EXPERIMENTAL NUCLEAR ASTROPHYSICS

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University of Bologna summer school, July 18, 2023

NSF

JINA-CEE

UNIVERSITY OF NOTRE DAME

- What is Nuclear Astrophysics?
- Nucleosynthesis
- Facilities
- Detectors
- Measurement Limits
- Underground Facilities
- New Types of Facilities
- Some Nice Example Projects

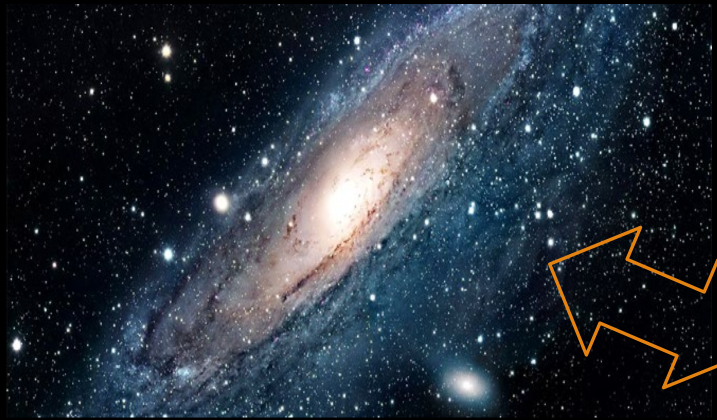
OUTLINE

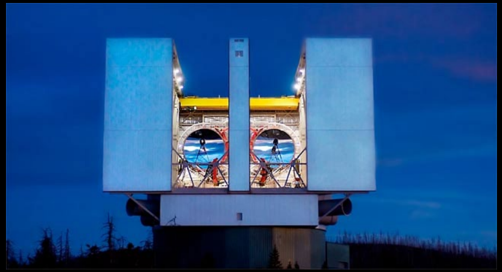
- How were the elements in the universe formed? (nucleosynthesis)
  - Why do they exist in the amounts that they do? (abundance)

THE QUESTION

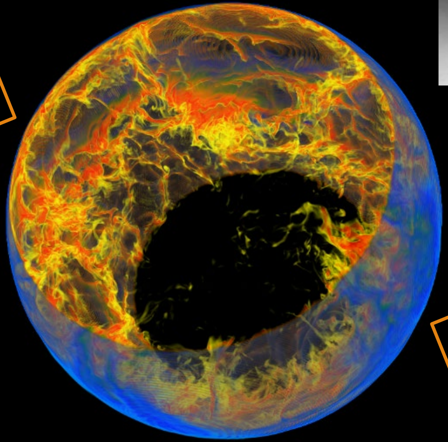
How is nuclear astrophysics a science?

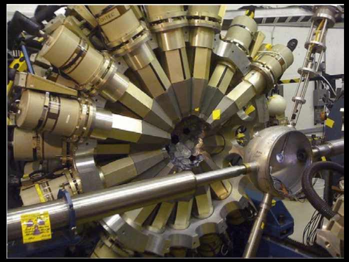
Observational Astronomy and Astrophysics





Astrophysics
(Stellar Simulations)





Experimental and Theoretical Nuclear Physics

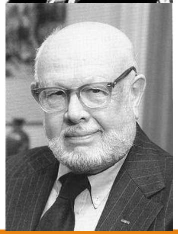
Birth of nuclear astrophysics

Eddington (1920)

- Conversion of four hydrogen nuclei into one helium nuclei can power the sun! Quantum Tunneling!

Hans Bethe (1939)

- Gives the first detailed description of how hydrogen burning works



Burbidge, Burbidge, Fowler, and Hoyle (1957)

- Set forth most of the processes that we now believe form the elements

$$4 \text{ X } M_{hydrogen} > M_{helium}$$

$$E = mc^2$$

$$C^{12} + H = N^{13} + \gamma, \qquad N^{13} = C^{13} + \epsilon^{+}$$

$$C^{13} + H = N^{14} + \gamma,$$

$$N^{14} + H = O^{15} + \gamma, \qquad O^{15} = N^{15} + \epsilon^{+}$$

$$N^{15} + H = C^{12} + He^{4}.$$

Hydrogen burning, helium burning, carbon burning, etc.

r-process, s-process, etc.

Physics concept: Quantum tunneling

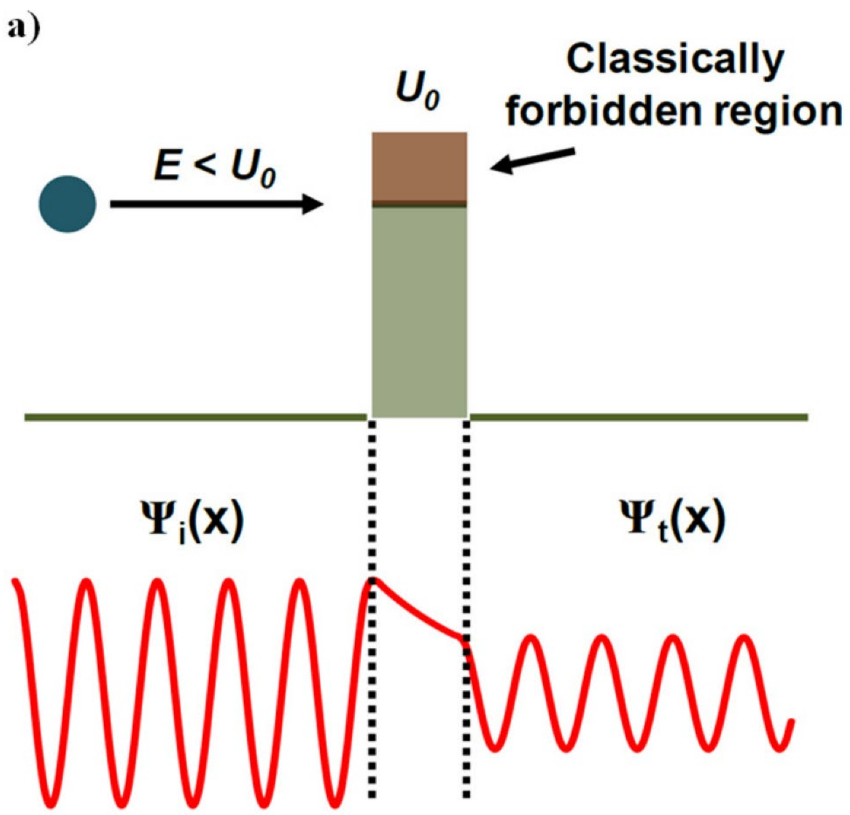
Probability of a particle penetrating through a classically impassible barrier.

This barrier is the repulsion of two like **charged particles** and angular momentum

The idea that quantum particles exist as "probability packets" not localized particles.

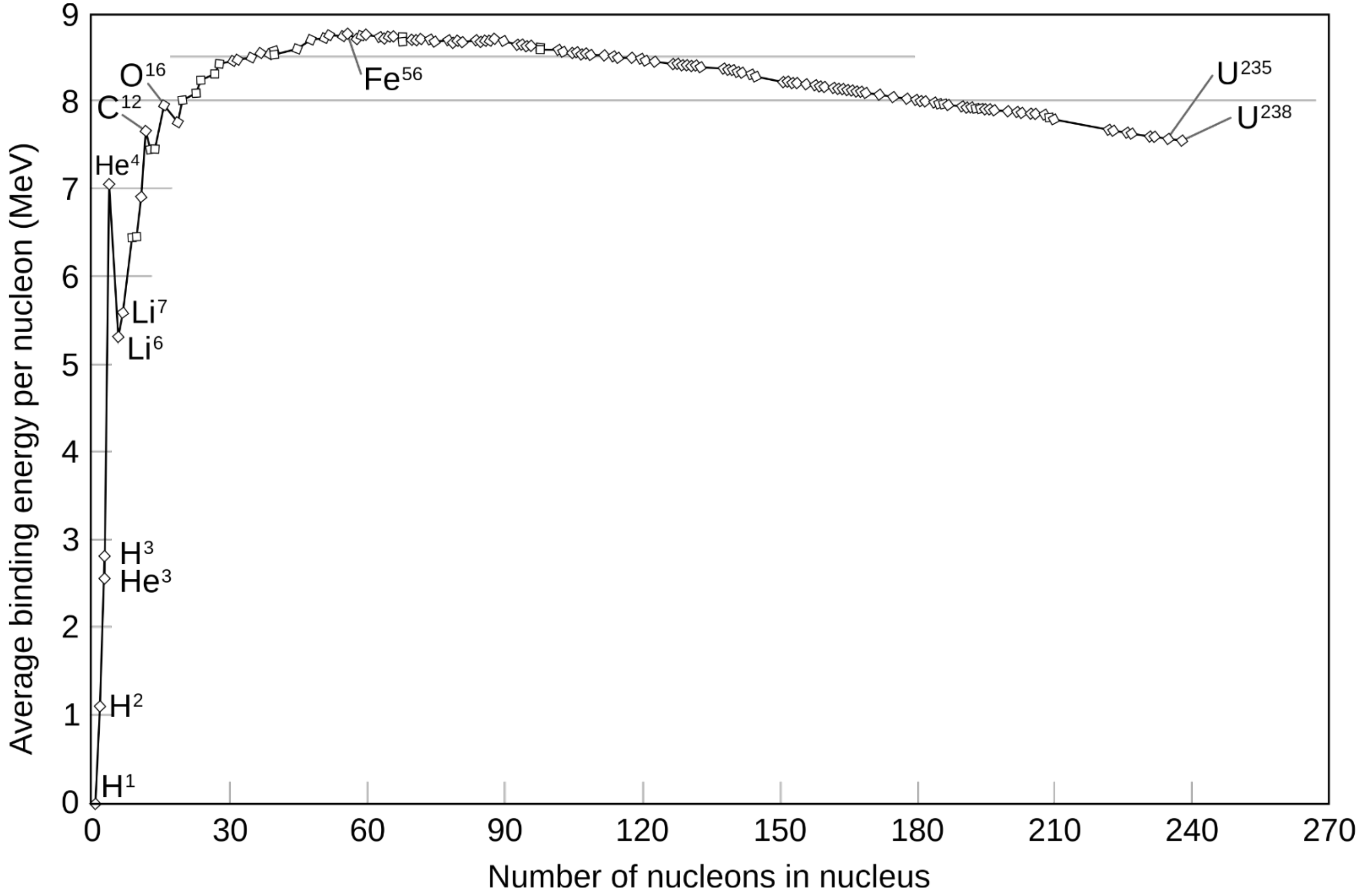
Without quantum tunneling, our sun would not "burn".

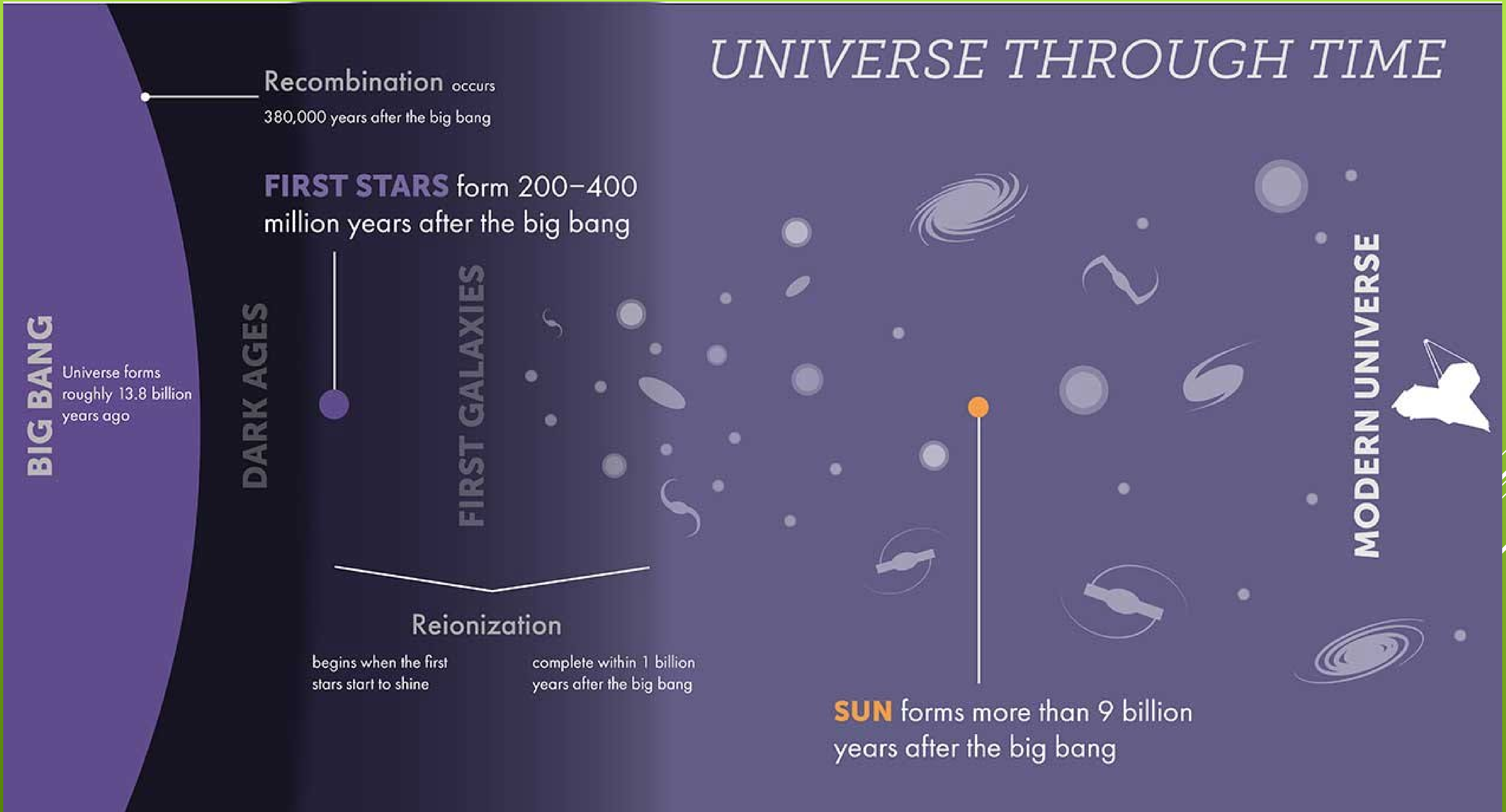
Cross Section = Tunneling Probability



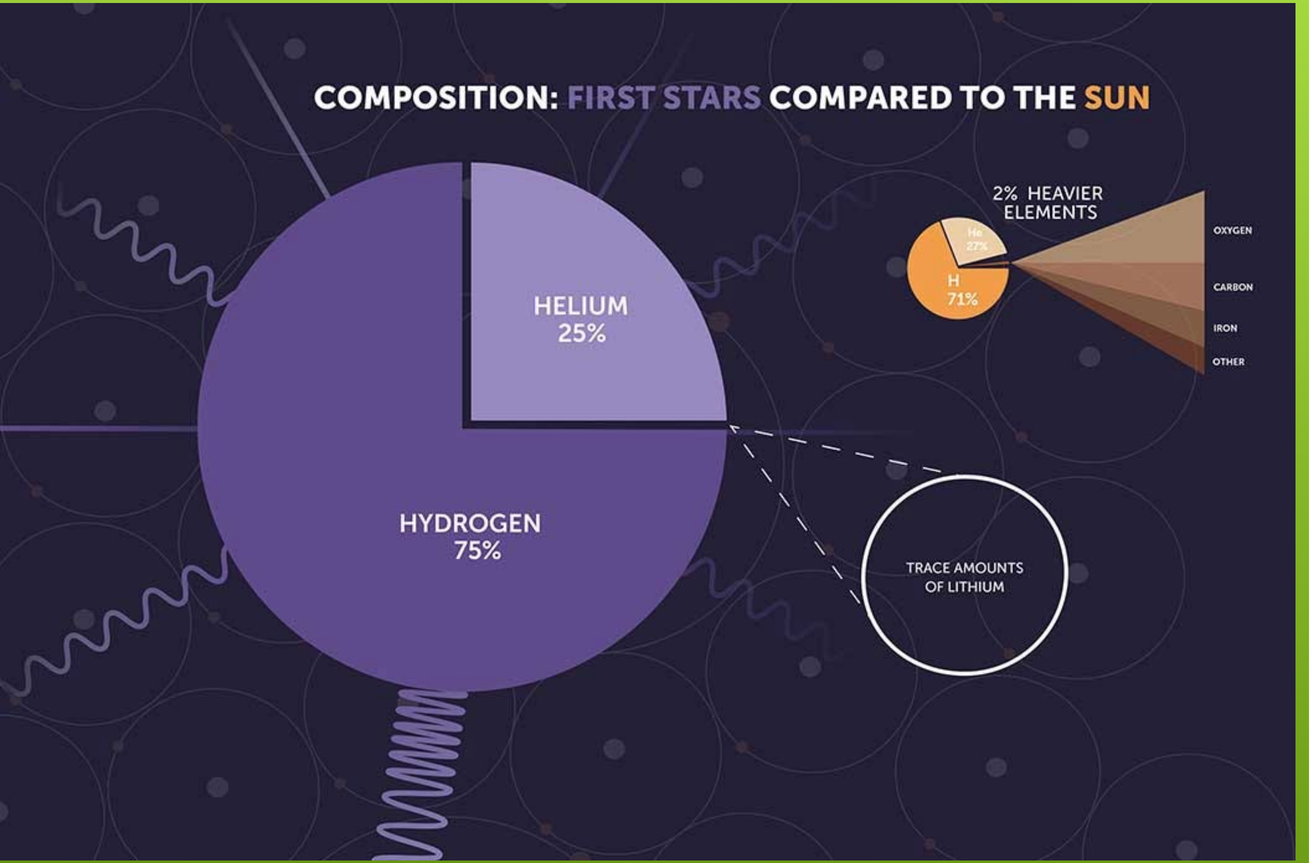
Banerjee and Mastrangelo, Micro 2022 2(4) 679-698 (2022)

Physics concept: binding energy





James Webb telescope website (Credit: STScI)



