nuclear astrophysics experiments

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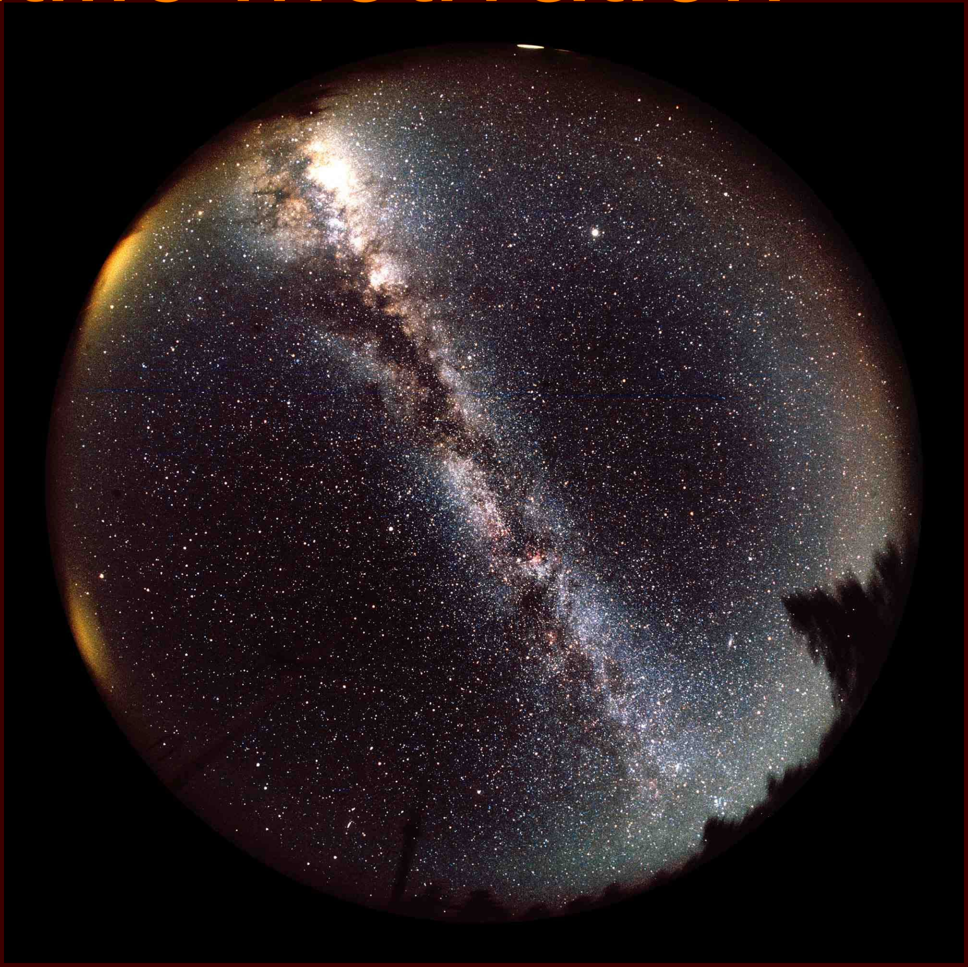
Outline – nuclear astrophysics experiments

- Astrophysics motivation – where does nuclear physics play a role?
- Reaction rate formalism – turning laboratory measurements into astrophysical input
- Brute force measurements – how our forefathers did nuclear astrophysics
- Direct measurements today
- Indirect techniques using stable beams

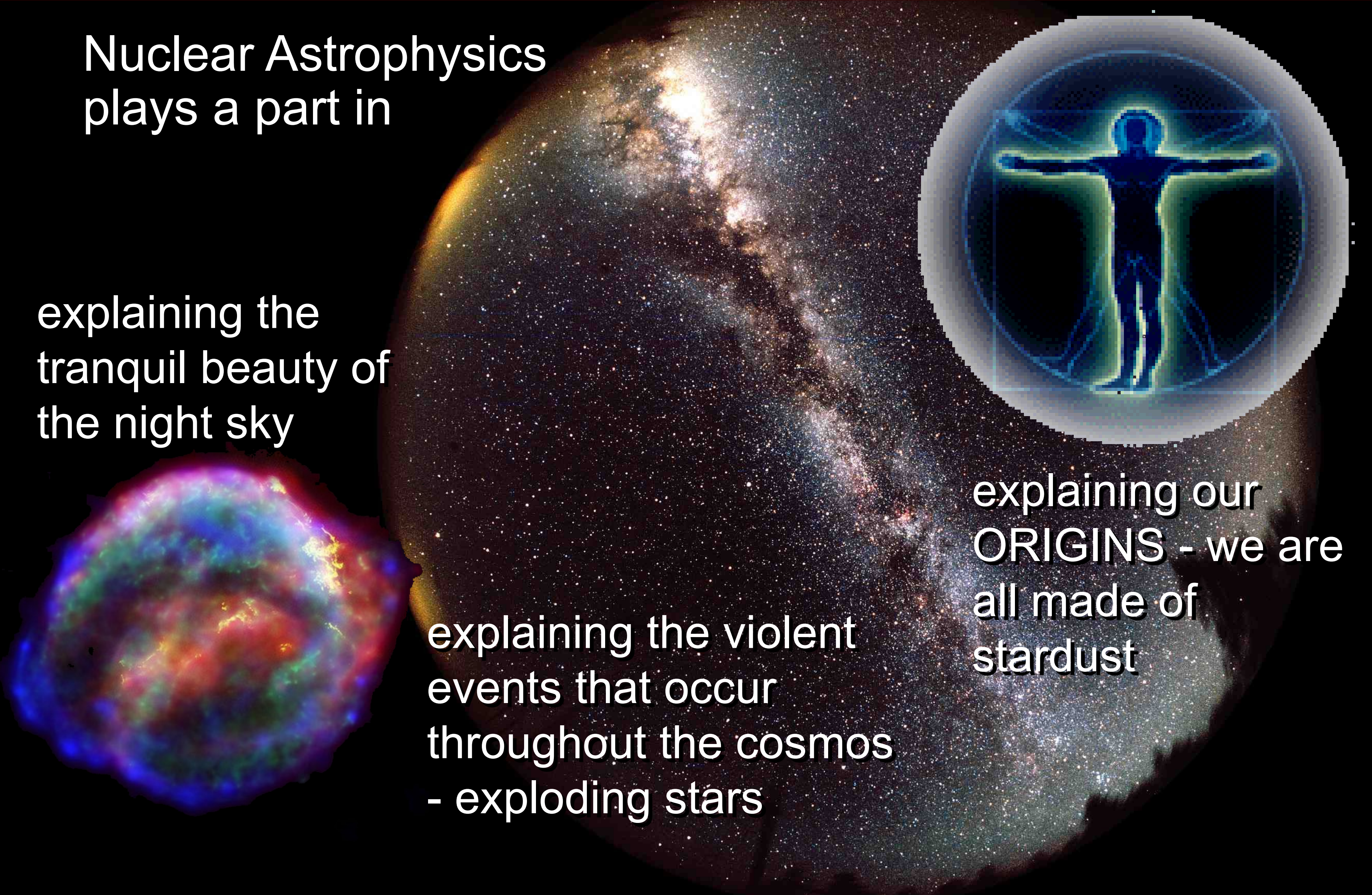
- Saturday : exotic beam measurements

Scientific Motivation



Overview of Nuclear Astrophysics

Nuclear Astrophysics plays a part in

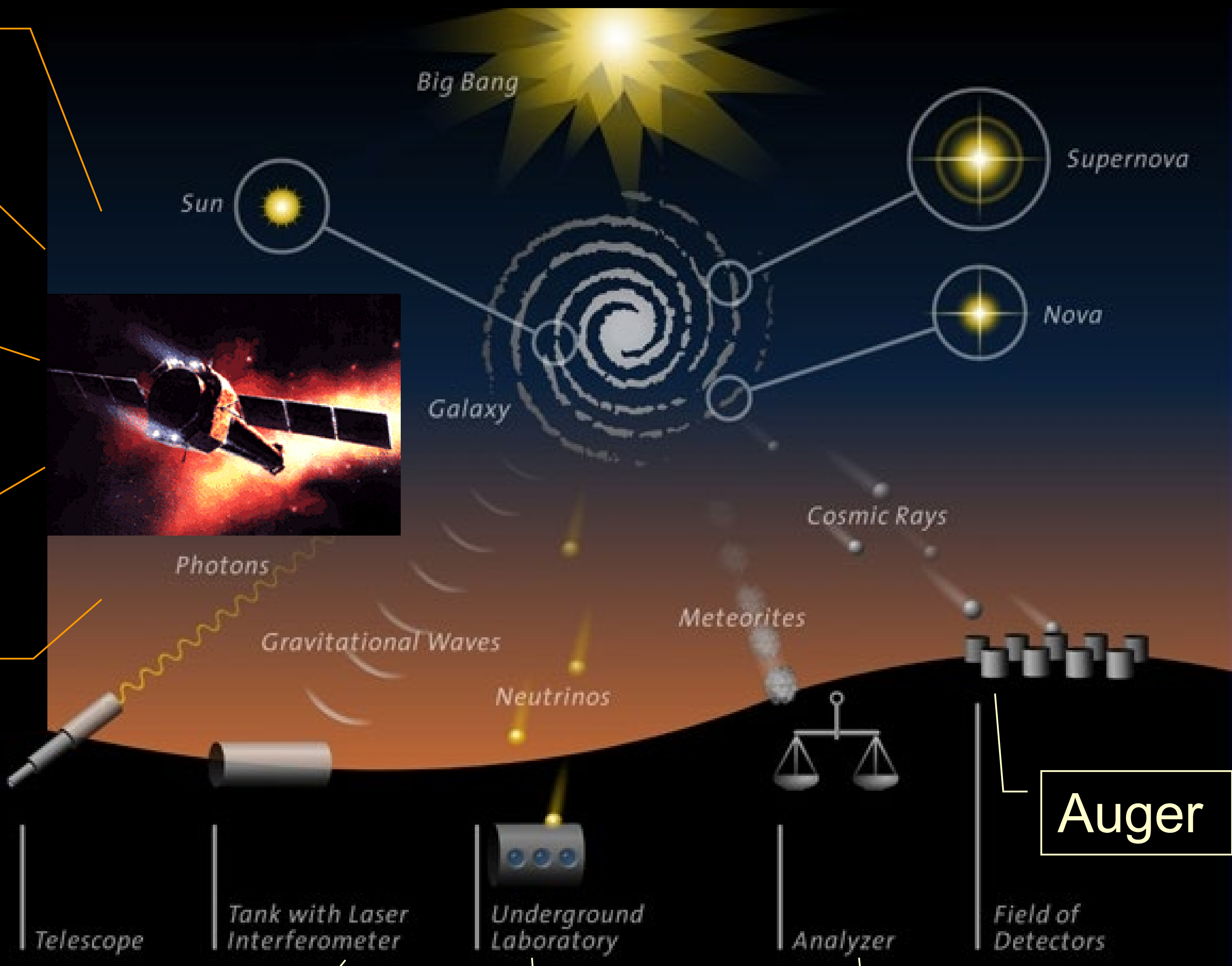


explaining the tranquil beauty of the night sky

explaining the violent events that occur throughout the cosmos - exploding stars

explaining our ORIGINS - we are all made of stardust

astrophysics observations



INTEGRAL
(γ-rays)

Hubble
(visible)

Chandra
(X-rays)

SIRTF
(infrared)

WMAP
(microwave)

Keck,
Subaru,
ESO

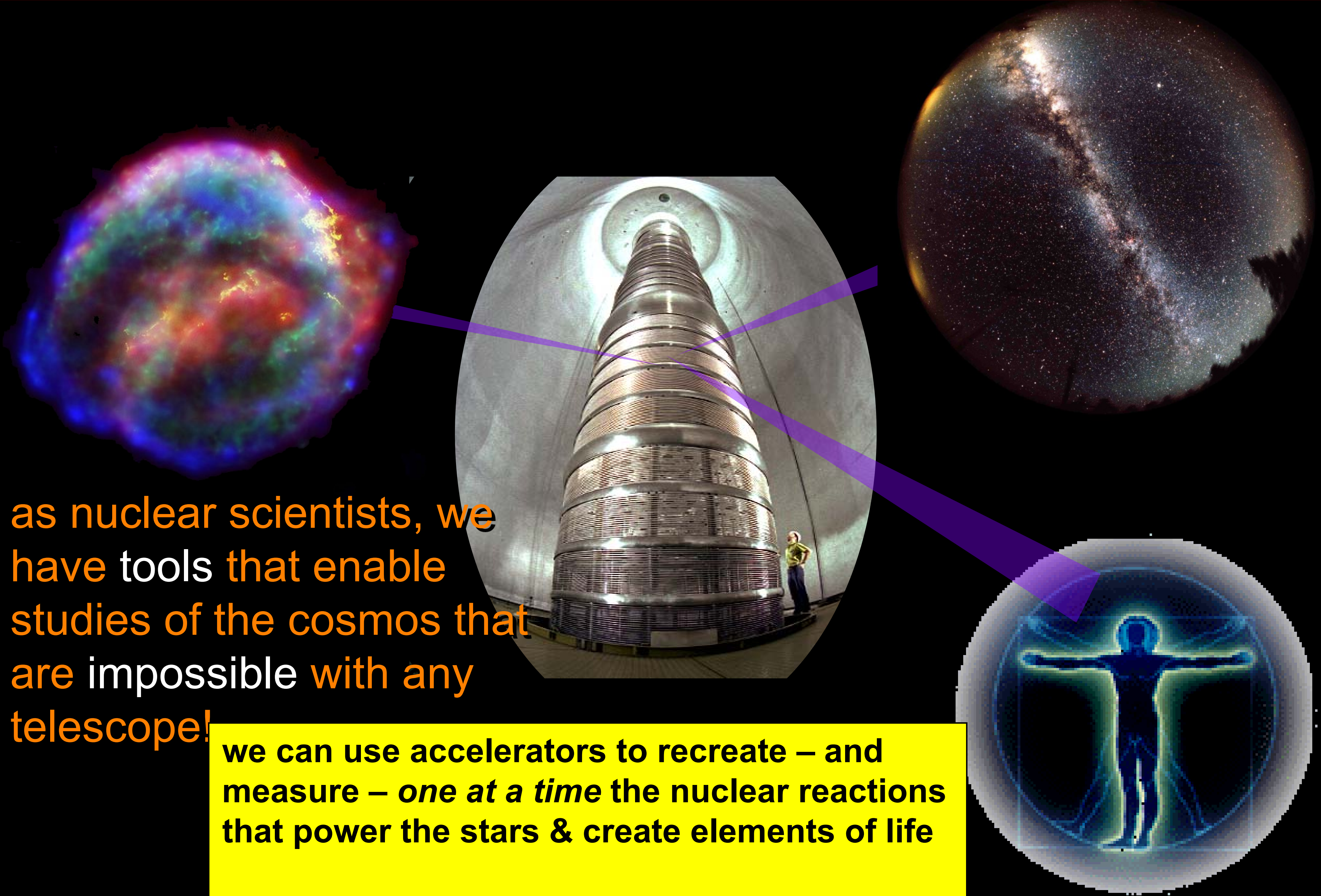
LIGO

SuperK

SIMS

Auger

Overview of Nuclear Astrophysics



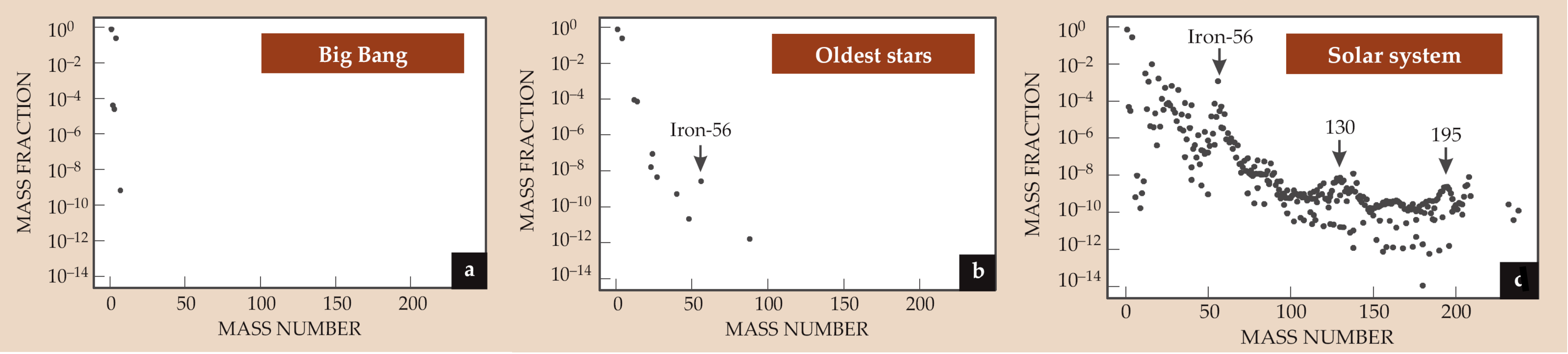
as nuclear scientists, we have tools that enable studies of the cosmos that are impossible with any telescope!

