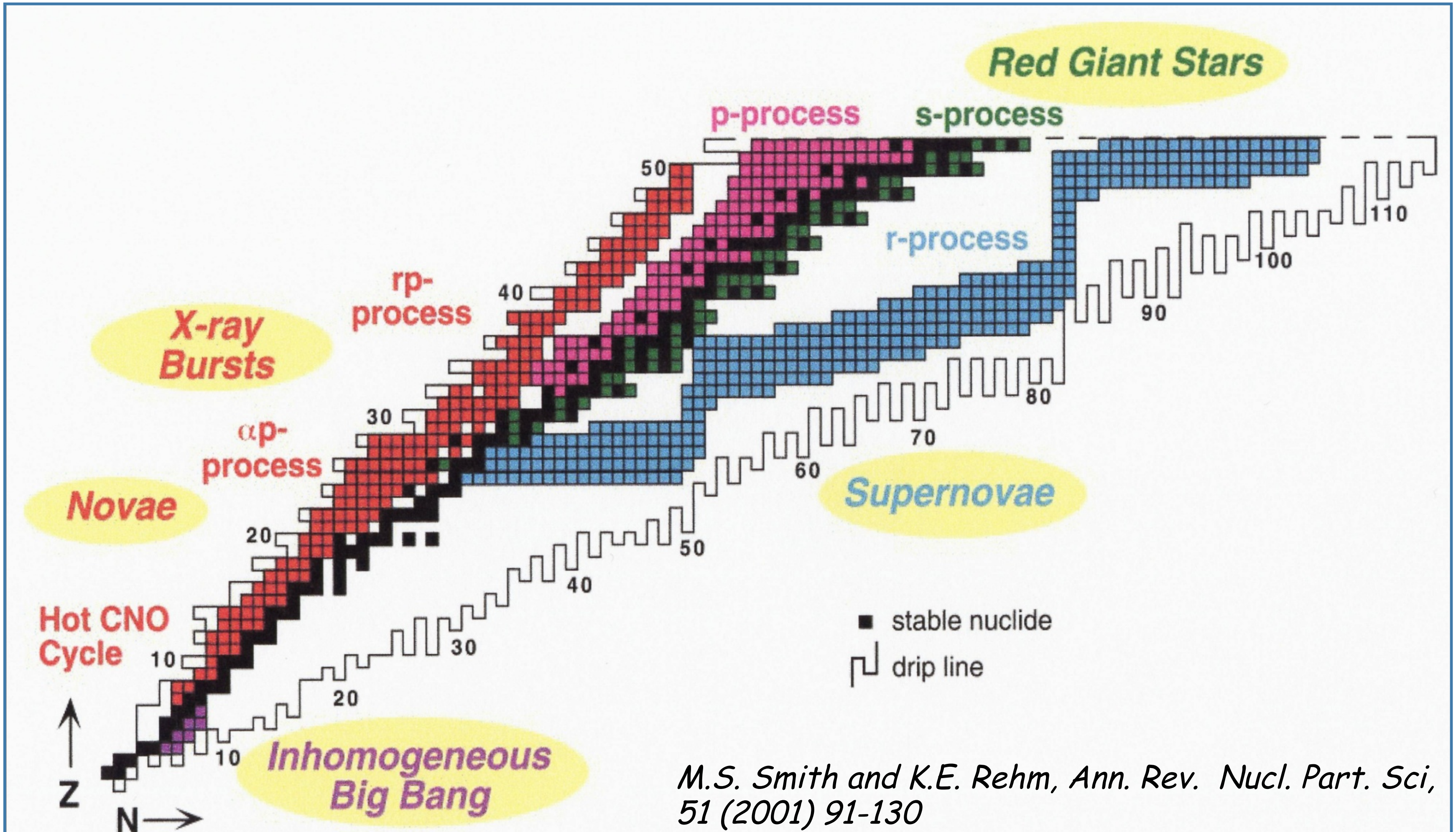
A. Banu et al, Phys Rev C 79, 025805 (2009)

Eleven Science Questions for the New Century (2003) – National Academy Study, Chair M. Turner