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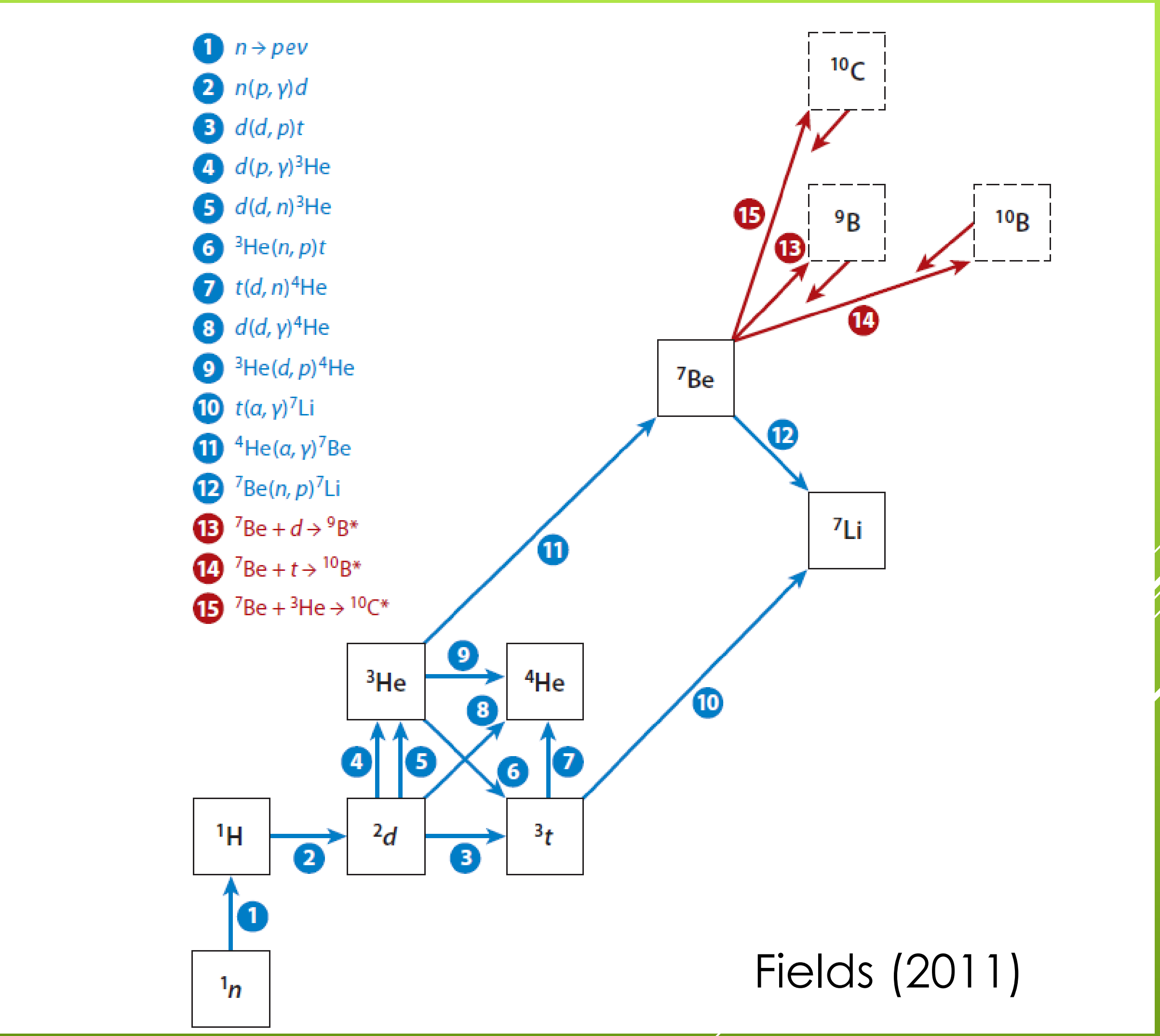
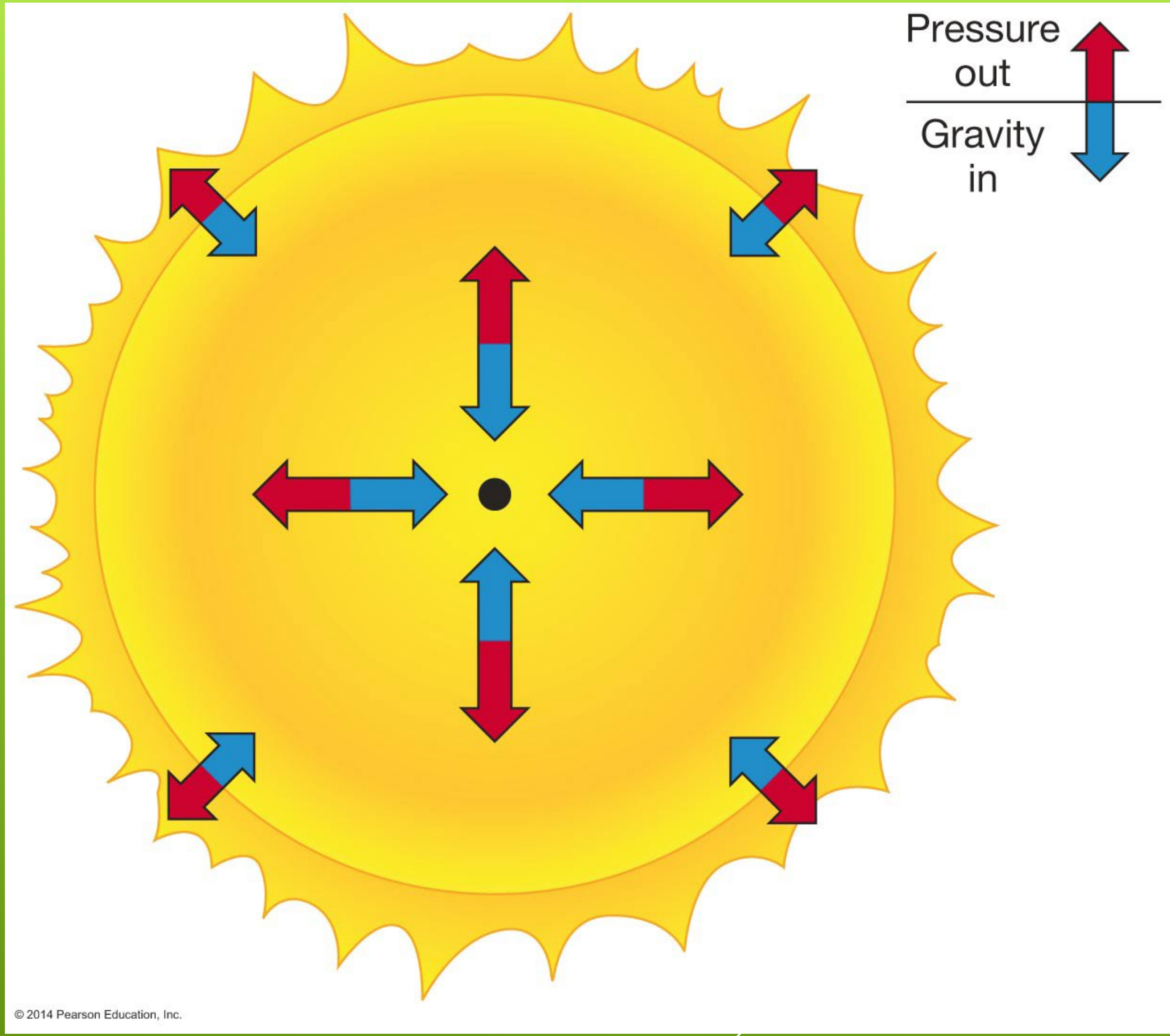


Fields (2011)

BIG BANG NUCLEOSYNTHESIS

PHYSICS CONCEPT: HYDROSTATIC EQUILIBRIUM

- Gravity fights nuclear energy production
- Stars burn hydrogen into helium for most of their lives
- Some nuclear reactions contribute both to nucleosynthesis and energy production
- Some only contribute to nucleosynthesis and happen "in the background" compared to energy production reactions



Hydrogen Burning

pp chains

$4\,^{1}H \rightarrow {}^{4}He + 2e^{+} + 2\nu_e + 2\,\gamma$

$({}^{3}He + {}^{4}He \rightarrow {}^{7}Be^{*} + \gamma \rightarrow {}^{7}Li\ )$

CNO cycle

${}^{12}C + {}^{1}H \rightarrow {}^{13}N + \gamma$

${}^{13}N \rightarrow {}^{13}C + e^{+} + \nu_e$

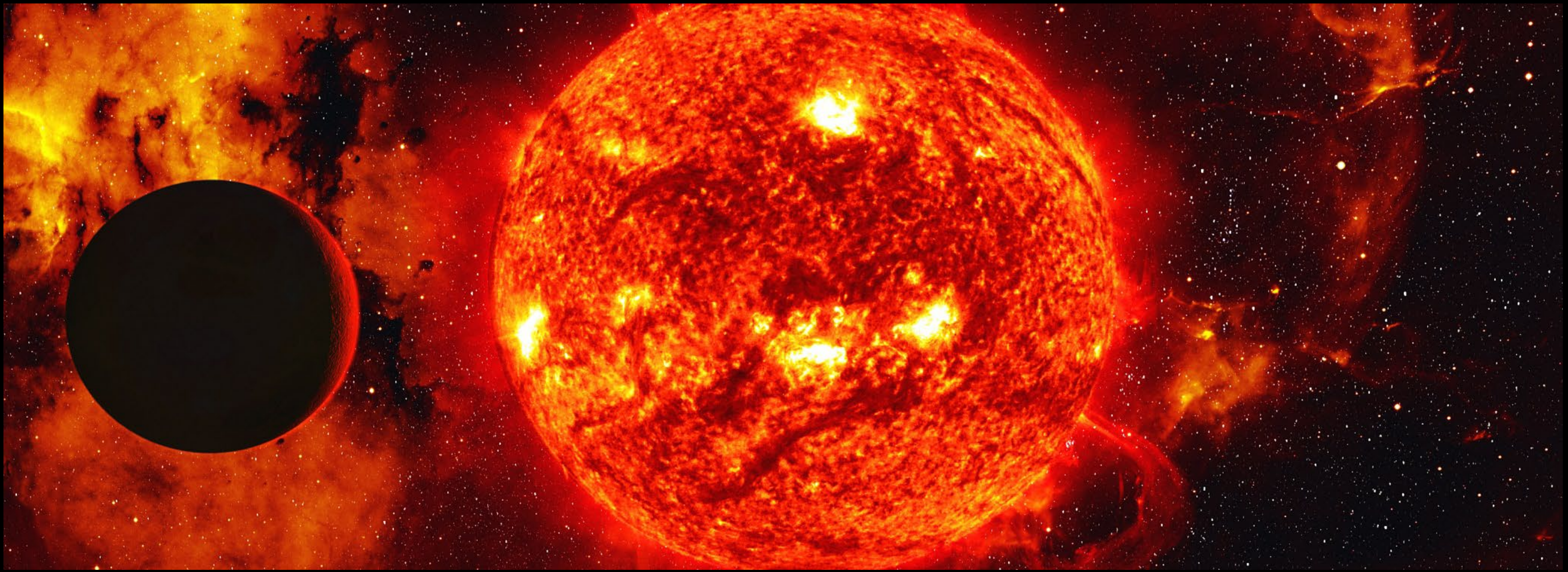
${}^{13}C + {}^{1}H \rightarrow {}^{14}N + \gamma$

${}^{14}N + {}^{1}H \rightarrow {}^{15}O + \gamma$

${}^{15}O \rightarrow {}^{15}N + e^{+} + \nu_e$

${}^{15}N + {}^{1}H \rightarrow {}^{12}C + {}^{4}He \uparrow$

Sites of nucleosynthesis: Stellar burning: Main Sequence



Helium Burning

$3\,^{4}He \rightarrow {}^{12}C + \gamma$

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

$^{16}O + {}^{4}He \rightarrow {}^{20}Ne + \gamma$

$(^{13}C + {}^{4}He \rightarrow {}^{16}O + n)$

$(^{22}Ne + {}^{4}He \rightarrow {}^{25}Mg + n)$

s process

$(n + {}^{+60}X$

$\rightarrow$ Heavy Nuclei)

Carbon Burning

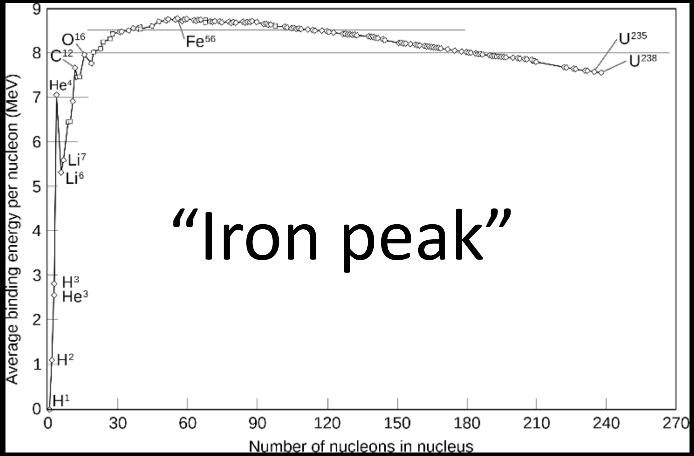
$^{12}C + {}^{12}C \rightarrow {}^{23}Na + {}^{1}H$

$\rightarrow {}^{20}Ne + {}^{4}He$

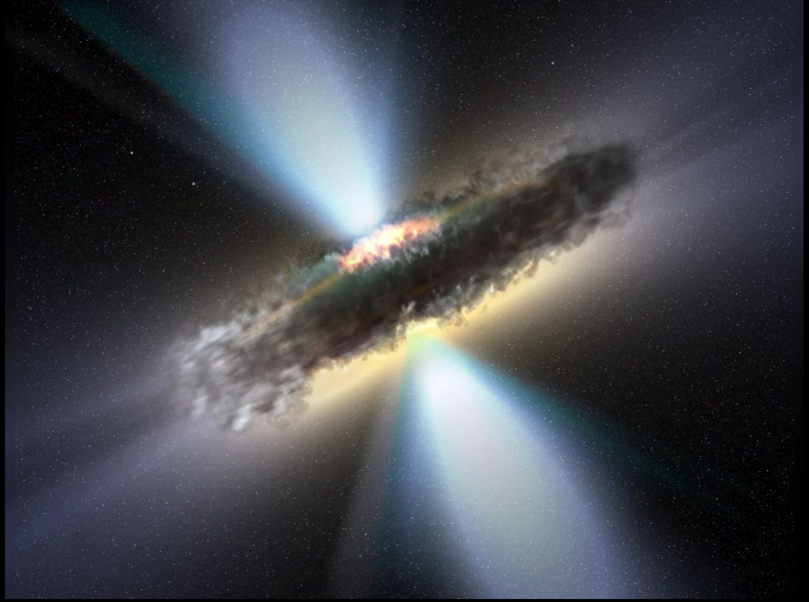
$\rightarrow {}^{24}Mg + \gamma$

Messy Burning

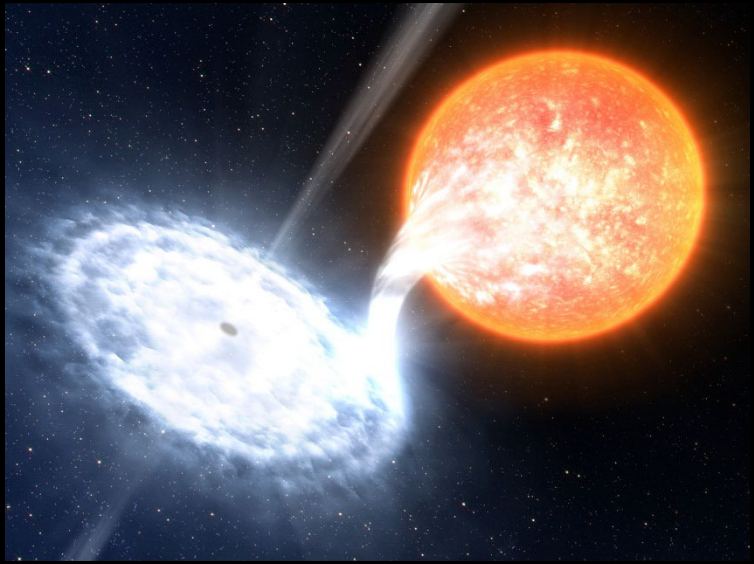
Stuff → Iron Peak



Sites of Nucleosynthesis: Red Giant stars



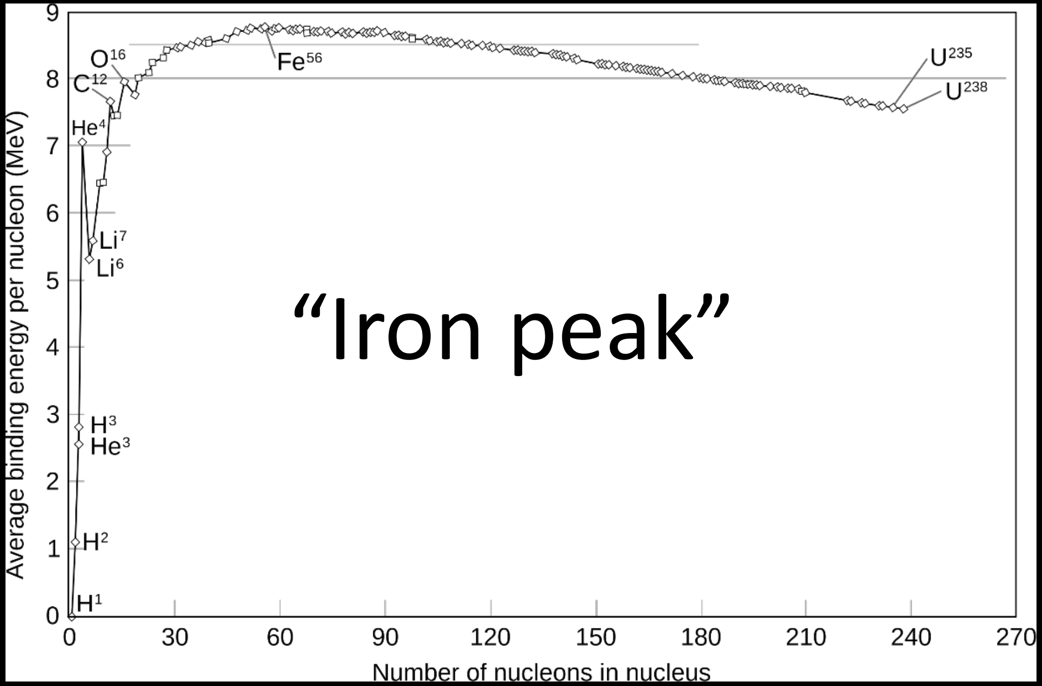
Hot CNO Cycle



r process
(n + $^{+60}X \rightarrow$ Heavy Nuclei)

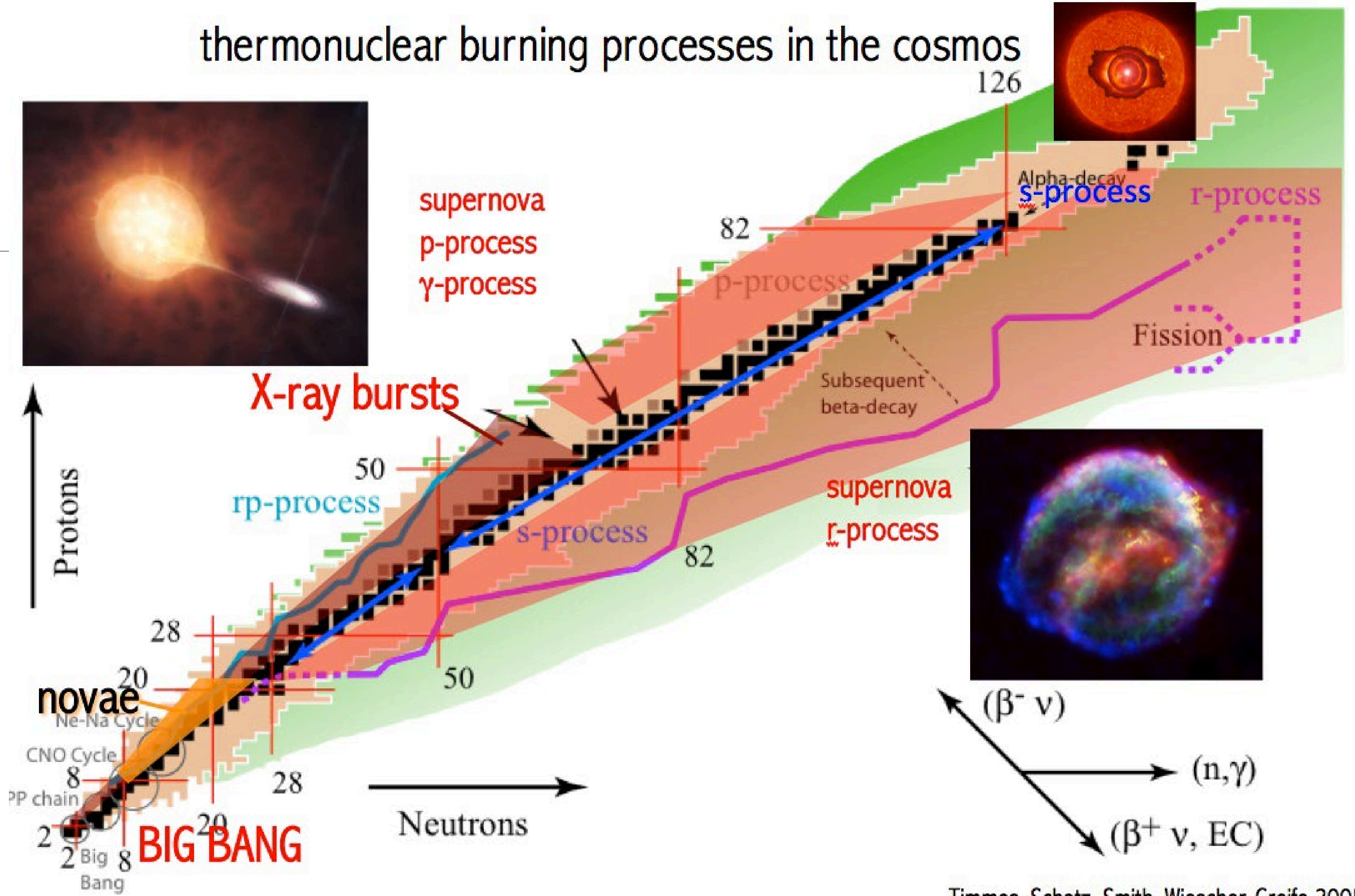
ν process
($\nu + X \rightarrow Y$)

???? Process(es)



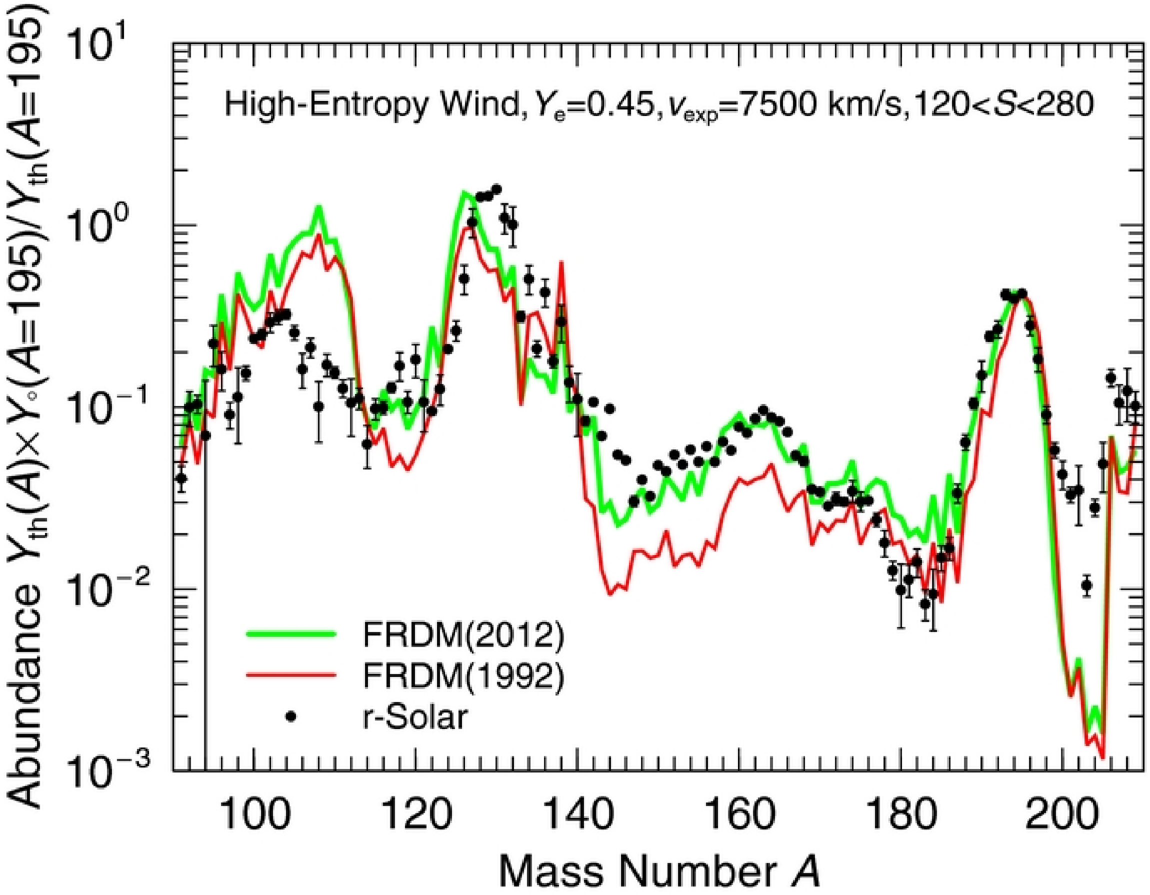
Sites of Nucleosynthesis: More exotic locals

thermonuclear burning processes in the cosmos



Timmes, Schatz, Smith, Wiescher, Greife 2005

Abundance patterns (r-process)