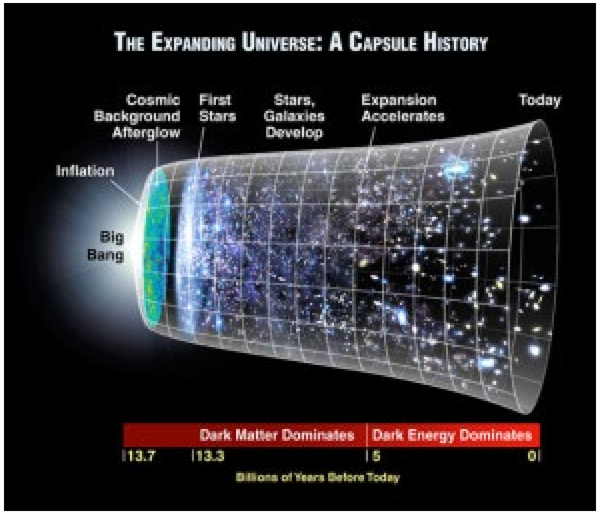
we can use accelerators to recreate – and measure – *one at a time* the nuclear reactions that power the stars & create elements of life

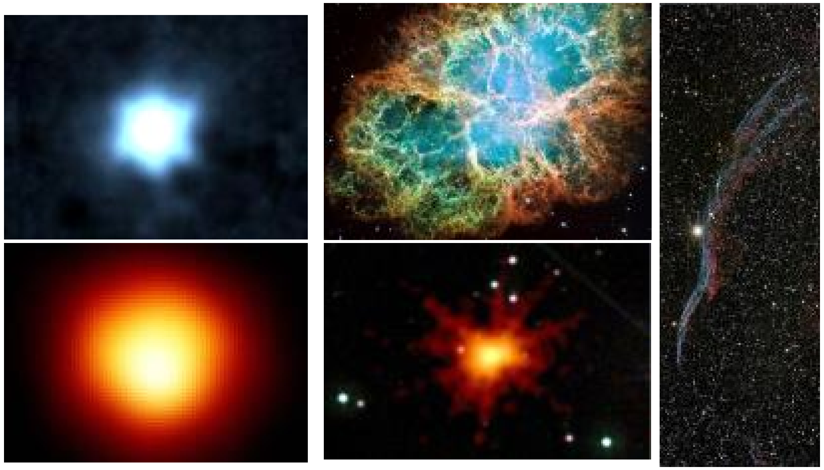
The Origin of the Elements

Observations provide picture of elemental abundance over time

Schatz, Physics Today (2008)

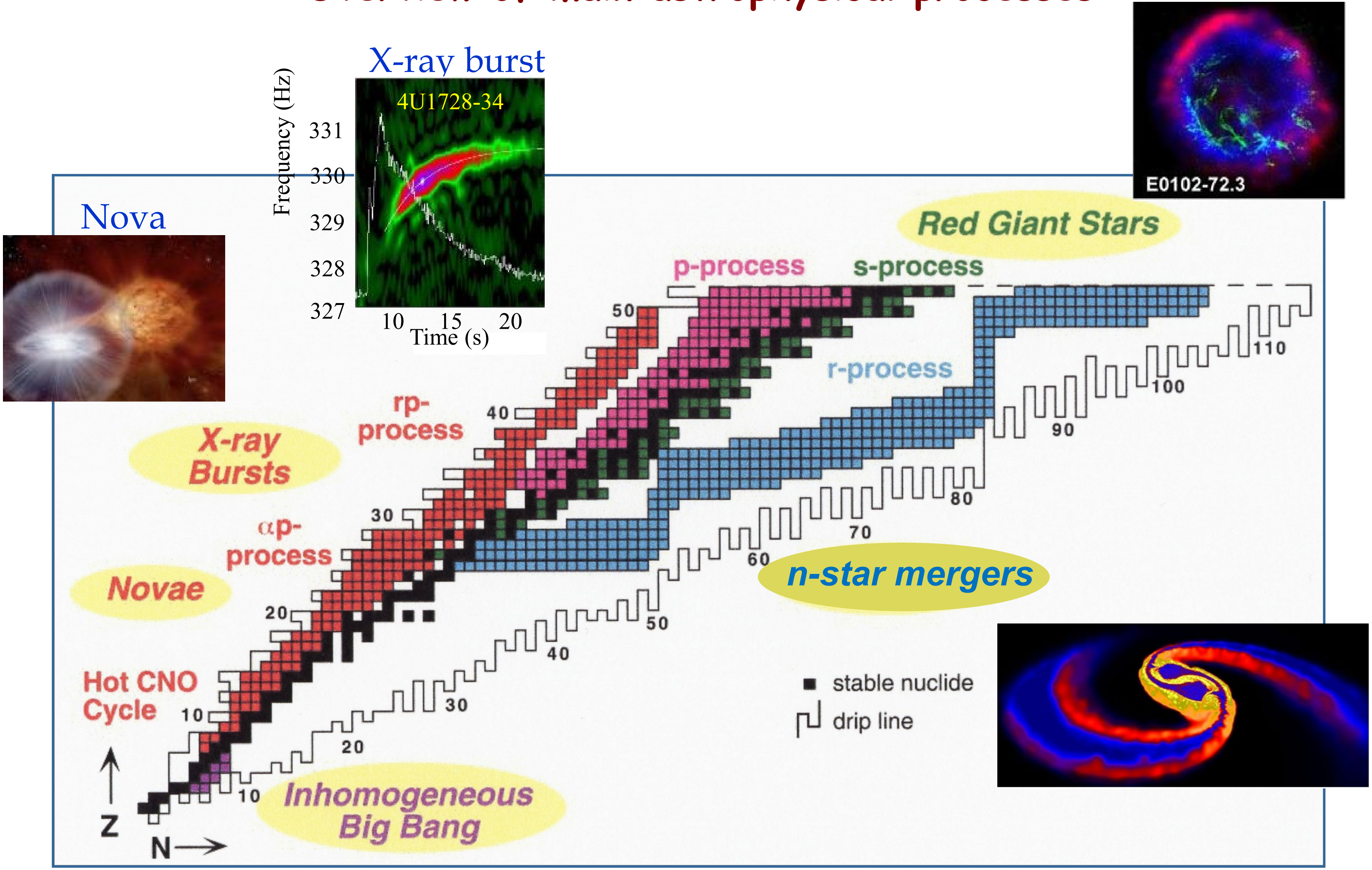






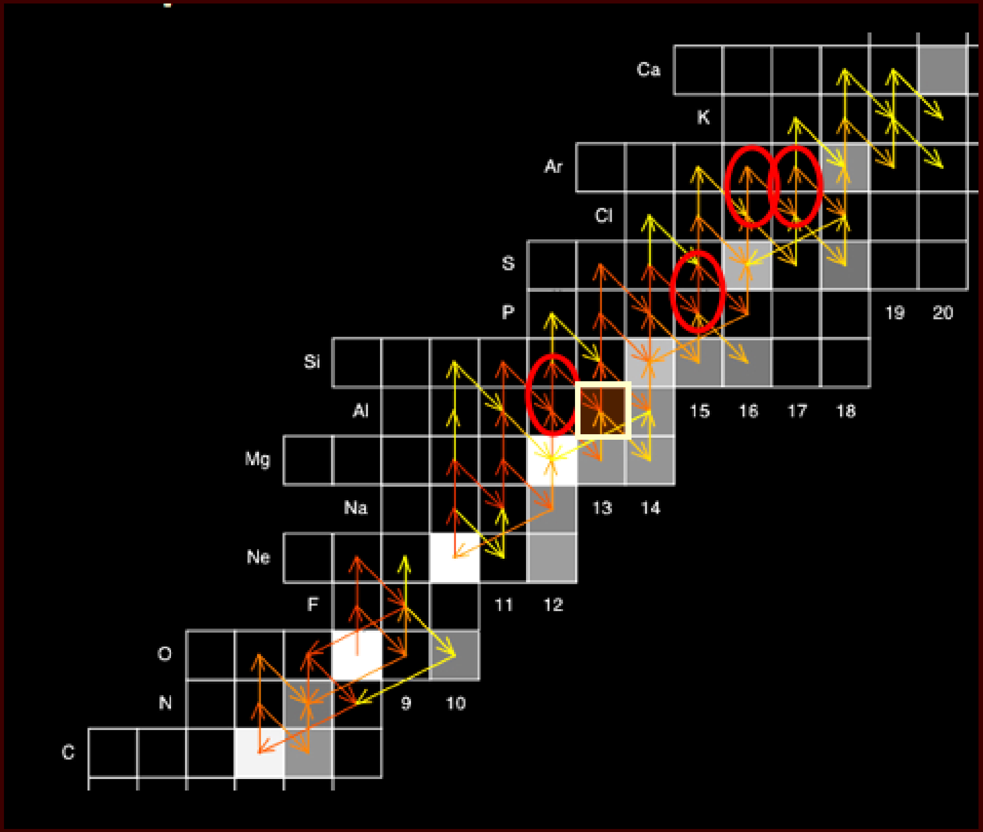
Must understand nucleosynthesis sites and events to explain the abundances

Overview of main astrophysical processes



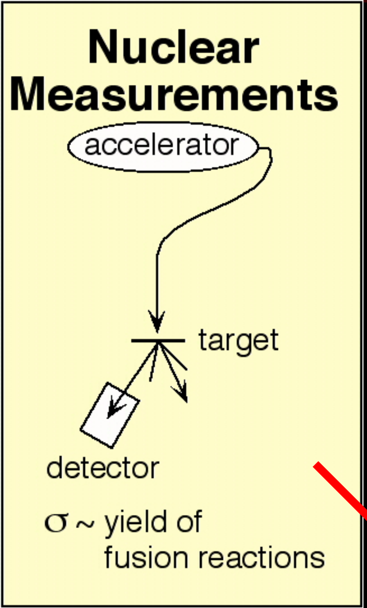
M.S. Smith and K.E. Rehm, Ann. Rev. Nucl. Part. Sci, 51 (2001) 91-130

Nuclear Astrophysics Studies



nuclear astrophysics studies (more in Luke Roberts’ lecture)

Nuclear Measurements



σ ~ yield of fusion reactions

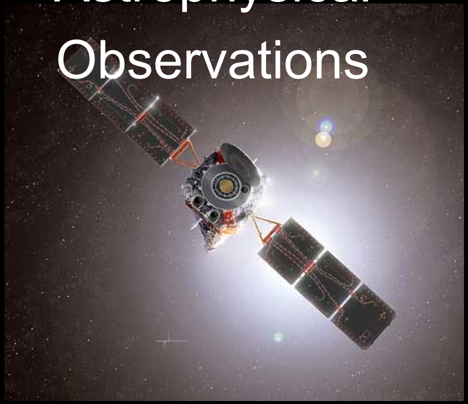
Nuclear Theory

nuclear properties
nuclei in a plasma
reaction rate formalism

Astrophysics Theory

Stellar Structure
Stellar Evolution
Hydrodynamics

Astrophysical Observations



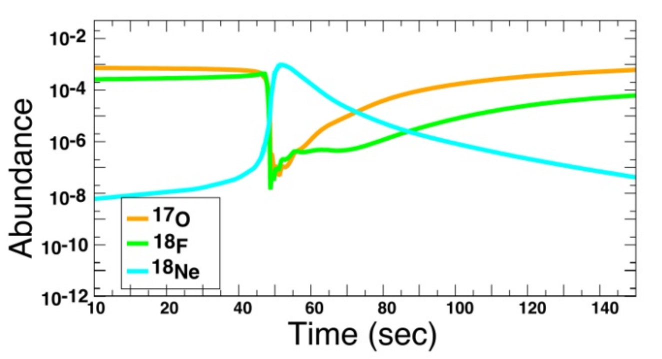
Thermonuclear Reaction Rates

Astrophysics Computer Simulation

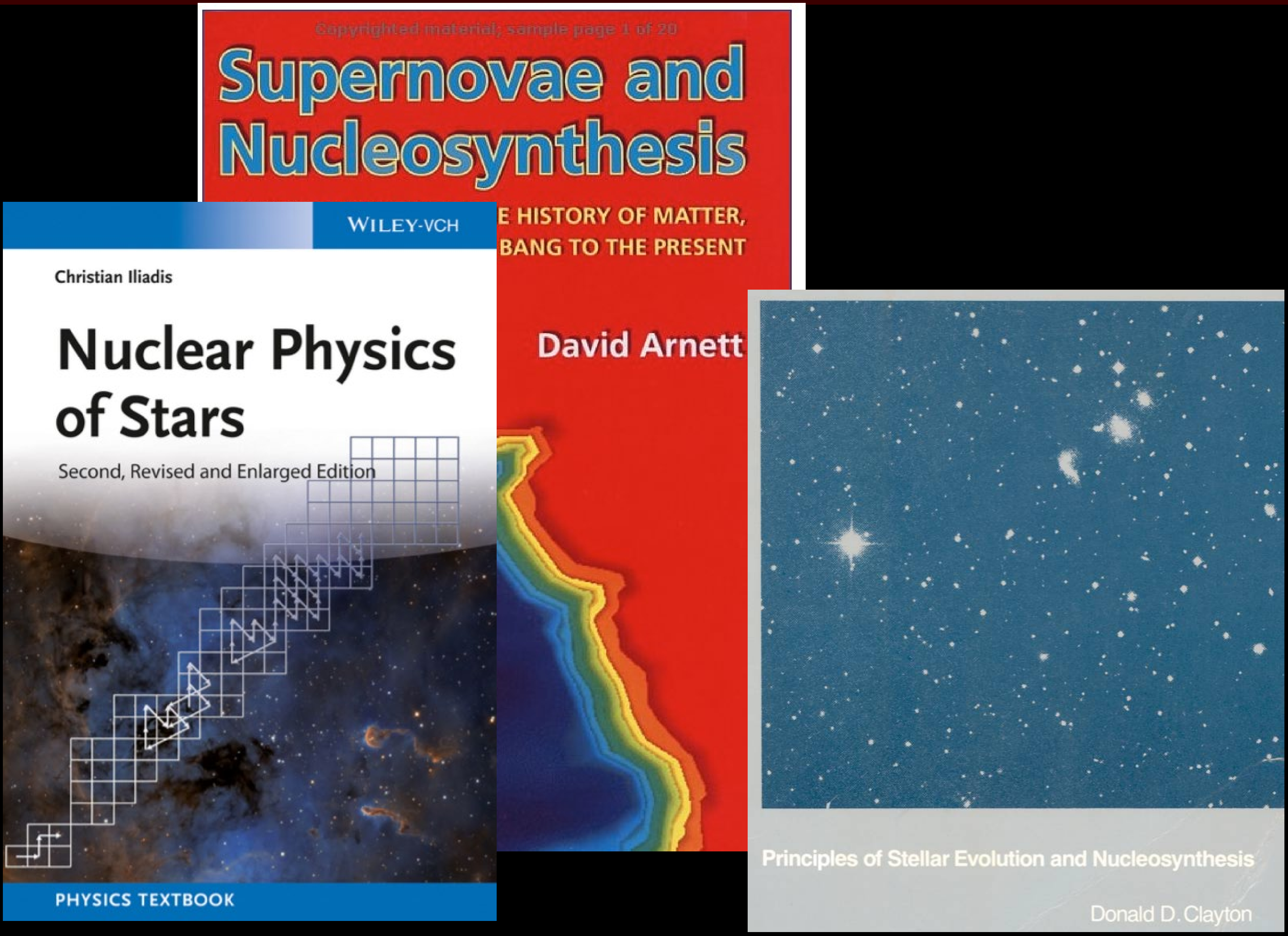
Goal: make simulation accurately represent working of stars

