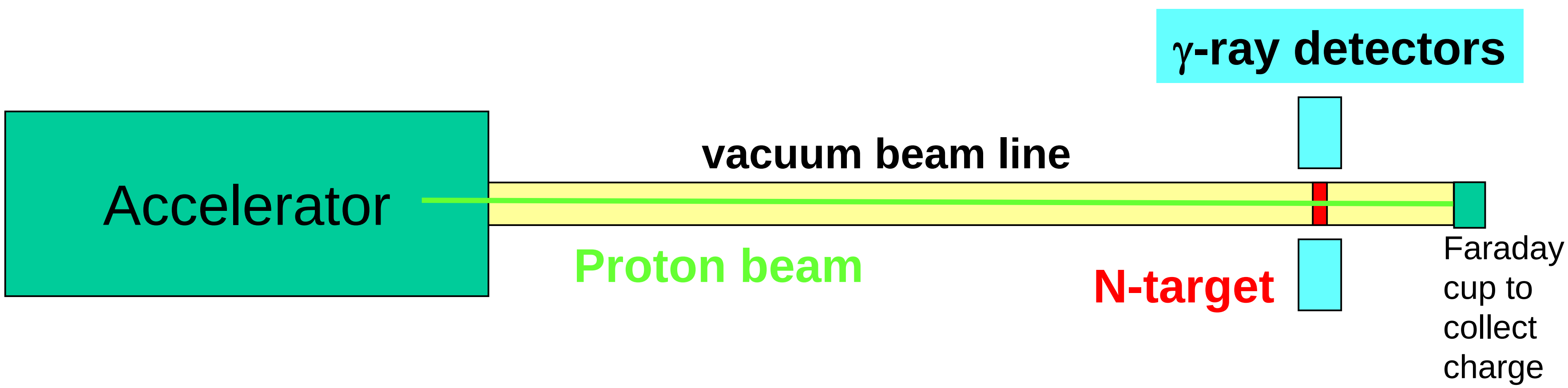
Reaction rates in the Laboratory

Example I: $^{14}N(p,\gamma)^{15}O$

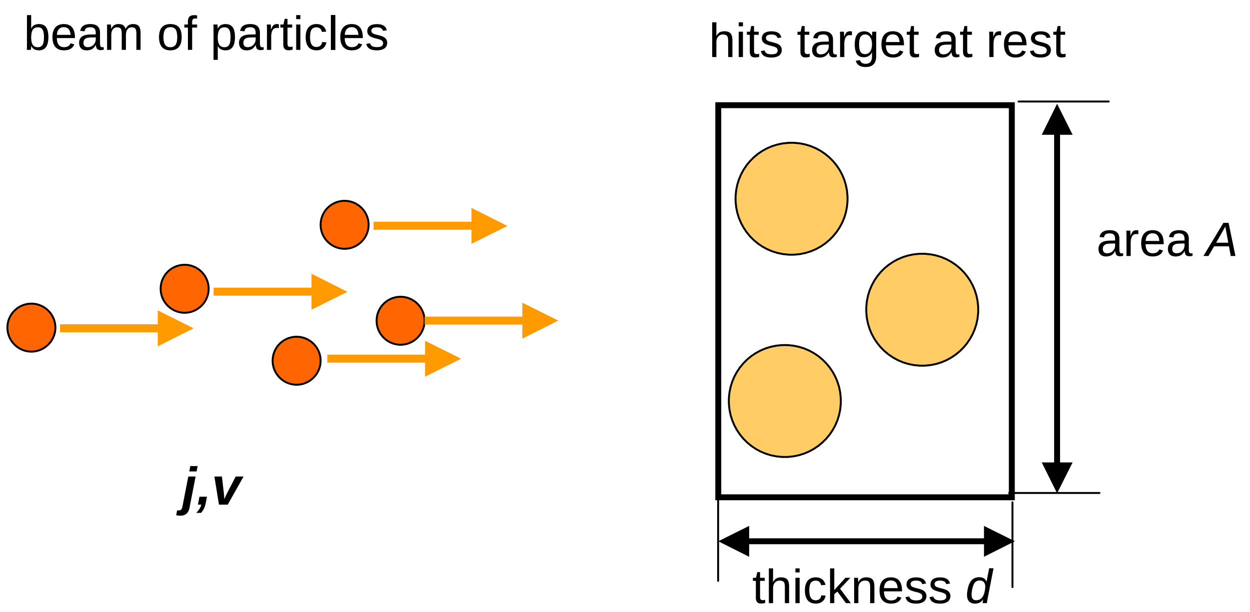
- slowest reaction in the CNO cycle
  → Controls duration of hydrogen burning
  → Determines main sequence turnoff – glob. cluster ages

- stable target → can be measured directly:



- but cross sections are extremely low:
  → Measure as low an energy as possible
  – then extrapolate to Gamow window

Calculating experimental event rates and yields



assume thin target (unattenuated beam intensity throughout target)

Reaction rate (per target nucleus): $\lambda = \sigma j$

Total reaction rate (reactions per second) $$R = \lambda A d n_T = \sigma I d n_T$$

with n_T : number density of target nuclei

$I = jA$: beam number current (number of particles per second hitting the target)

note: dn_T is number of target nuclei per cm^2. Often the target thickness is specified in these terms.

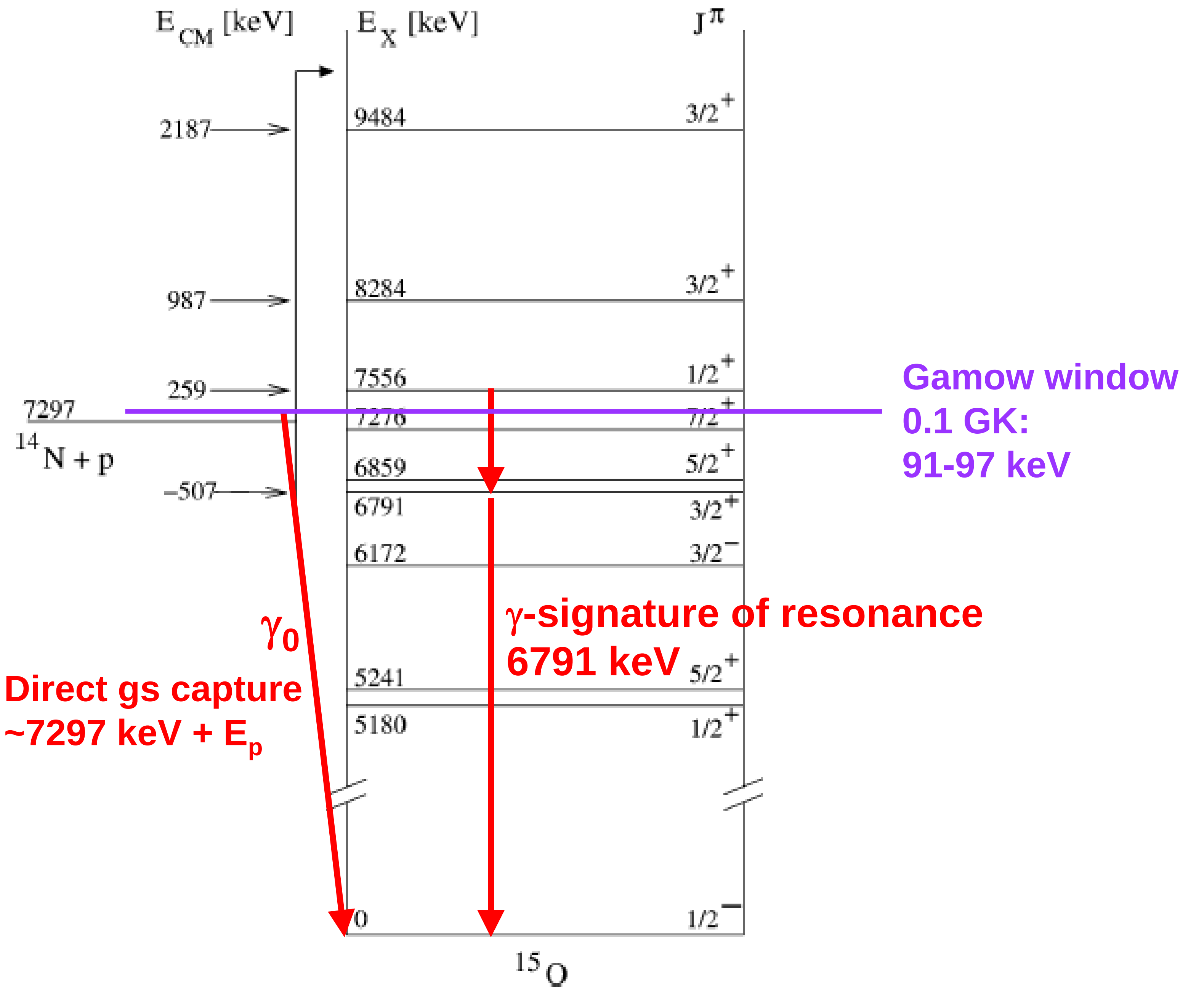
Events detected in experiment per second R_{det}