Kratz et al. (2014)

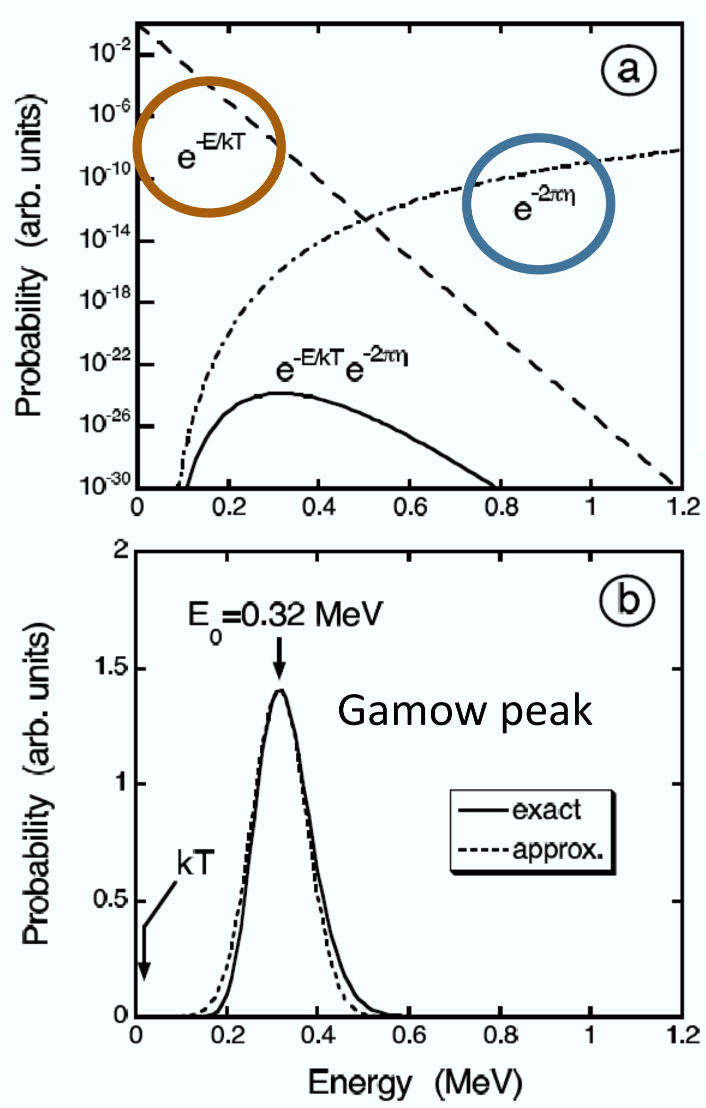
Maxwellian averaged reaction rate

$$N_A\langle\sigma v\rangle = N_A \frac{(8/\pi)^{1/2}}{\mu^{1/2}(k_B T)^{3/2}} \int_0^\infty \sigma E \exp(-E/k_B T)\,dE,$$

goes as $e^{-2\pi\eta}$ at low energy
where $\eta = Z_1 Z_2/E$

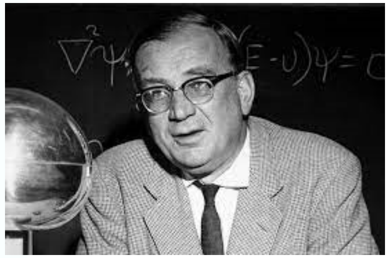
Reaction Rate

$^{12}C(\alpha,\gamma)^{16}O$ at T = 0.2 GK

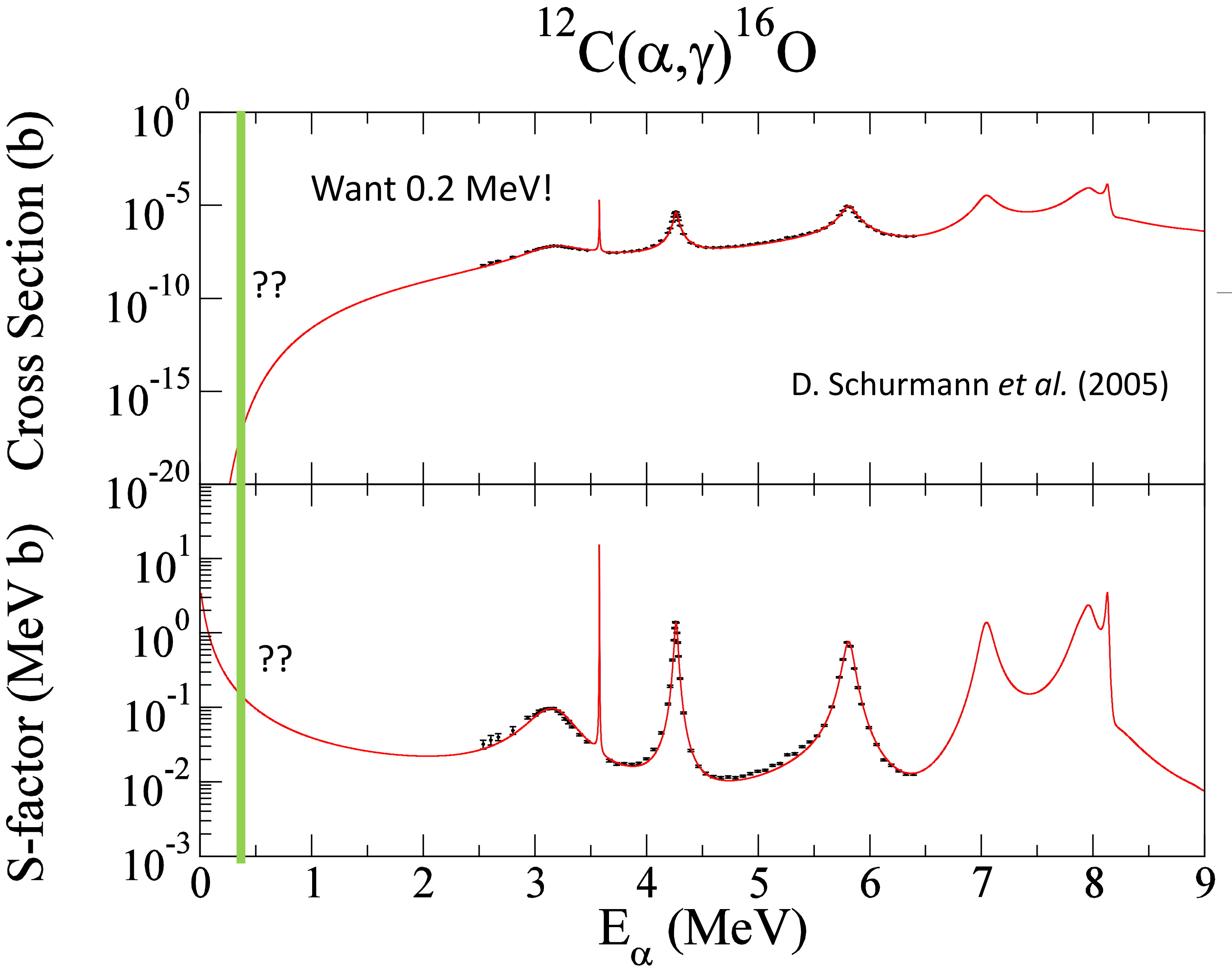


Number of particle available at some energy

Penetrability between two particles fusing



George Gamow



Energy of interest to nuclear astro: 10 to 500 keV.

Often can't be measured: Coulomb barrier, background reactions

$$S(E) = \sigma(E) E \exp(2\pi\eta)$$

$$\eta = \sqrt{\mu/2E}\, Z_1 Z_2 e^2/\hbar^2$$

The temperature in stars corresponds to a low accelerator energy!

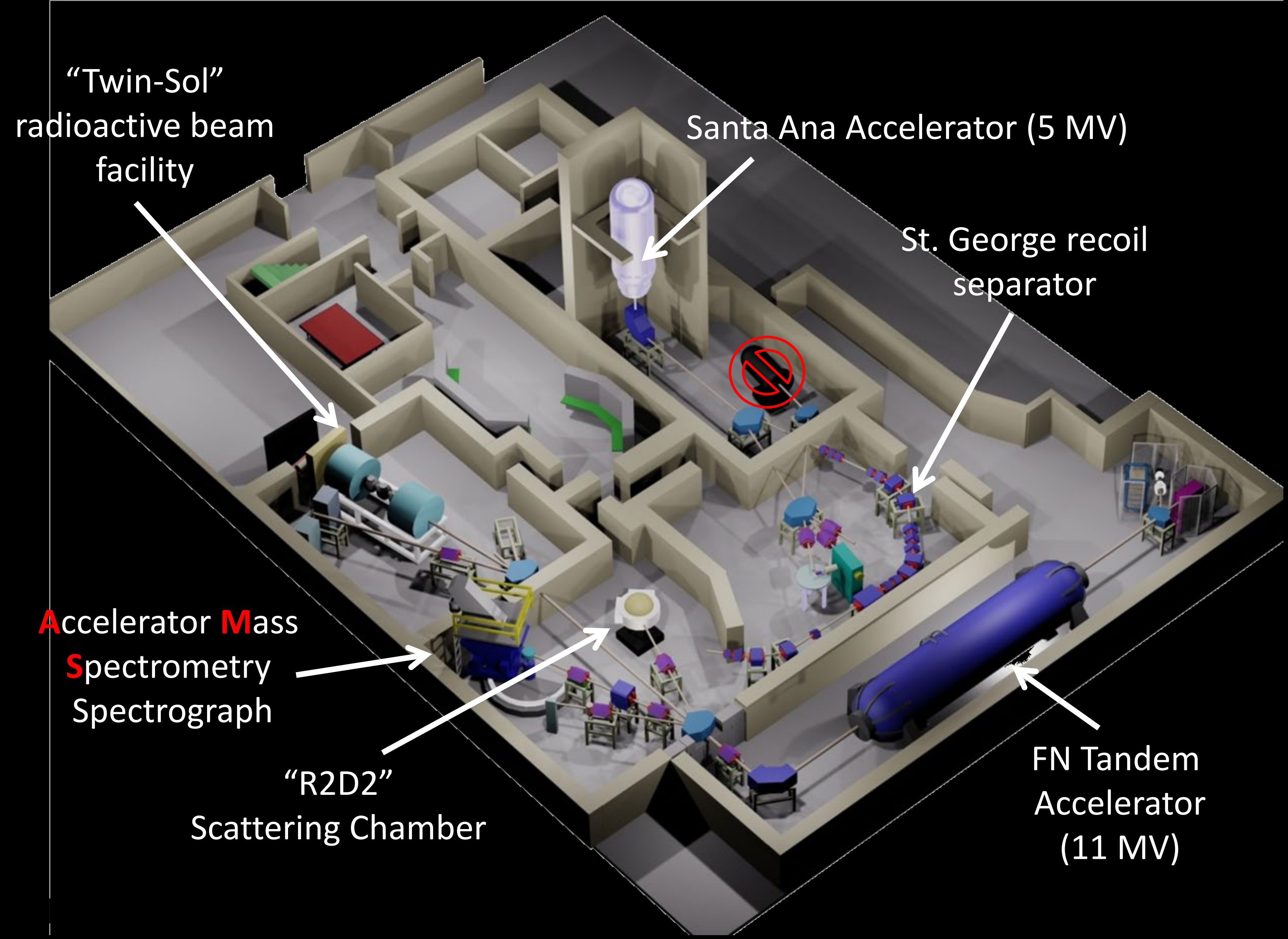
Nuclear structure and reaction mechanisms

- We don’t fully understand the mechanisms that govern these reactions because we don’t know how to fully describe the underlying nuclear forces
  - A theory problem that nuclear physics has never been able to solve

- We therefore try to understand the behavior of specific reactions by measuring over a wide energy range

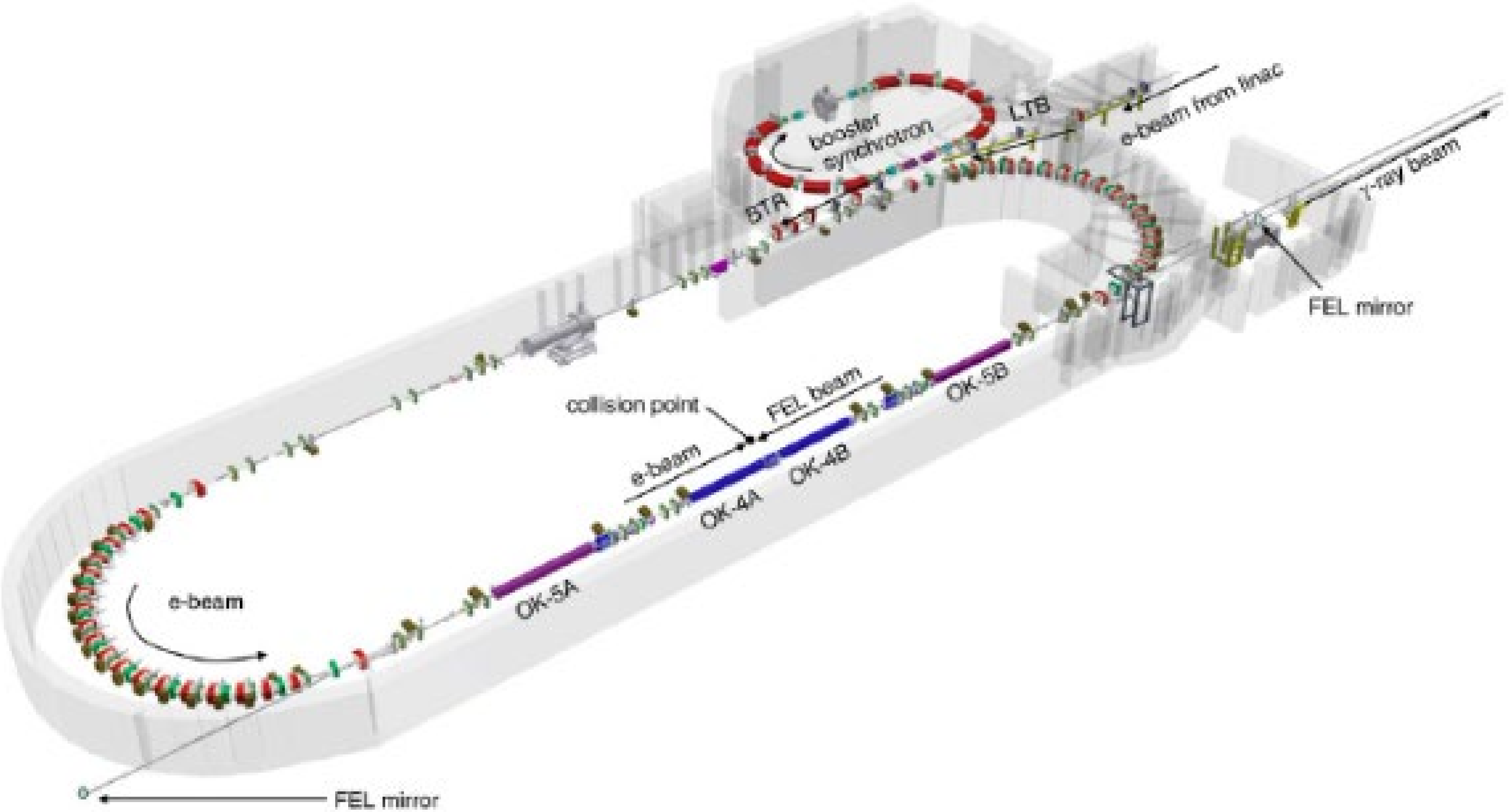
- If we can describe the cross section over a wide energy range with a phenomenological model (partial physics, partial free parameters), we can then try to extrapolate to very low energies

A few example facilities



Example low energy nuclear physics lab for charged particle beams: the University of Notre Dame

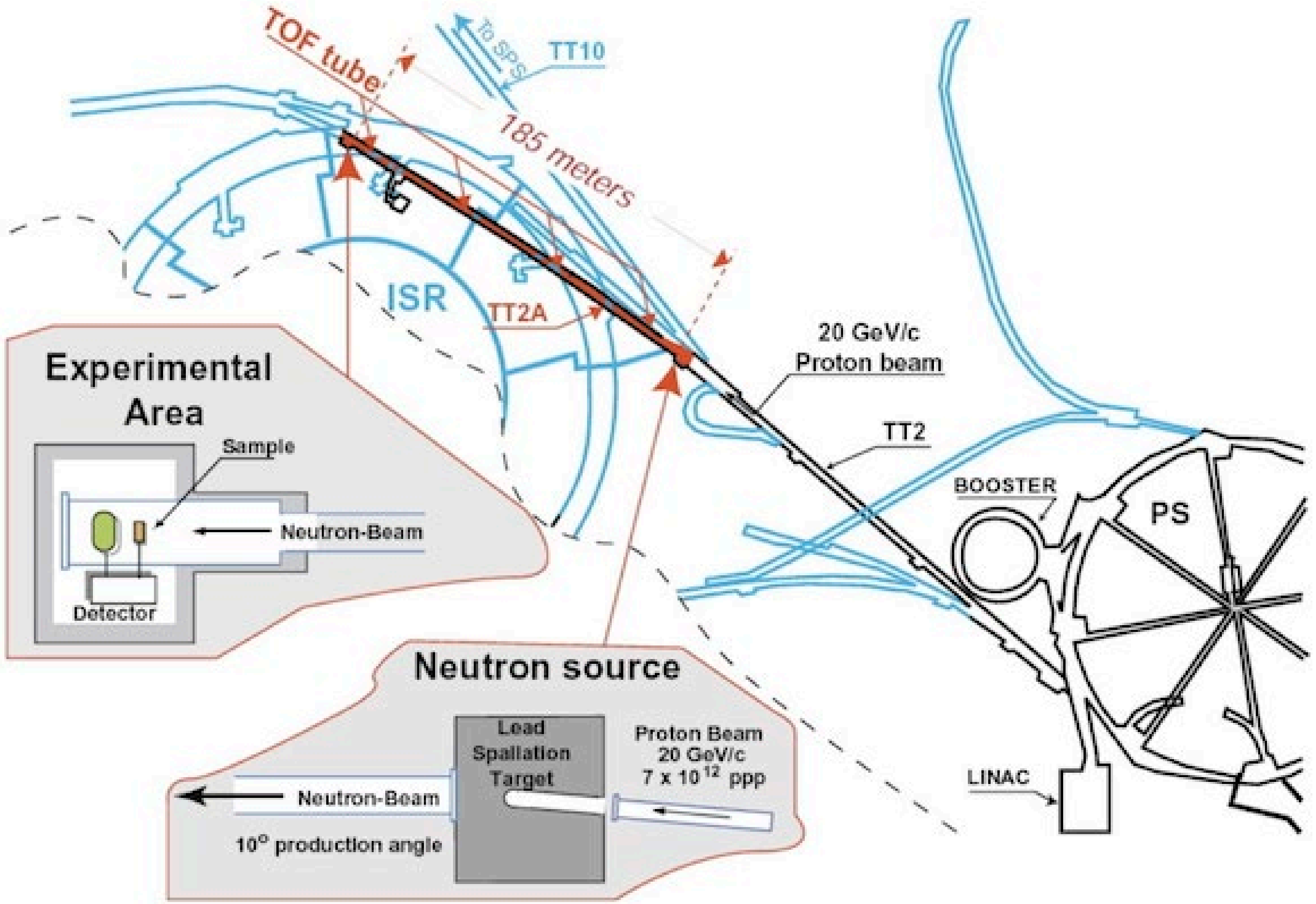
High Intensity γ-ray Source (HIγS)