Repeat to improve models

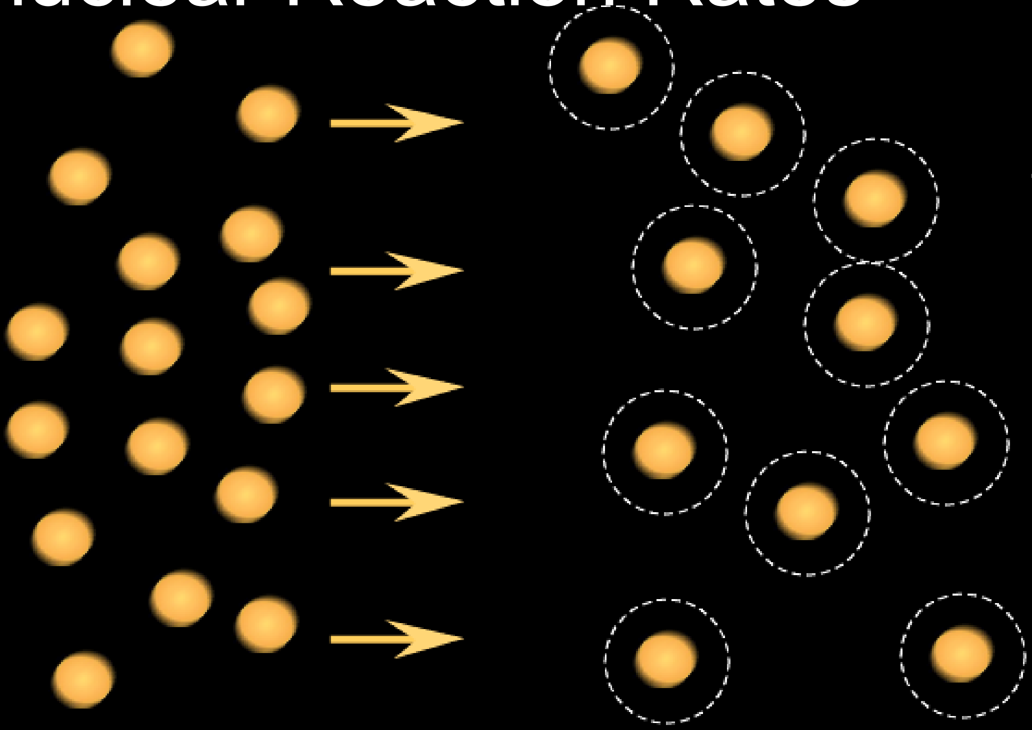
Astrophysical Observations ↔ Predictions



nuclear astrophysics studies



Thermonuclear Reaction Rates



Particles of type “1”

Particles of type “2”

effective area

Reactions / cm^3 / s =

relative flux particles “1” (cm^{-2} s^{-1})

• (number of particles “2” cm^{-3})

• effective area of each particle “2” for a reaction (cm^2)

Thermonuclear Reaction Rates

Define

N_1 = number of particles of type "**1**" per volume (cm^{-3})

N_2 = number of particles of type "**2**" per volume (cm^{-3})

v = relative velocity ($cm\ s^{-1}$)

$\sigma(v)$= effective cross sectional area of each particle "**2**" for a reaction (cm^2)

Then

$N_1 \cdot v$ = relative flux of "**1**" relative to "**2**" (particles $cm^{-2}\ s^{-1}$)

Reactions / cm^3 / s =

relative flux particles "**1**" ($cm^{-2}\ s^{-1}$)
• (number of particles "**2**" cm^{-3})
• effective area of each particle "**2**"
for a reaction (cm^2)

$$\text{Reactions / cm}^3\text{ / s} = (N_1 \cdot v) \cdot N_2 \cdot \sigma(v) = N_1\ N_2\ \sigma(v)\ v$$

$$\boxed{dN_1/dt = -N_1 N_2 \sigma(v)\ v}$$

Maxwell - Boltzmann Distribution

Rolfs & Rodney, pg.

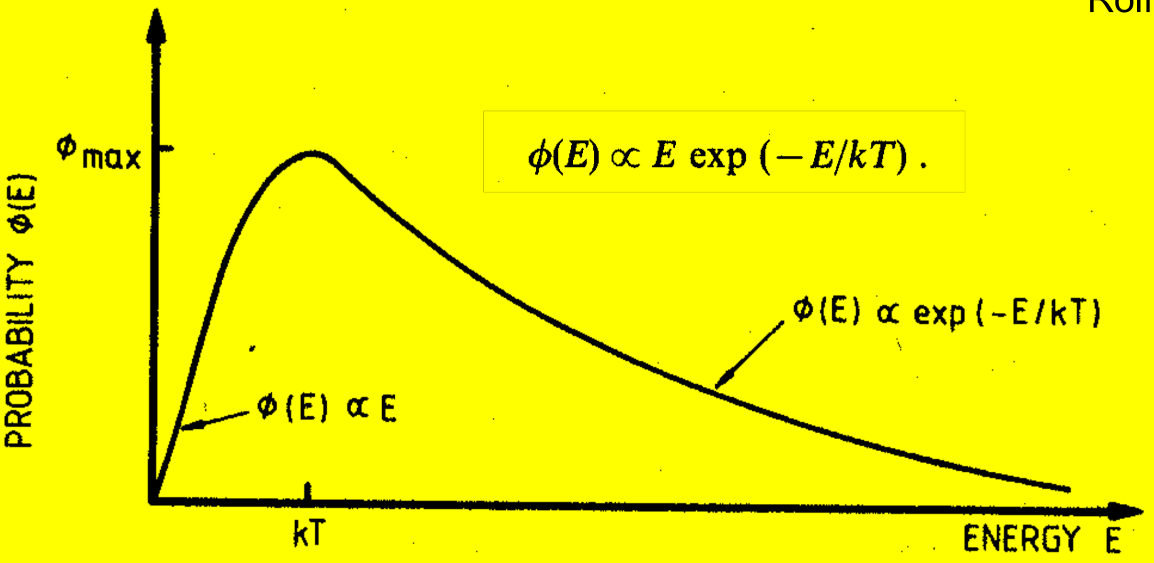


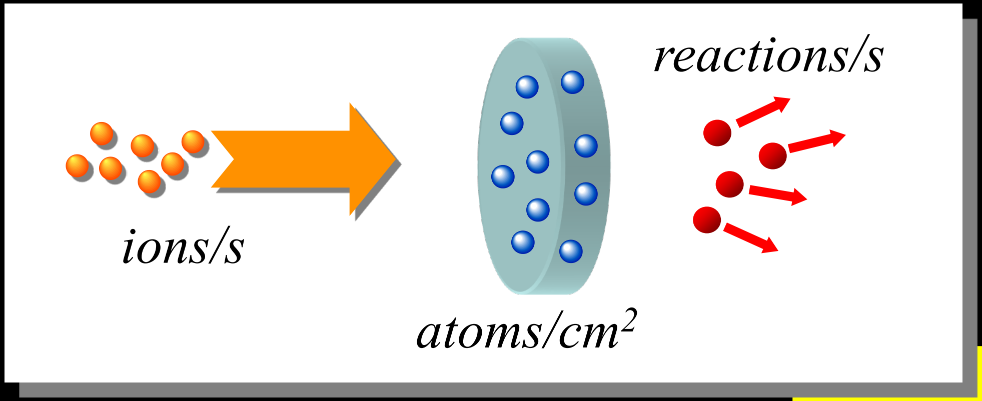
FIGURE 3.2. Shown schematically is the Maxwell-Boltzmann energy distribution of a gas characterized by the temperature T. The distribution exhibits a maximum at $E = kT$.

At any given **temperature**, there is a **distribution** of relative velocities (relative energies) between any pair of particles in the star

Need to **average** over these relative velocities to determine the interaction **rate** at a given **temperature**

velocity averaged cross section

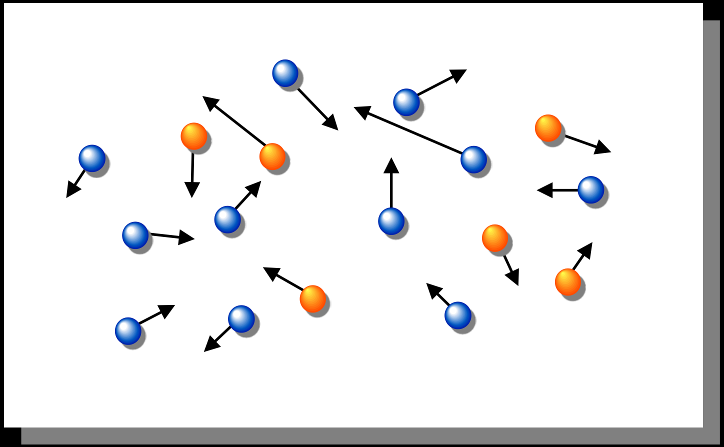
What you are used to in the lab:



cross section

$$\frac{reactions}{s} = \frac{ions}{s}\,\frac{atoms}{cm^2}\,\sigma$$

In astrophysical events:



reaction rate

$$\frac{reactions}{cm^3 s} = \int \frac{n_x}{cm^3}\,\frac{n_y}{cm^3}\, v\,\sigma(v)\,\phi(v)\,dv$$

$$\phi(v) = 4\pi v^2 \left(\frac{\mu}{2\pi kT}\right)^{3/2} \exp\left(-\frac{\mu v^2}{2kT}\right)$$

$$\frac{reactions}{cm^3 s} = \frac{n_x}{cm^3}\,\frac{n_y}{cm^3}\,\langle \sigma v \rangle$$

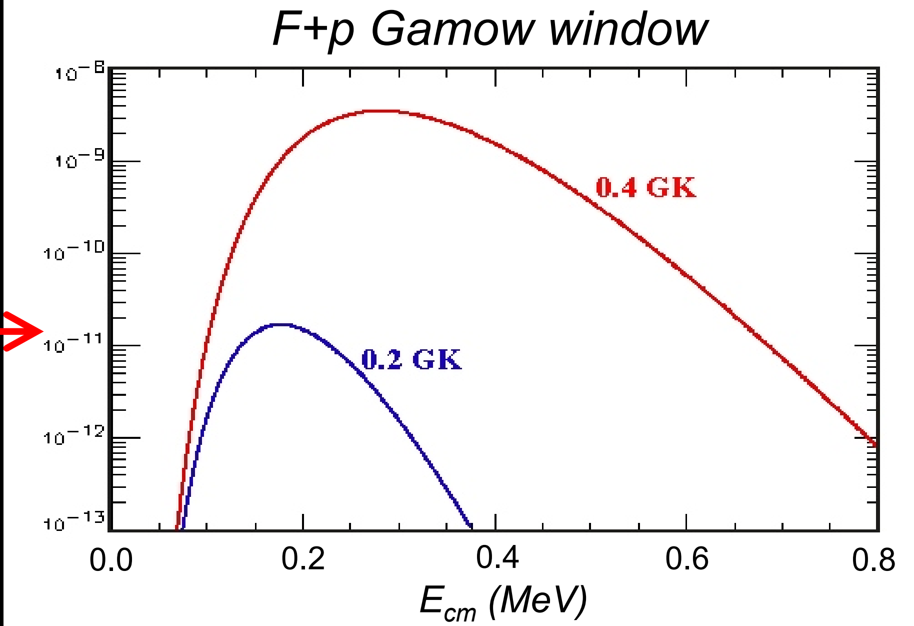
$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi\mu}}\,(kT)^{-3/2} \int_0^\infty \sigma E e^{-E/(kT)}\,dE$$

Gamow window

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

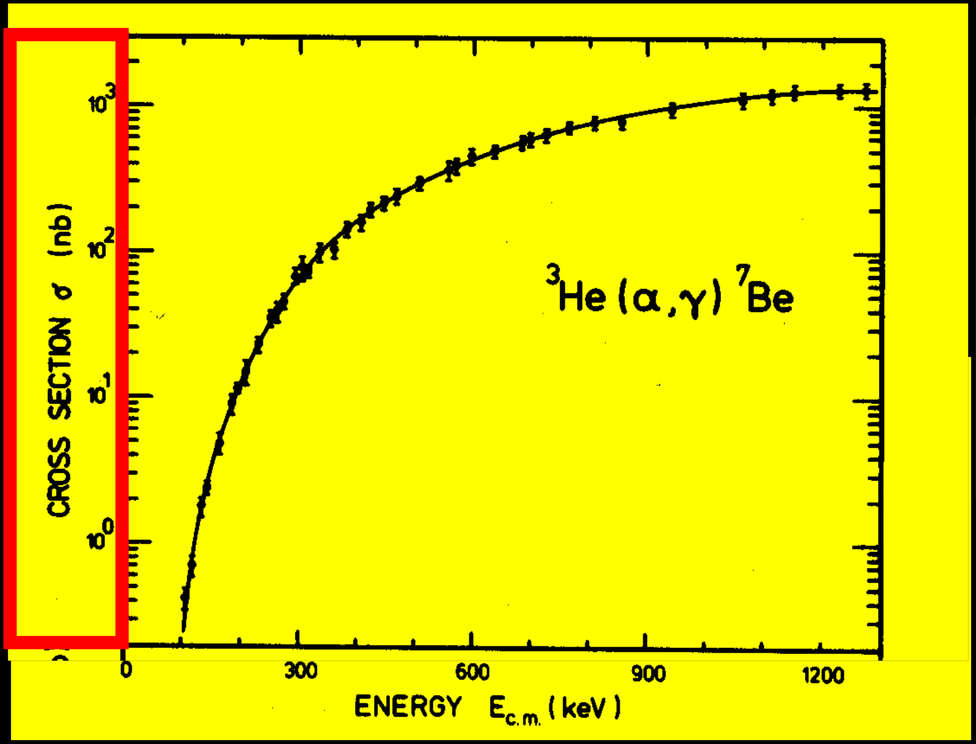
$$\sigma \equiv \frac{S}{E} e^{-\sqrt{E_G/E}} \qquad E_G \equiv \frac{2\mu}{\hbar^2} \left(\pi Z_1 Z_2 e^2\right)^2$$

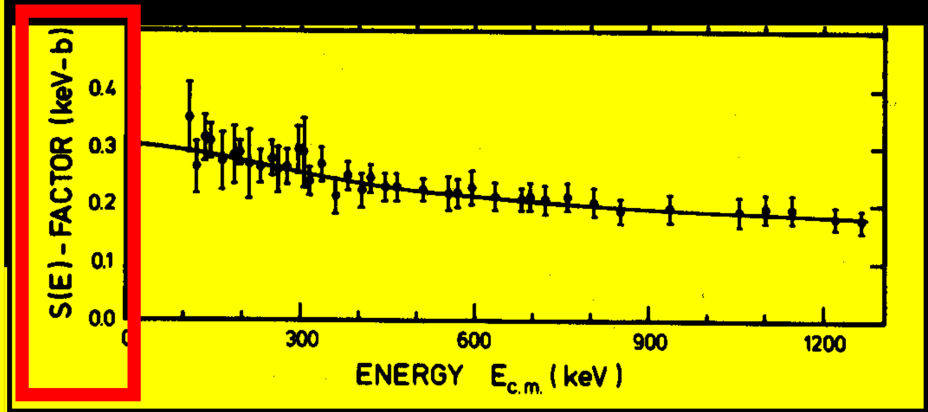
$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi \mu}} (kT)^{-3/2} \int_0^\infty S \overbrace{e^{-\sqrt{E_G/E}} e^{-E/(kT)}} dE$$



Reaction	*site*	*T (10^6 K)*	*kT (keV)*	*r_{turn} (fm)*	*r (fm)*	*E_0 (keV)*
p+p	sun	15	1.3	1100	2.5	6
p+^{14}N	CNO	30	2.6	3900	4.3	42
α+^{12}C	red giant	190	16	1060	4.8	300
p+^{17}F	nova	300	26	500	4.5	230
α+^{30}S	x-ray burst	1000	86	500	5.9	1800
^{3}He+^{4}He	big bang	2000	170	33	3.8	580