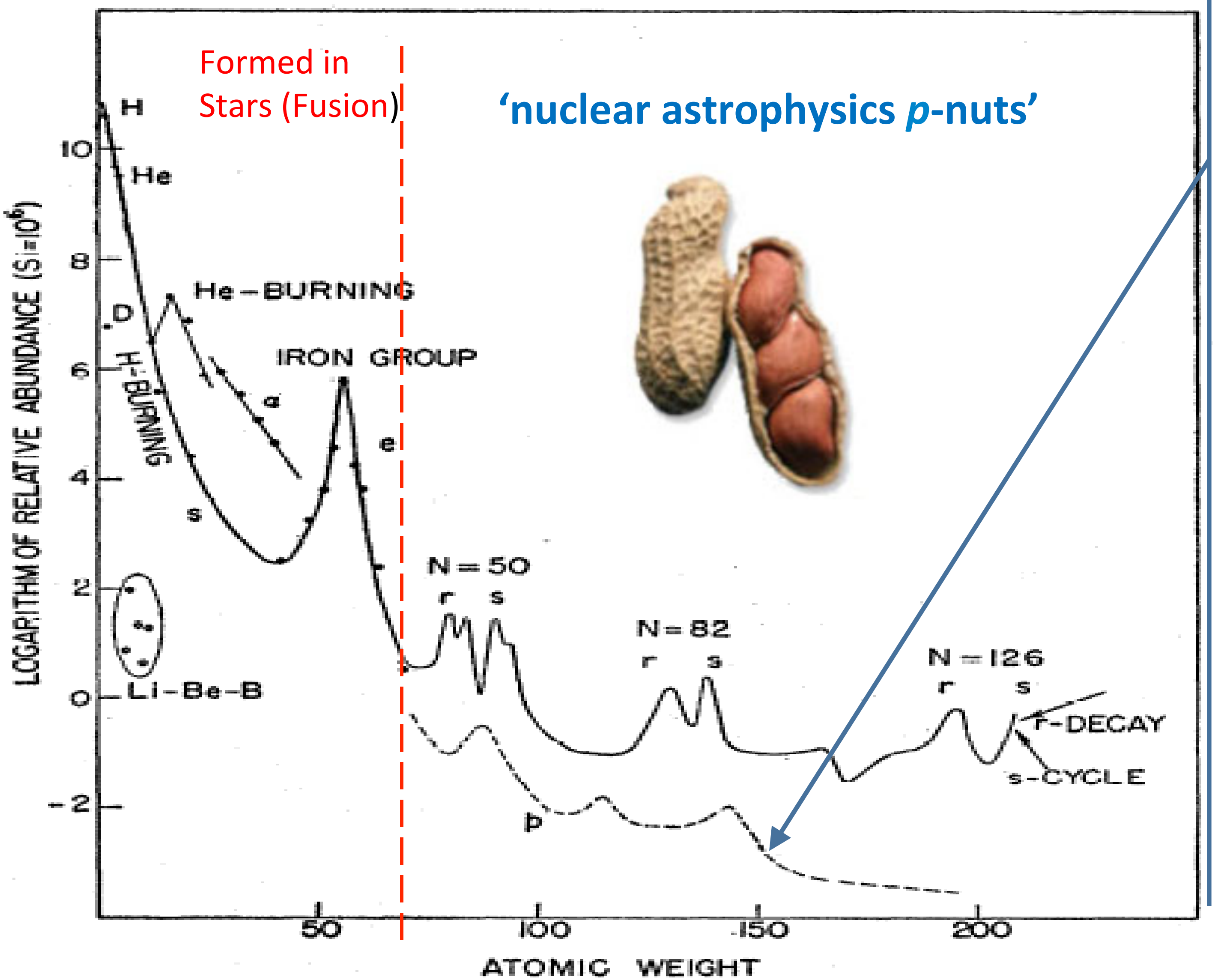
—What is dark matter?
—What is the nature of the dark energy?
—How did the Universe begin?
—Did Einstein have the last word on gravity?
—What are the masses of the neutrinos and how have they shaped the evolution of the universe?
—How do cosmic accelerators work?
—Are protons unstable?
—Are there new states of matter at exceedingly high density and temperature?
—Are there additional space-time dimensions?
✓ How were the heavy elements from iron to uranium made?
—Is a new theory of matter and light needed at the highest energies?

Overview of main astrophysical processes



M.S. Smith and K.E. Rehm, Ann. Rev. Nucl. Part. Sci, 51 (2001) 91-130

Elemental Abundances and the Study of *p*-Nuclei



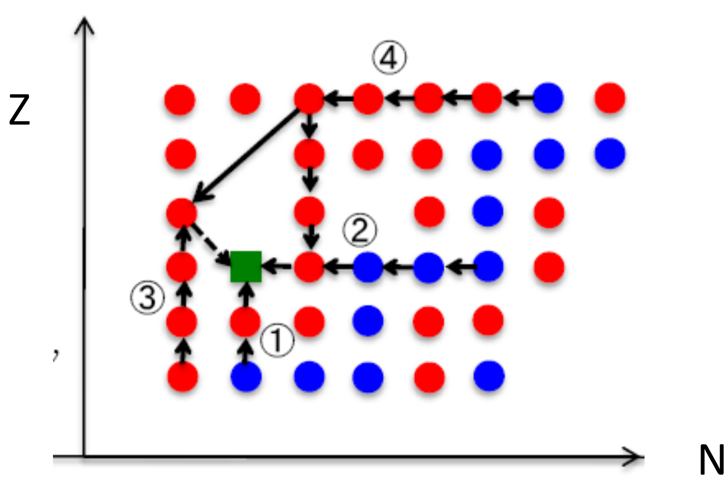
Research goals:

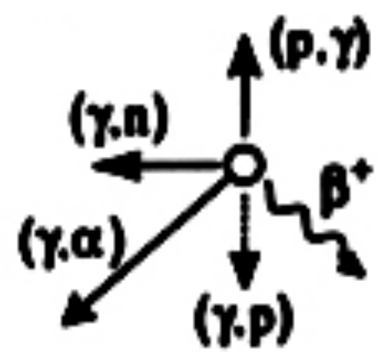
Understanding the origin of *p*-Nuclei

Acquiring experimental data for use to validate astrophysical models.

p-Nuclei Abundances

Isotope	% Abundance	Isotope	% Abundance	Isotope	% Abundance
^{74}Se	0.87	^{114}Sn	0.66	^{156}Dy	0.0524
^{78}Kr	0.354	^{115}Sn	0.35	^{158}Dy	0.0902
^{84}Sr	0.56	^{120}Te	0.089	^{162}Er	0.136
^{92}Mo	15.84	^{124}Xe	0.126	^{164}Er	1.56
^{94}Mo	9.04	^{126}Xe	0.115	^{168}Yb	0.135
^{96}Ru	5.51	^{130}Ba	0.101	^{174}Hf	0.18
^{98}Ru	1.87	^{132}Ba	0.0097	^{180m}Ta	0.0123
^{102}Pd	0.96	^{138}La	0.091	^{180}W	0.135
^{106}Cd	1.215	^{136}Ce	0.193	^{184}Os	0.018
^{108}Cd	0.875	^{138}Ce	0.25	^{190}Pt	0.0127
^{113}In	4.28	^{144}Sm	3.09	^{196}Hg	0.146
^{112}Sn	0.96	^{152}Gd	0.20		