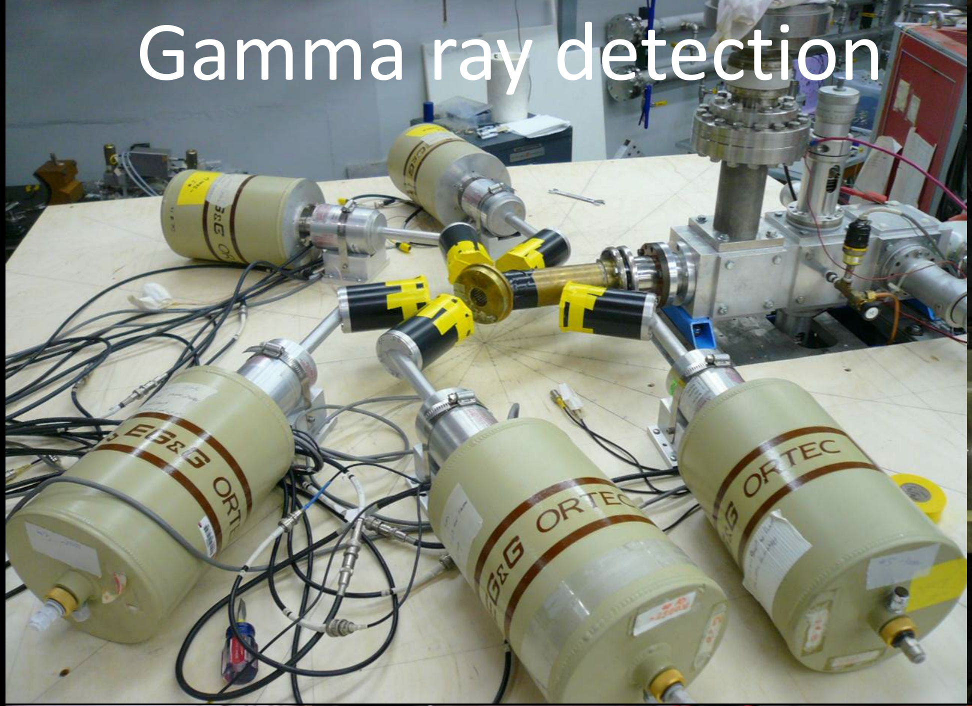


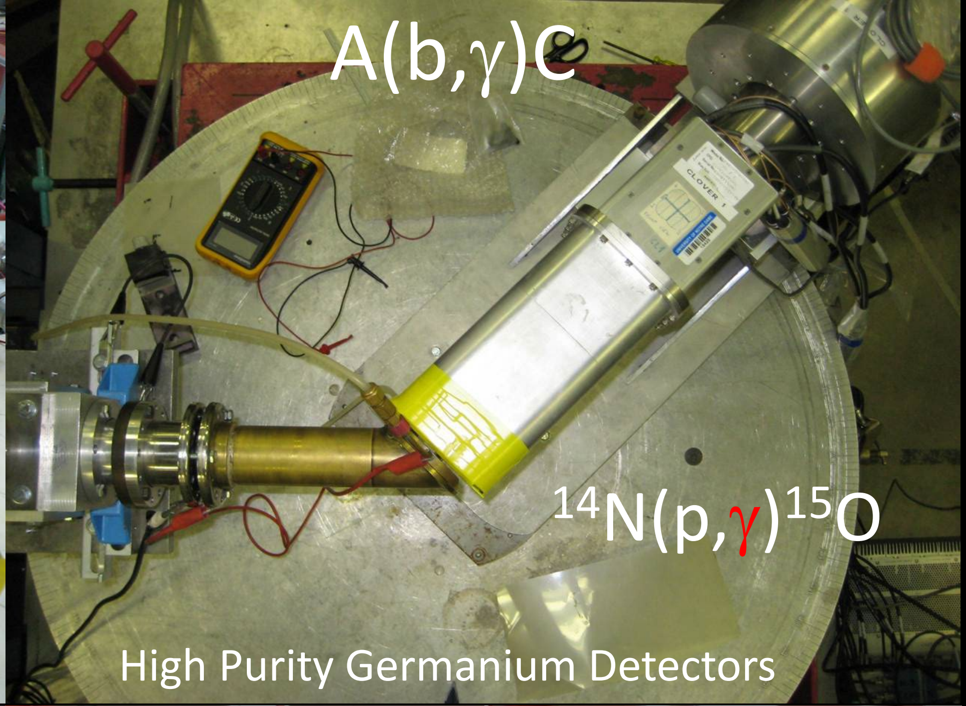
Neutron Time of Flight

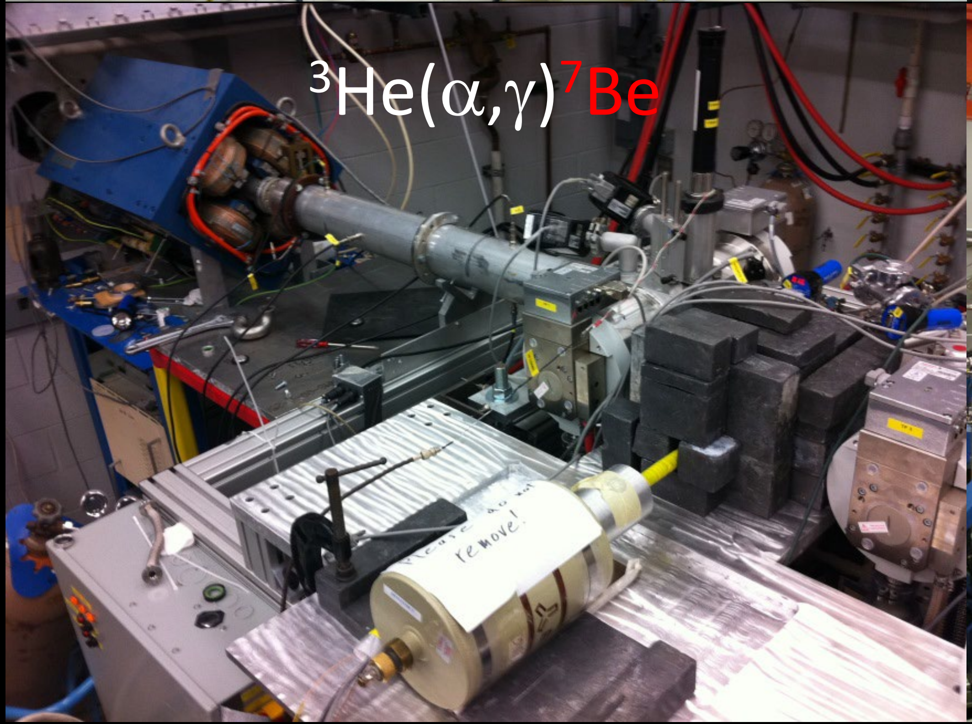
Neutrons only have a half life of about 10 minutes

They are responsible for the creation of nearly all of the elements heavier than iron.




Gamma ray detection
ORTEC

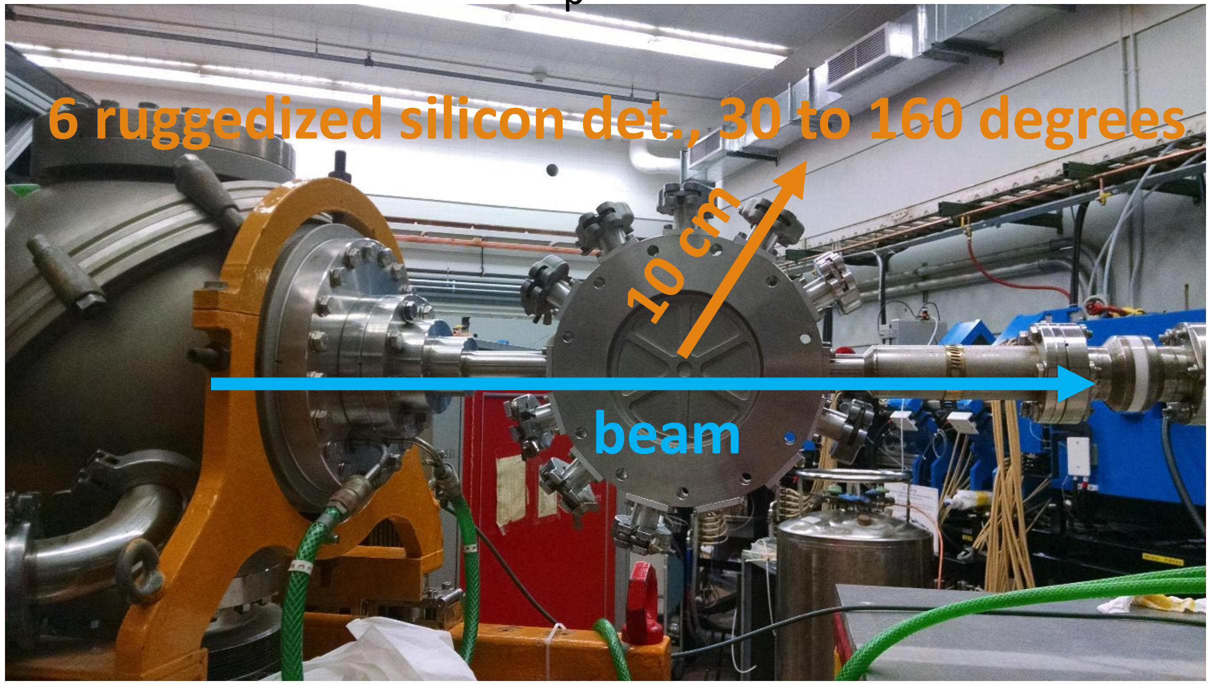

A(b,γ)C
$^{14}N(p,\gamma)^{15}O$
High Purity Germanium Detectors


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


WRIGHT 5
St. George recoil separator

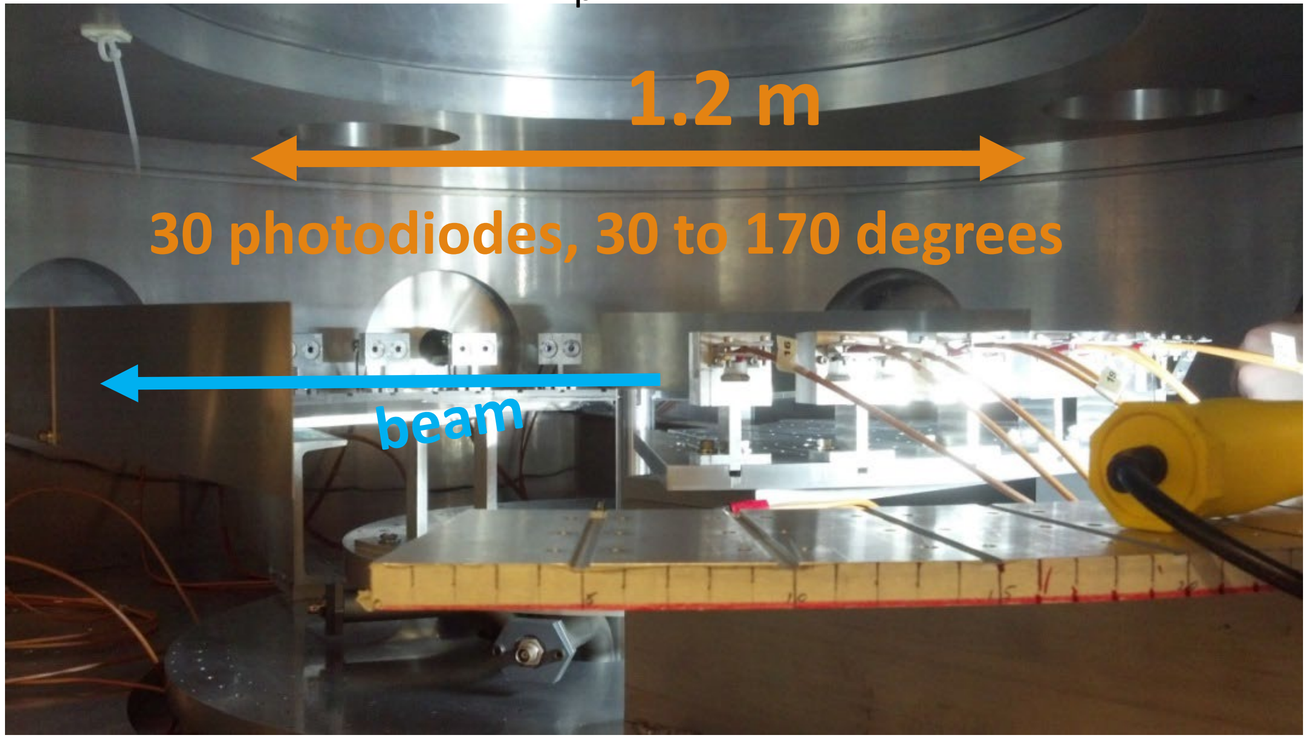
Scattering measurements at ND, charged particle detection

KN accelerator E_p = 1.0 to 3.0 MeV



^{15}N gas target, about 3 ug/cm^2 (0.1 keV at 1 MeV)

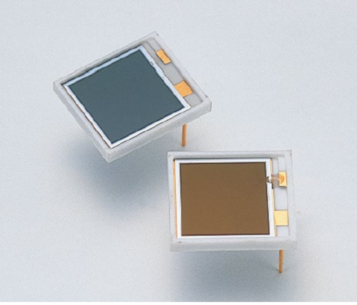
FN accelerator E_p = 1.8 to 4.0 MeV



Solid Adenine ($C_5H_5N_5$) target, about 20 ug/cm^2 (3 keV at 2 MeV)

Some example charged particle detectors

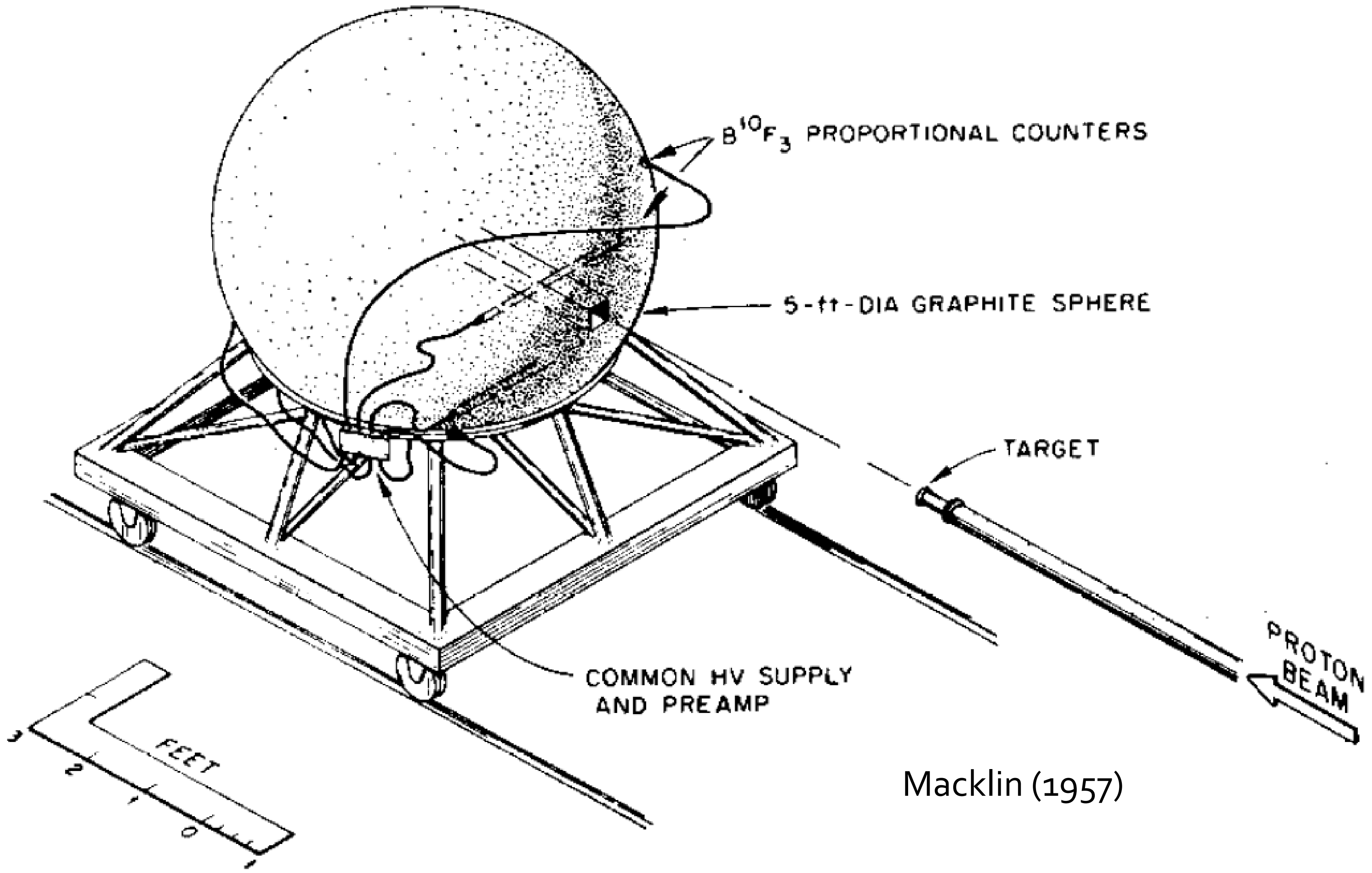
Hammatsu photo pin diodes



Mirian technologies silicon detectors

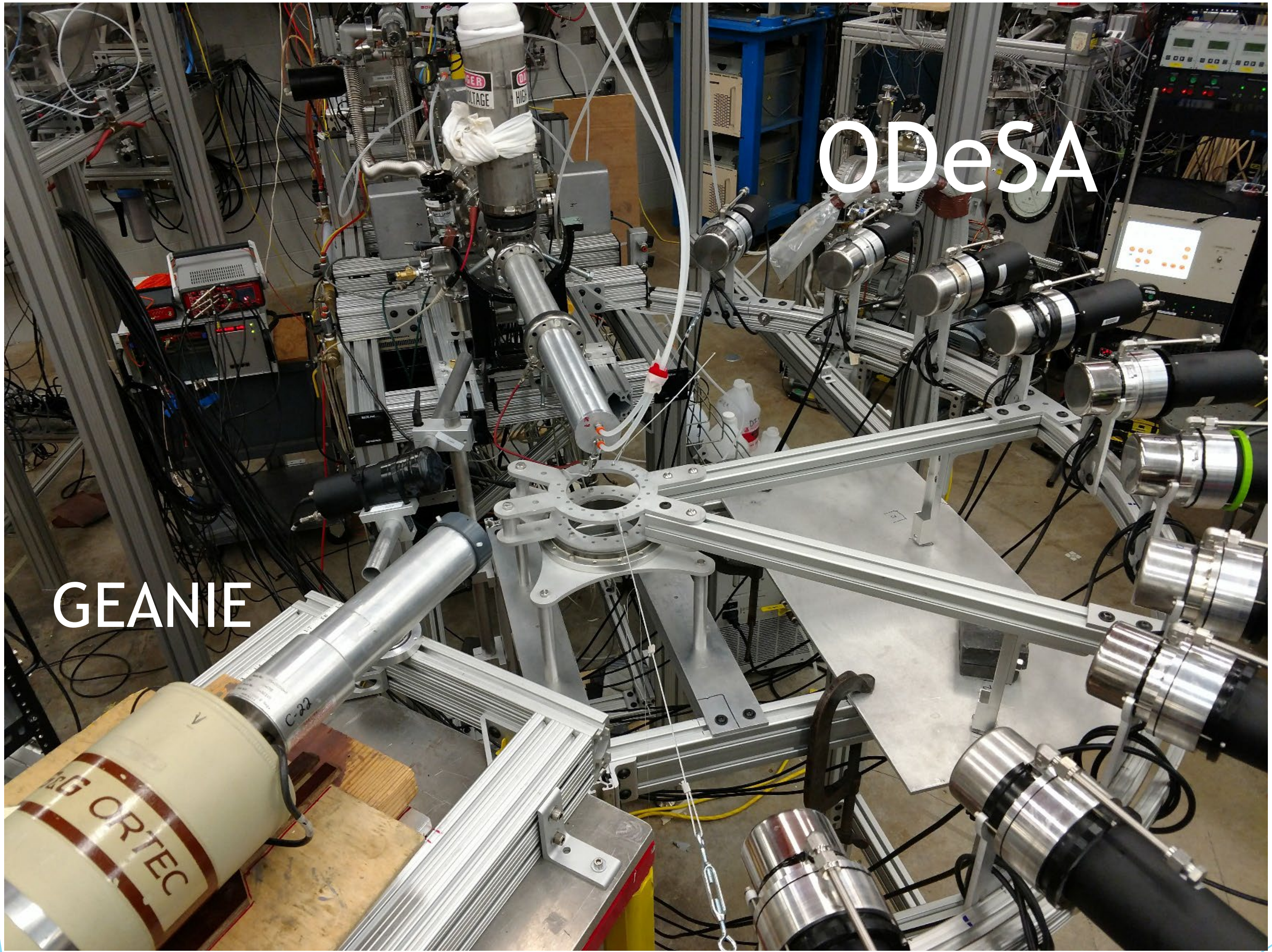
"Lampshade" array

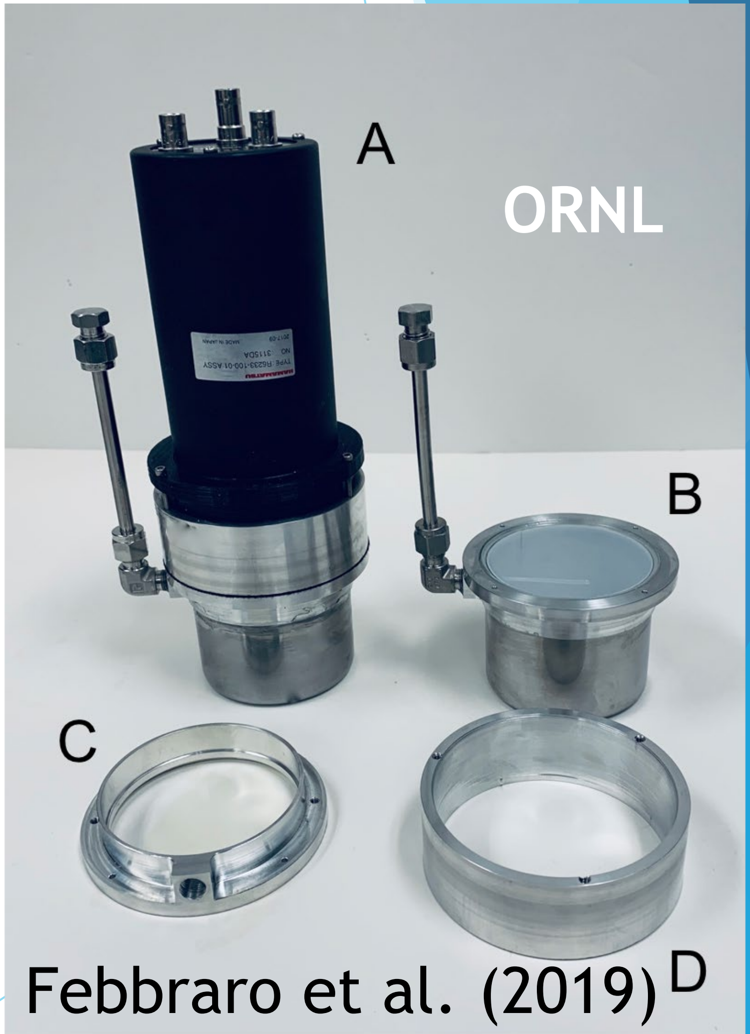
"4π" neutron moderator type detector



Macklin (1957)

Liquid scintillators for neutron detection





What limits our measurements?