Non-Resonant Reactions





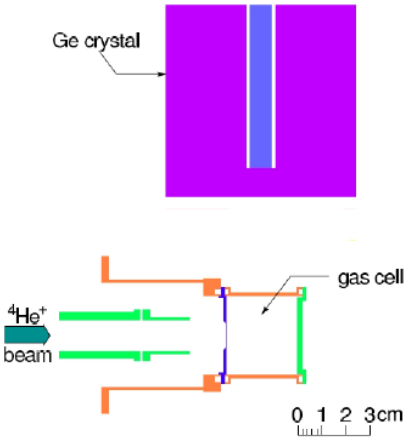
For many reactions, MOST of the energy dependence in σ(E) is described by the penetrability & nuclear size terms

→ S(E) is very slowly varying

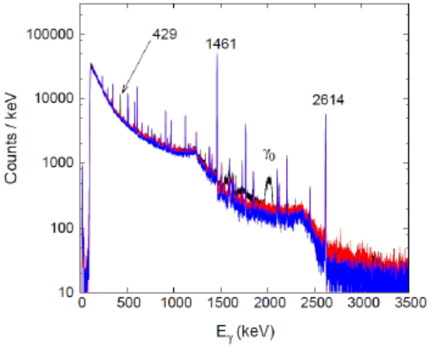
→ Advantageous to work with S(E) rather than σ(E)

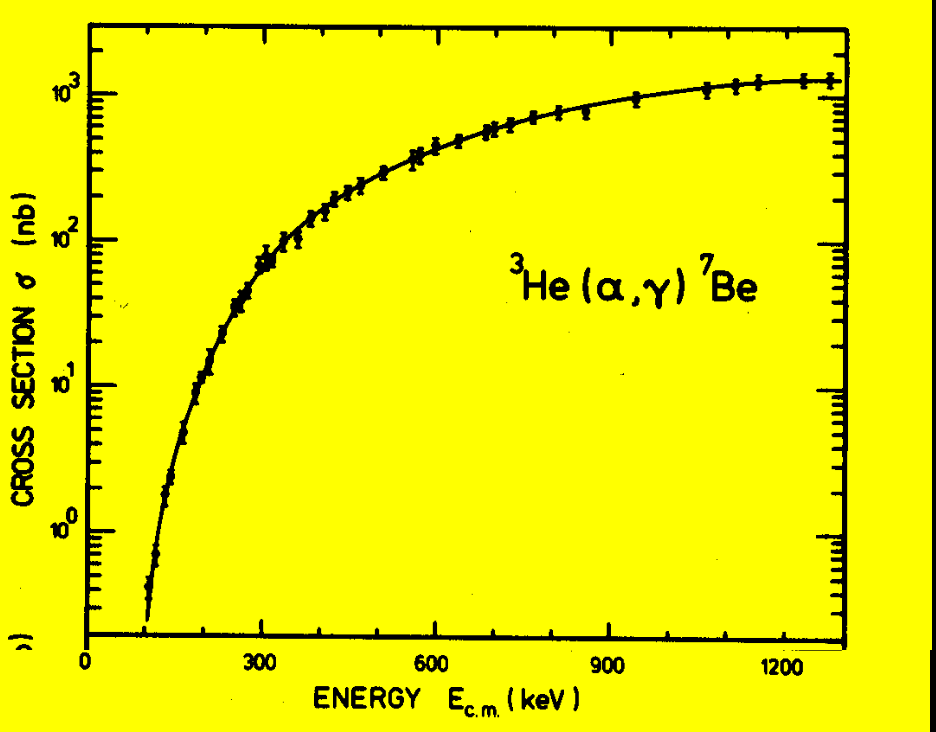
measure the cross section at all energies

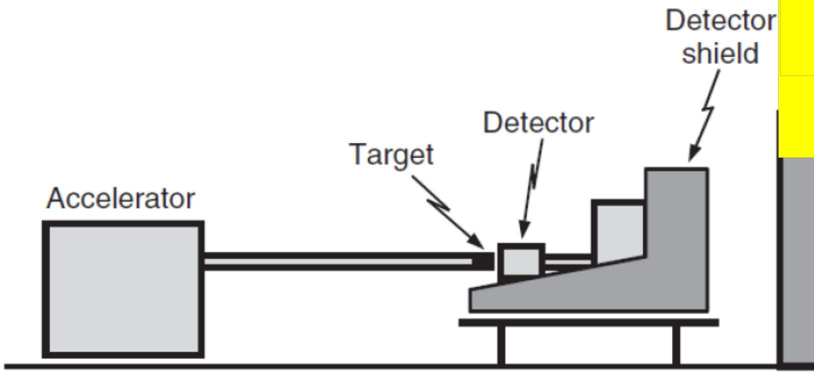
Setup



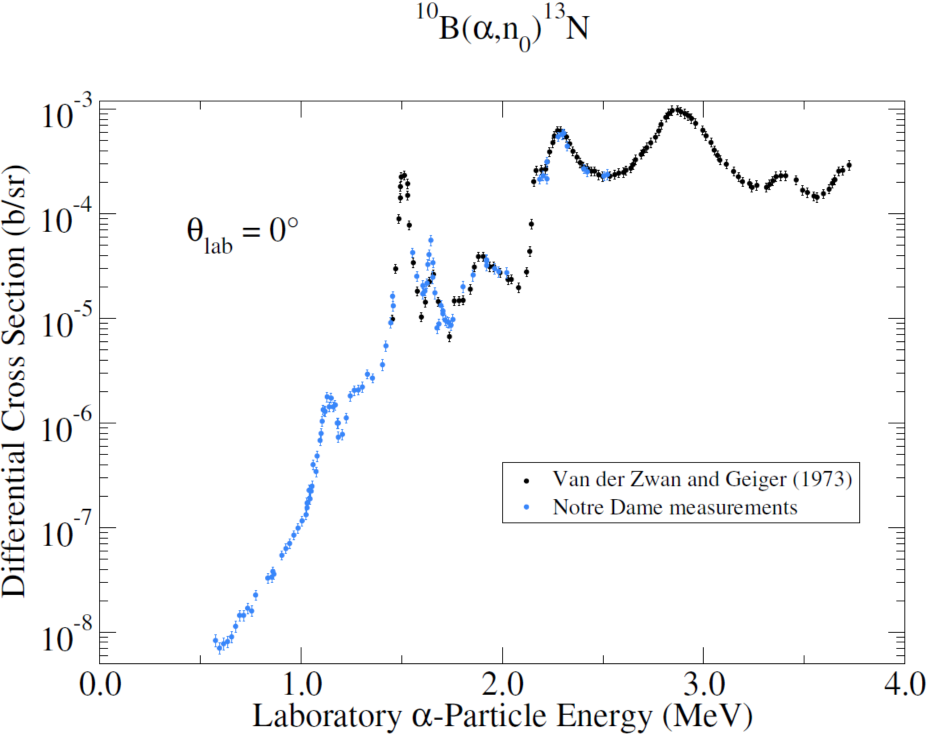
Spectrum at E_{cm} = 0.43 MeV



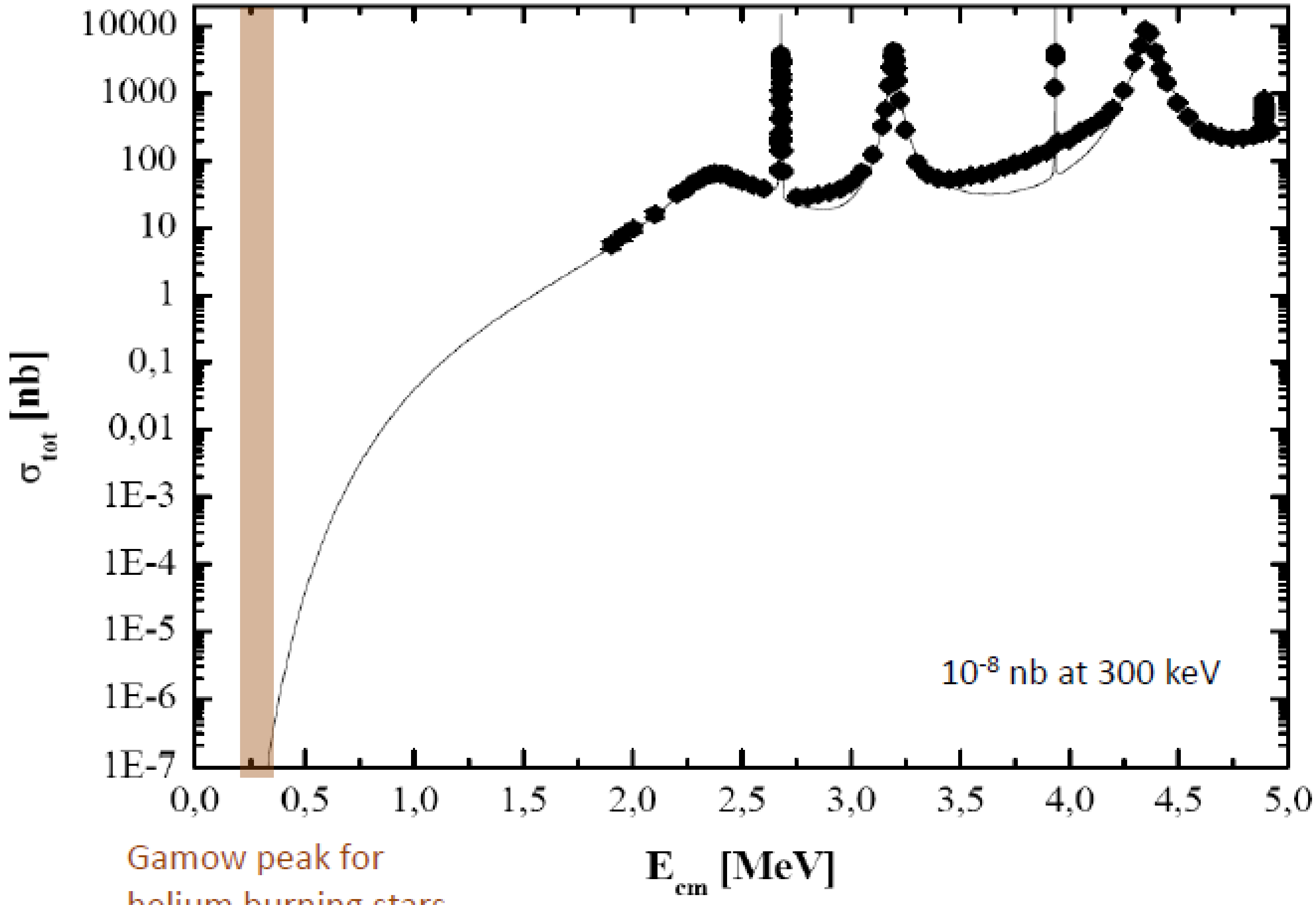




- Accelerator produces ion beam of one reactant at an appropriate energy
- Beam directed on a chemically stable target composed of other reactant
- Reaction like $A(a,\gamma)B$ or $A(a,b)B$ takes place in target
- Reaction products (usually γ rays or light particles) measured in detector
- Reduce background as much as possible (pure beam, clean target, shielding, …)


$^{10}B(\alpha,n_0)^{13}N$
$\theta_{lab} = 0°$
Differential Cross Section (b/sr)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
Laboratory α-Particle Energy (MeV)
0.0
1.0
2.0
3.0
4.0
Van der Zwan and Geiger (1973)
Notre Dame measurements

$^{12}C(\alpha,\gamma)^{16}O$: Experimental status of the art



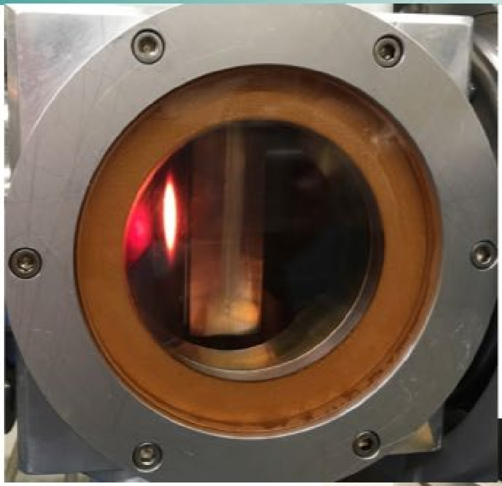
Gamow peak for
helium burning stars

Available data extend down to 1 MeV, **well above the Gamow peak energy** (about 200-300 keV) corresponding to the stellar temperatures experienced within the core of Helium burning stars (100 to 200 MK).

Research Highlights – Nuclear Astrophysics

LENA 240-keV ECR accelerator

Magnet upgrade planned, late 2018



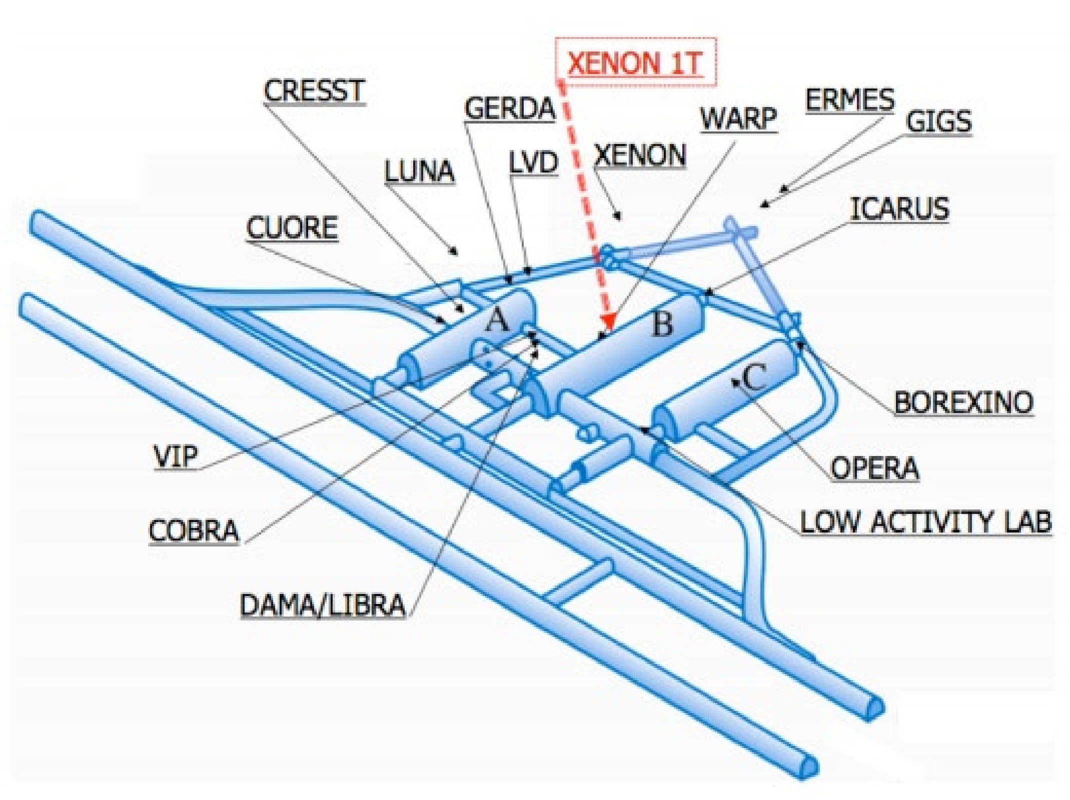
H⁺ beam on target:
~ 5.2 mA @ 200 keV

See:
https://m.phys.org/news/2018-08-renovations-big-nuclear-astrophysics-lab.html

Laboratory for Underground Nuclear Astrophysics

Laboratory
Underground
Nuclear
Astrophysics

LNGS
(1400 m rock shielding ≡ 4000 m w.e.)