$$R_{\text{det}} = R\varepsilon$$

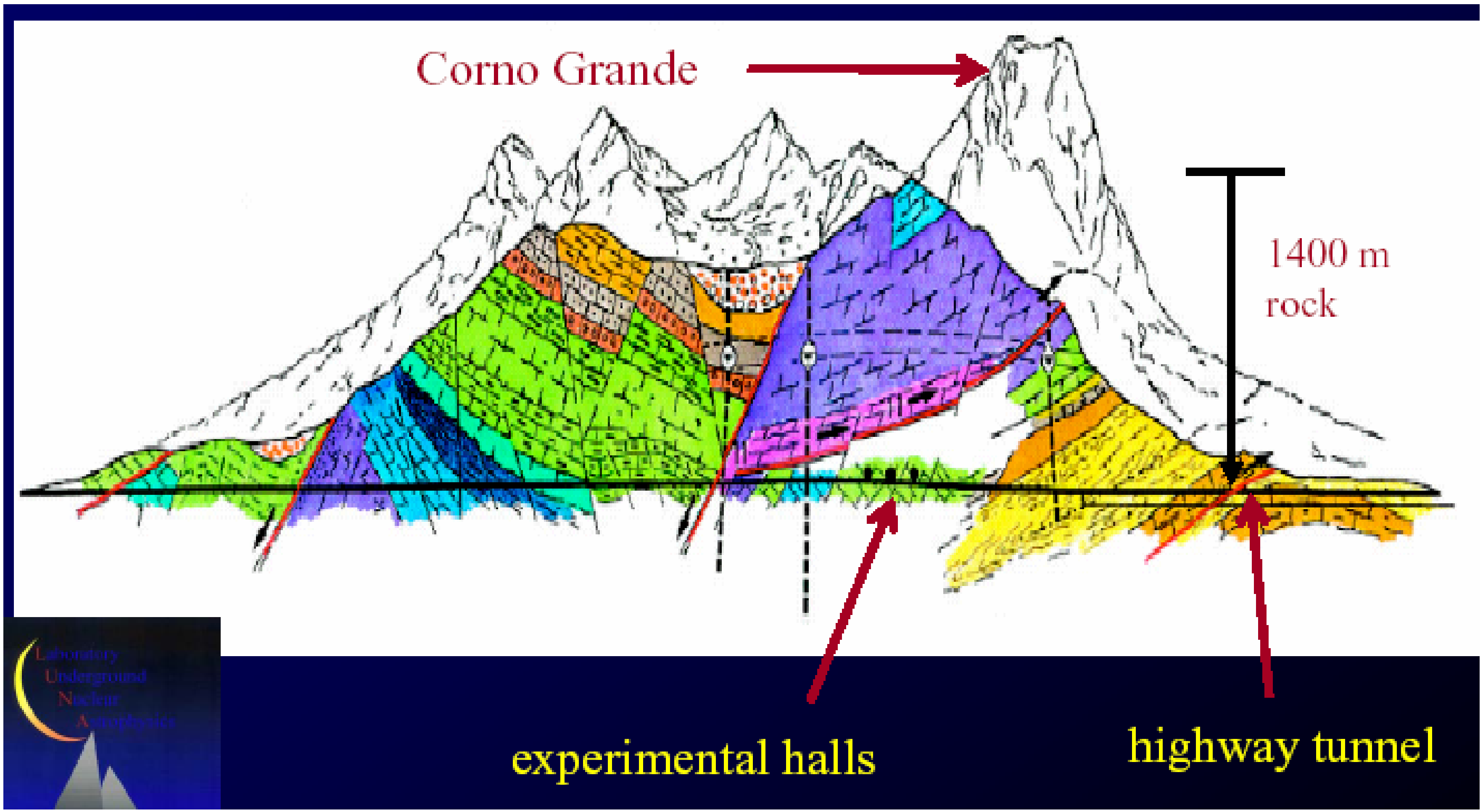
ε is the detection efficiency and can accounts for:

- detector efficiency
  (fraction of particles hitting a detector
  that produce a signal that is registered)
- solid angle limitations
- absorption losses in materials
- energy losses that cause particles energies to slide
  below a detection threshold
- …

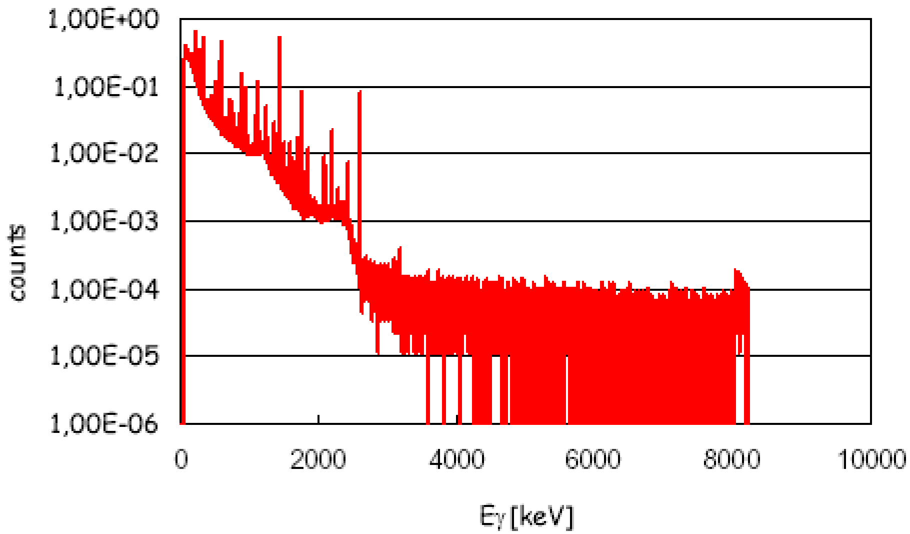
$^{14}N(p,\gamma)$ level scheme



LUNA
Laboratory Underground for Nuclear Astrophysics
(Transparencies: F. Strieder http://www.jinaweb.org/events/tucson/Talk_Strieder.pdf)