Beam intensity
- We can make a super intense particle beam, but then we melt our target!

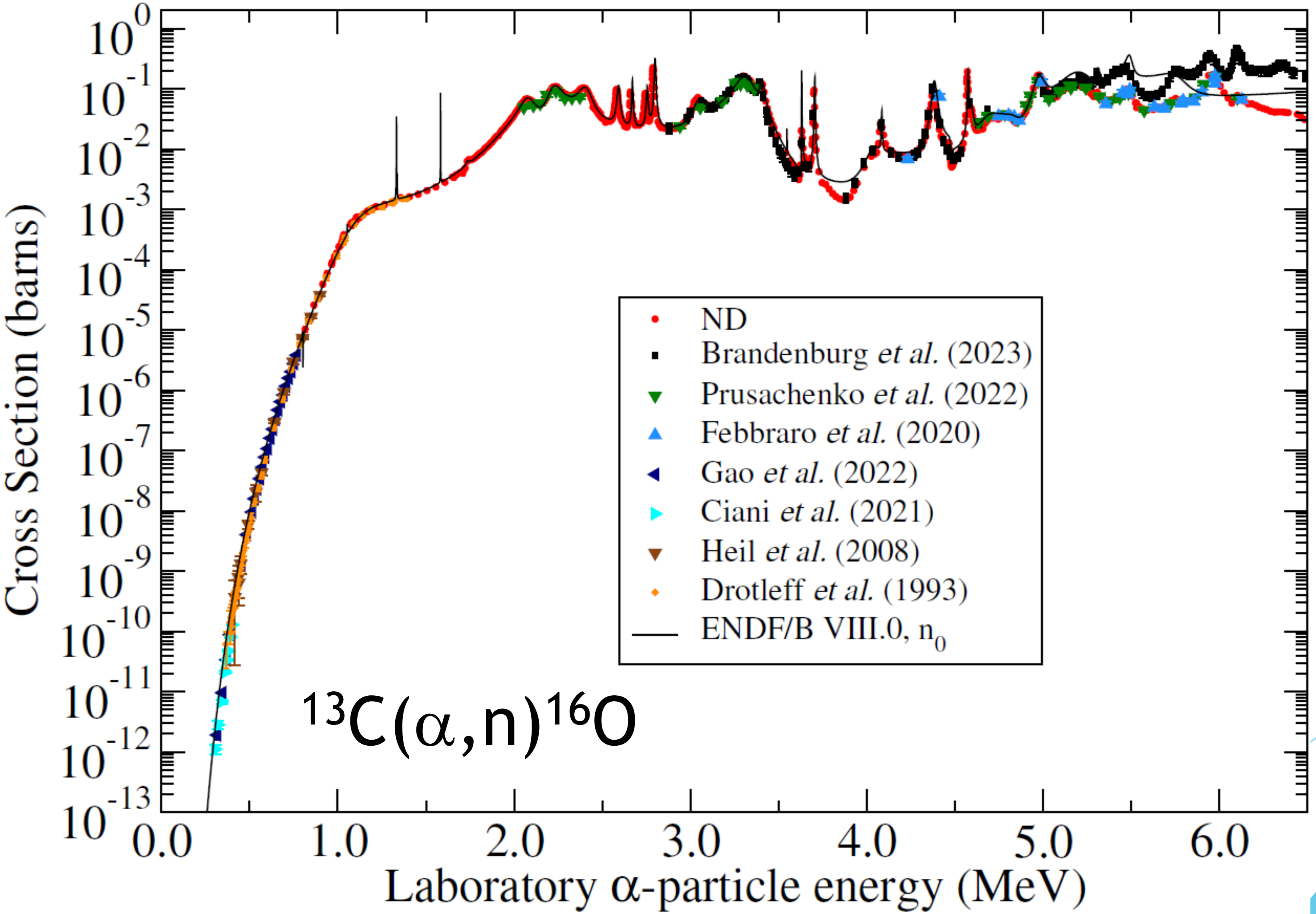
Target thickness
- We can make a very thick target, but then we loose energy resolution, making the results harder to understand

Detectors
- Our detectors are limited by energy resolution and efficiency, but this is where there is the most development

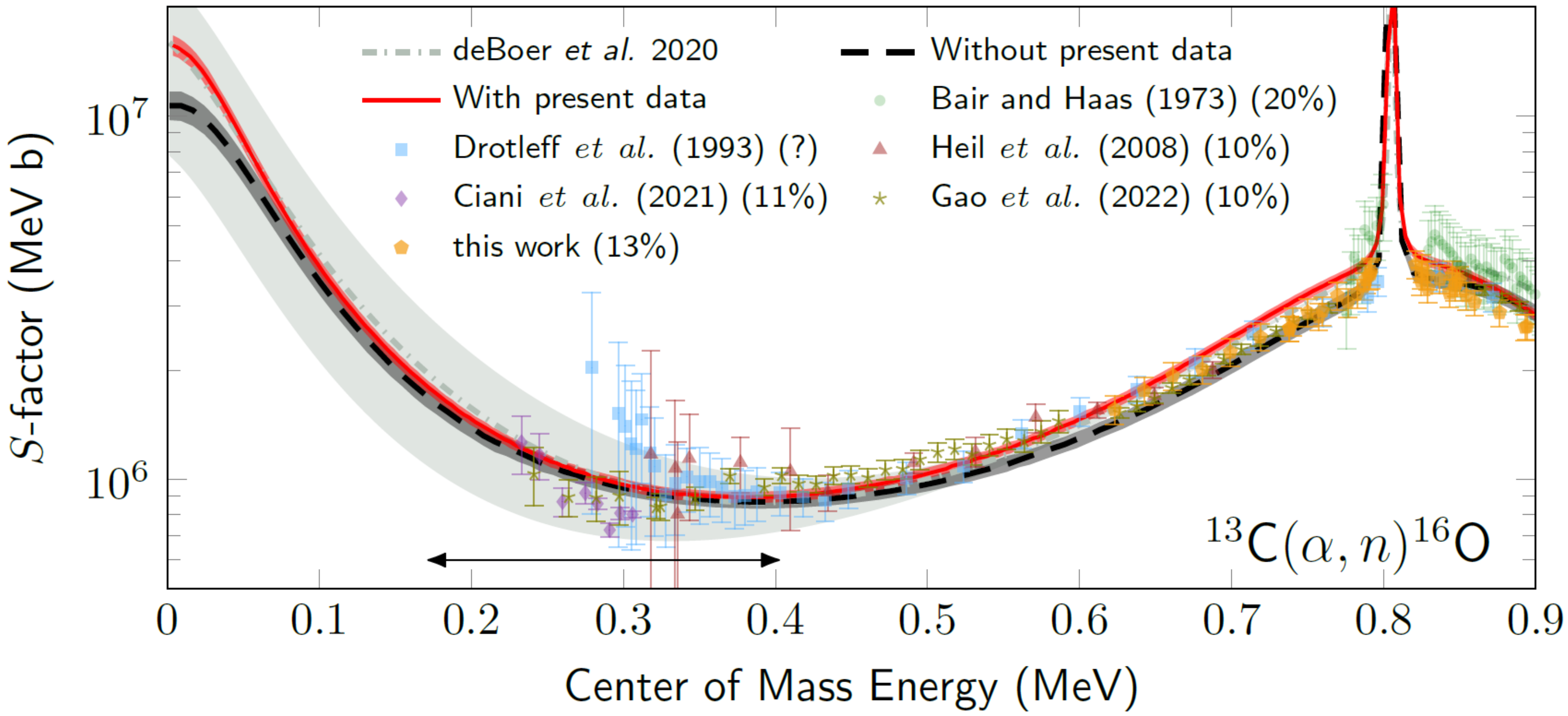
Background
- Very often, the signals that we want to detect are very weak compared to other signals coming from unwanted reactions
- These can be the result of impurities in our target or particle beam
- They can just come from natural decaying radioactive nuclei in building material and detector material
- They can be from cosmic rays

Time
- Students want to graduate at some point

Cross Section measurements over a wide energy range

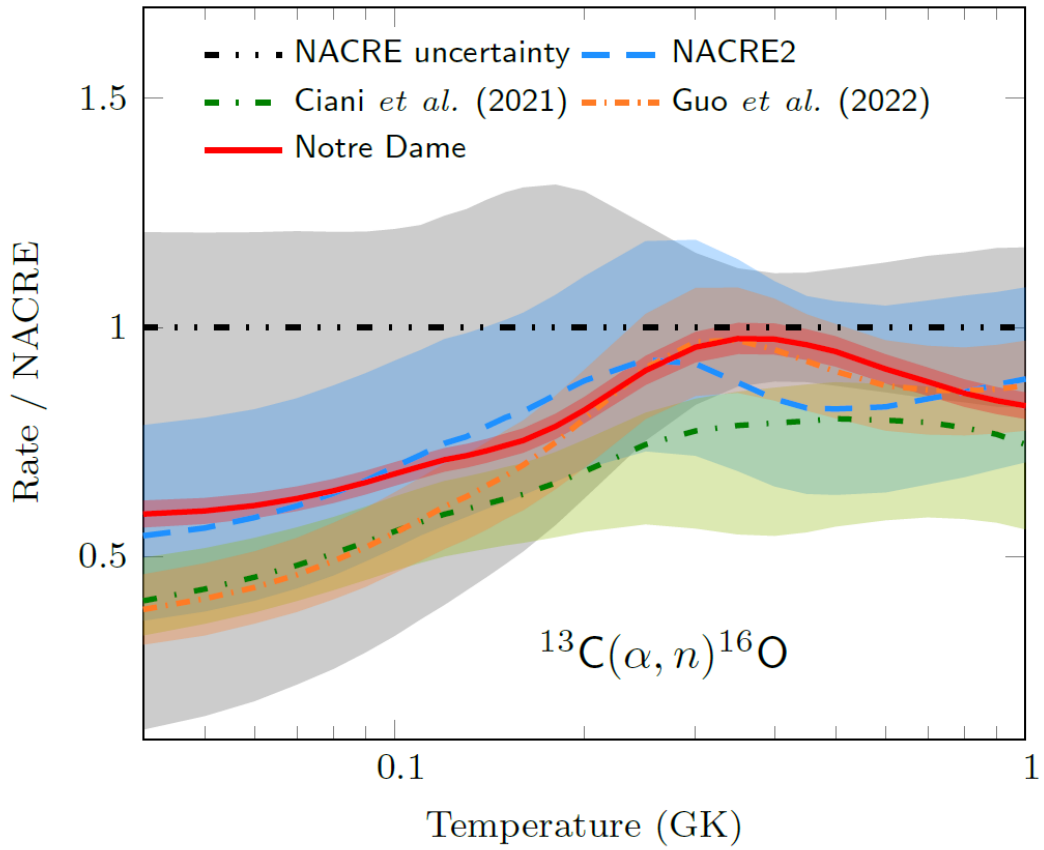


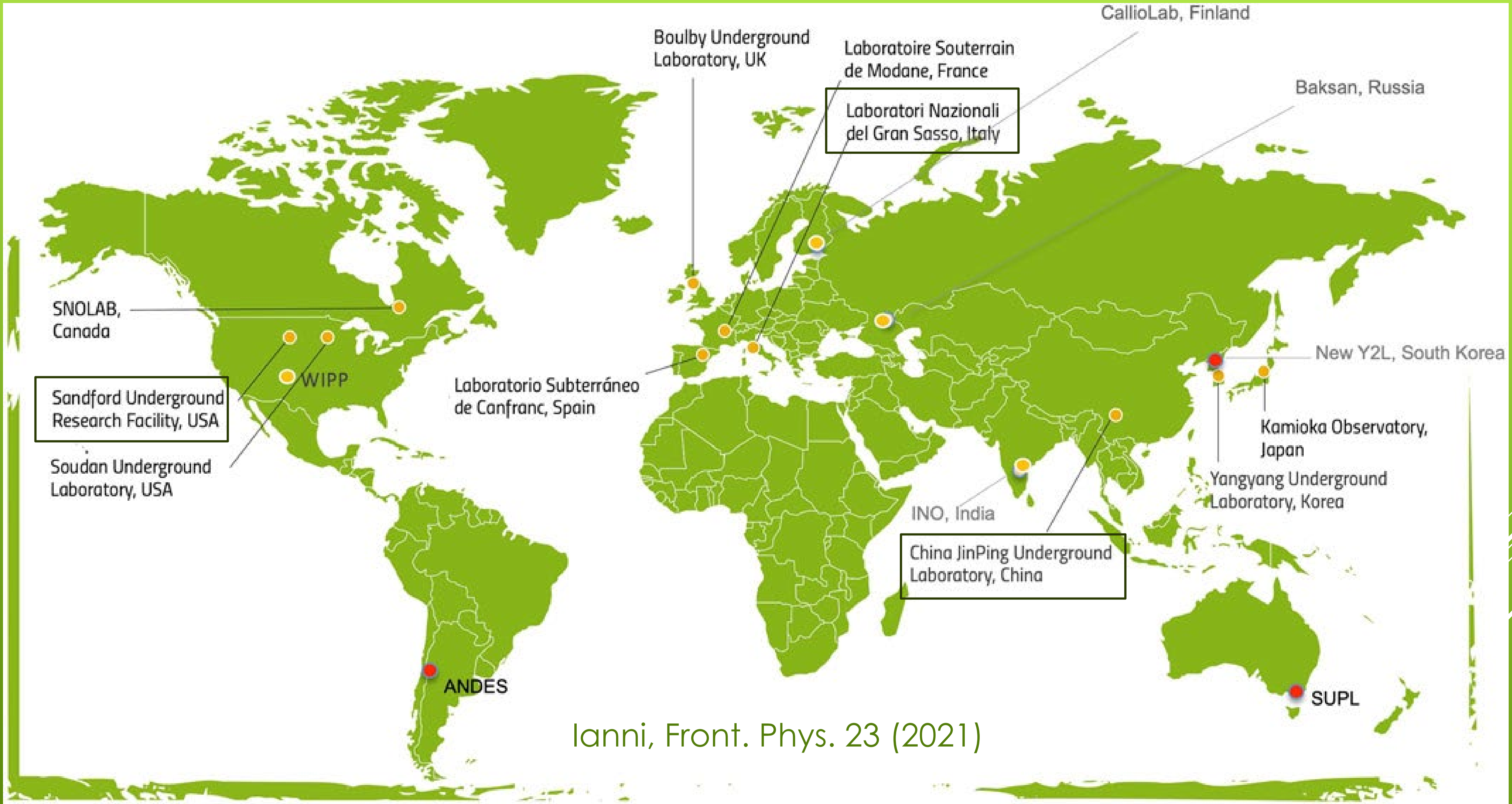
Data set comparison and uncertainty evaluation (Bayesian methods now becoming popular)



S-factor to reaction rate

We take the reaction rate with an improved determination and uncertainty and feed it back into the astrophysics simulations.



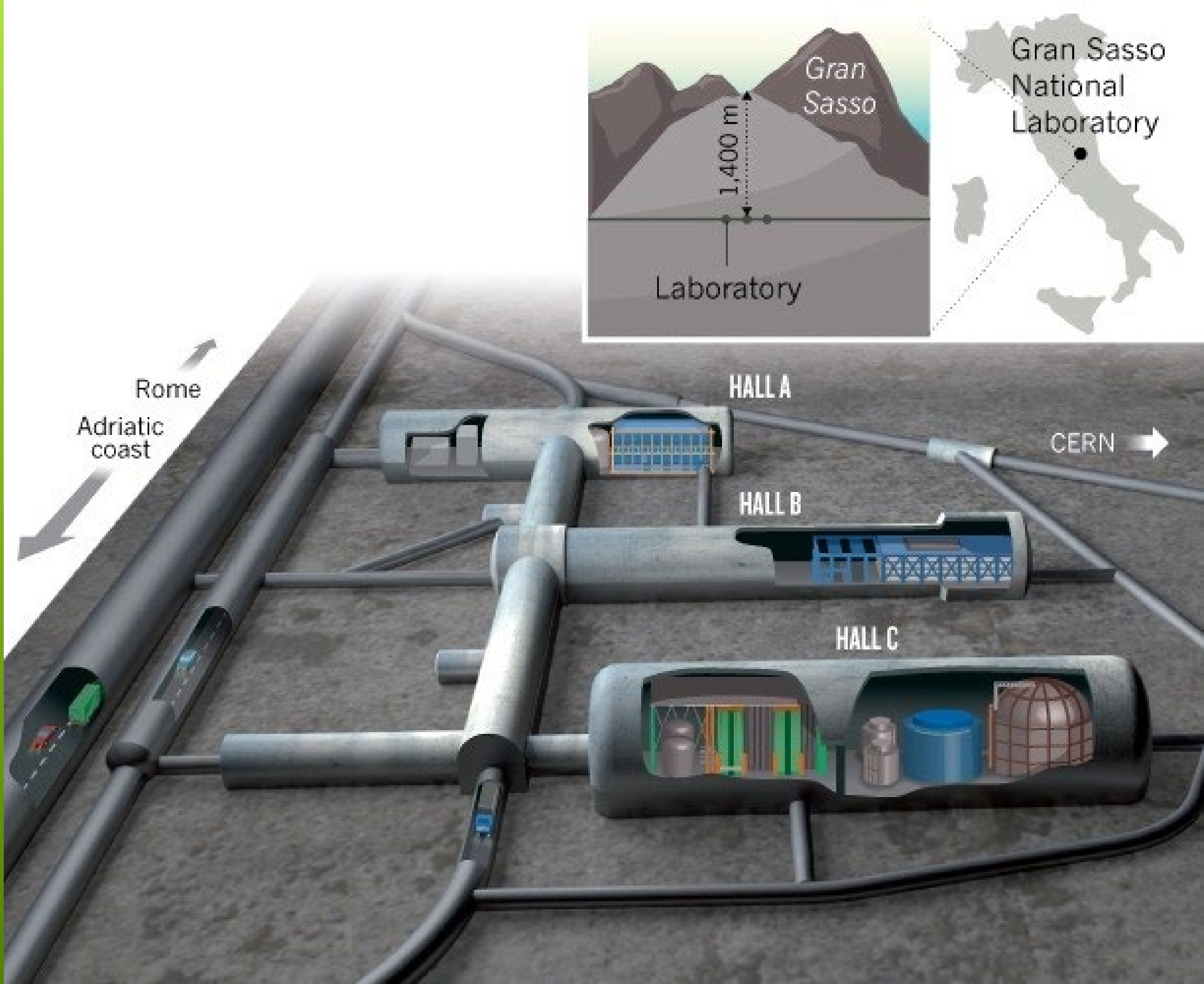


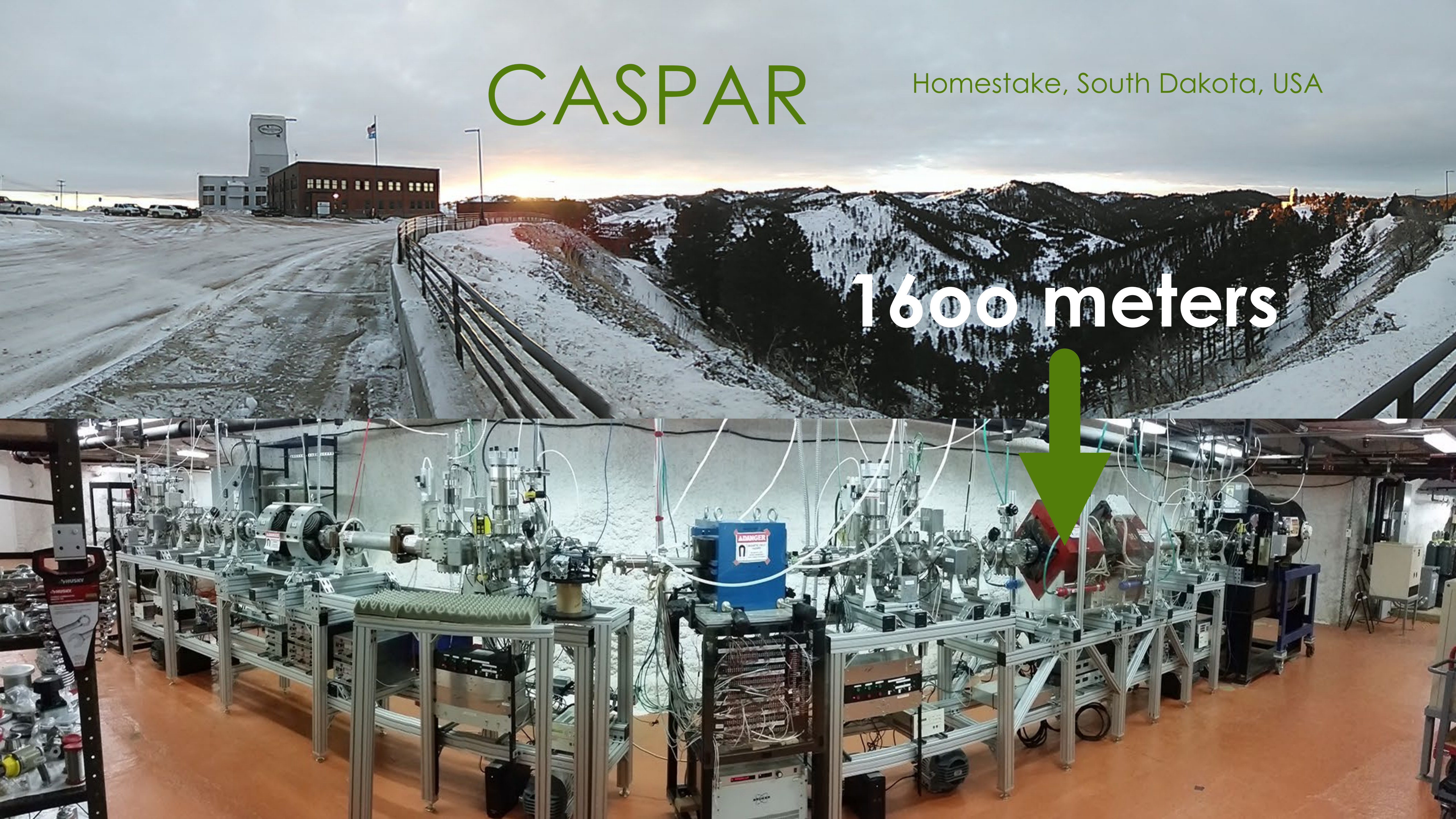
Ianni, Front. Phys. 23 (2021)