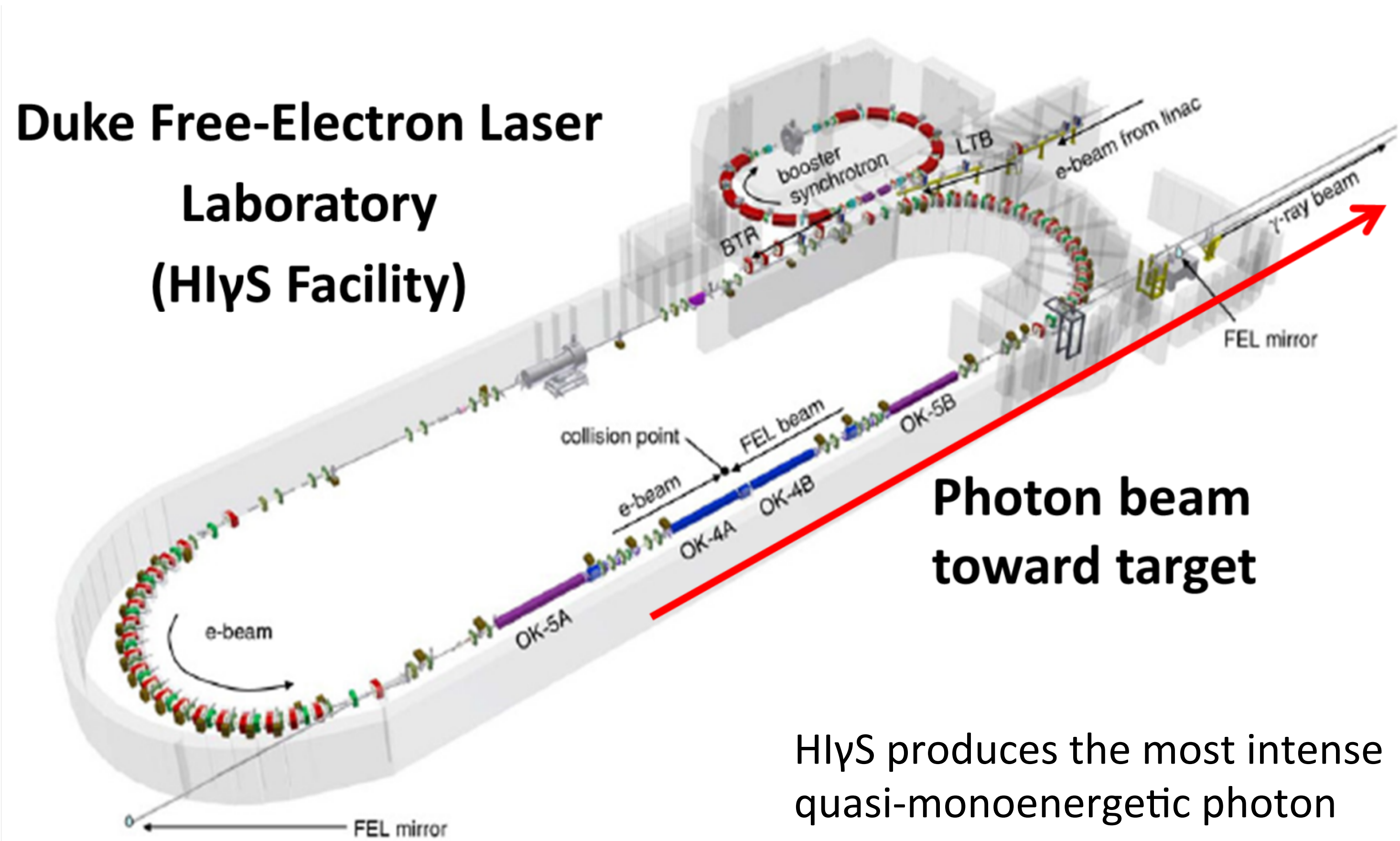




Study of the ^{94}Mo(γ,n)^{93}Mo Photodisintegration Cross Section at HIγS

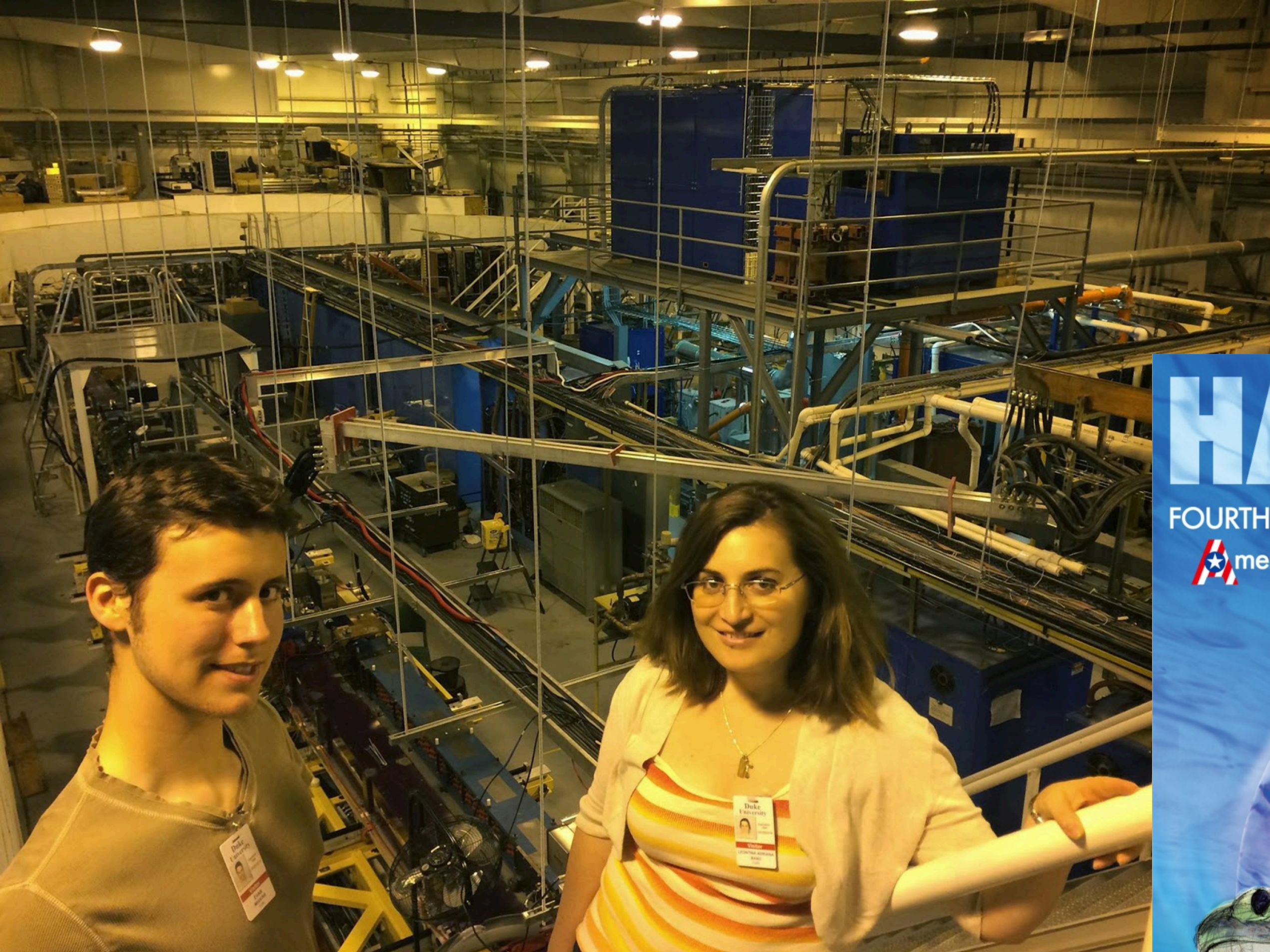
Duke Free-Electron Laser Laboratory

(HIγS Facility)



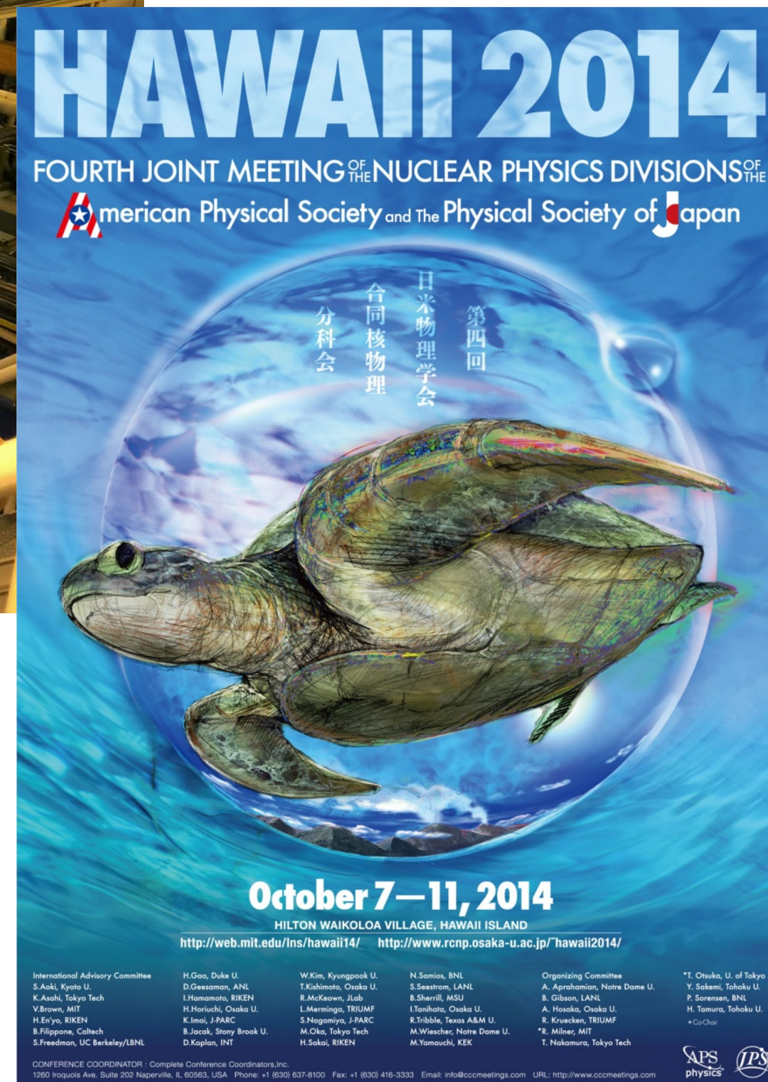
To attain results with a good degree of accuracy, a high photon flux is needed.

HIγS produces the most intense quasi-monoenergetic photon beam in the world, making it ideal for studying ^{94}Mo(γ,n).



Physics major involved:
E. Meekins (2013-2016)

* Honors thesis in progress!