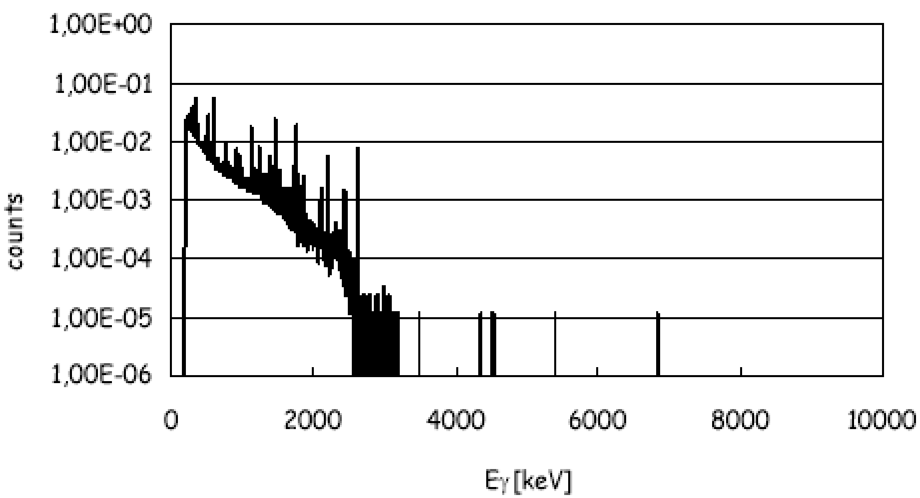


1:1 Mio cosmic ray suppression



HP Ge-Detector
earth surface
detector without any shielding

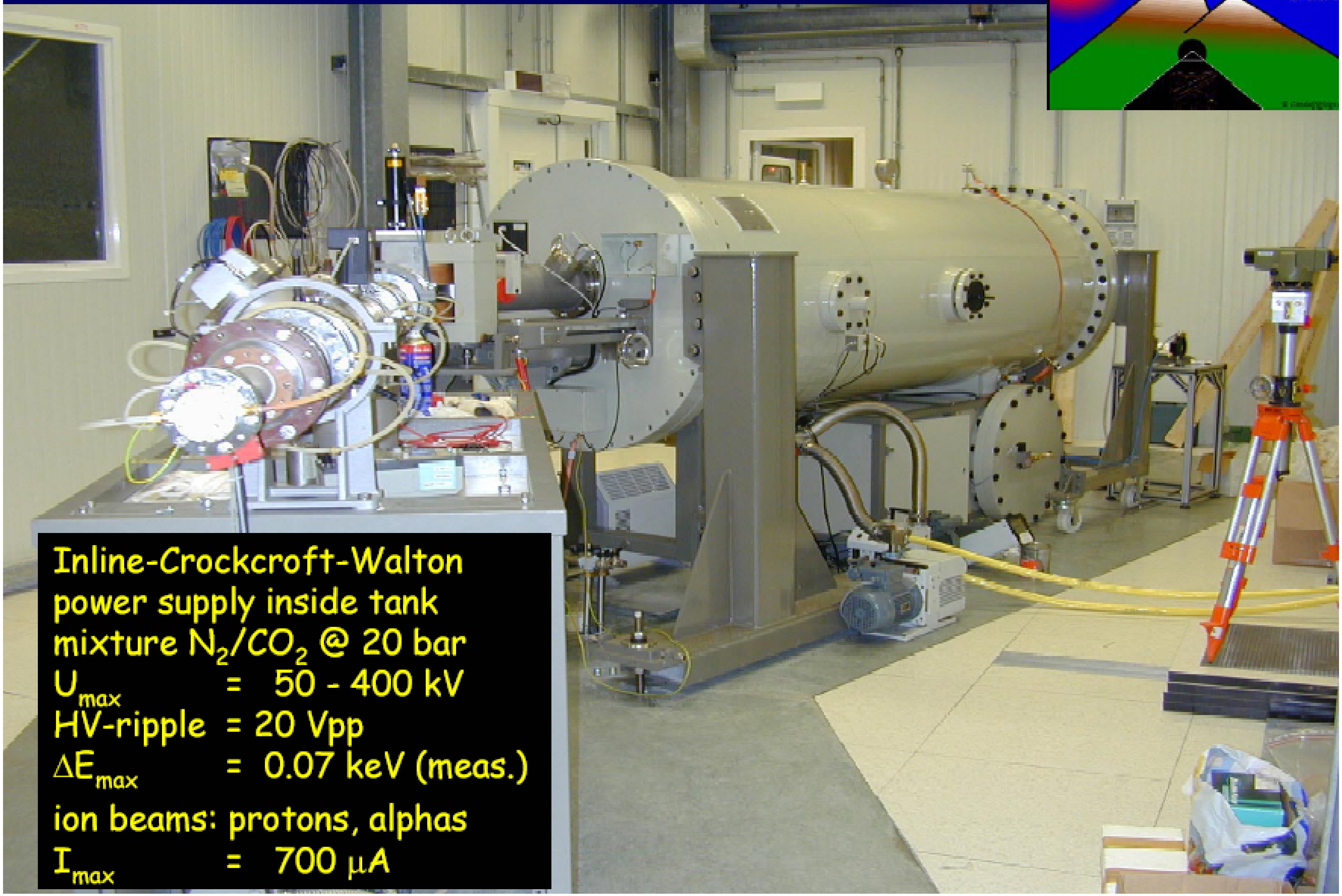
3 MeV < E_γ < 8 MeV
⇒ 0.5 counts/s



HP Ge-Detector
LNGS underground
detector with Pb shielding

3 MeV < E_γ < 8 MeV
⇒ 0.0002 counts/s

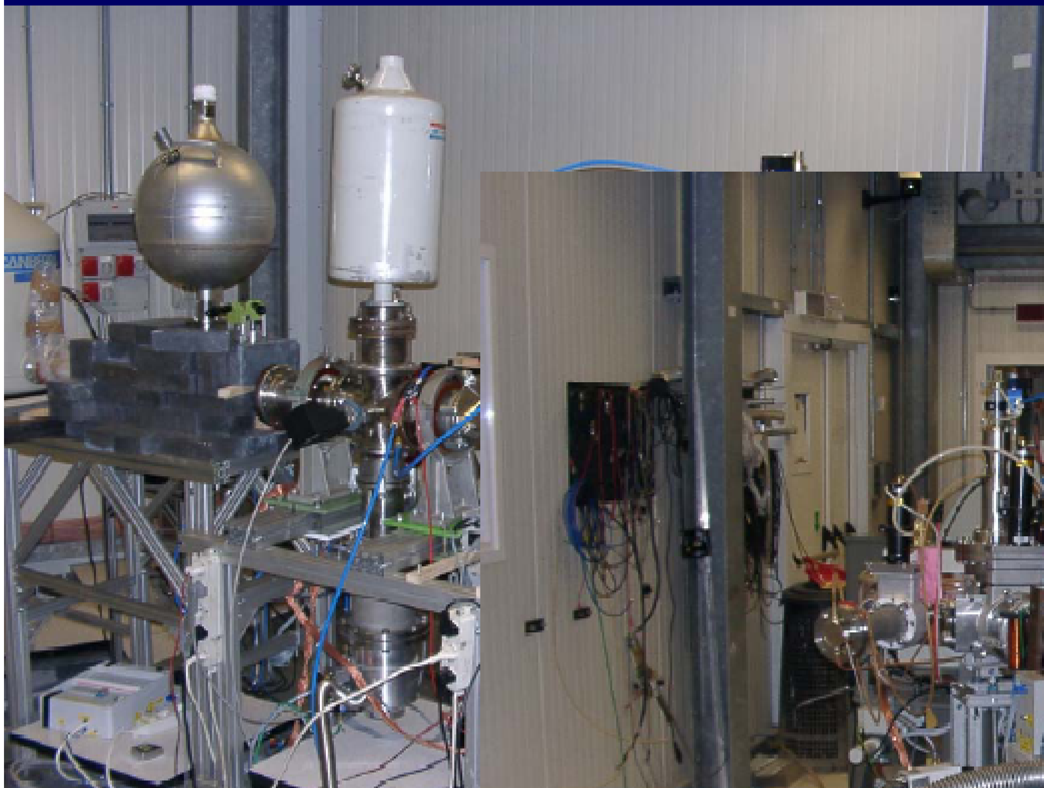
400 kV LUNA accelerator

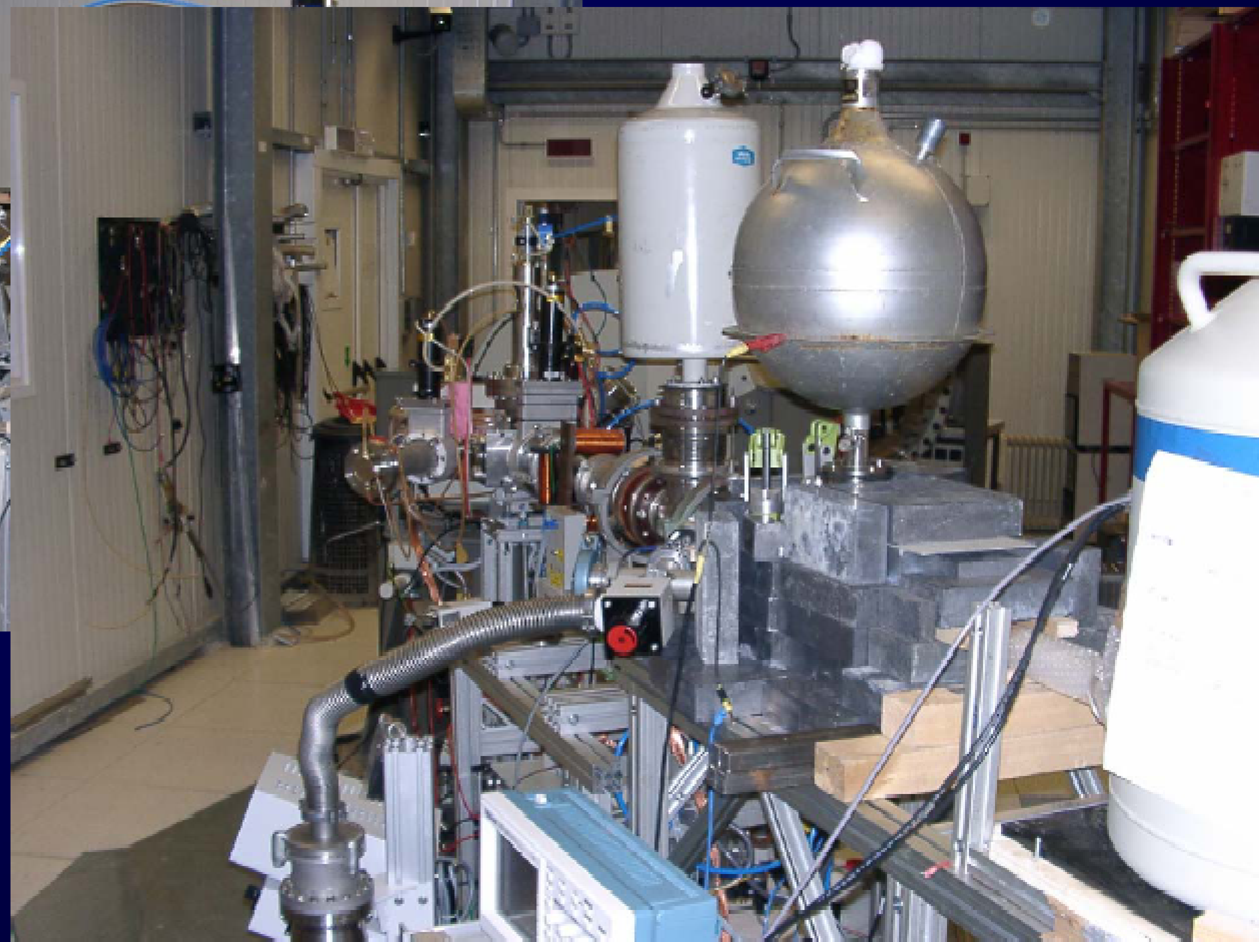


Inline-Crockcroft-Walton power supply inside tank
mixture N_2/CO_2 @ 20 bar
U_{max} = 50 - 400 kV
HV-ripple = 20 Vpp
ΔE_{max} = 0.07 keV (meas.)
ion beams: protons, alphas
I_{max} = 700 μA