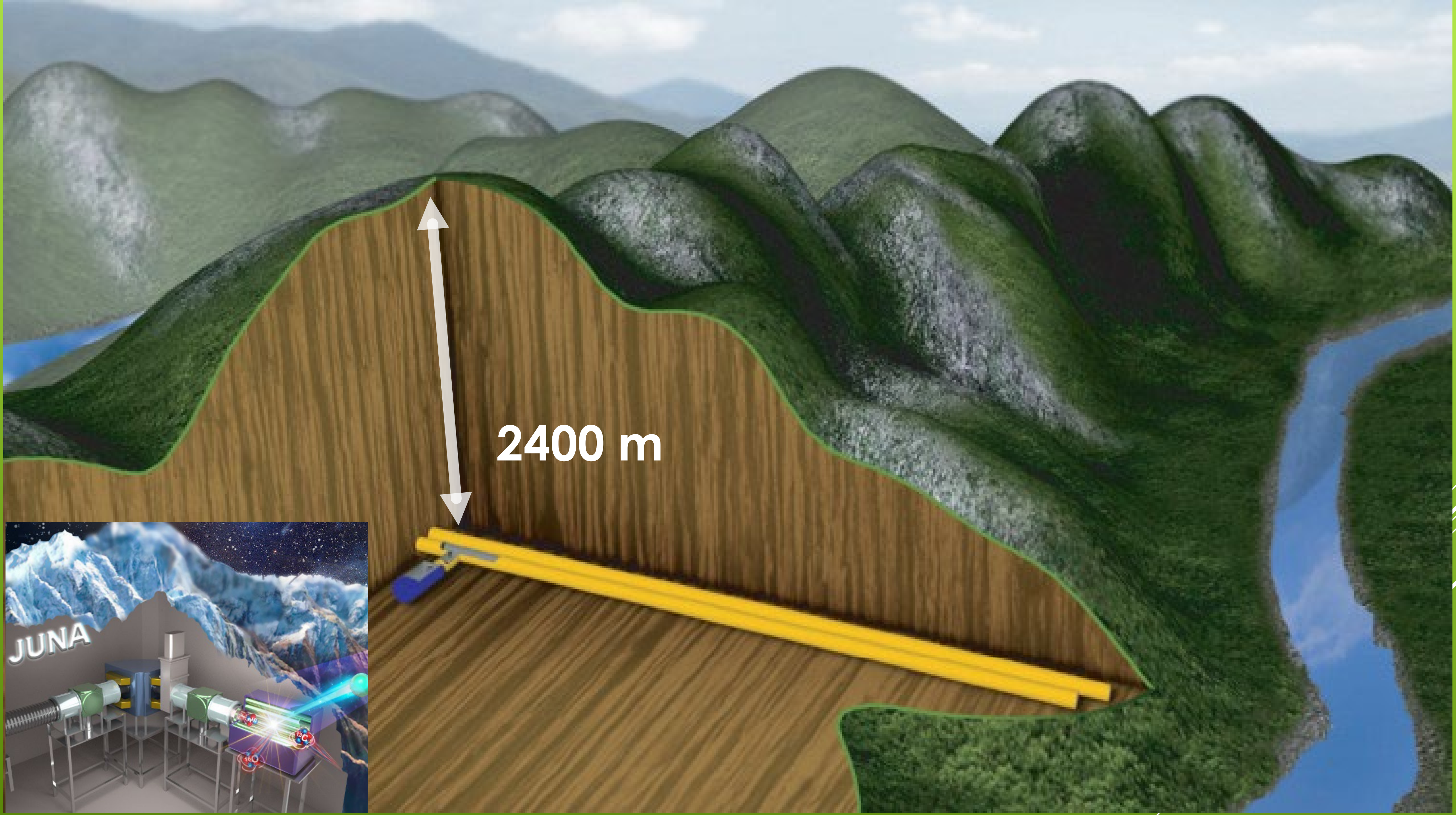
FOREFRONT FACILITIES: UNDERGROUND LOW BACKGROUND

- One of the experimental facilities in Hall B
- Two particle accelerators underground!

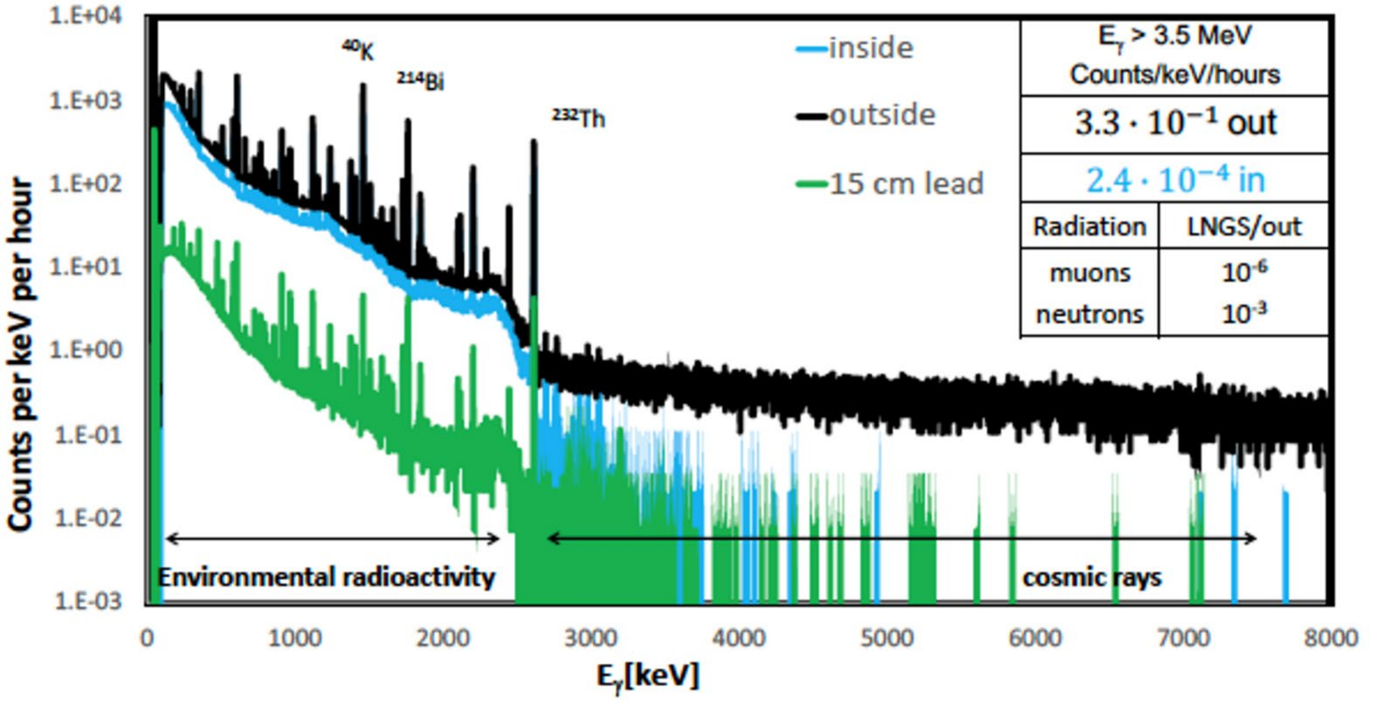
LUNA



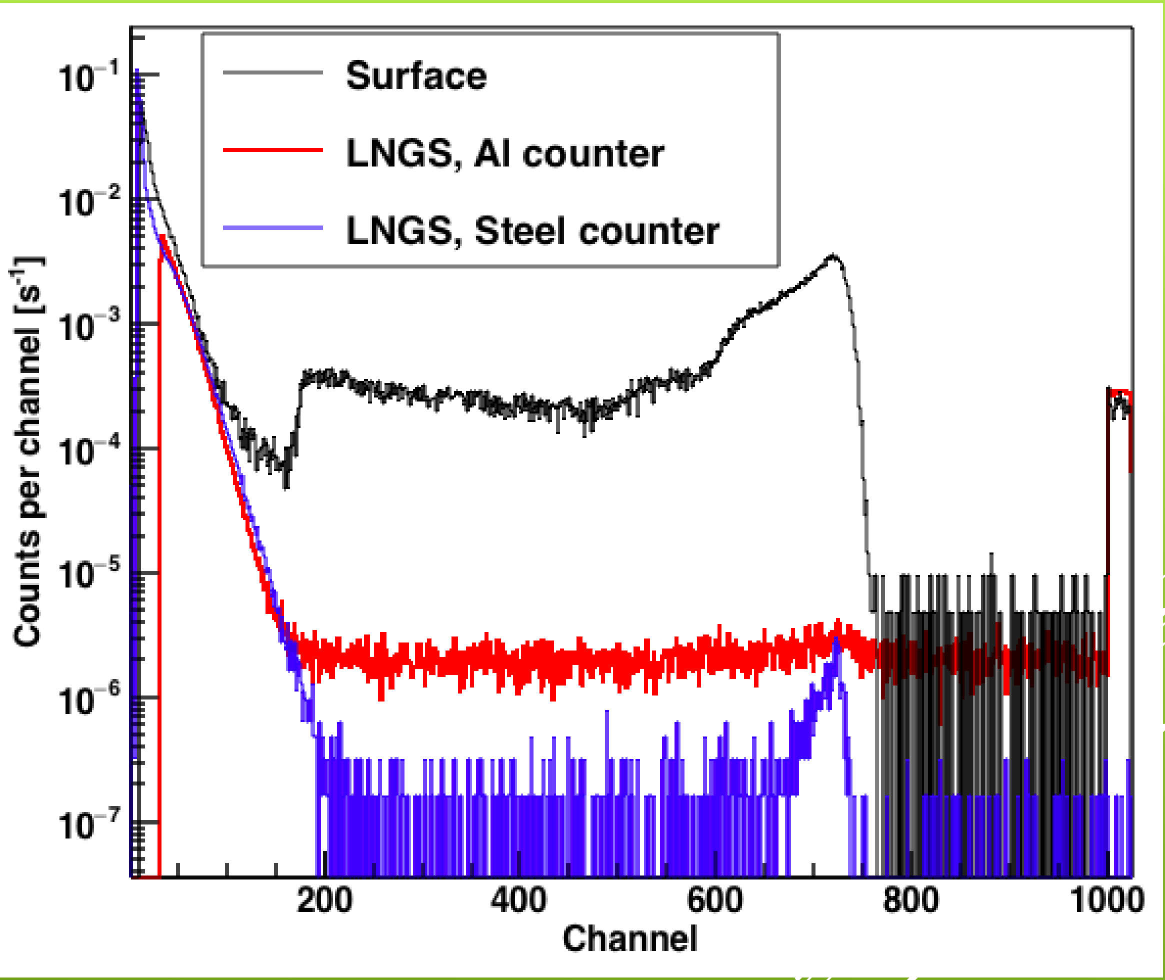

CASPAR
Homestake, South Dakota, USA
1600 meters
DANGER



CHINA JINPING UNDERGROUND LABORATORY



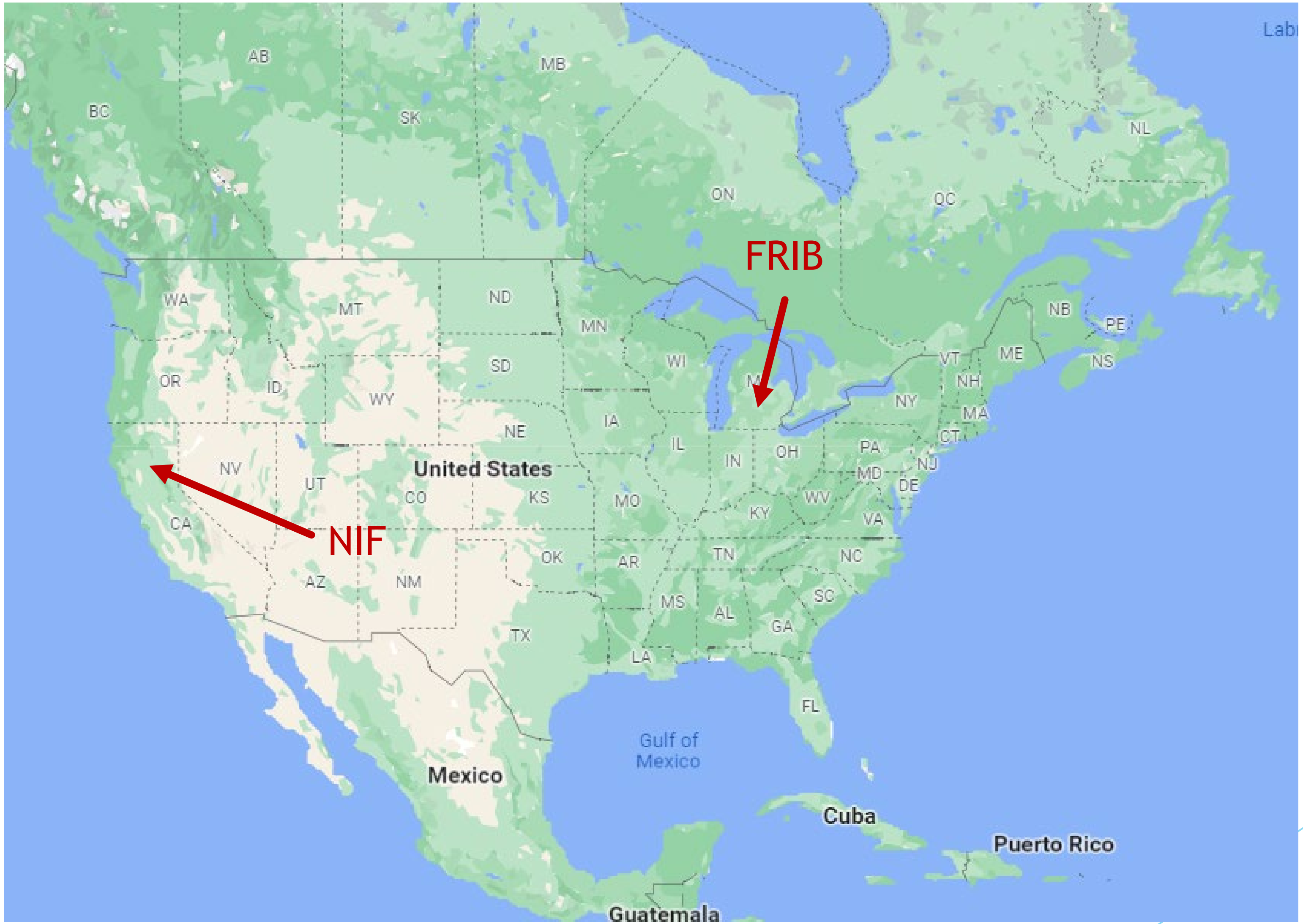
J. Phys. G: Nucl. Part. Phys. **45** (2018) 025203