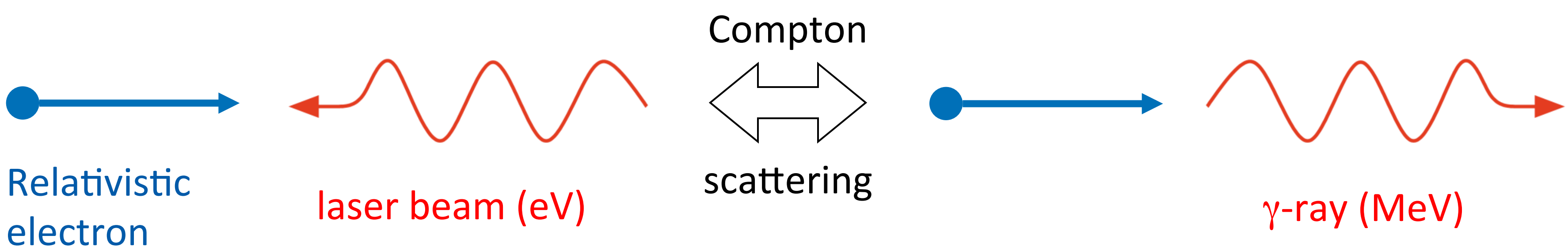


Working at Duke University's HIGS facility (spring 2014)

http://jmuphysics.blogspot.com/search?updated-max=2014-07-17T17:24:00-04:00

Proposal funded by Research Corporation!

How HIγS Works: Laser Compton Backscattering (LCB)



$$E_\gamma = \frac{\hbar\omega \cdot (1 - \beta \cdot \cos\theta_i)}{1 - \beta \cdot \cos\theta_f + \frac{\hbar\omega}{E_{electron}}(1 - \cos\theta_{photon})} \approx 4\gamma^2 \cdot E_{laser}$$

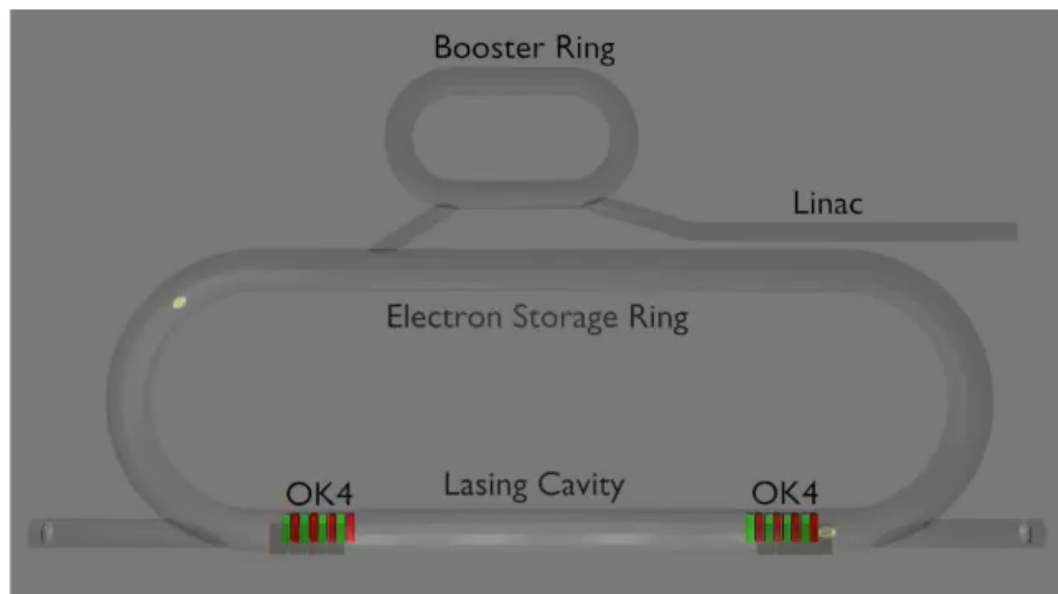
Example:

E_{laser} = 3.3 eV

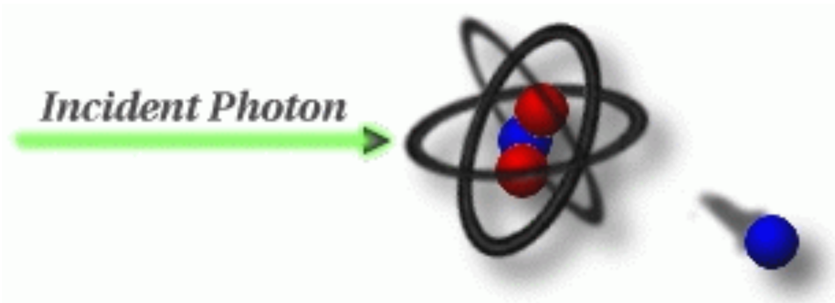
$E_{electron}$ = 450 MeV (γ = 882)

E_γ = 10 MeV

http://www.tunl.duke.edu/web.tunl.2011a.howhigsworks.php



Experimental (γ,n) Cross Section



$$\gamma + {}^{94}Mo \rightarrow {}^{93}Mo + n$$

The cross section, σ, is similar to the probability of reaction.

Along with the dimensionalities of the reaction, this probability changes with E_γ.