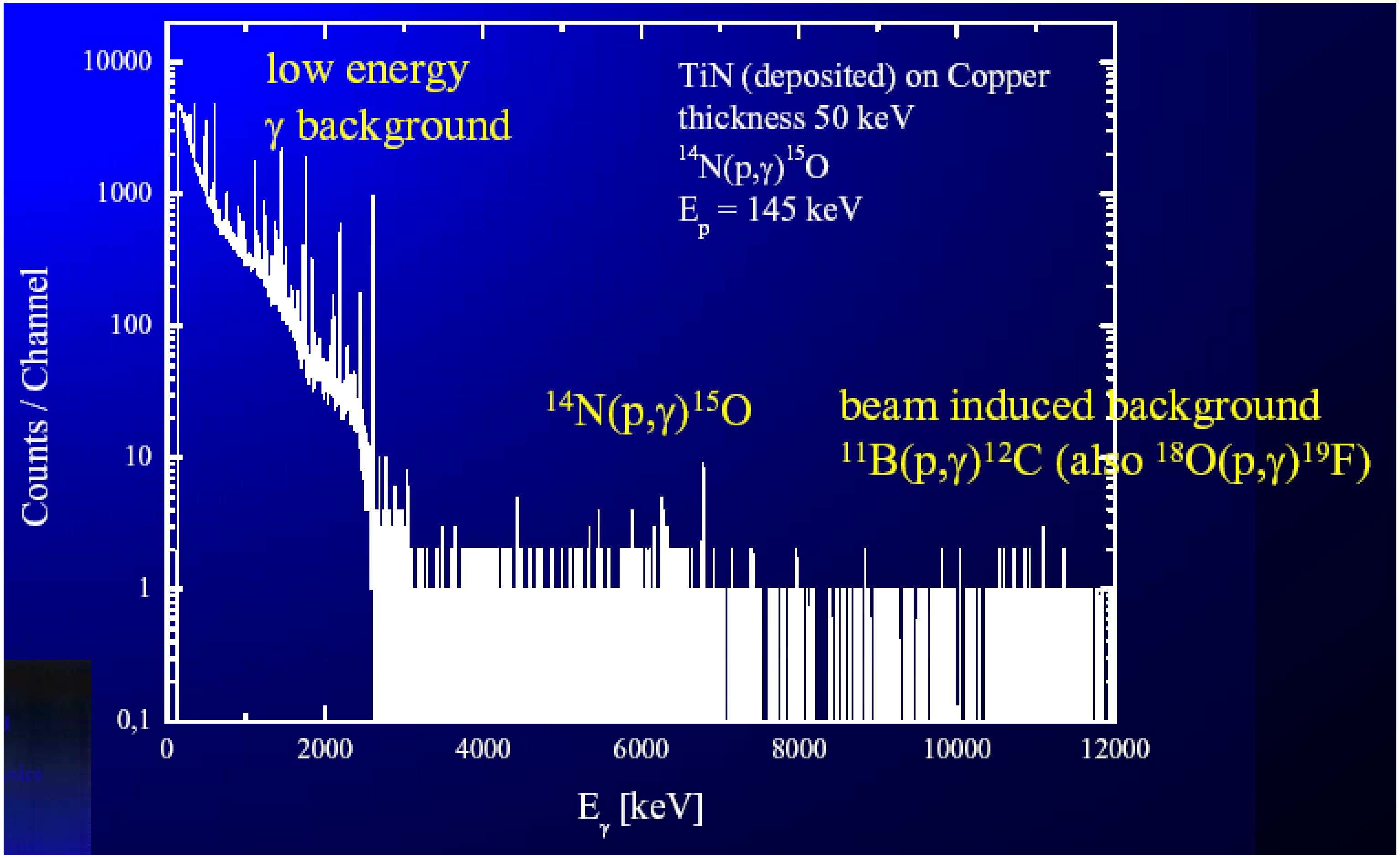
Experiment – additional shielding

INFN
Laboratorio Nazionale del Gran Sasso



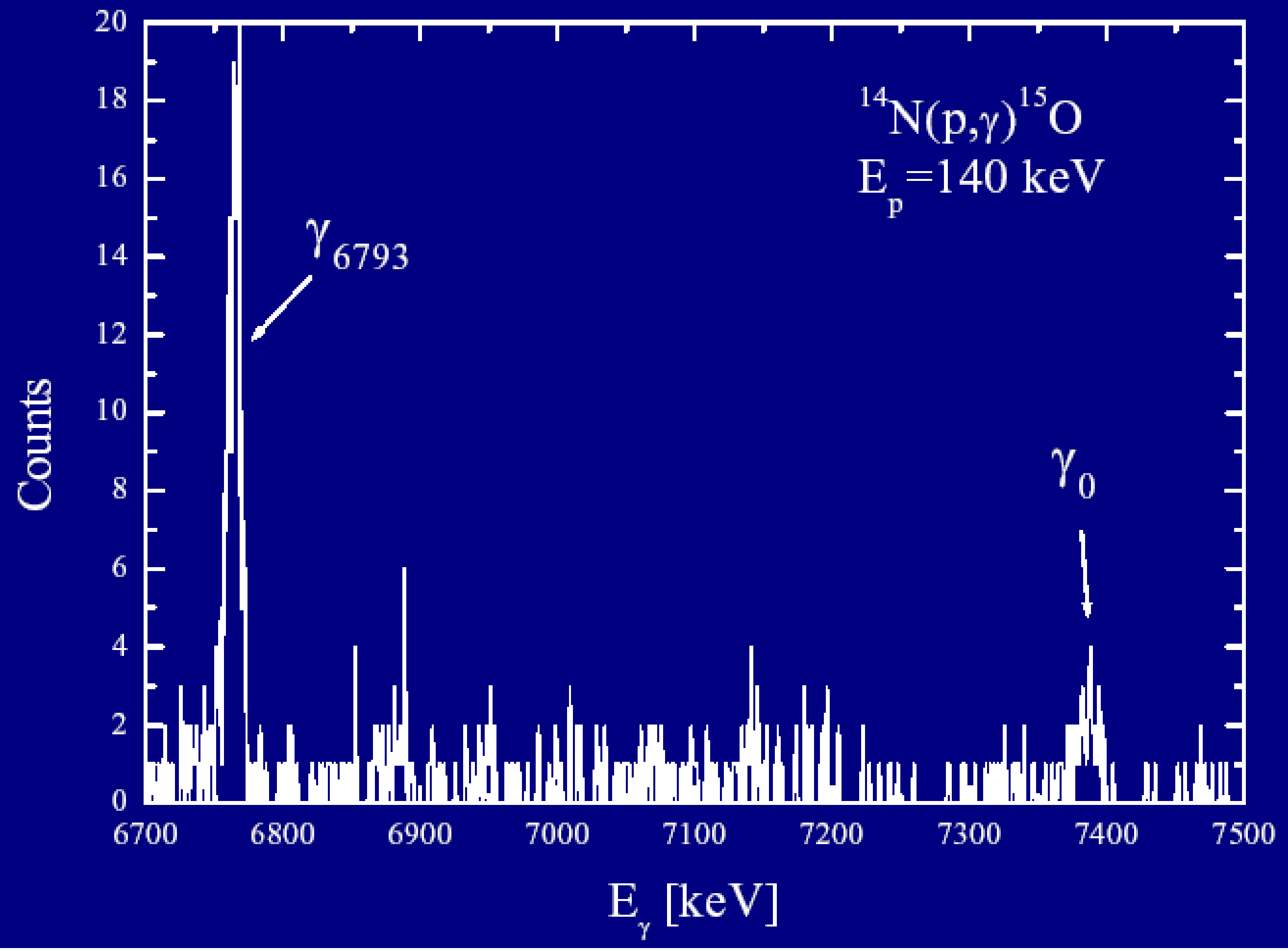


Laboratory
Underground
Nuclear
Astrophysics

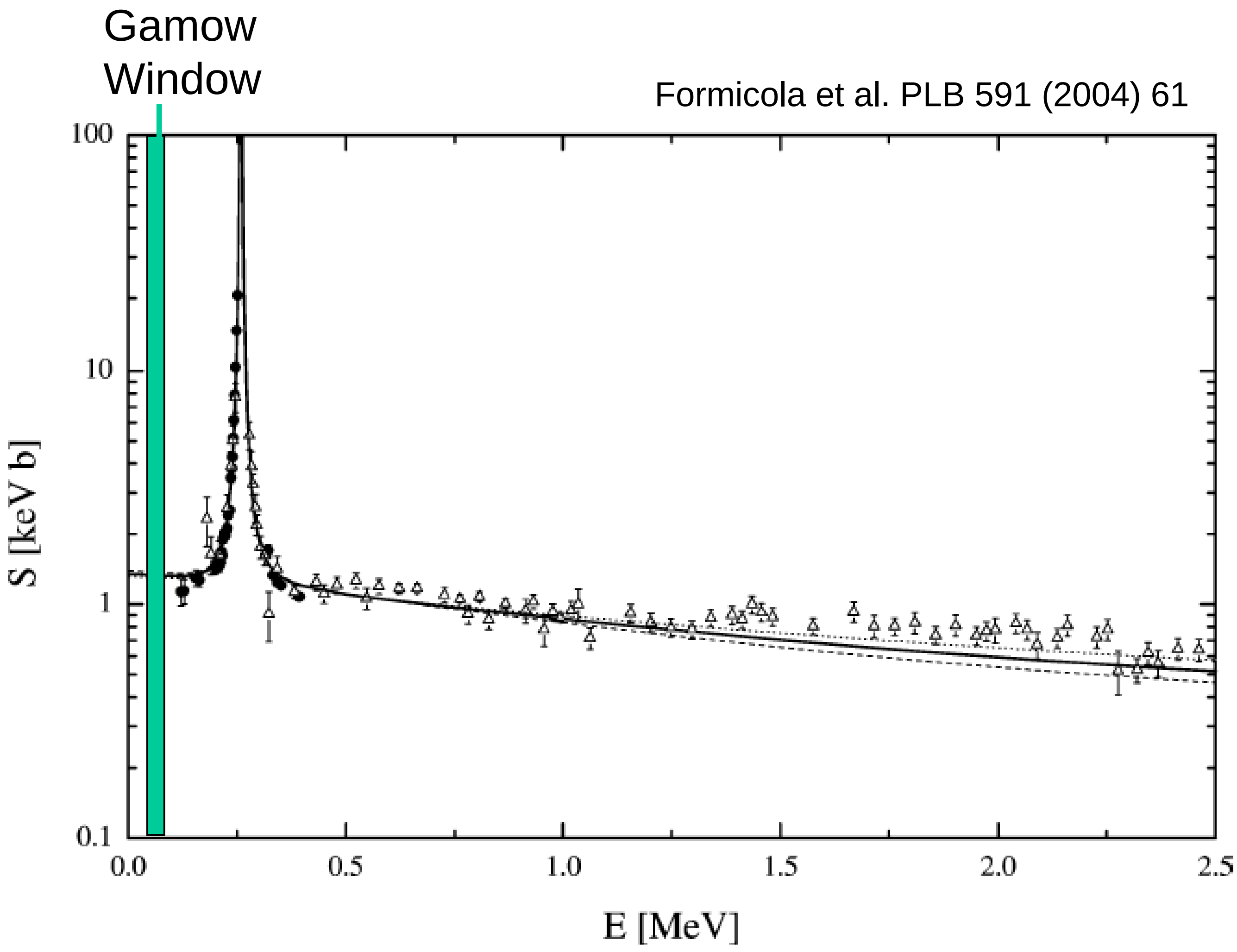


low energy
γ background
TiN (deposited) on Copper
thickness 50 keV
14N(p,γ)15O
Ep = 145 keV
14N(p,γ)15O
beam induced background
11B(p,γ)12C (also 18O(p,γ)19F)
Counts / Channel
10000
1000
100
10
1
0,1
0
2000
4000
6000
8000
10000
12000
Eγ [keV]

γ spectrum (HP-Ge) for $^{14}N(p,\gamma)^{15}O$



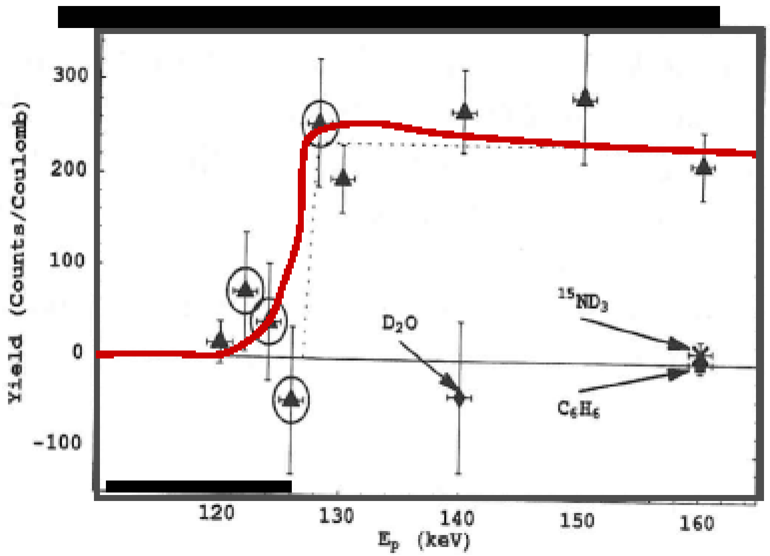
Results:

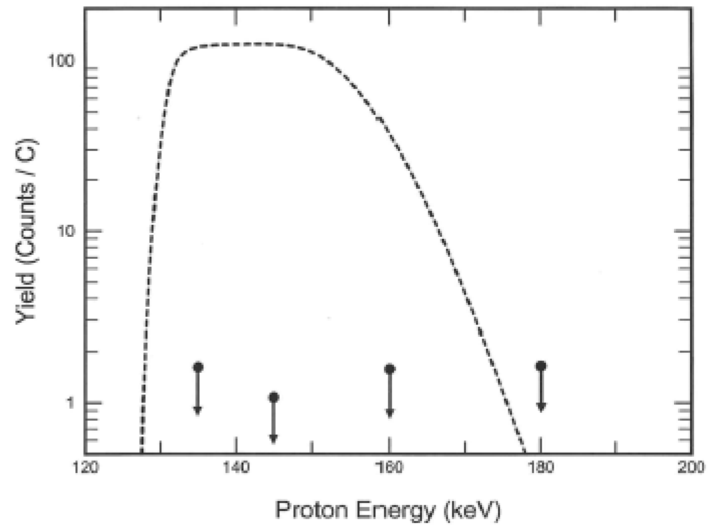


New S(0)=1.7 +- 0.2 keVb (NACRE: 3.2 +- 0.8)

New Resonance ?