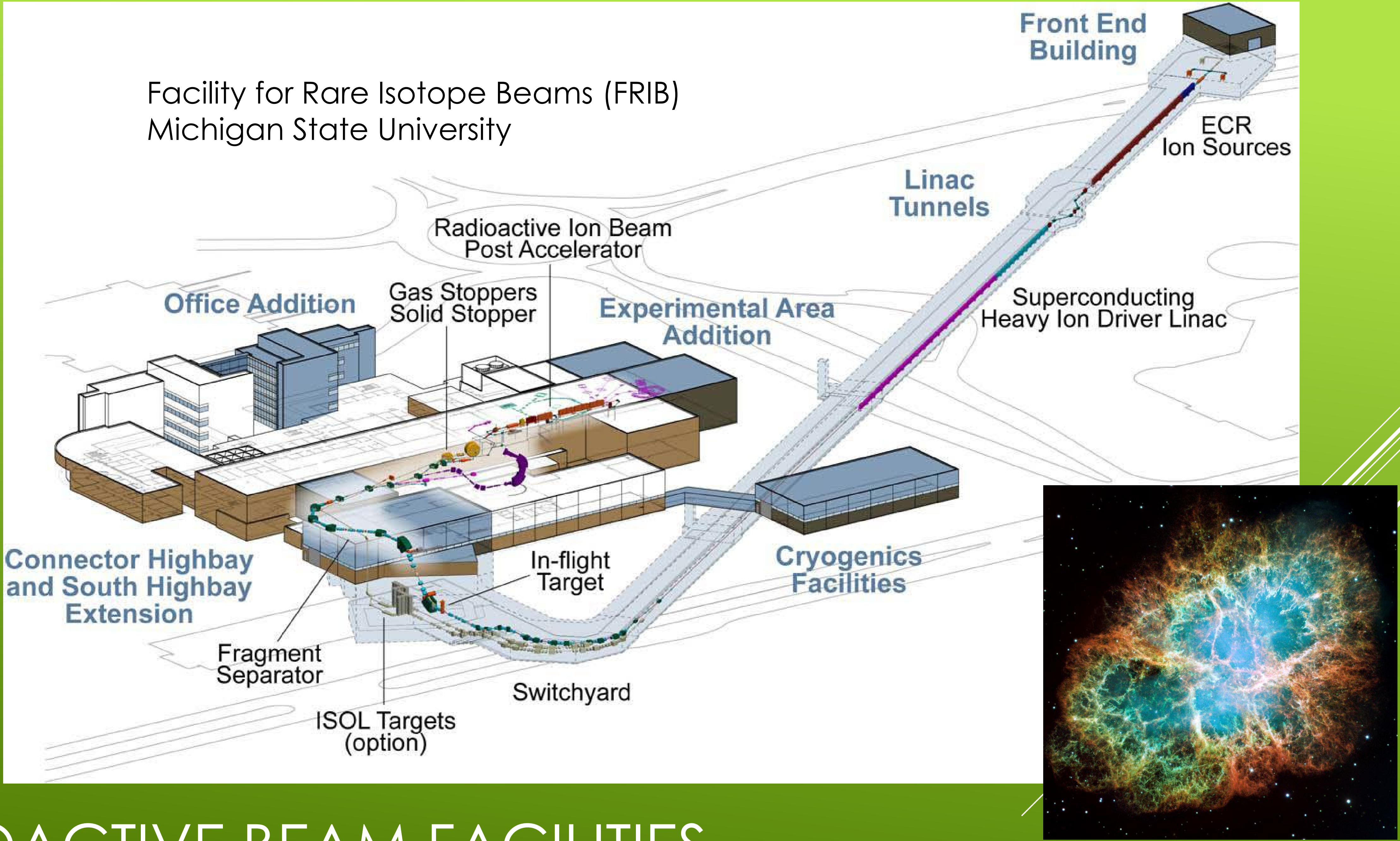


Figures from Andreas Best

SPECTRUM BACKGROUND SUPPRESSION FROM ROCK SHIELDING

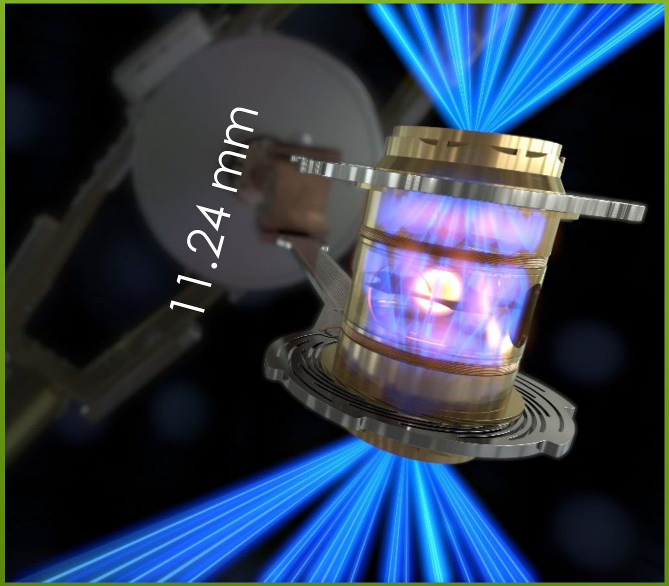
A few example facilities

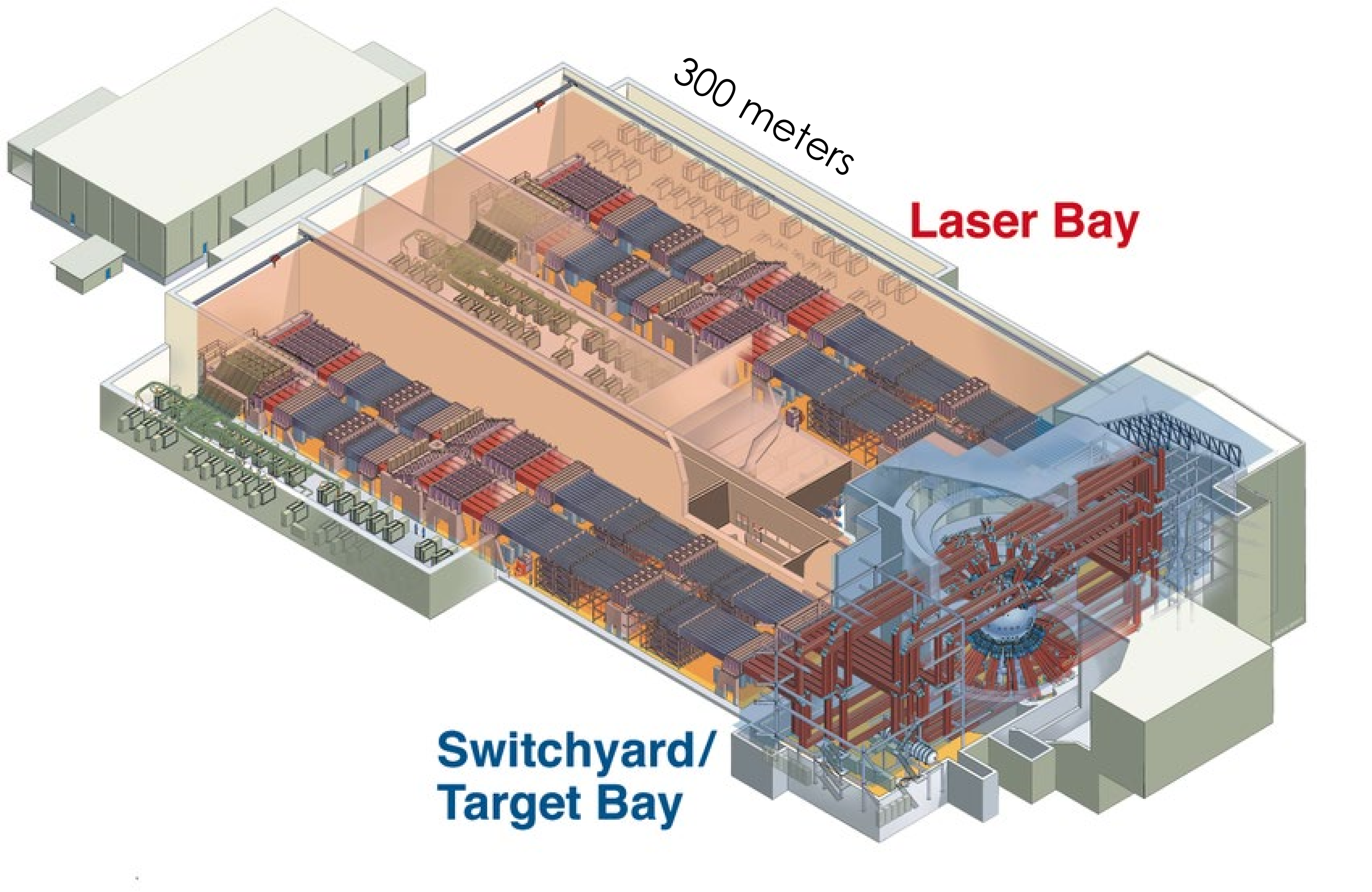




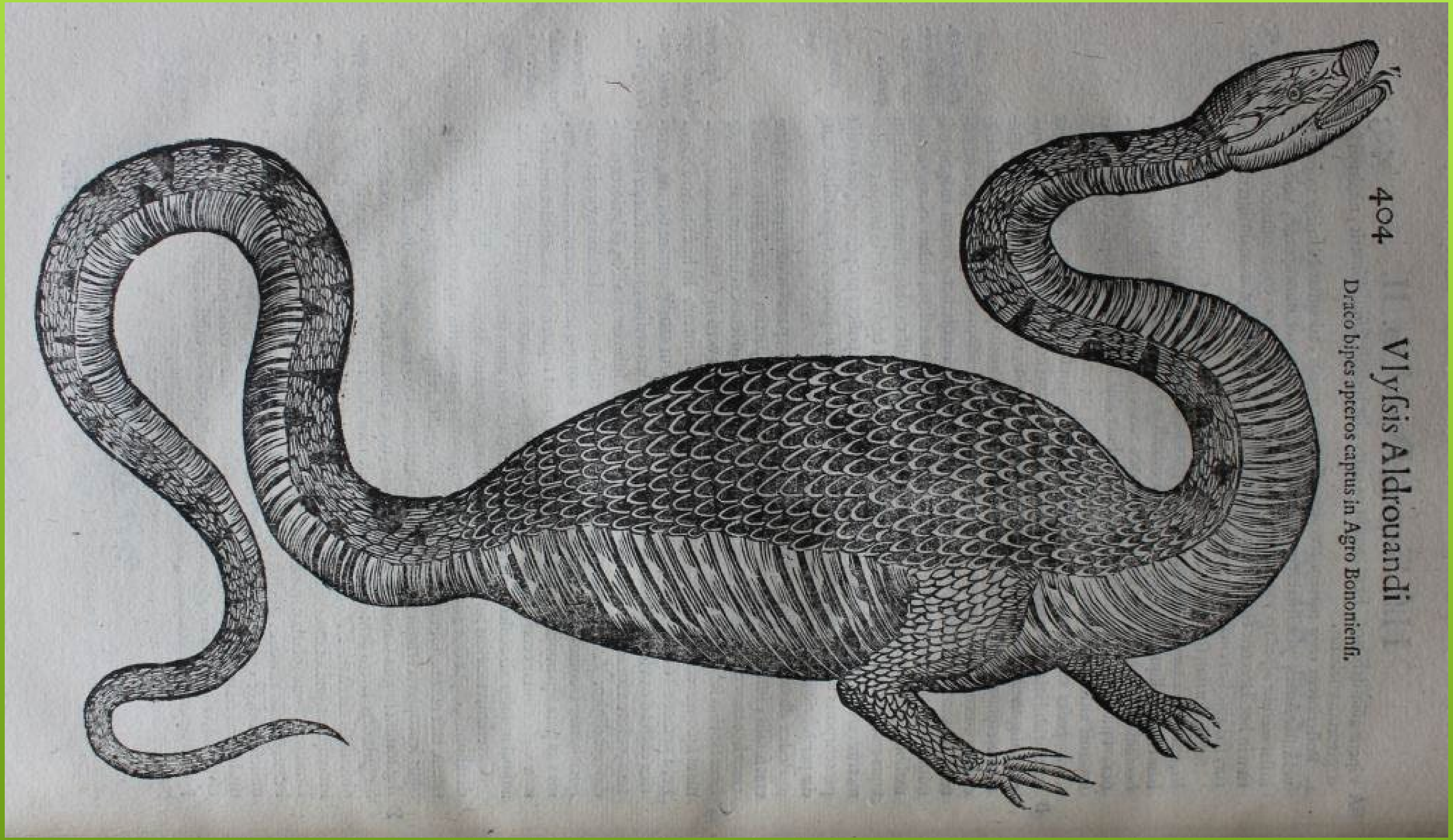
RADIOACTIVE BEAM FACILITIES

- Closely reproduce the temperature and density conditions of a stellar interior
- But only for a few nanoseconds at a time





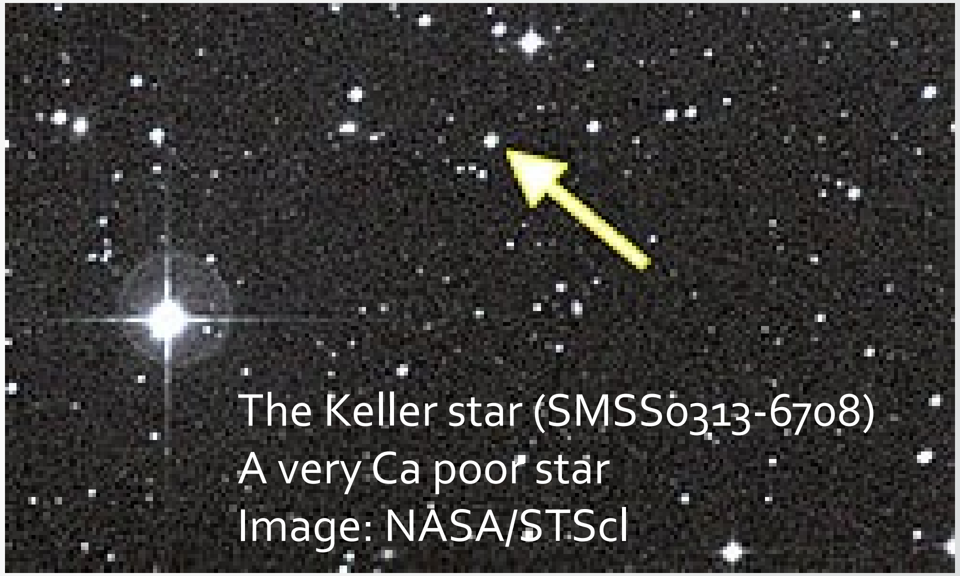
NATIONAL IGNITION FACILITY (NIF)

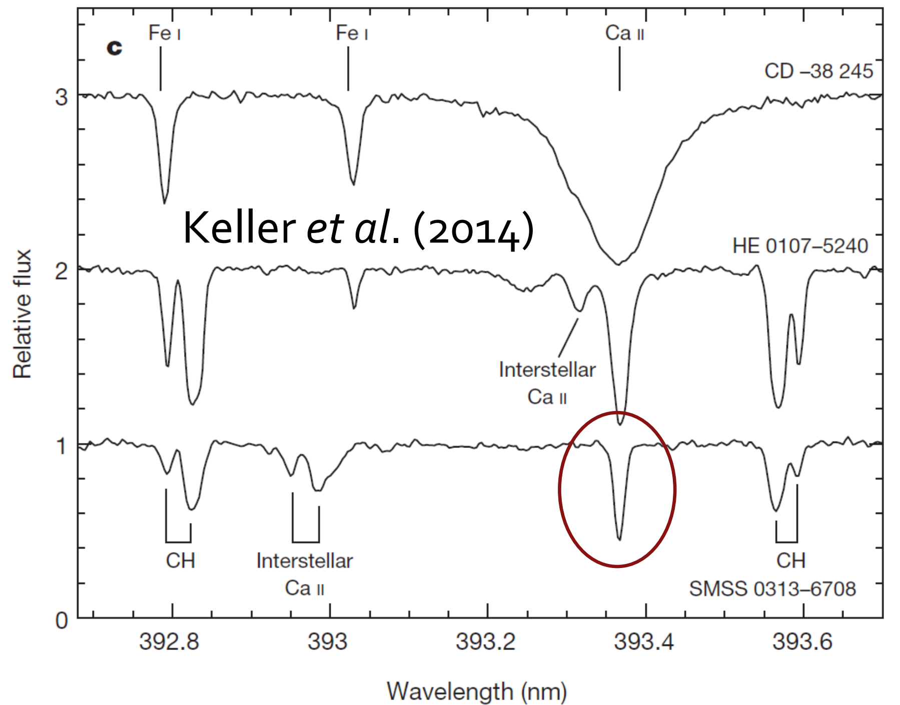


SOME “IDEAL” RESEARCH PROJECTS

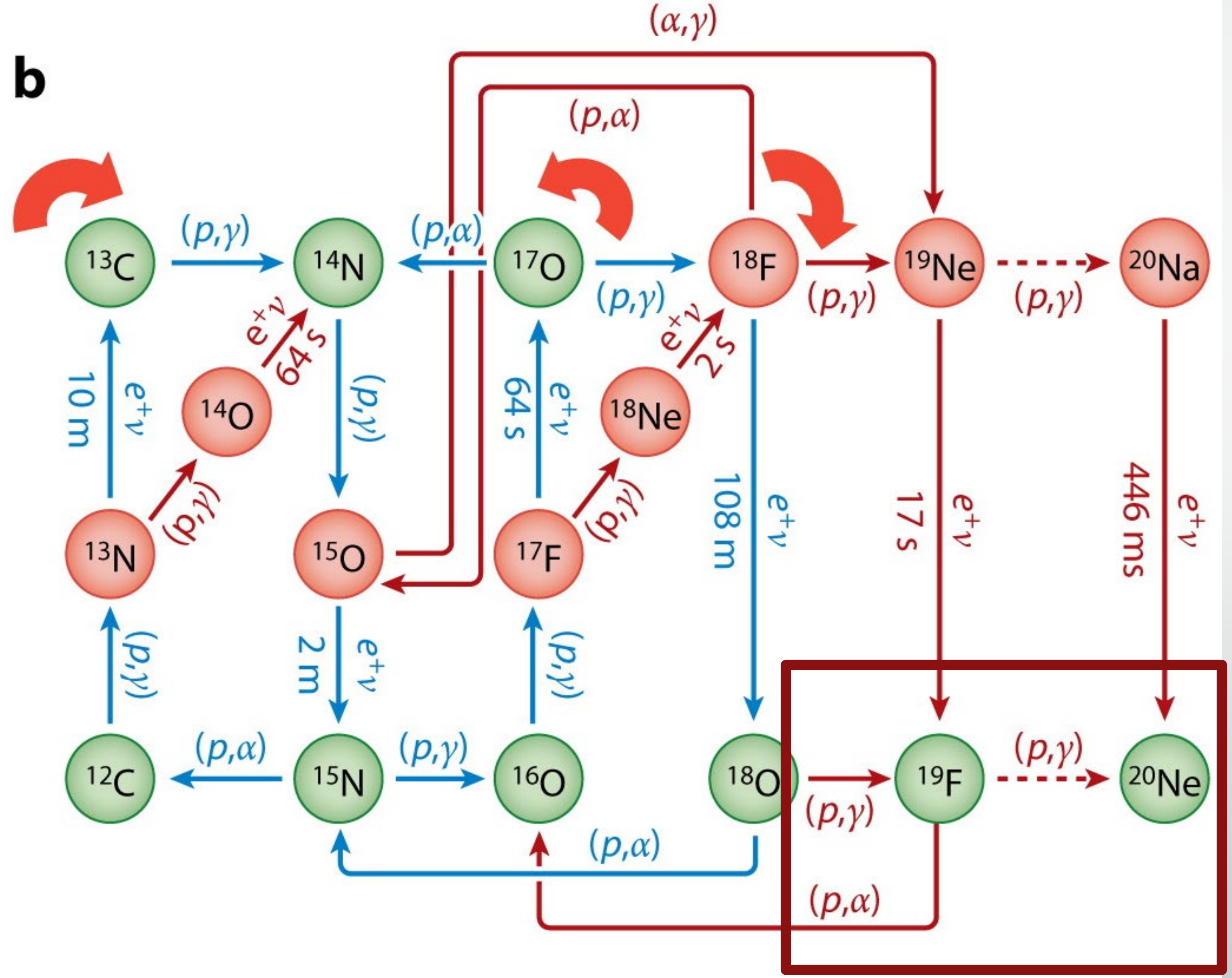
Ca production in POP III stars

- The Keller star is extremely metal poor, yet it has a measurable abundance of Ca
- What was the method for this Ca production?
- Hot CNO breakout is suggested
- Yet simulations by Ondrea Clarkson and Falk Herwig, Mon. Not. R. Astron. Soc. 500, 2685 (2020) say **it can't work, unless the reaction rate of $^{19}F(p,\gamma)^{20}Ne$ / $^{19}F(p,\alpha)^{16}O$ is 10 times higher** than predicted





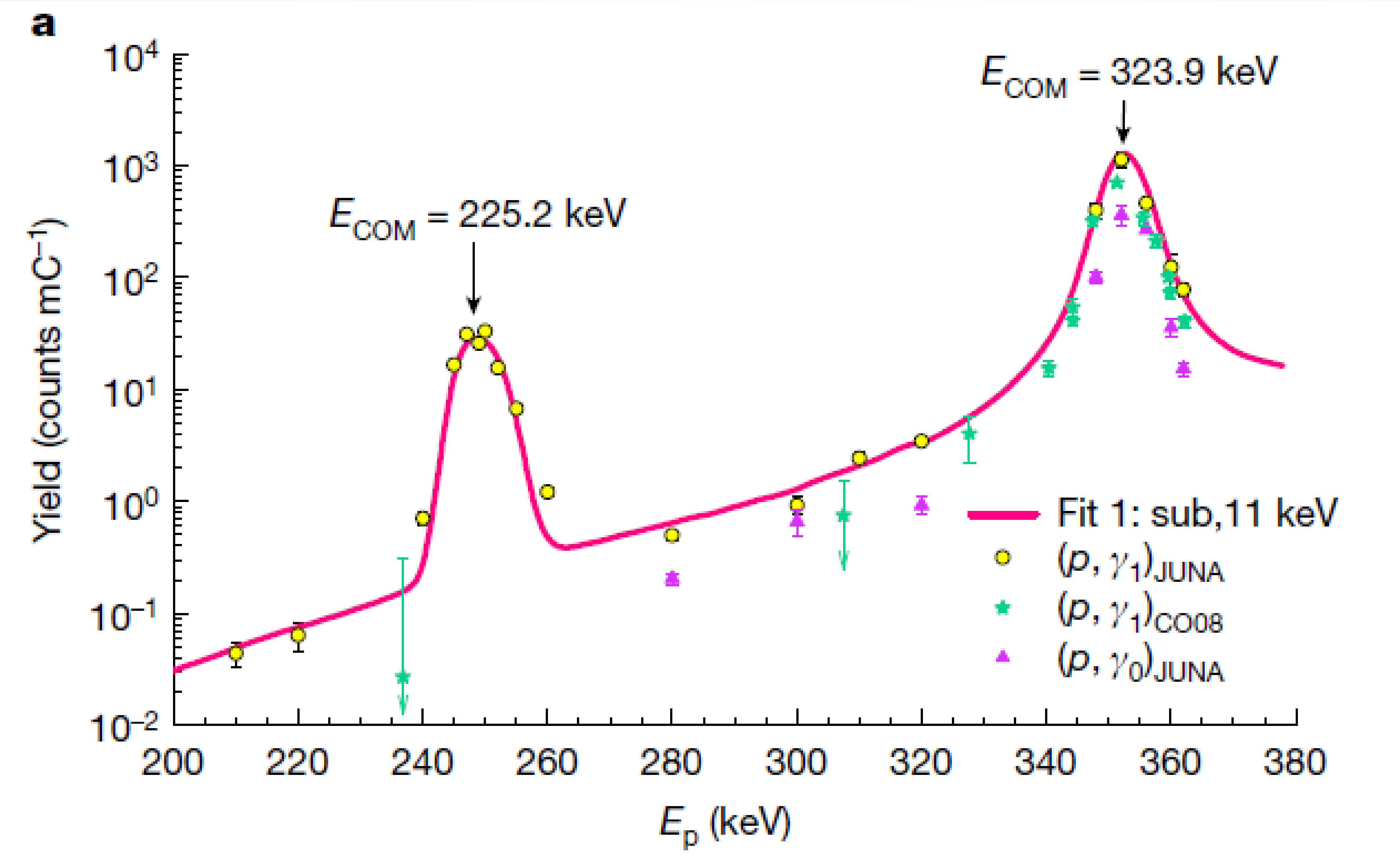
What's the hot CNO cycle?



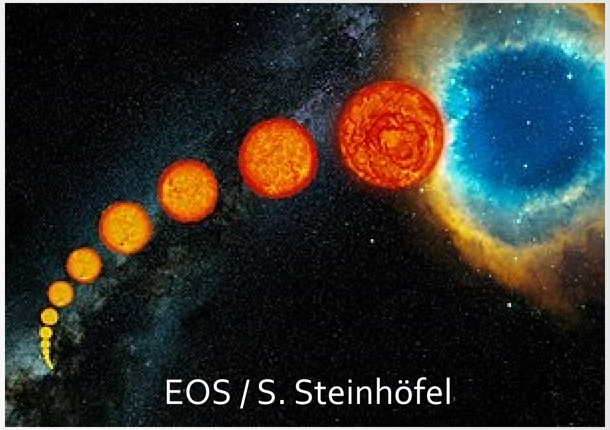
Breakout!