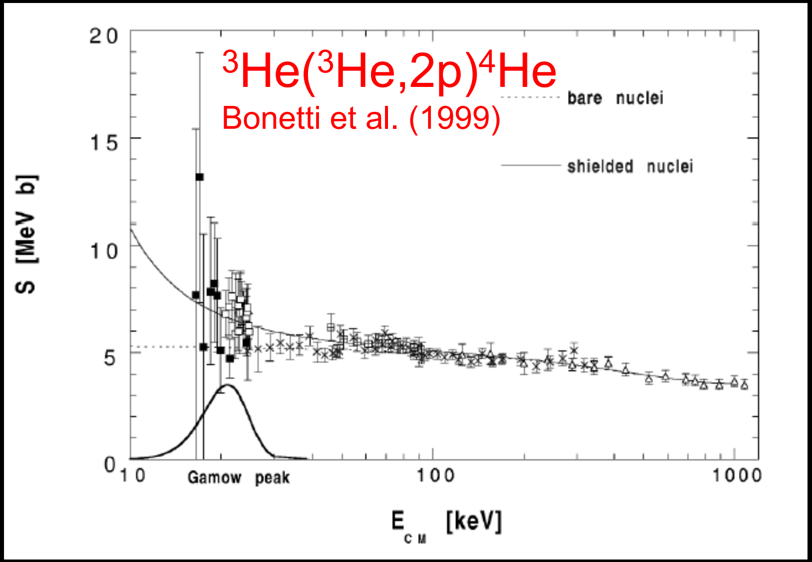


Radiation	LNGS/surface
Muons	10^{-6}
Neutrons	10^{-3}

Laboratory
Underground
Nuclear
Astrophysics

- Luna recent

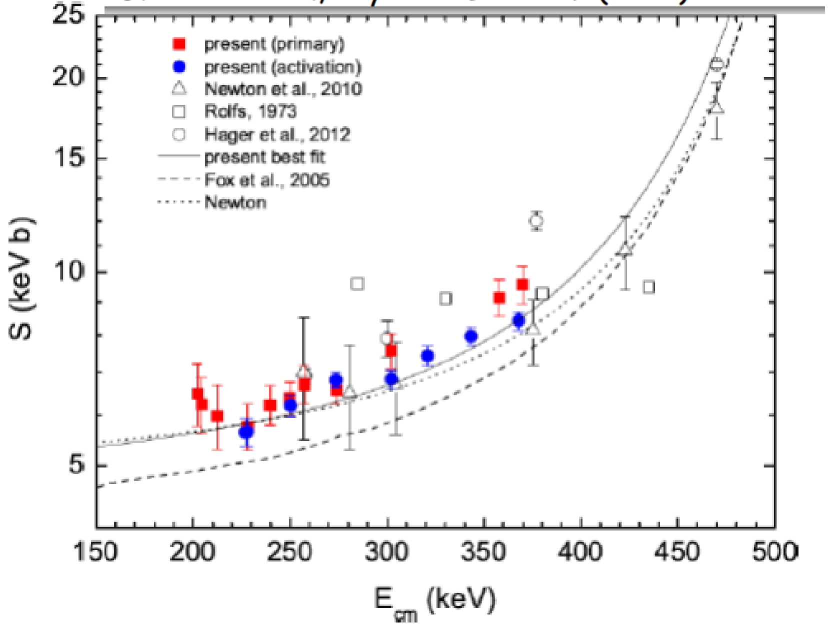
	reaction	Q-value (MeV)
completed	$^{17}O(p,\gamma)^{18}F$	5.6
just started	$^{17}O(p,\alpha)^{14}N$	1.2
	$^{18}O(p,\gamma)^{19}F$	8.0
	$^{18}O(p,\alpha)^{15}N$	4.0
	$^{23}Na(p,\gamma)^{24}Mg$	11.7
just started	$^{22}Ne(p,\gamma)^{23}Na$	8.8
completed	$D(\alpha,\gamma)^{6}Li$	1.47



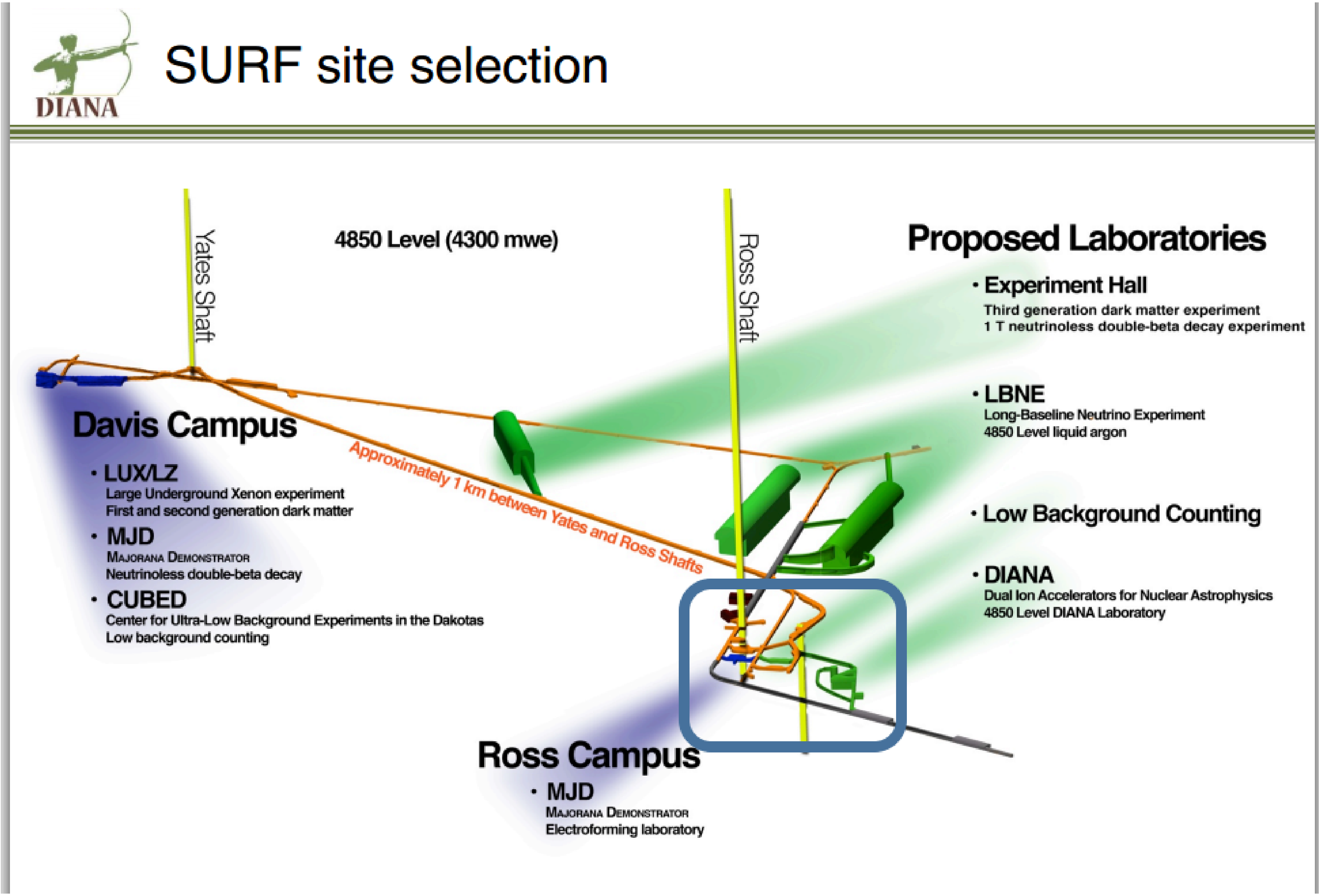
$^{3}He(^{3}He,2p)^{4}He$
Bonetti et al. (1999)

$^{17}O(p,\gamma)^{18}F$ results

D. Scott et al., Phys Rev Lett 109 (2012) 202501



Underground Lab in the U.S.



DIANA

SURF site selection

4850 Level (4300 mwe)

Davis Campus

- **LUX/LZ**
  Large Underground Xenon experiment
  First and second generation dark matter
- **MJD**
  Majorana Demonstrator
  Neutrinoless double-beta decay
- **CUBED**
  Center for Ultra-Low Background Experiments in the Dakotas
  Low background counting

Proposed Laboratories

- **Experiment Hall**
  Third generation dark matter experiment
  1 T neutrinoless double-beta decay experiment
- **LBNE**
  Long-Baseline Neutrino Experiment
  4850 Level liquid argon
- **Low Background Counting**
- **DIANA**
  Dual Ion Accelerators for Nuclear Astrophysics
  4850 Level DIANA Laboratory

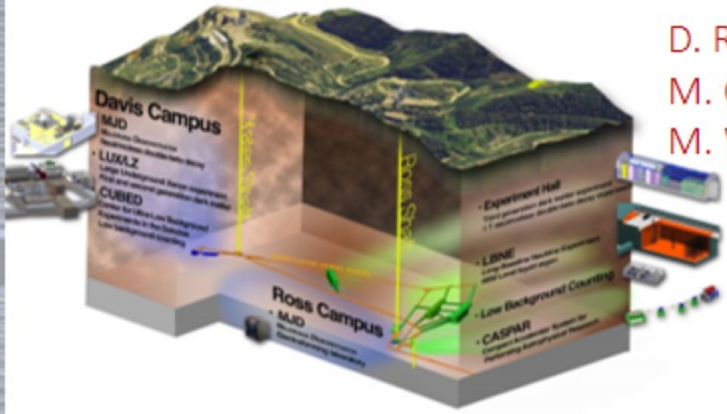
Ross Campus

- **MJD**
  Majorana Demonstrator
  Electroforming laboratory

CASPAR Status

CASPAR (**C**ompact **A**ccelerator **S**ystem for **P**erforming **A**strophysical **R**esearch) initiated with NSF, ND, CSM, SDSM&T & SURF funding.

First underground accelerator in the U.S.



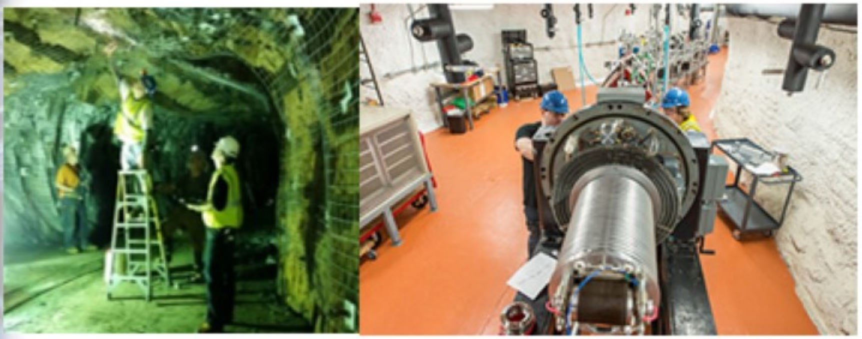
D. Robertson
M. Couder
M. Wiescher


Fall 2015


Spring 2016


Fall 2016

JN accelerator moved from NSL.



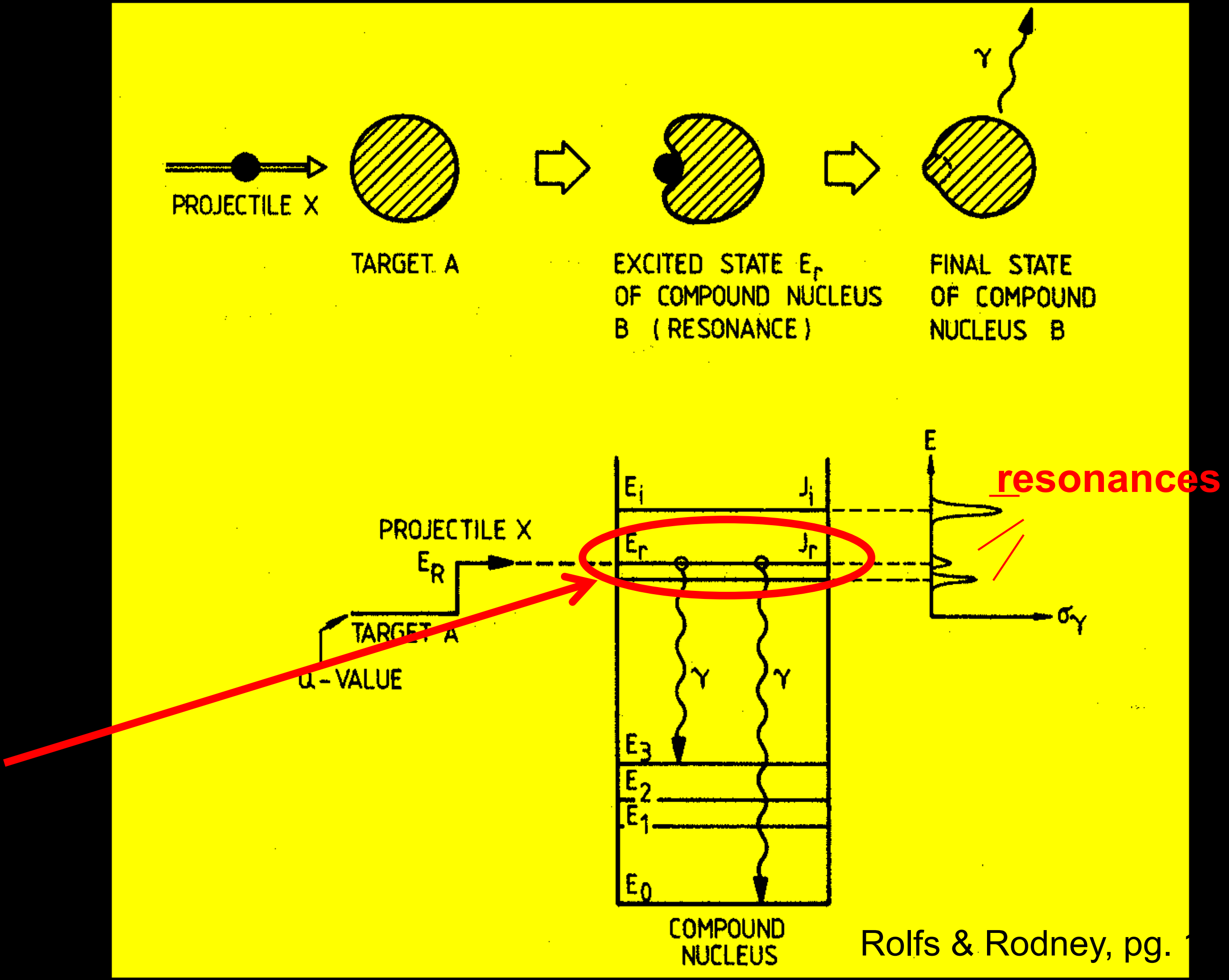
Commissioned March 2018.

First operating deep-underground accelerator in the U.S.