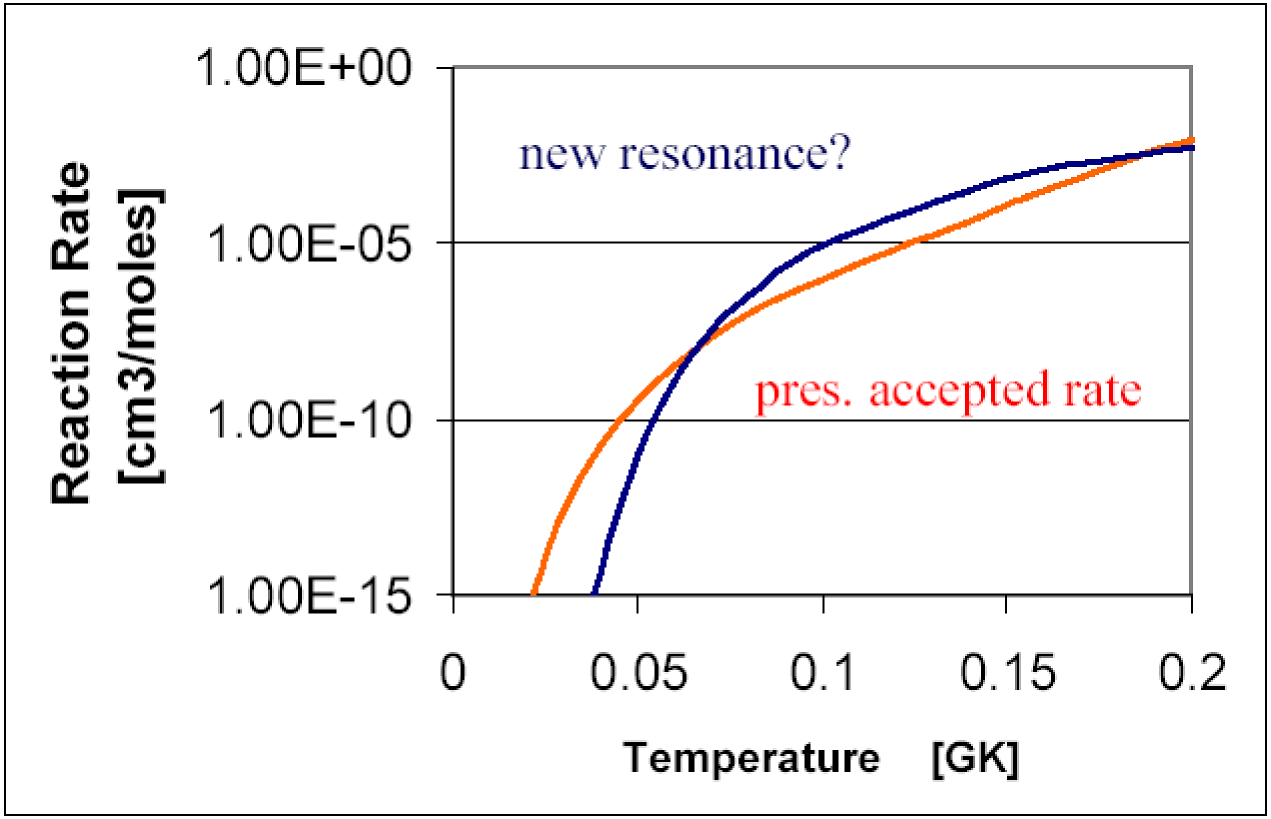
Infinite thick target measurement TUNL 2001





No confirming evidence in UNC data 2002

Effect that speculative resonance would have had

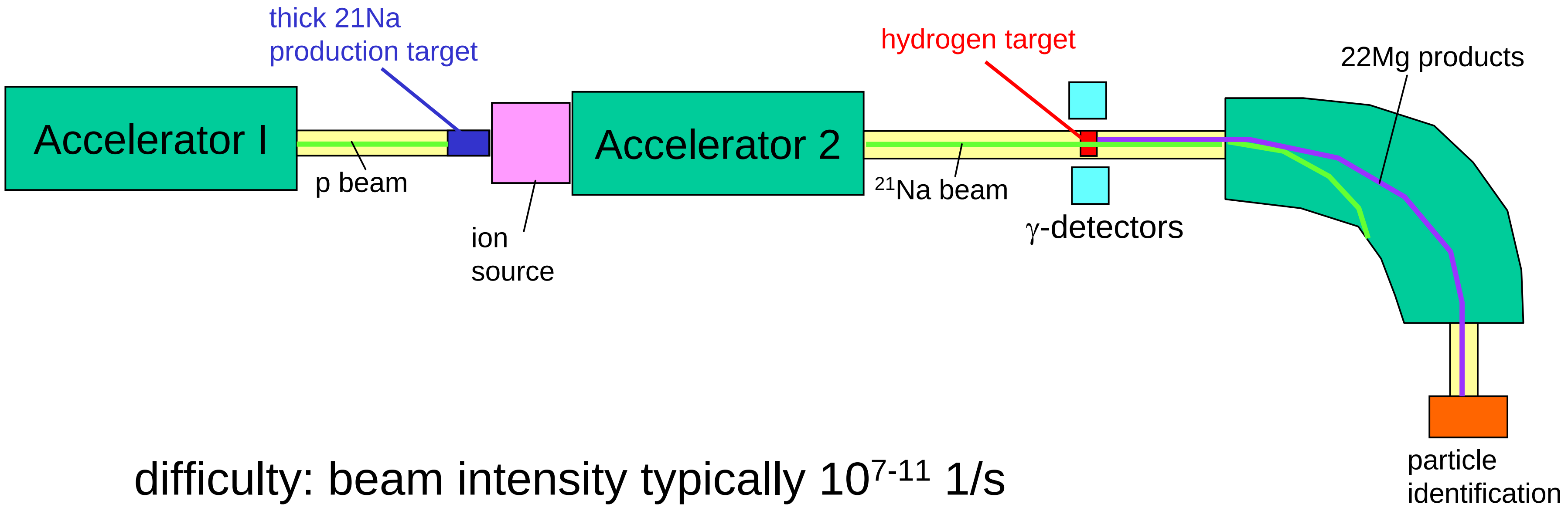


Example II: $^{21}Na(p,\gamma)^{22}Mg$

problem: ^{21}Na is unstable (half-life 22.5 s)

solution: radioactive beam experiment in inverse kinematics:

21Na + p → 22Mg + γ

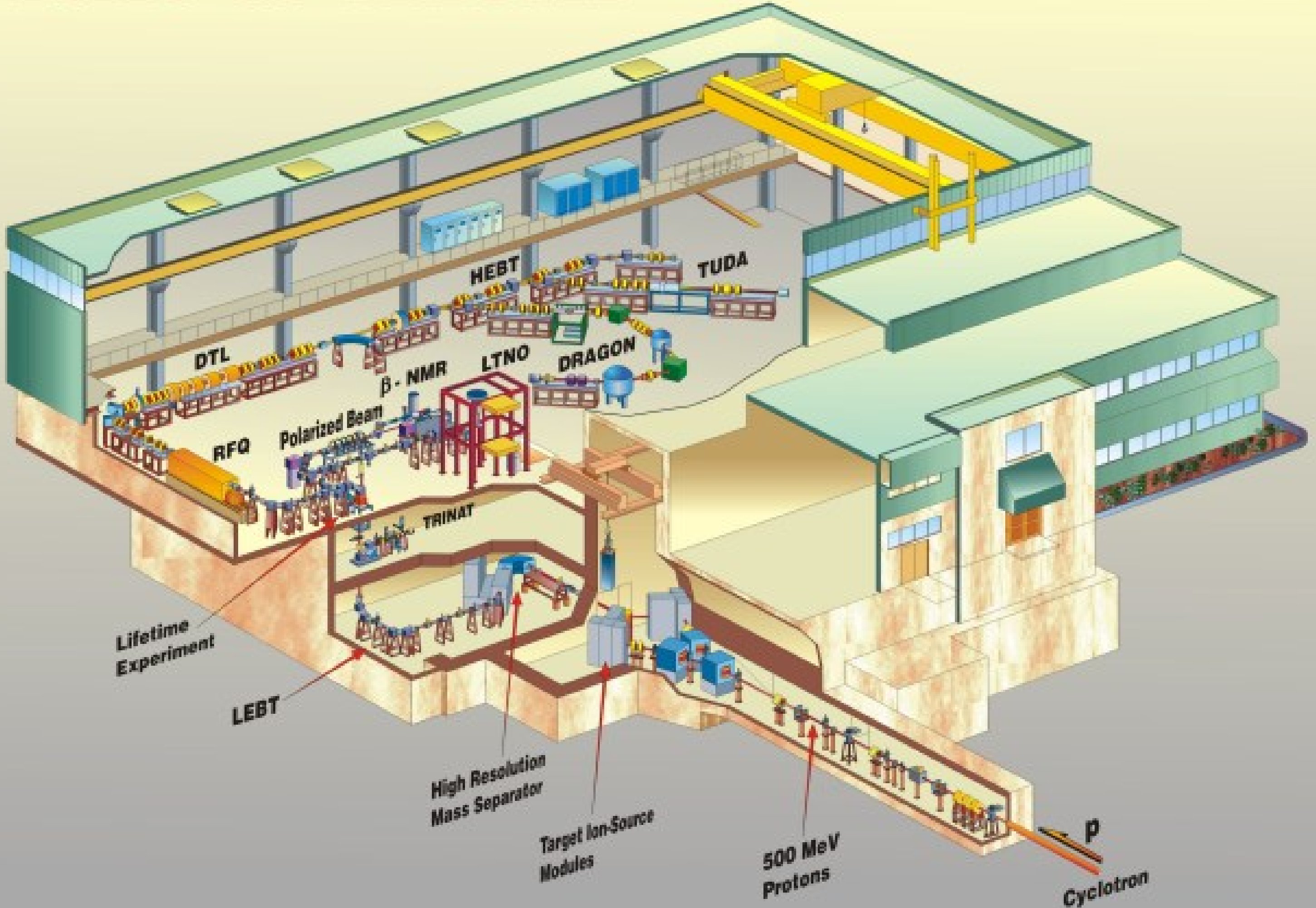


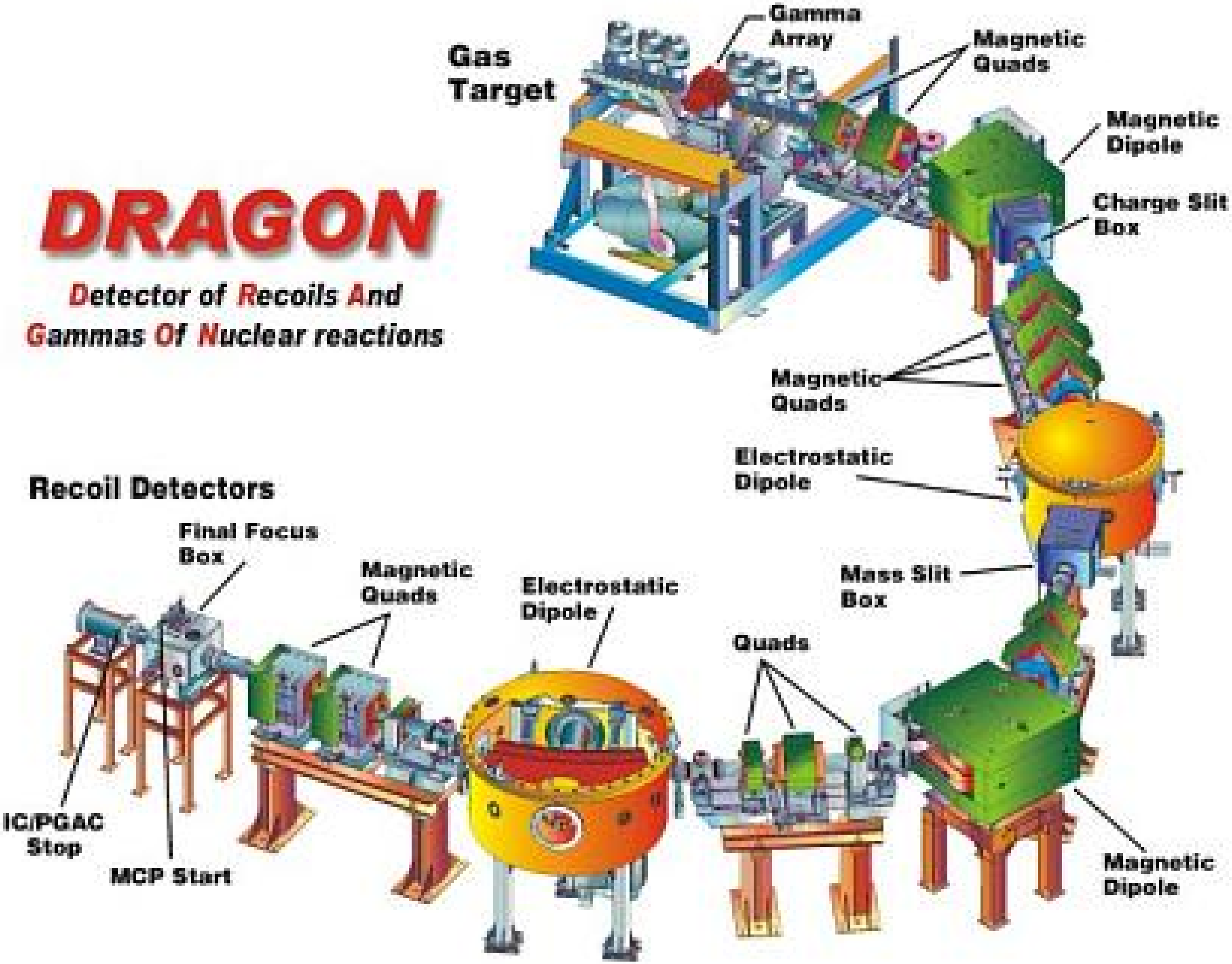
difficulty: beam intensity typically 10^{7-11} 1/s

(compare with 100 μA protons = $6x10^{14}$/s)

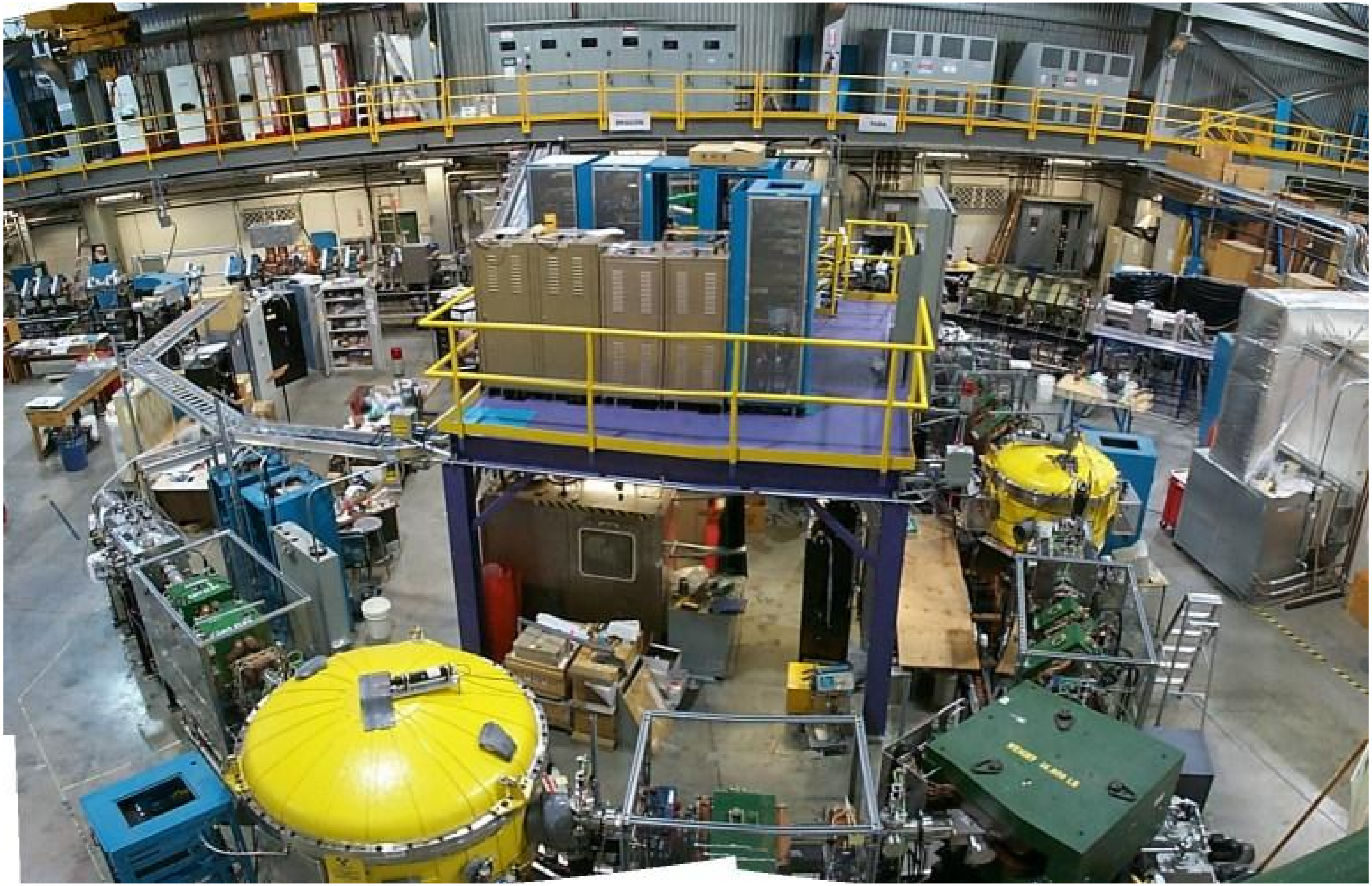
→ so far only succeeded in 2 cases: 13N(p,γ) at Louvain la Neuve and 21Na(p,γ) in TRIUMF (for capture reaction)

ISAC at TRIUMF

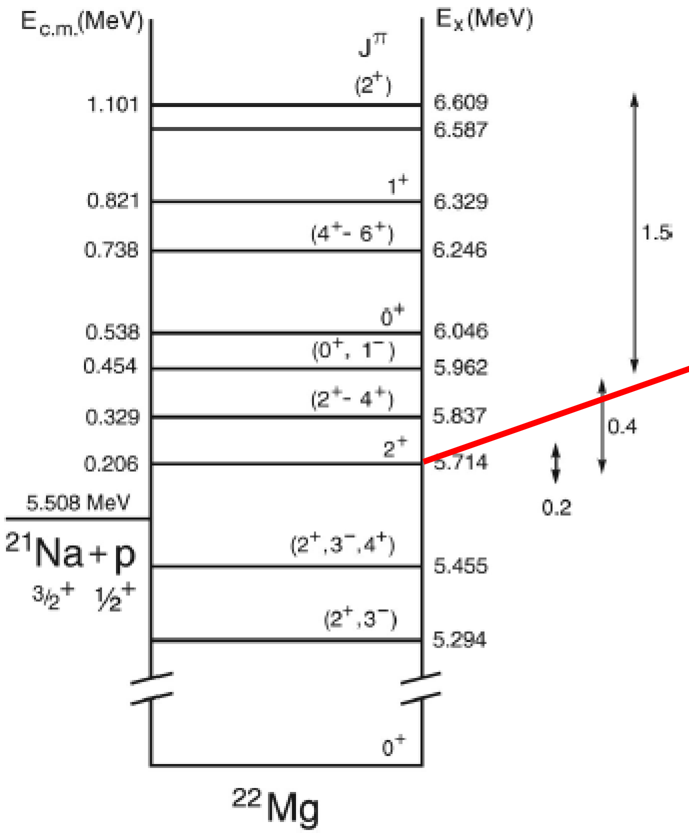



DRAGON
Detector of Recoils And
Gammas Of Nuclear reactions
Gas
Target
Gamma
Array
Magnetic
Quads
Magnetic
Dipole
Charge Slit
Box
Magnetic
Quads
Electrostatic
Dipole
Mass Slit
Box
Quads
Magnetic
Dipole
Electrostatic
Dipole
Magnetic
Quads
Final Focus
Box
Recoil Detectors
IC/PGAC
Stop
MCP Start

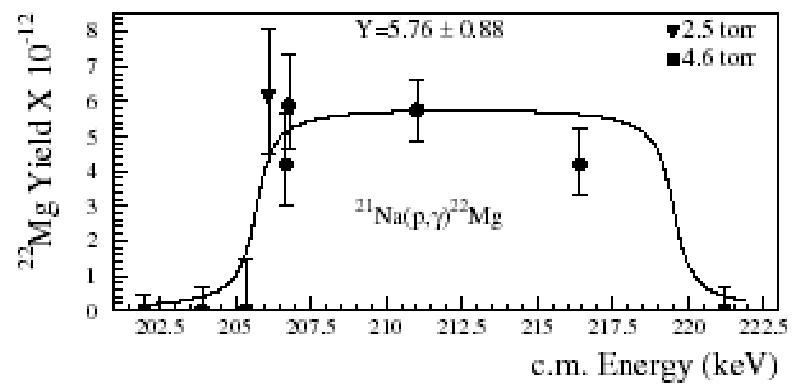
DRAGON @ TRIUMF



Results



Result for 206 keV resonance:

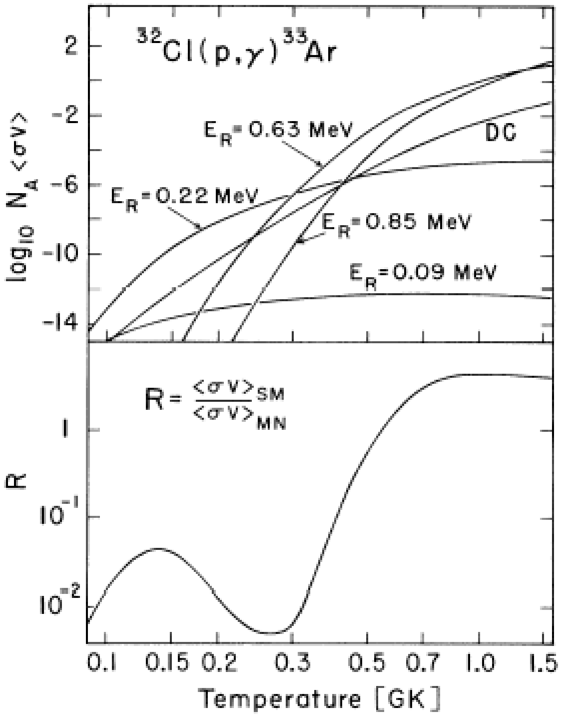


S. Bishop et al. Phys. Rev. Lett. 90 (2003) 2501

Example III: $^{32}Cl(p,\gamma)^{33}Ar$

TABLE V. Nonresonant direct capture transitions and the astrophysical S factors; resonance energies, γ widths, proton widths, and resonance strengths for $^{32}Cl(p,\gamma)^{33}Ar$.