Ca

$^{19}F(p,\gamma)^{20}Ne$ at JUNA



Motivation

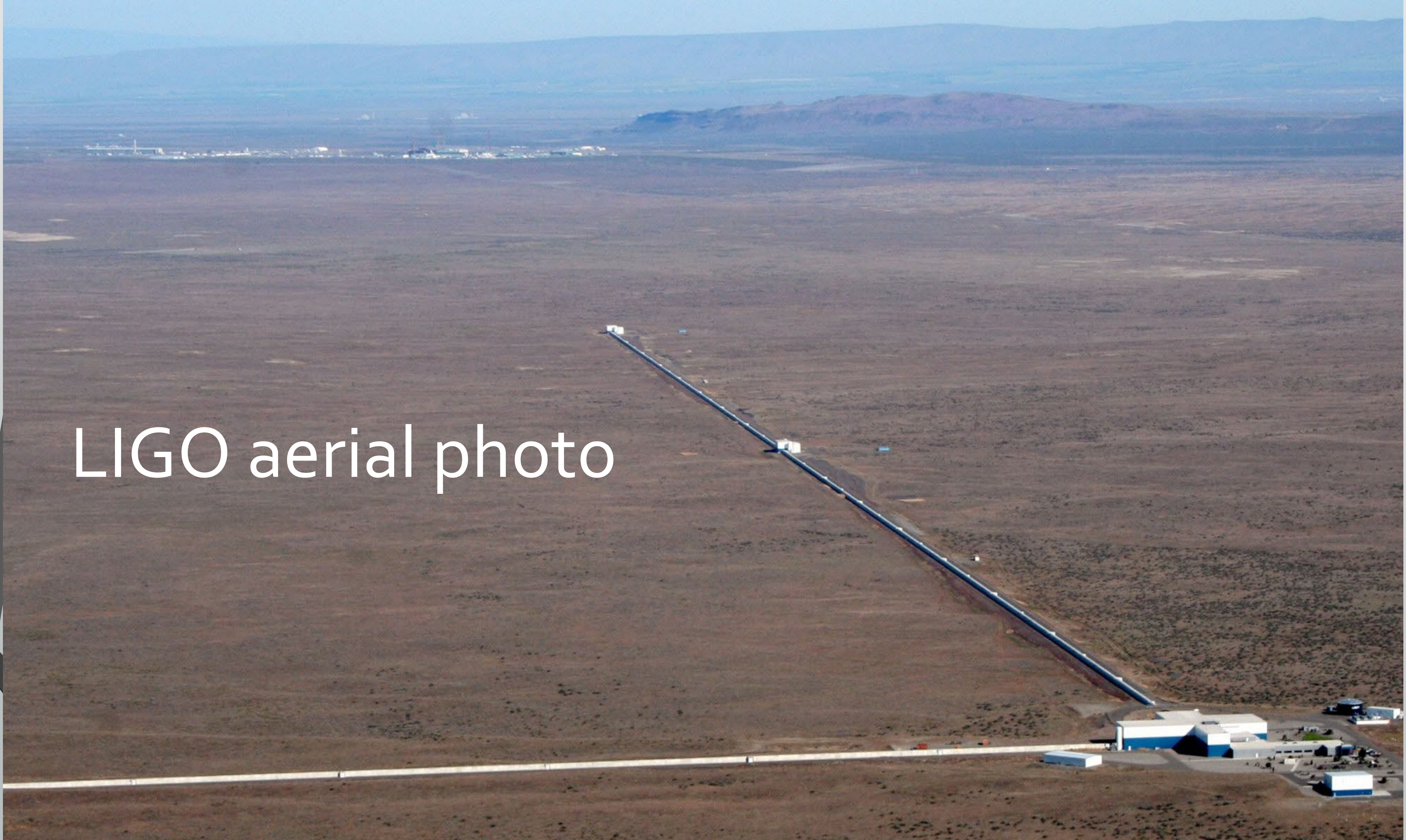


- Together with the 3α process, the **$^{12}C(\alpha,\gamma)^{16}O$** reaction determines the $^{12}C/^{16}O$ ratio in the universe.
- For stellar evolution, the $^{12}C/^{16}O$ ratio determines the evolution of massive stars, which in turn effects all later stages of nucleosynthesis.

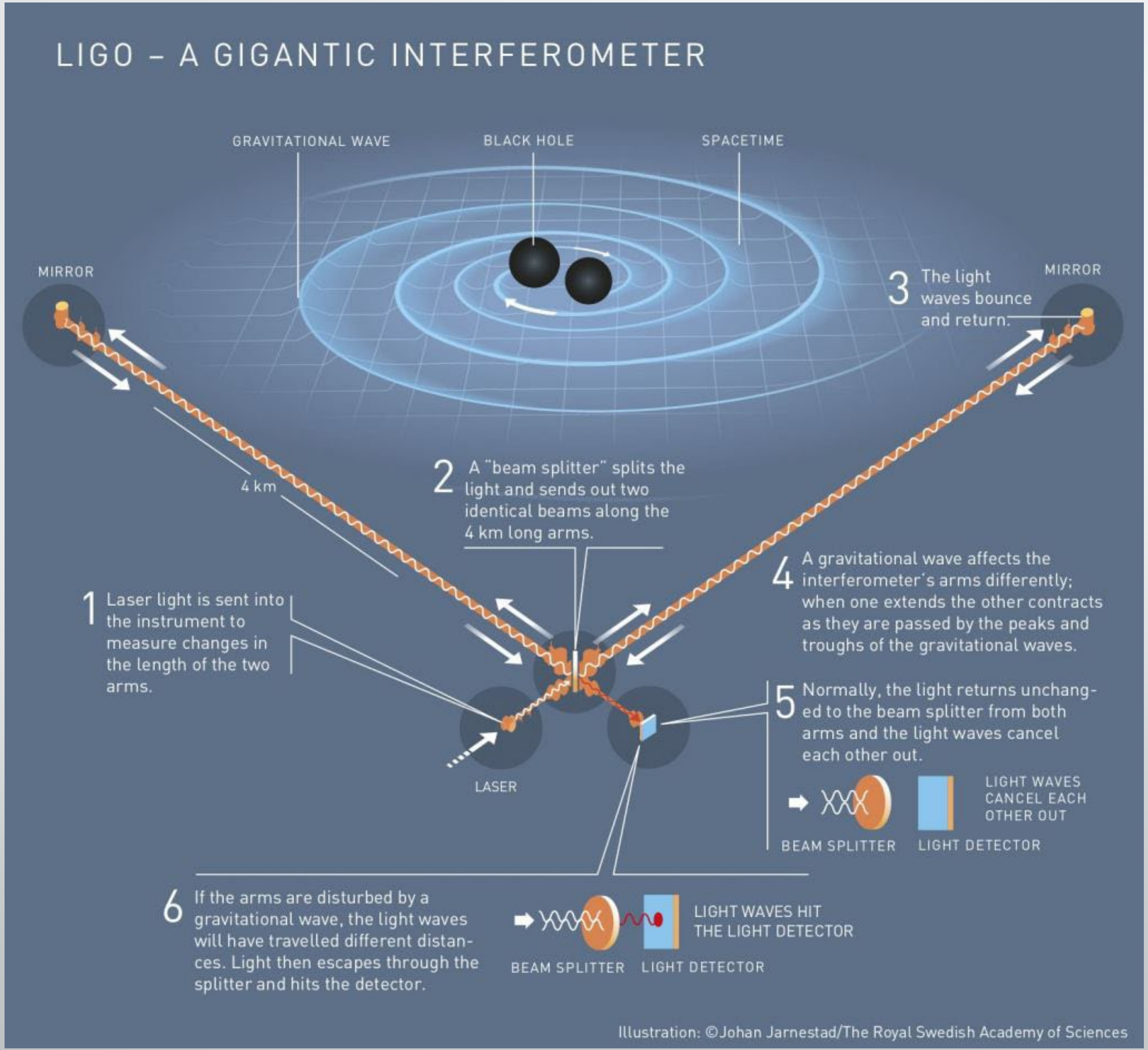
TABLE I. Astrophysical environments and burning stages where the $^{12}C(\alpha,\gamma)^{16}O$ reaction plays an important role. The temperatures of these environments dictate the energy ranges where the $^{12}C(\alpha,\gamma)^{16}O$ cross section must be well known for an accurate calculation of the reaction rate.

Burning stages	Astrophysical sites	Temperature range (GK)	Gamow energy range (MeV)
Core helium burning	AGB stars and massive stars	0.1–0.4	0.15–0.65
Core carbon and oxygen burning	Massive stars	0.6–2.7	0.44–2.5
Core silicon burning	Massive stars	2.8–4.1	1.1–3.4
Explosive helium burning	Supernovae and x-ray bursts	≈ 1	0.6–1.25
Explosive oxygen and silicon burning	Supernovae	> 5	> 1.45

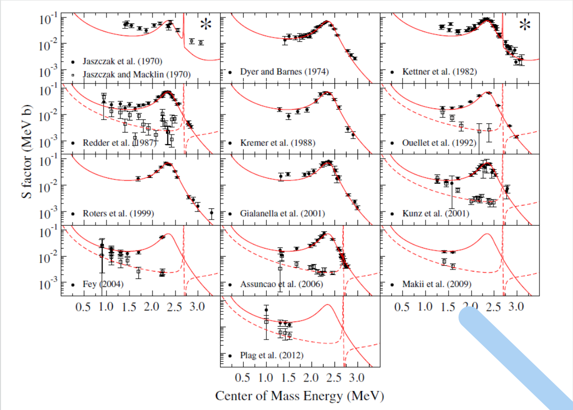
LIGO aerial photo



Motivation Highlight: Black Hole Mass Gap

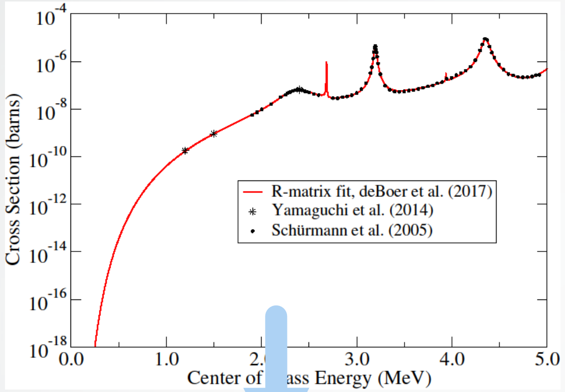


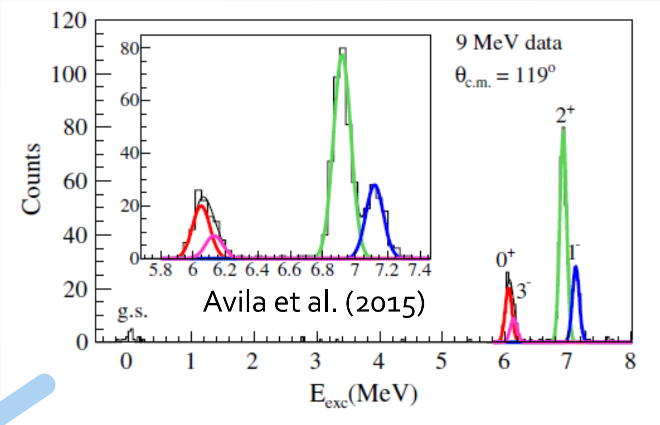
Many experimental studies help determine this reaction rate



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

Total capture cross sections (recoils)

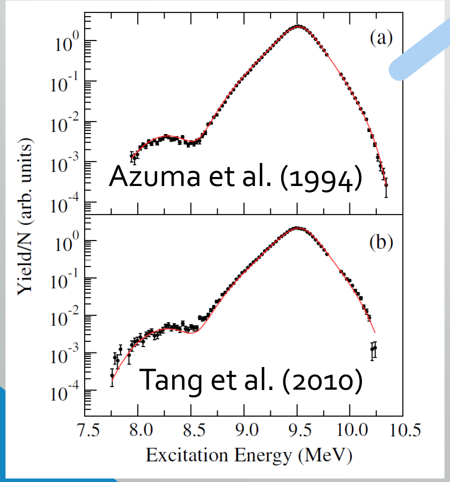




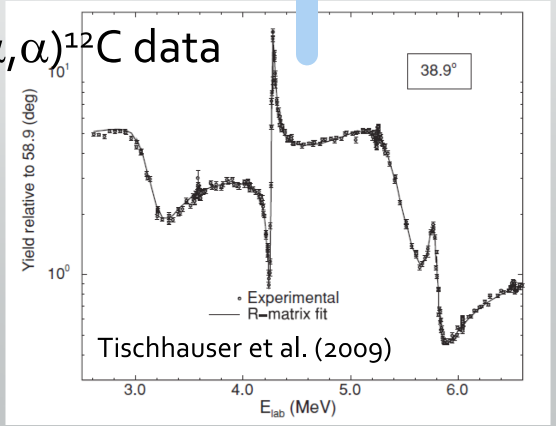
Bound state ANCs

Reaction rate

$^{16}N(\beta\alpha)^{12}C$ spectrum



$^{12}C(\alpha,\alpha)^{12}C$ data



Multichannel R-matrix

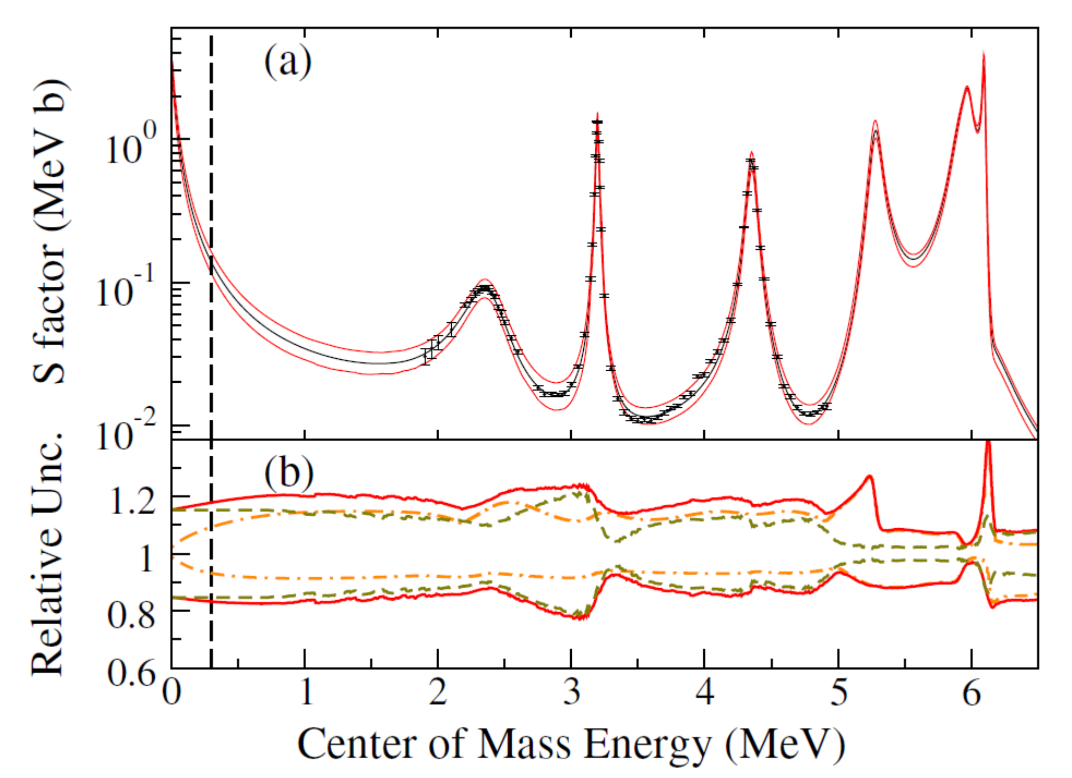
$$\mathbf{U} = \rho^{\frac{1}{2}}\mathbf{O}^{-1}(\mathbf{1}-\mathbf{RL}_0)^{-1}(\mathbf{1}-\mathbf{RL}_0^*)\mathbf{I}\rho^{-\frac{1}{2}}$$

$$T_{cc'} = e^{2i\omega_c}\delta_{cc'} - U_{cc'},$$

$$\sigma_{\alpha\alpha'} = \frac{\pi}{k_\alpha^2}\sum_{Jll'ss'} g_J \left|T_{cc'}^J\right|^2,$$

Simple Monte Carlo

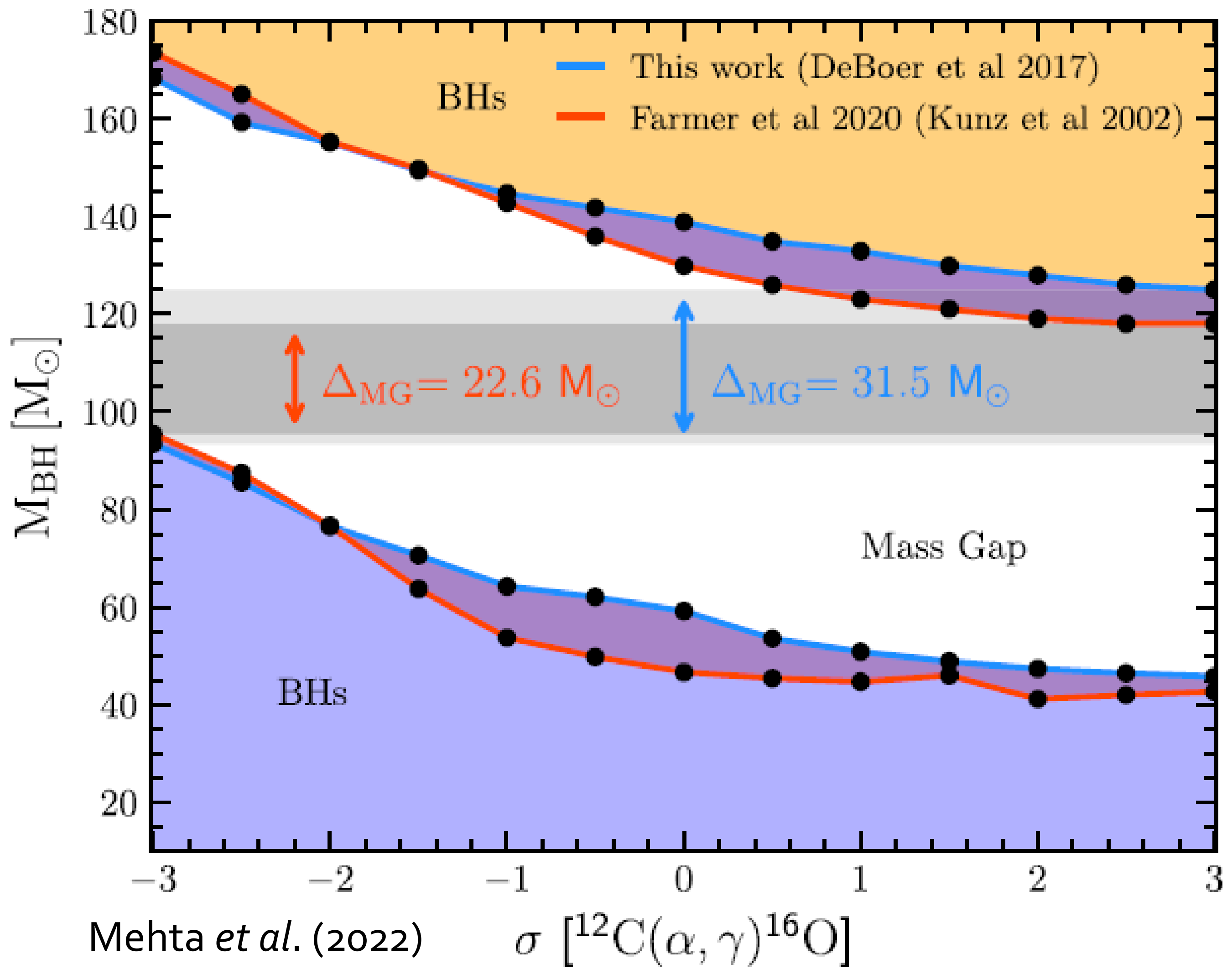
- Created thousands of "synthetic" data sets by assuming that the error bars on the data represented an underlying Gaussian (probably should have used lognormal) Probability Density Function.
- Refit
- Histogrammed S-factor calculated at many energies to get uncertainty.
- Calculated many different variations on assumptions about the *R*-matrix fit and included those as well.
- Even more computationally expensive



Monte Carlo of experimental data

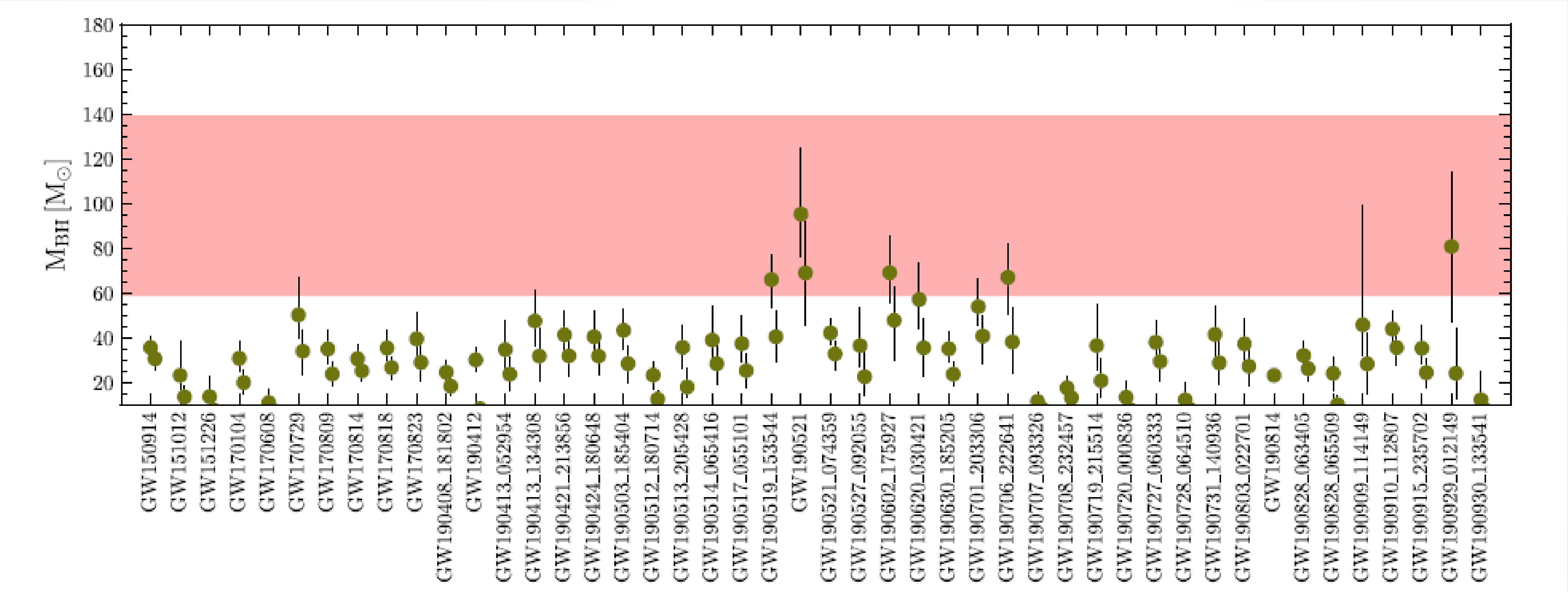
Model uncertainties

Feeding cross section data back into the model



Mehta *et al.* (2022)

Comparing with LIGO observations of gravitational waves from black hole mergers:
A new frontier for nuclear astrophysics



Mehta *et al.* (2022)

Thank you!