Resonant Reaction Rates

The presence of a **nuclear resonance** with an energy in the Gamow Window can dramatically increase the reaction rate - by factors of 10 to 10^7 in some cases

The **search** for these resonances and **measurement** of their properties is **extremely important**

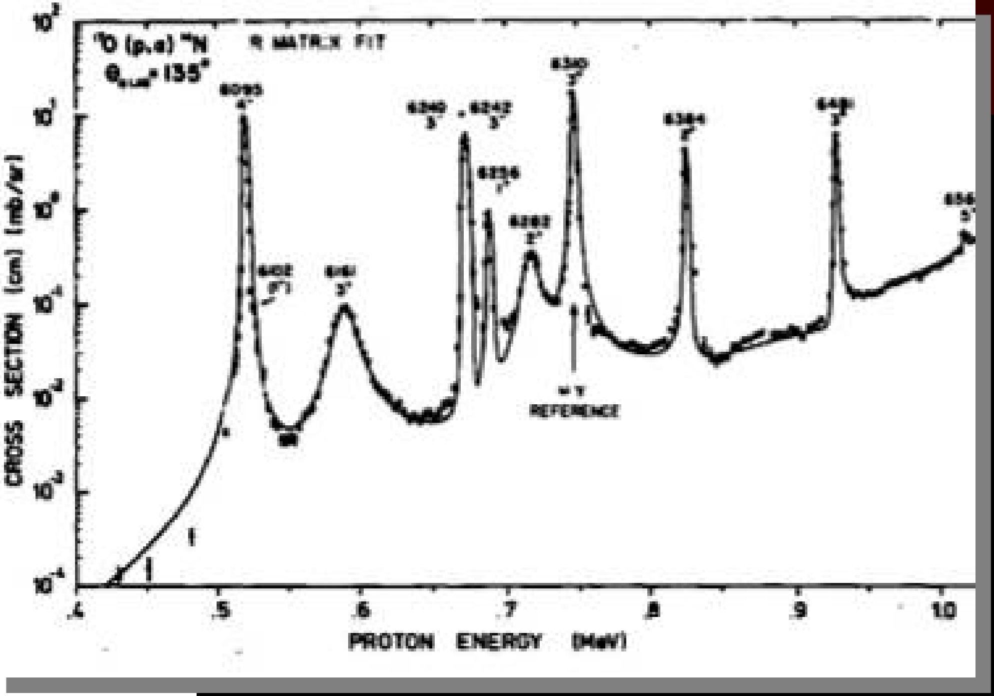


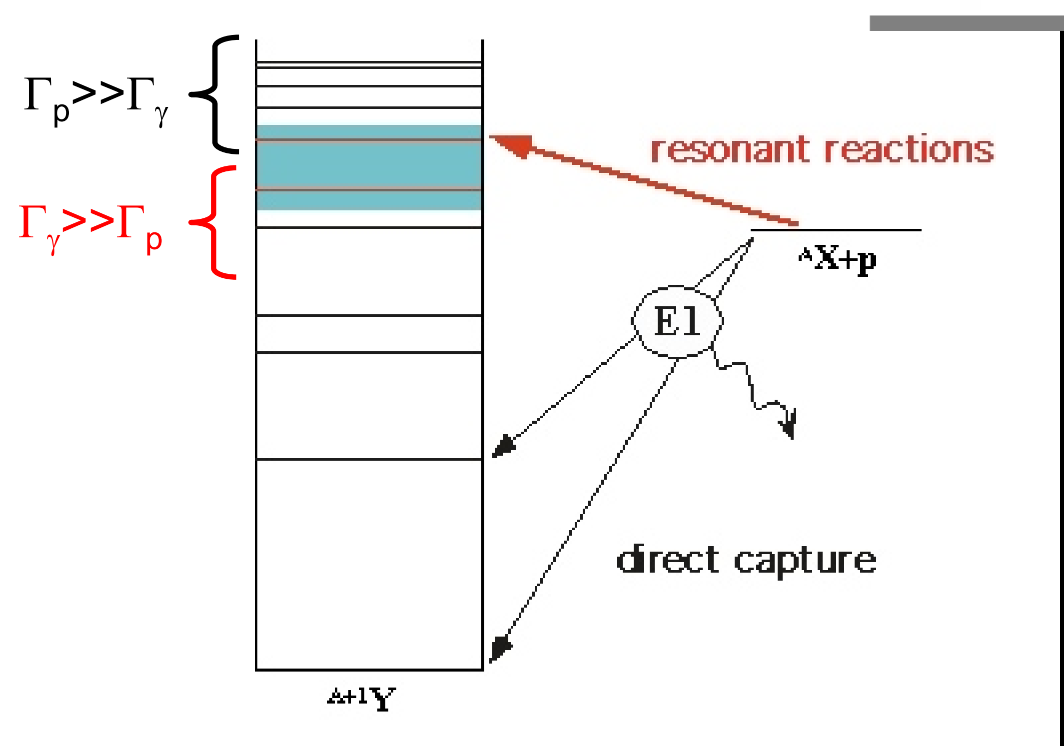
Rolfs & Rodney, pg.

resonance reaction rates

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

$$\sigma(E) = \pi \lambda\!\!\!^{-2} \frac{2J+1}{(2J_x+1)(2J_y+1)} \frac{\Gamma_x \Gamma_y}{(E-E_r)^2 + (\Gamma/2)^2}$$





If resonance is narrow

$$\langle \sigma v \rangle = \left(\frac{2\pi}{\mu} kT\right)^{3/2} \hbar^2 (\omega\gamma) e^{-E_r/kT}$$

E_r & J^π are most important

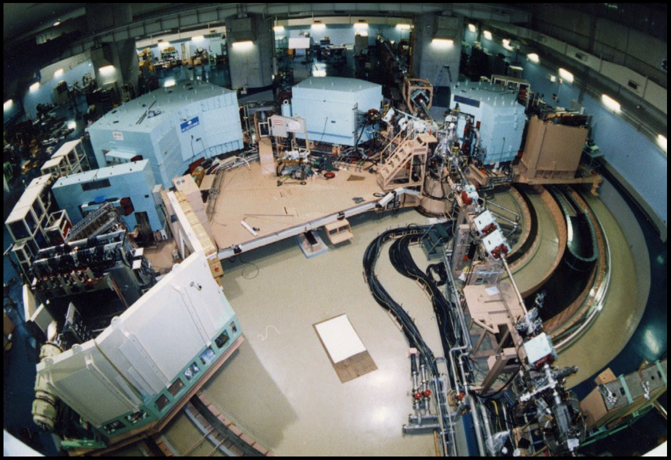
$$\omega\gamma = \frac{2J+1}{(2J_x+1)(2J_y+1)} \frac{\Gamma_x \Gamma_y}{\Gamma}$$

“resonance strength”

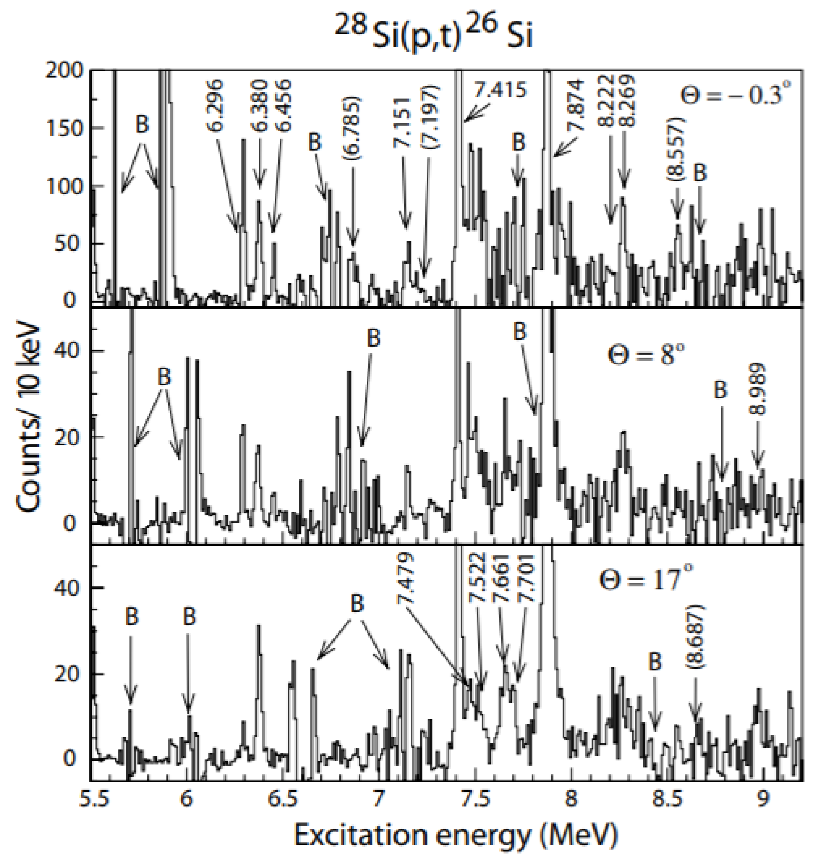
Indirect Approach – Measure E_x With Alternative Reaction

A(a,b)B* - energies of ejectiles (b's) imprinted with quantized energies populating E_x in B*

Magnetic Spectrometers can precisely measure ejectile E

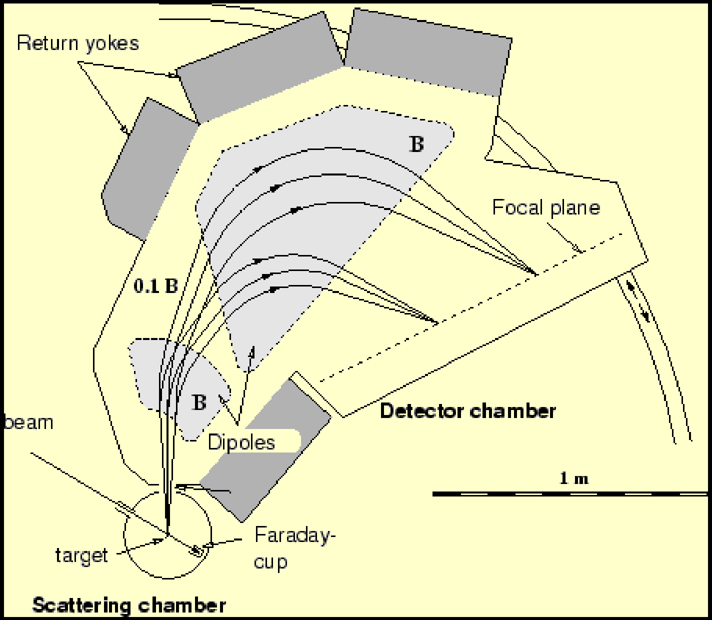


Grand Raiden Spectrometer (Osaka)

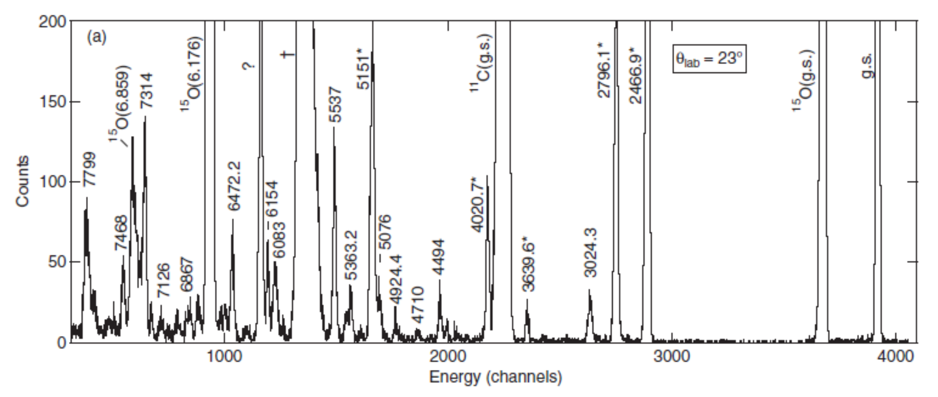


Matic et al. (2010)

Enge Split Pole Spectrometer



$^{40}Ca(^{3}He,^{4}He)^{39}Ca$

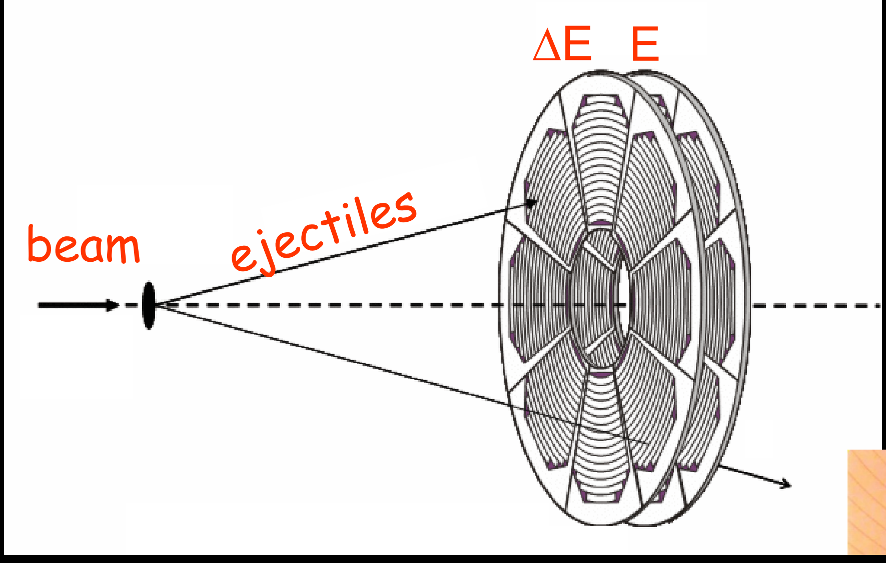


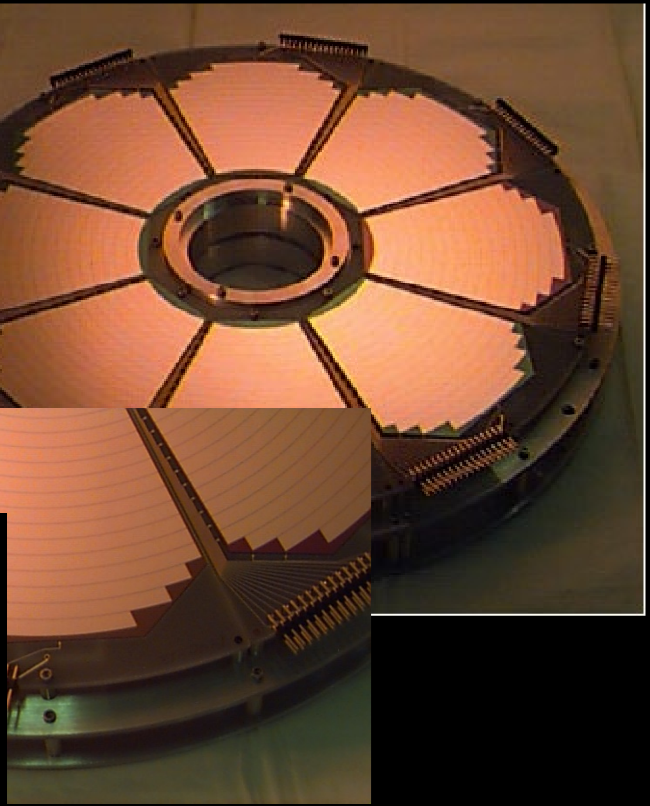
Setoodehnia et al. (2018)

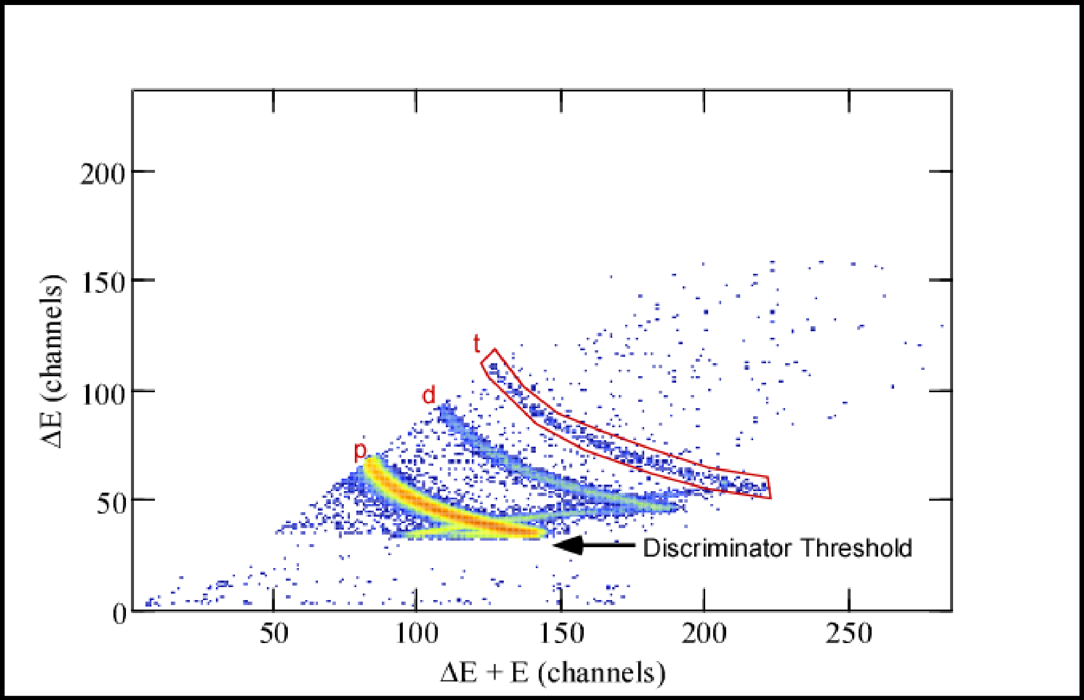
In the U.S., Enge spectrometers at TUNL, Florida State, and Notre Dame. Other spectrometers at Texas A&M and Michigan State.