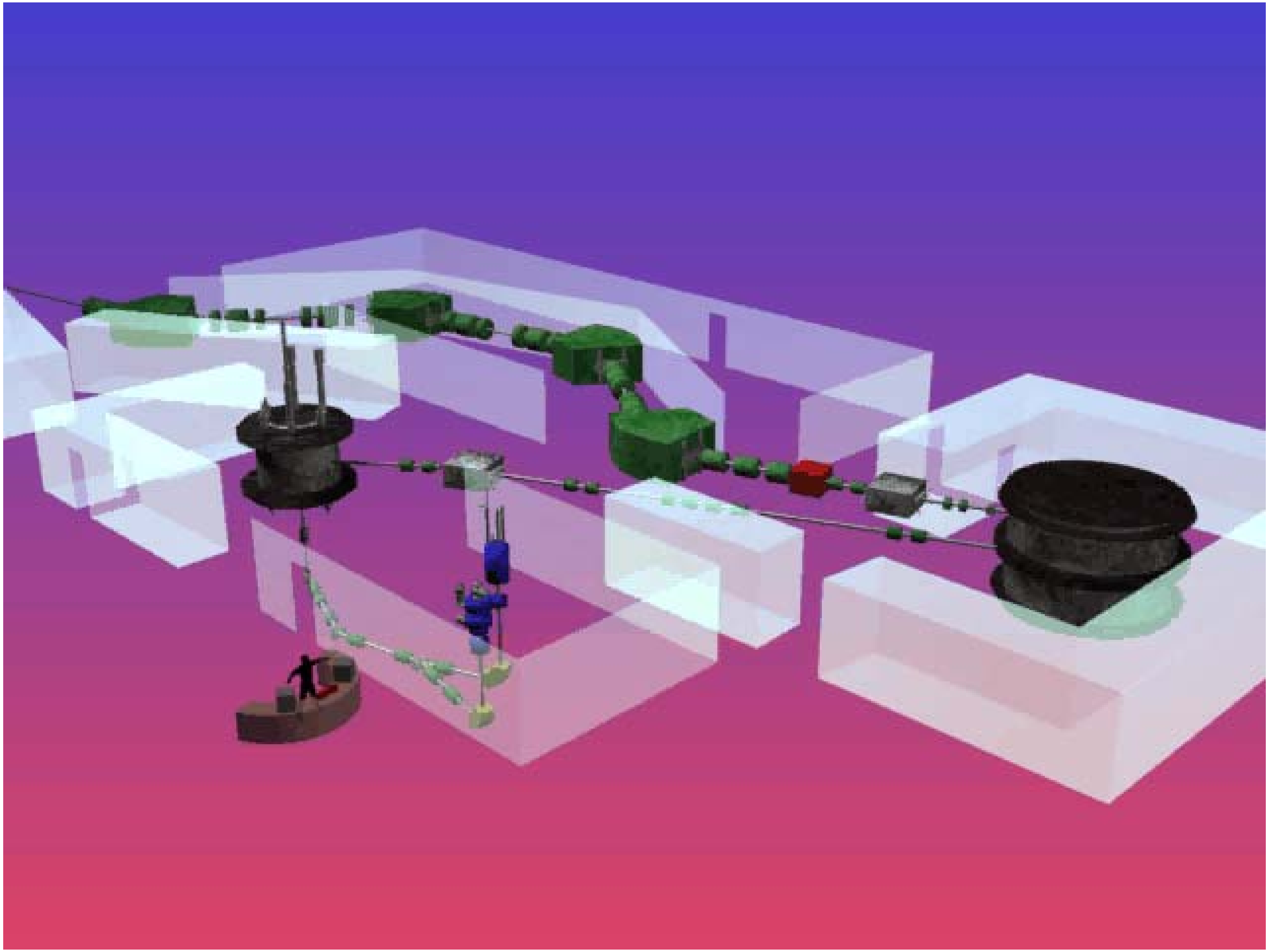
$^{32}Cl(p,\gamma)^{33}Ar$			$Q = 3.34$ MeV		
E_x	J^π	ℓ_i	$n\ell_f$	C^2S_f	$S(E_0)$ (MeV b)
0.00	$\frac{1}{2}^+_1$	p	$2s_{1/2}$	0.080	7.00×10^{-3}
		p	$1d_{3/2}$	0.672	6.14×10^{-3}
1.34	$\frac{3}{2}^+_1$	p	$1d_{3/2}$	0.185	2.62×10^{-3}
1.79	$\frac{5}{2}^+_1$	p	$1d_{3/2}$	0.145	2.74×10^{-3}
2.47	$\frac{3}{2}^+_2$	p	$2s_{1/2}$	0.031	6.16×10^{-3}
		p	$1d_{3/2}$	0.167	1.67×10^{-3}
3.15	$\frac{3}{2}^+_3$	p	$2s_{1/2}$	0.068	1.46×10^{-2}
		p	$1d_{3/2}$	0.516	3.01×10^{-3}
E_x	E_p	J^π	Γ_γ (eV)	Γ_p (eV)	$\omega\gamma$ (eV)
3.43	0.09	$\frac{5}{2}^+_2$	1.77×10^{-2}	8.7×10^{-18}	8.7×10^{-18}
3.56	0.22	$\frac{7}{2}^+_2$	1.94×10^{-3}	1.13×10^{-9}	1.51×10^{-9}
3.97	0.63	$\frac{5}{2}^+_3$	1.54×10^{-2}	2.22×10^{-2}	9.09×10^{-3}
4.19	0.85	$\frac{1}{2}^+_2$	1.54×10^{-1}	46.74	5.12×10^{-2}
4.73	1.39	$\frac{3}{2}^+_4$	8.48×10^{-2}	100.3	5.65×10^{-2}



Shell model calculations
Herndl et al. Phys. Rev. C 52(1995)1078

→ proton width strongly energy dependent
→ rate strongly resonance energy dependent

NSCL Coupled Cyclotron Facility



Installation of D4 steel, Jul/2000

Fast radioactive beams at the NSCL:

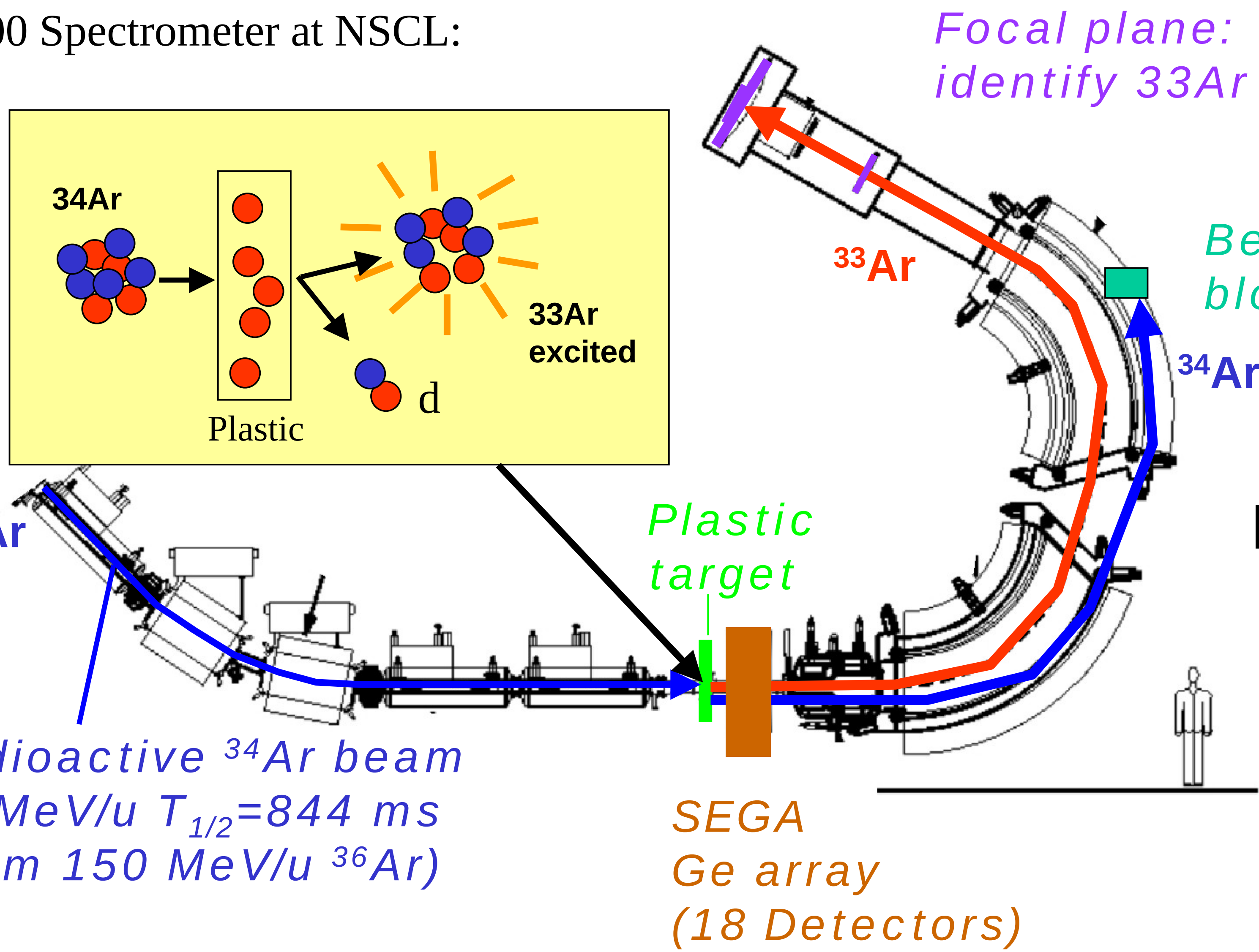
- low beam intensities
- Impure, mixed beams
- high energies (80-100 MeV per nucleon)
  (astrophysical rates at 1-2 MeV per nucleon)