$$\sigma(E_\gamma) = \frac{N_n}{N_\gamma N_t \varepsilon_n}$$

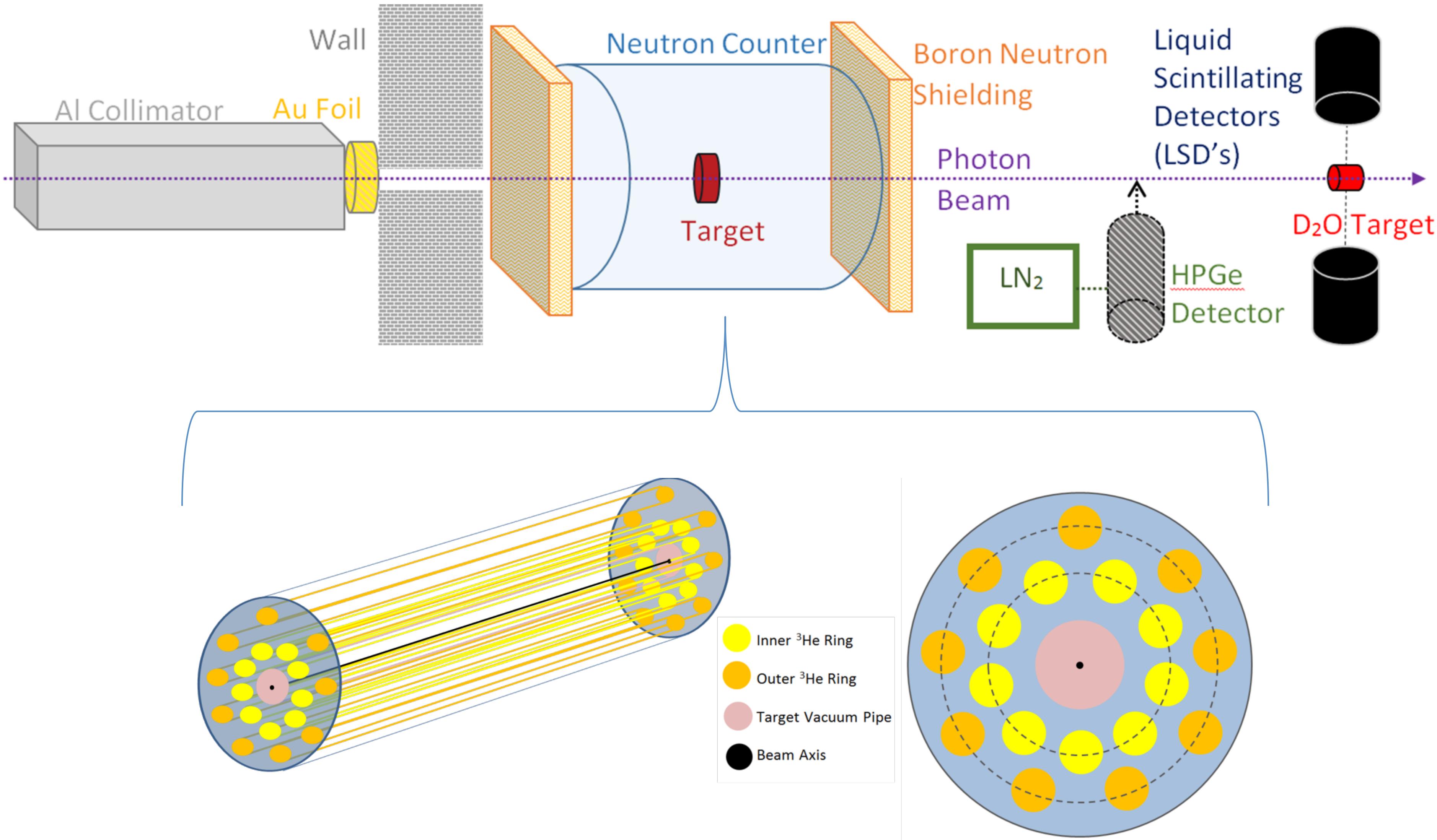
N_n – number of neutrons detected using ^{3}He counters

N_γ - number of incident photons

N_t – number of target atoms per unit area (enriched target)