- Advantages: High resolution, Scattered beam steered away from detectors.
- Disadvantage: low acceptance, long counting times, difficult to measure angular distribution

High Efficiency Detector Arrays

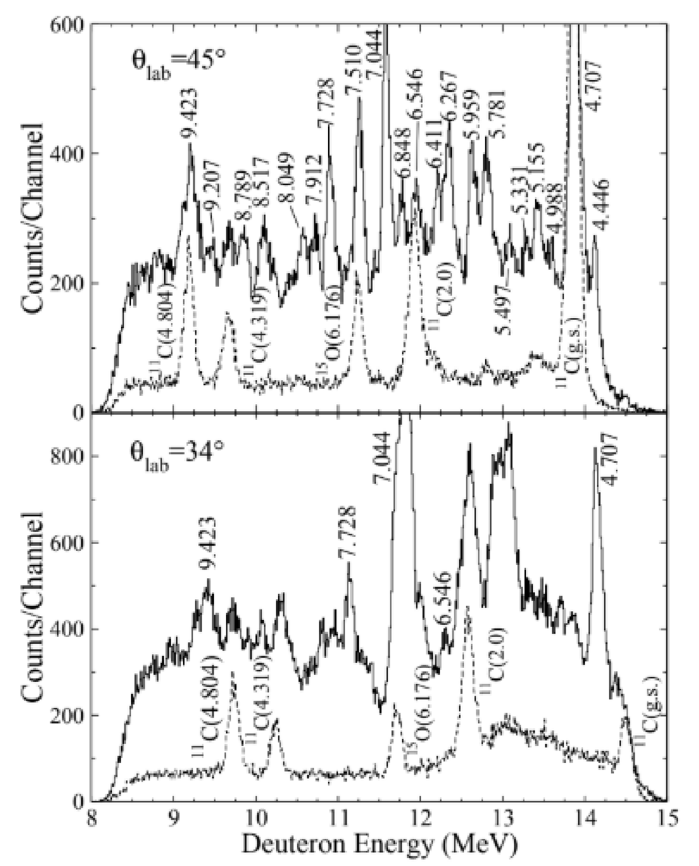


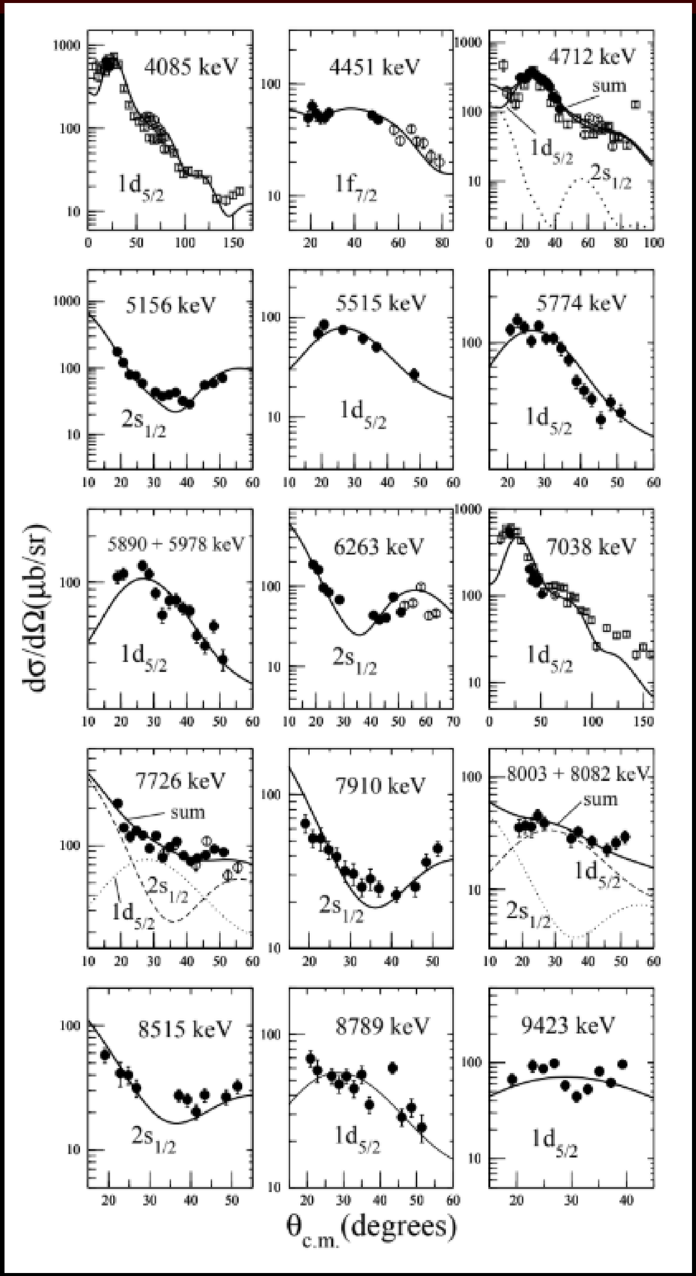




tract angular
of strips
verage to reduce uncertainties

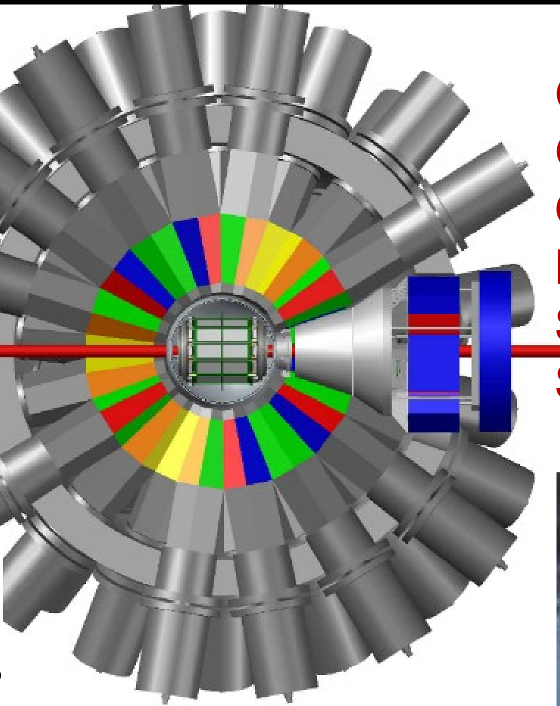
^{32}S(p,d)^{31}S – Z. Ma et al. (2007)



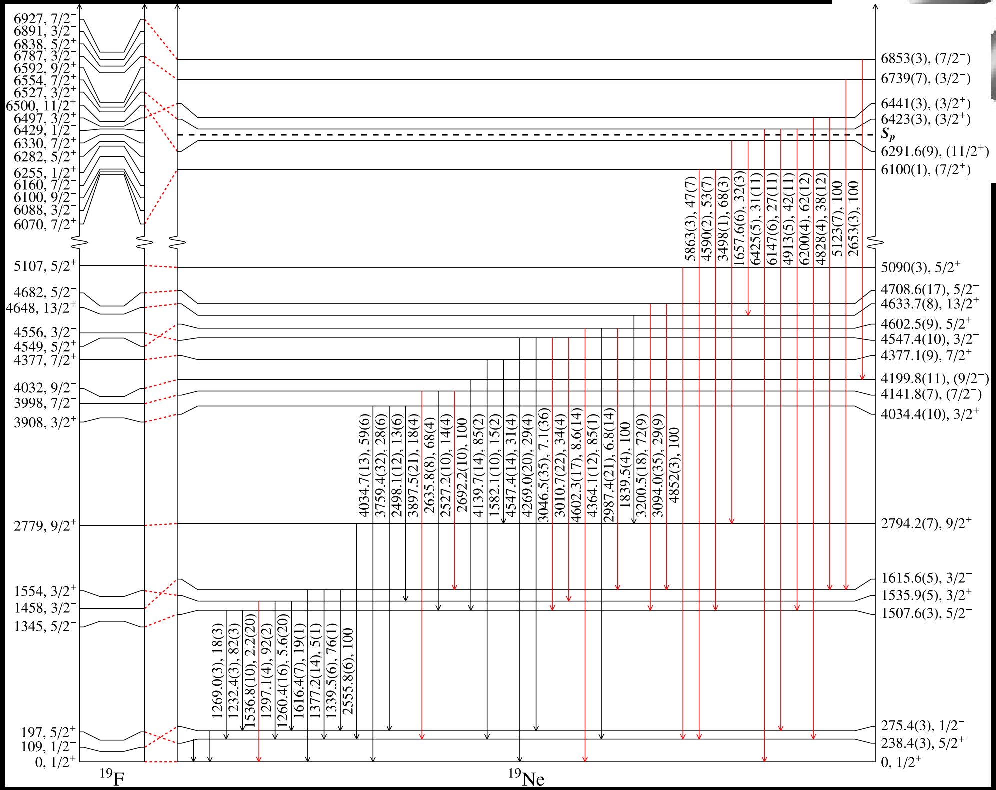


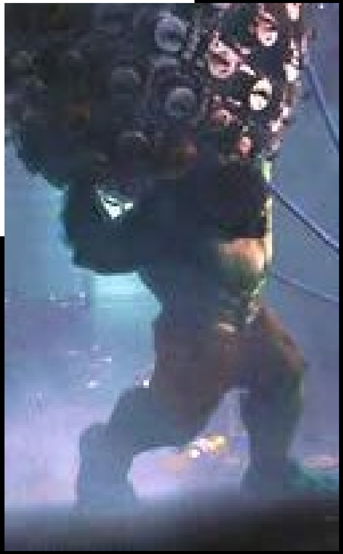
If studying a transfer reaction that proceeds in a single step, Distorted Wave Born Analysis (DWBA) can be used to extract angular momentum transfer from angular distributions. Can be used to constrain spins.

Measuring decay γ-rays to determine level scheme



GODDESS – Gammasphere ORRUBA Dual Detectors for Structure Studies





Hall et al. (2019) – $^{19}F(^{3}He,t)^{19}Ne^{*}(\gamma)$ reaction with GODDESS.

21 New transitions observed.

Determining partial widths

If resonance is narrow

$$\langle \sigma v \rangle = \left(\frac{2\pi}{\mu} kT \right)^{3/2} \hbar^2 (\omega\gamma) e^{-E_r/kT}$$

E_r & J^π are most important

$$\omega\gamma = \frac{2J+1}{(2J_x+1)(2J_y+1)} \frac{\Gamma_x \Gamma_y}{\Gamma}$$

"resonance strength"

If $\Gamma = \Gamma_x + \Gamma_y$ then factor $\Gamma_x\Gamma_y/\Gamma$ can be re-written in terms of

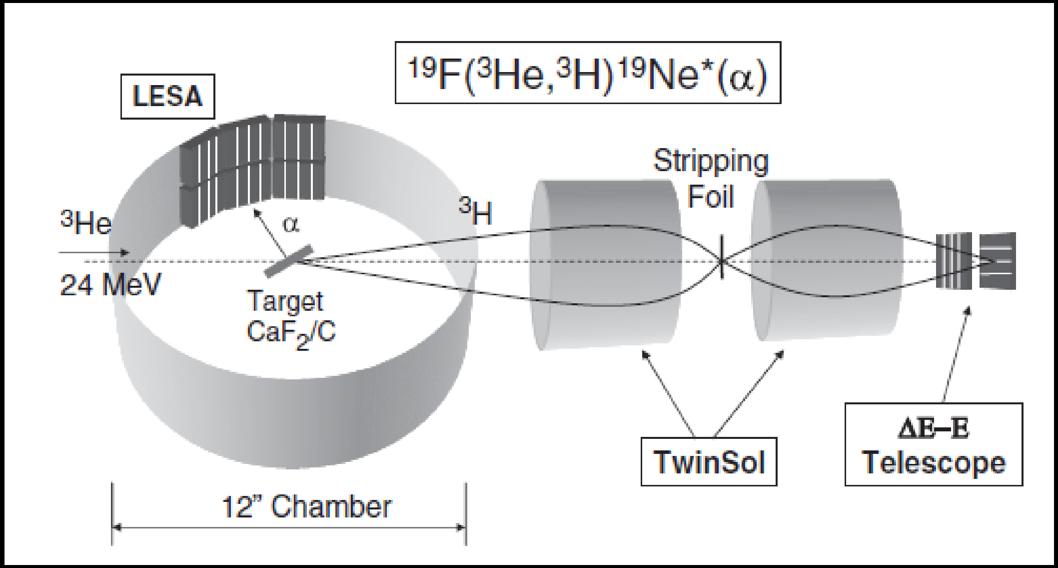
Branching ratio of one decay $B_x = \Gamma_x/\Gamma$ and

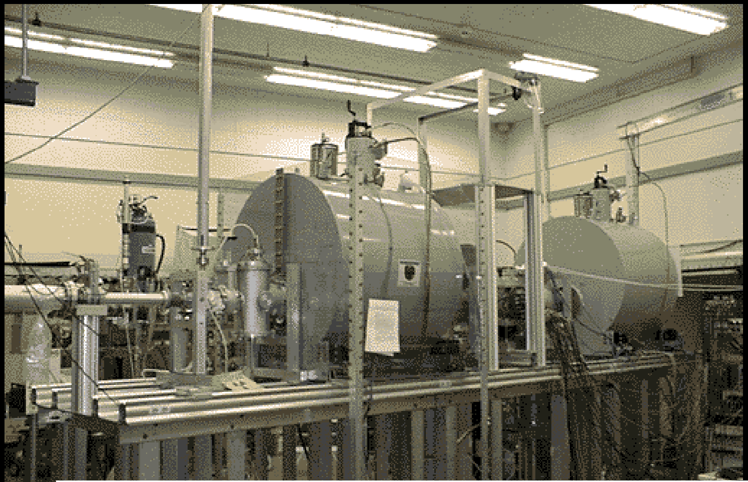
Lifetime = $\tau = \hbar/\Gamma$ as

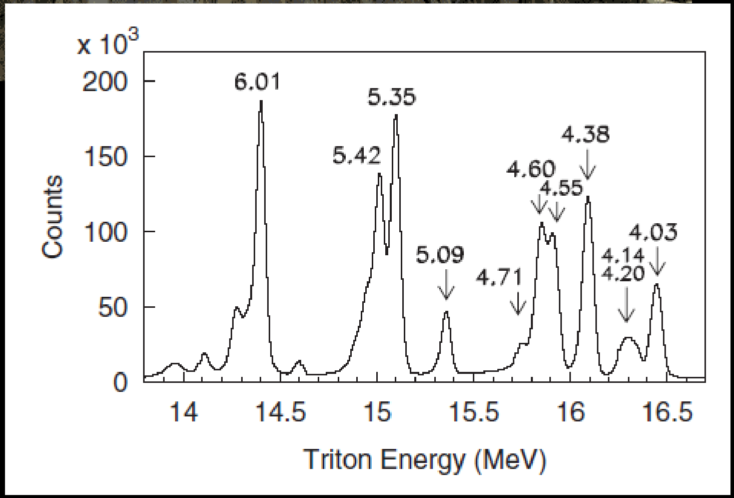
$$\frac{\Gamma_x \Gamma_y}{\Gamma} = \frac{B_x(1-B_x)\hbar}{\tau}$$

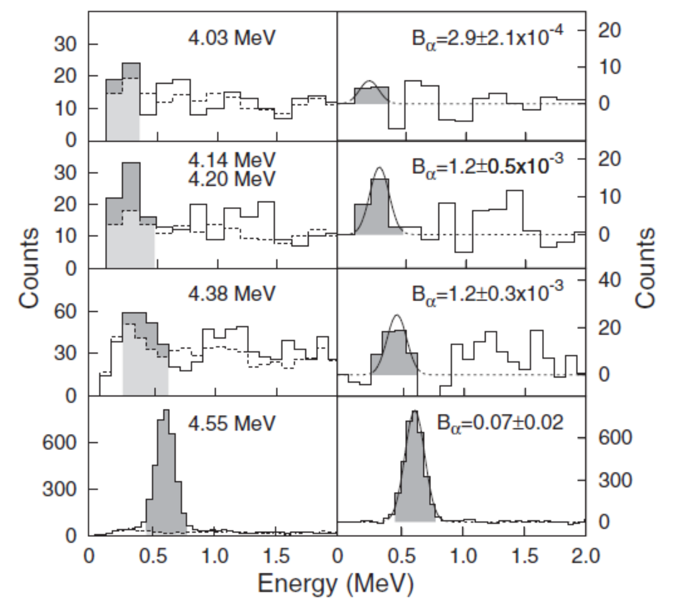
If we measure decay branching ratios and lifetimes for astrophysically important states, we can estimate the reaction rate.