ε_n – neutron detection efficiency

Experimental Setup

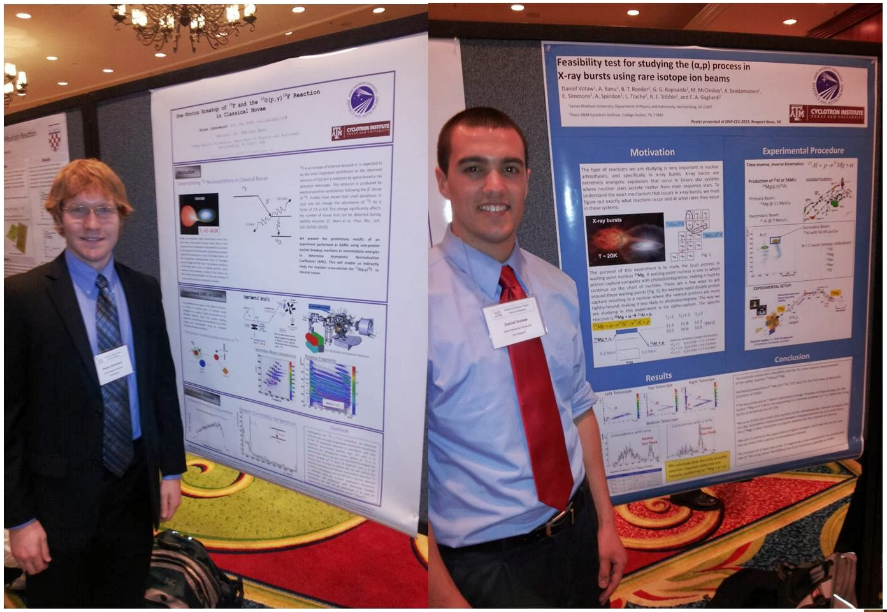


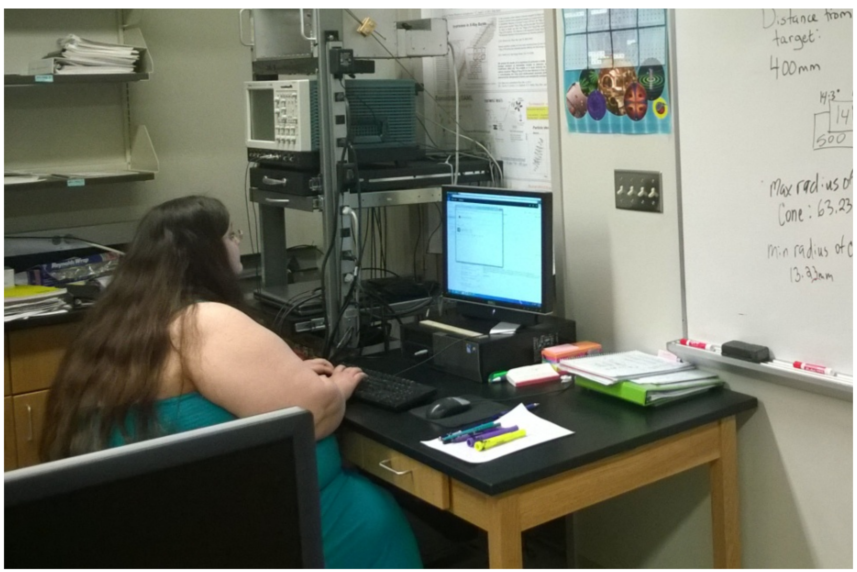
Acknowledgments

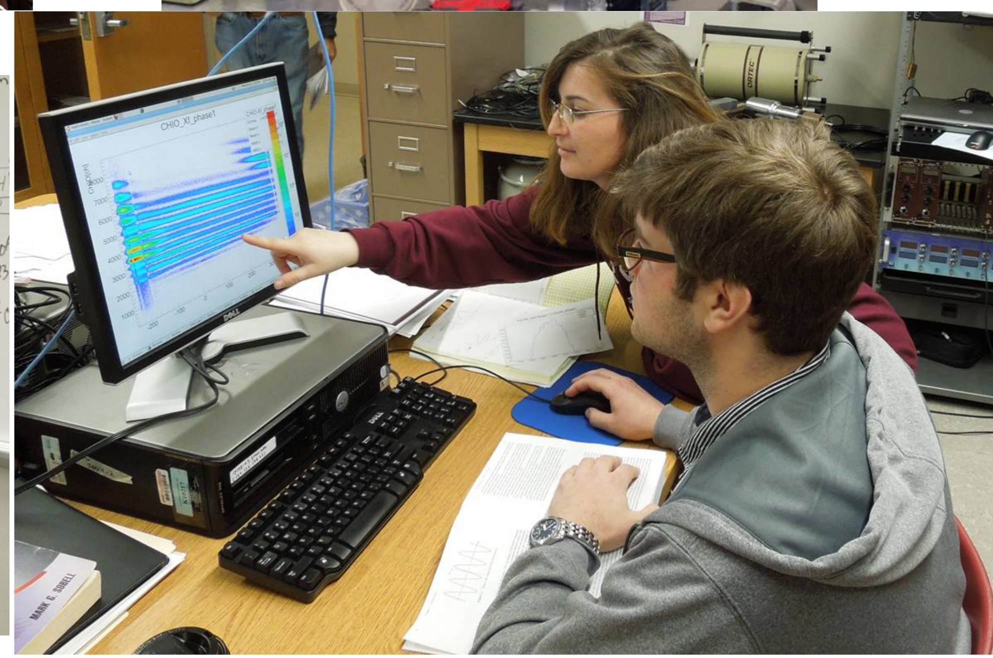
This research is funded by the Research Corporation for Science Advancement – The Cottrell College Science Award

Triangle
Universities
Nuclear
Laboratories
(host of HIγS facility)

My research undergrads in action….



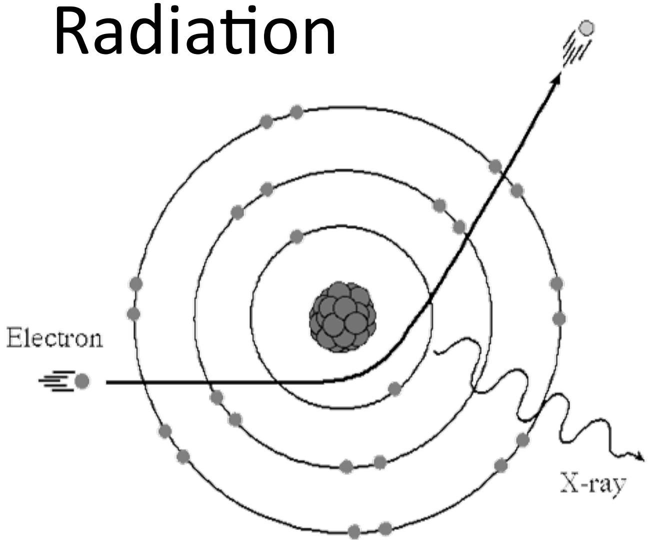




From HIγS to JMU

Madison Radiation Laboratory (2016)

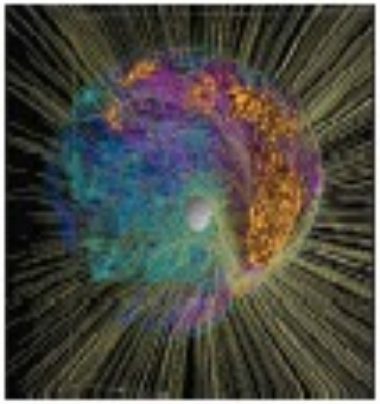
Bremsstrahlung Radiation

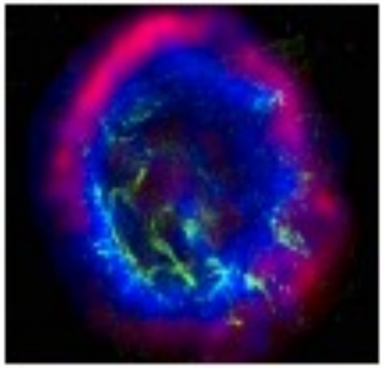


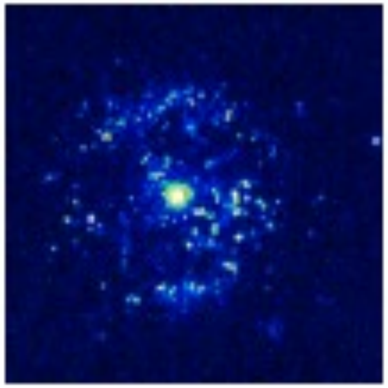
Away from Stability!