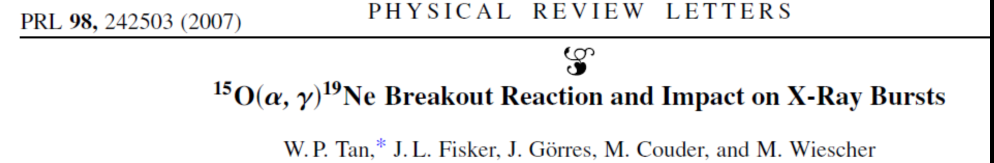
Measuring α branching ratio of important ^{19}Ne state











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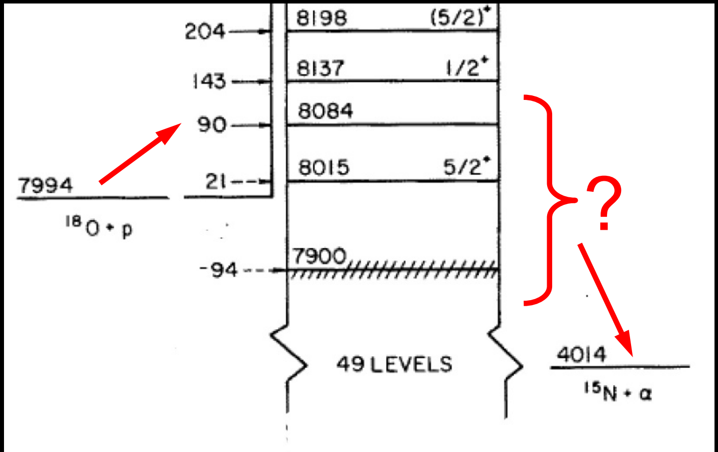
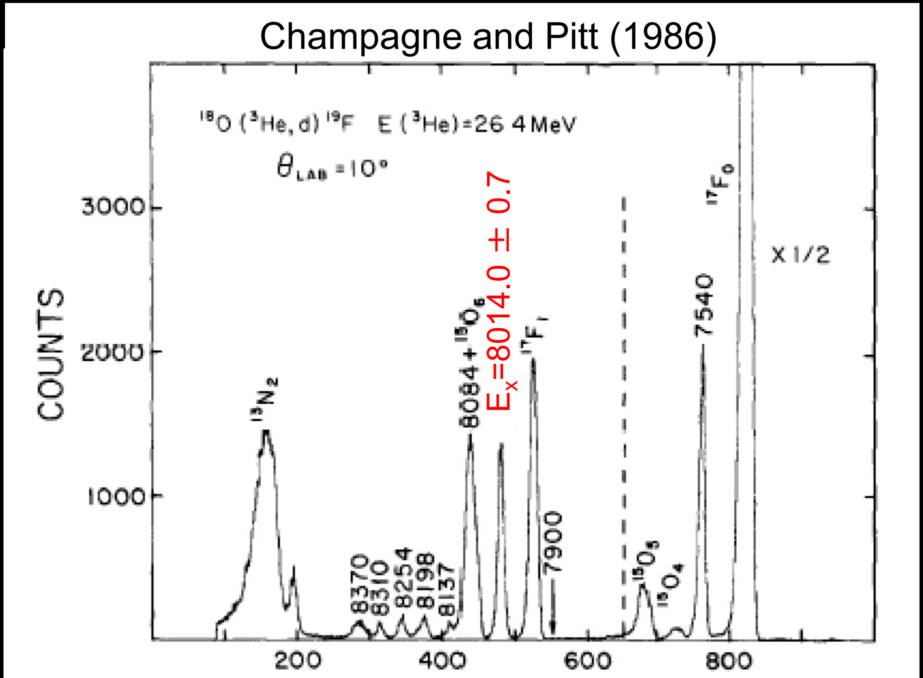
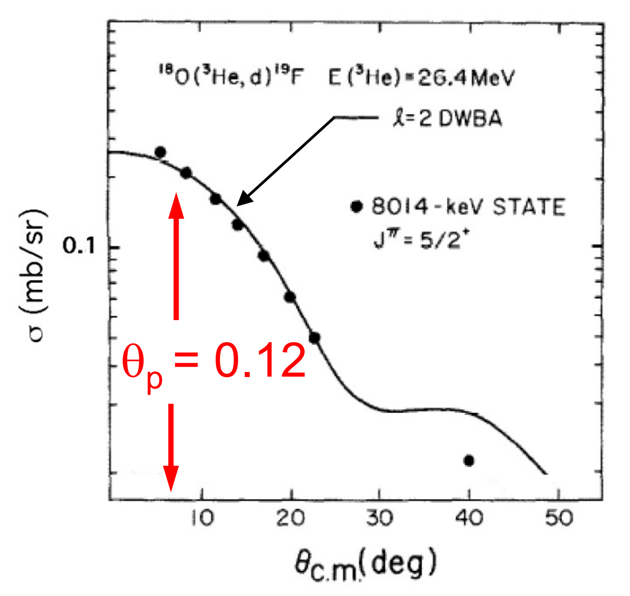
$^{15}O(\alpha,\gamma)^{19}$Ne Breakout Reaction and Impact on X-Ray Bursts

W. P. Tan,* J. L. Fisker, J. Görres, M. Couder, and M. Wiescher

(^{3}He,d) on stable targets to determine (p,γ) rates




Champagne and Pitt (1986)



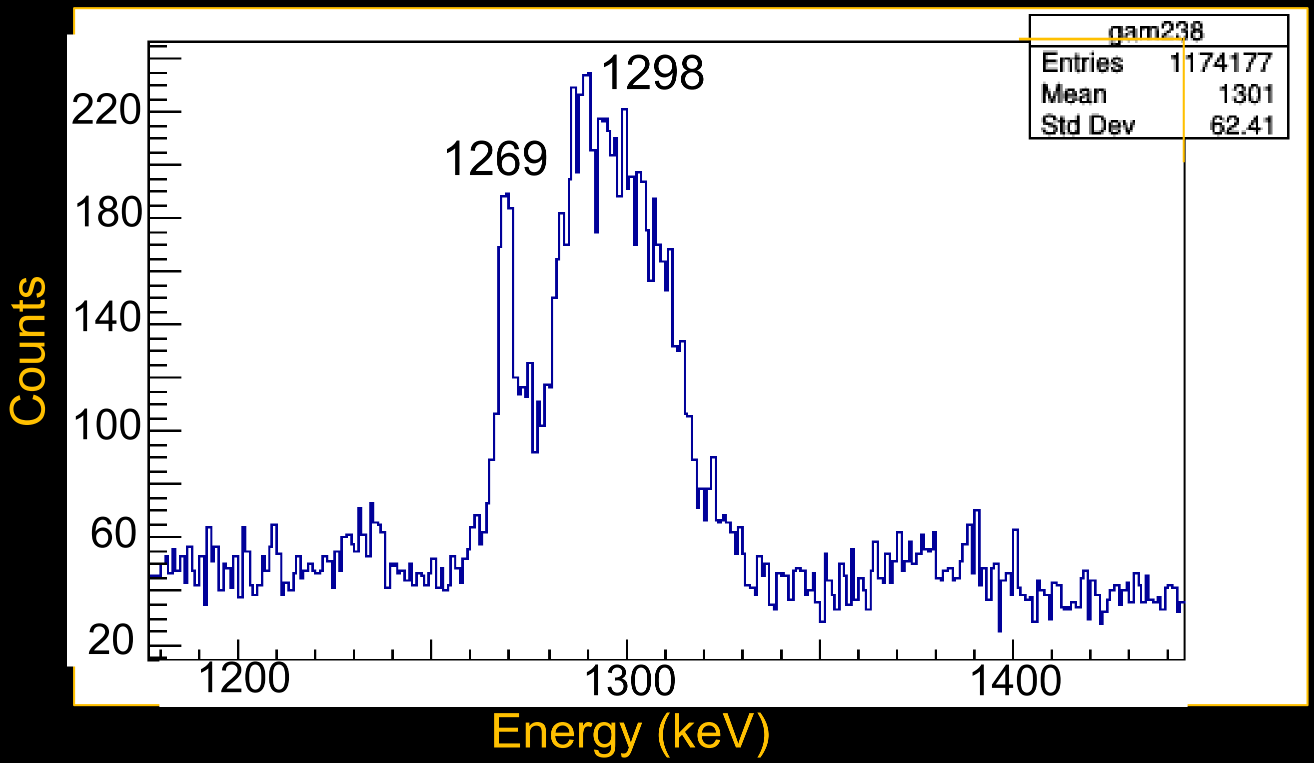
$$\Gamma_p = 2\left(\frac{\hbar^2}{\lambda\mu R}\right)\left(\frac{\theta_p^2}{F_\ell^2 + G_\ell^2}\right) \longrightarrow \Gamma_p = 2\text{x}10^{-19}\ \text{eV}$$

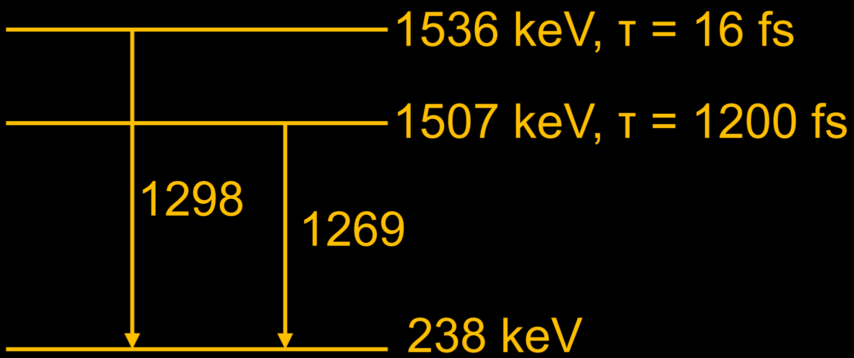
1 mA p + ^{18}O → 1 event / 3x10^5 years

γ-ray line shapes sensitive to lifetime

Hall et all. (2019)

^{19}F(^{3}He,t)^{19}Ne*(γ)




1536 keV, τ = 16 fs

1507 keV, τ = 1200 fs

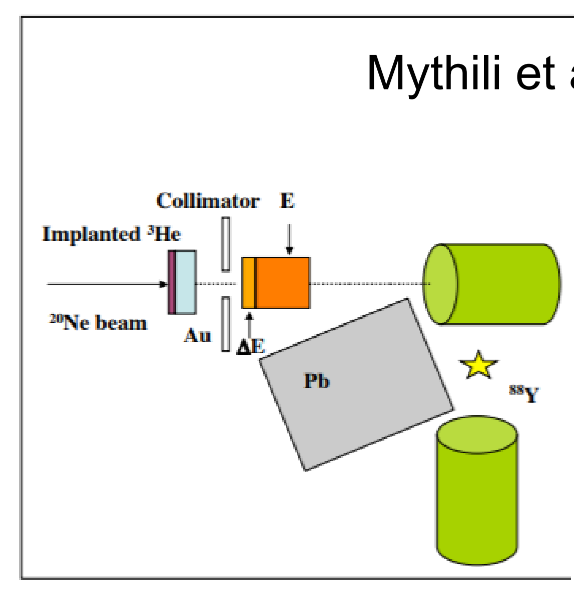
1298

1269

238 keV

- ^{19}Ne kinetic energy ranged from 0.5 to 4 MeV
- β ranged from 0.005 to 0.025

Doppler Shift Attenuation Method



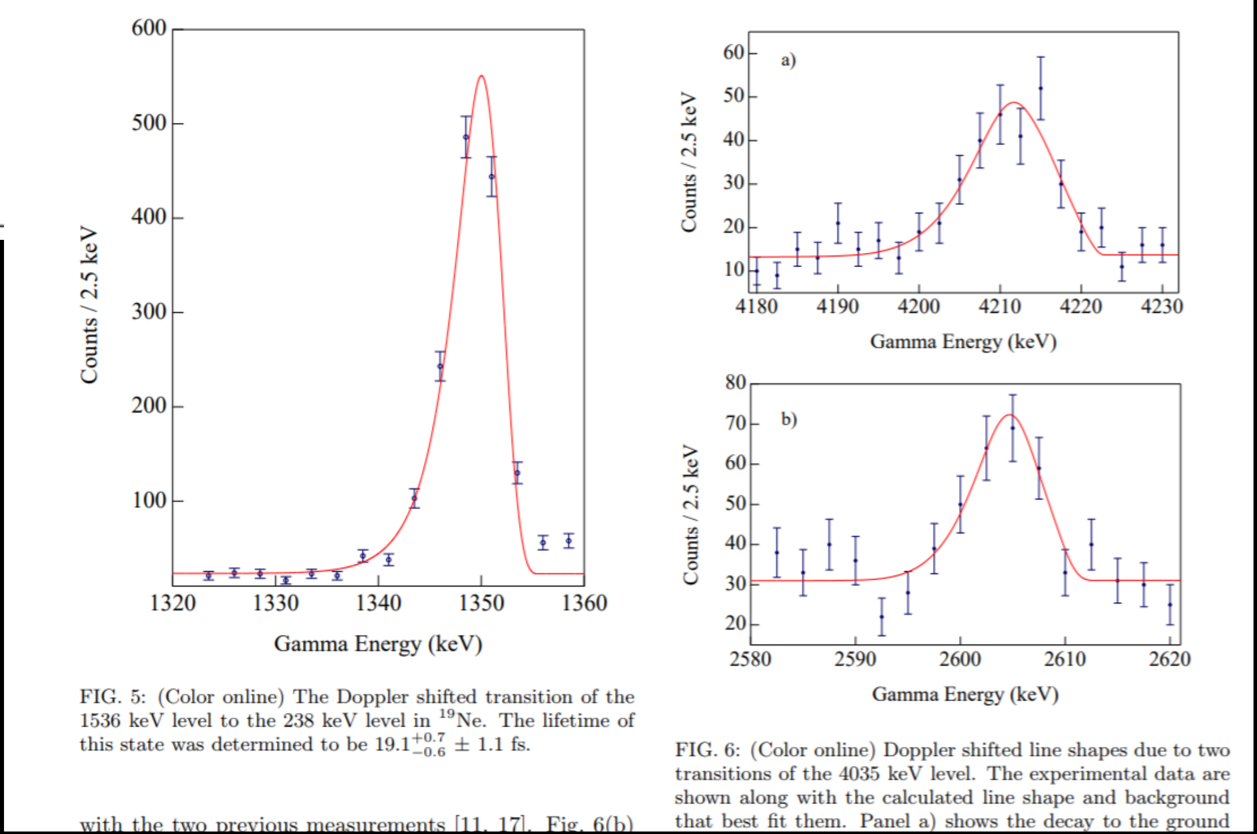


FIG. 5: (Color online) The Doppler shifted transition of the 1536 keV level to the 238 keV level in ^{19}Ne. The lifetime of this state was determined to be $19.1^{+0.7}_{-0.6} \pm 1.1$ fs.

with the two previous measurements [11, 17]. Fig. 6(b)

FIG. 6: (Color online) Doppler shifted line shapes due to two transitions of the 4035 keV level. The experimental data are shown along with the calculated line shape and background that best fit them. Panel a) shows the decay to the ground

Conclusions

- Nuclear astrophysics involves a wide array of tools and techniques to explain the world around us.
- Nuclear physics plays a critical role. Many astrophysical events shows direct impact of nuclear physics.
- Laboratory measurements are necessary ingredients to astrophysical models.
- Both direct and indirect measurements are useful.
- Next time: Focus on exotic beams…