Understanding nuclear processes at the extreme density and temperature conditions of stellar environments!

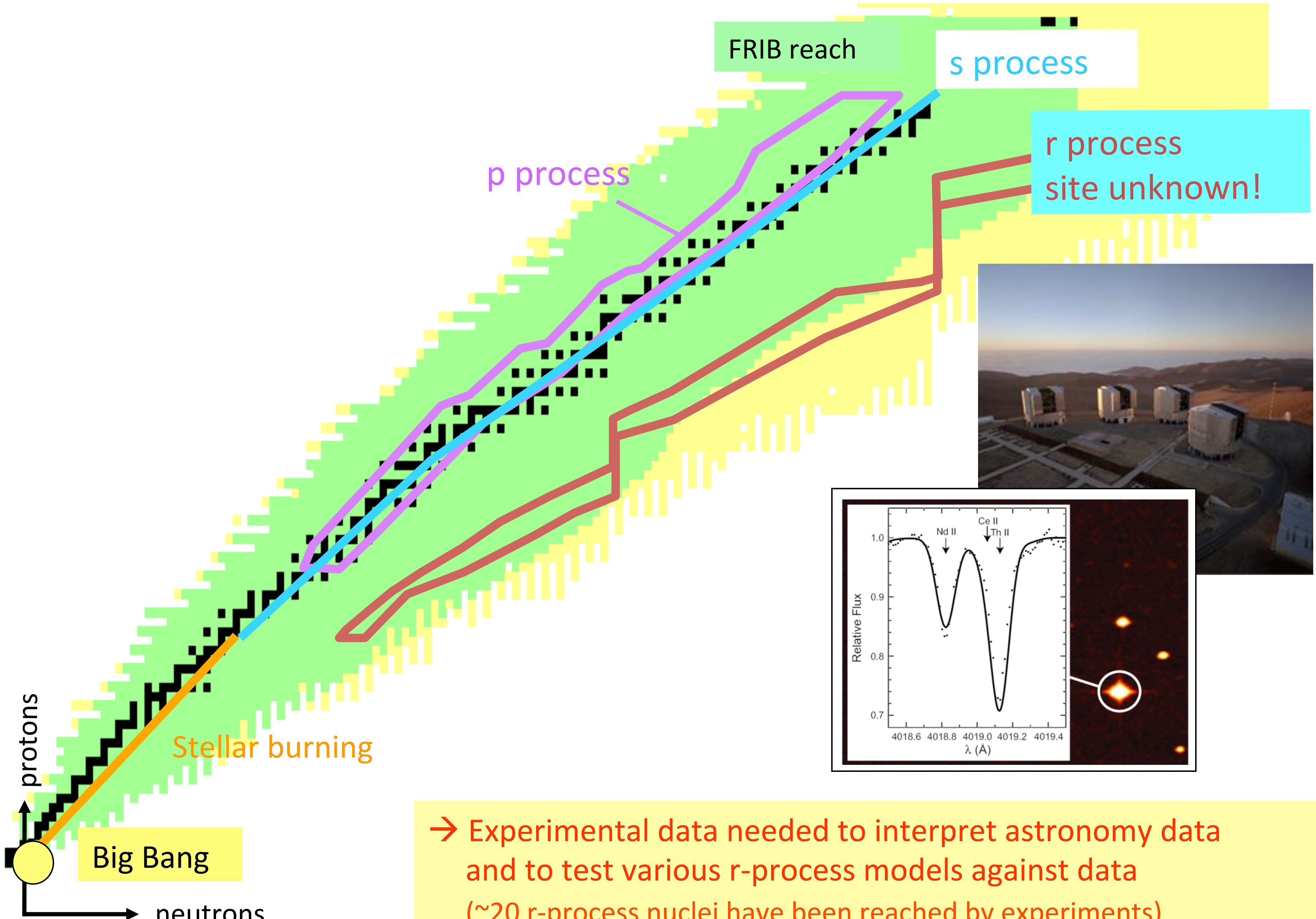
Facility for Rare Isotope Beams (FRIB)
(located at Michigan State University)







What is the origin of the elements in the cosmos?



→ Experimental data needed to interpret astronomy data and to test various r-process models against data

(~20 r-process nuclei have been reached by experiments)

- Messages to take away…

Nuclear reactions play a crucial role in the Universe:

1. **they provide the energy in stars including that of the Sun.**
2. **they produced all the elements we depend on.**
3. **nucleosynthesis is on-going process in our galaxy**

There are ~300 stable nuclei in the Universe. By studying reactions between them we have produced ~3000 more (unstable) nuclei.

There are ~4000 more (unstable) nuclei which we know nothing about and which will hold many surprises and applications. Present techniques are unable to produce them in sufficient quantities.

It will be the next generation of accelerators and the next generation of scientists (*why not some of you?!)* which will complete the work of this exciting research field.

"If in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generations of creatures, what statement would contain the *most* information in the *fewest* words?

Everything is made of atom -Richard Feynman

Nobel Prize in Physics, 1965

"If you want to make an apple pie from scratch, you must first create the universe…"

"We are star-stuff…" - Carl Sagan

CHEMICAL GALAXY II

A NEW VISION OF THE PERIODIC SYSTEM OF THE ELEMENTS