→ great for indirect techniques

- Coulomb breakup
- Transfer reactions
- Decay studies
- …

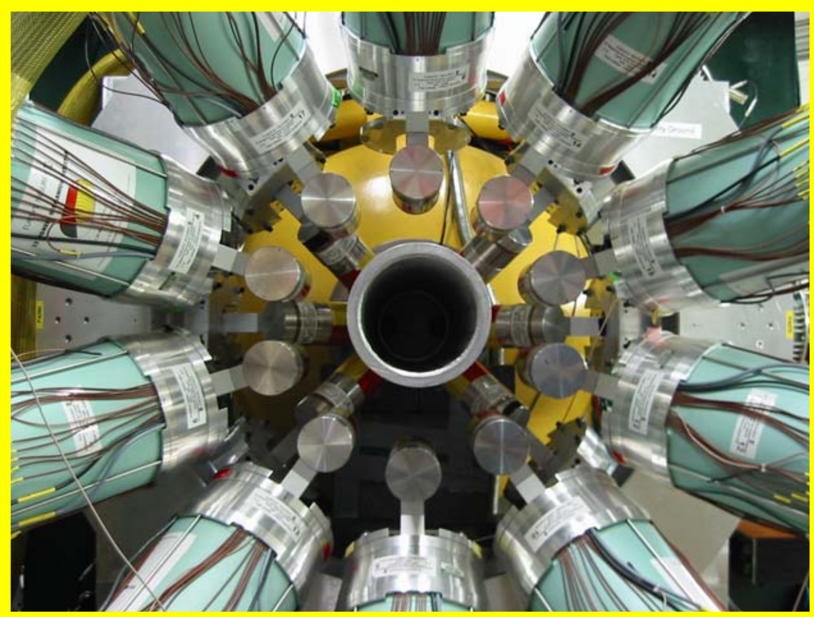
Setup

S800 Spectrometer at NSCL:



People:

- D. Bazin
- **R. Clement**
- A. Cole
- A. Gade
- T. Glasmacher
- B. Lynch
- W. Mueller
- H. Schatz
- B. Sherrill
- M. VanGoethem
- M. Wallace



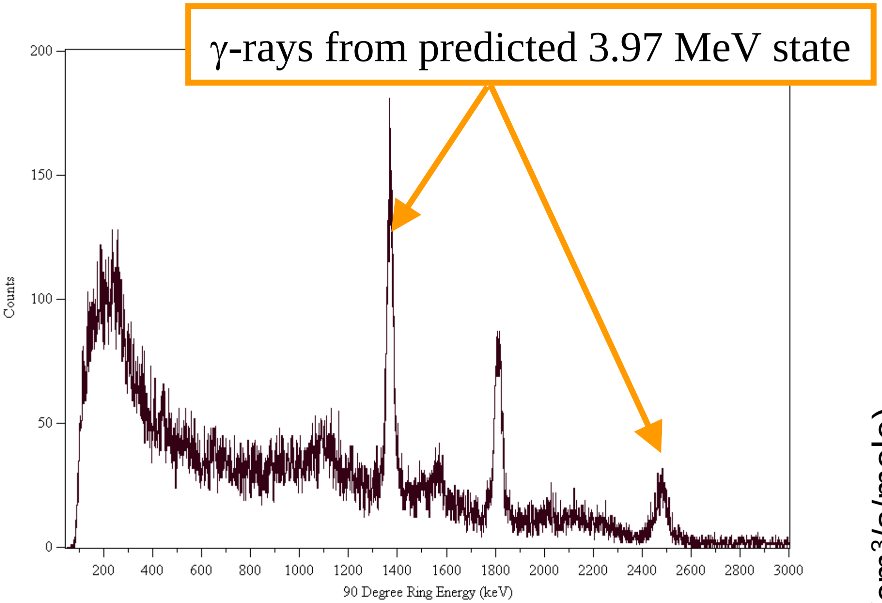
SEGA Ge-array

S800 Spectrometer

NSCL

New $^{32}Cl(p,\gamma)^{33}Ar$ rate – Clement et al. PRL 92 (2004) 2502

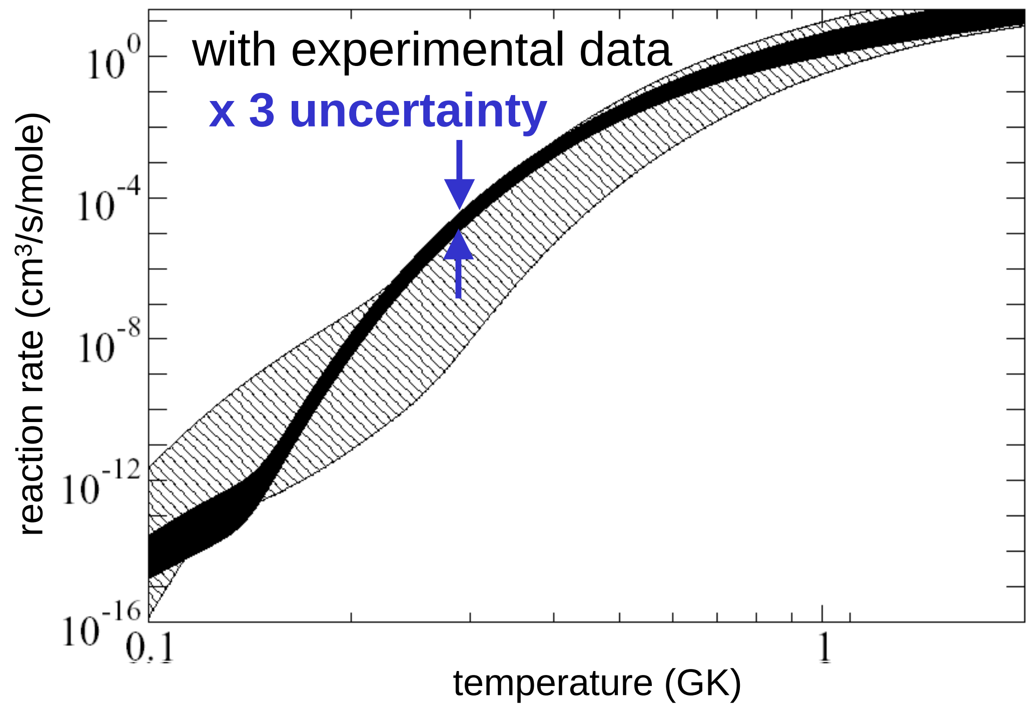
Doppler corrected γ-rays
in coincidence with 33Ar in S800 focal plane:



^{33}Ar level energies measured:

3819(4) keV (150 keV below SM)
3456(6) keV (104 keV below SM)

stellar reaction rate



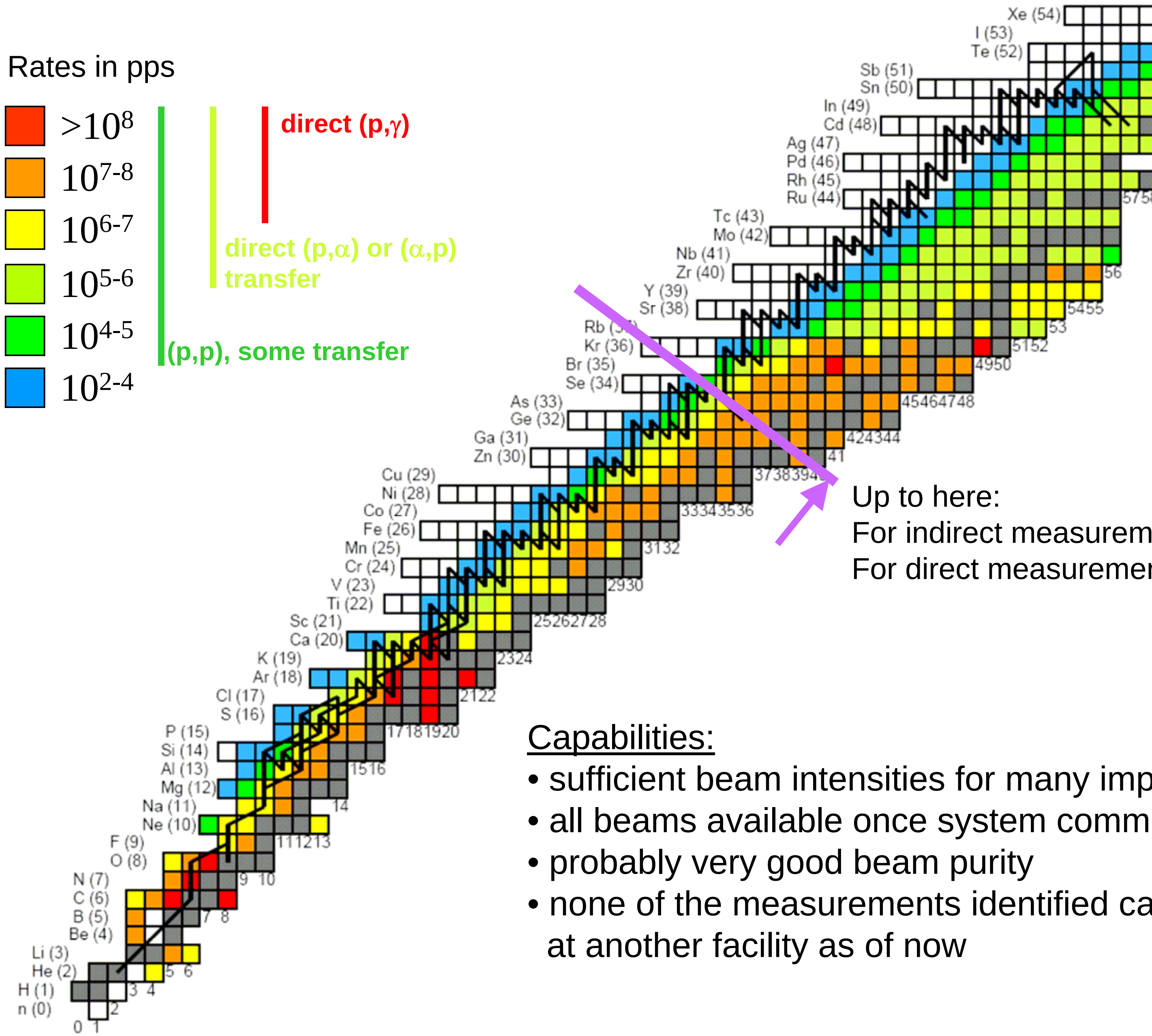
Typical X-ray burst temperatures

NSCL ReA3

Fast beams

Gas cell

Science with CCF reaccelerated beams



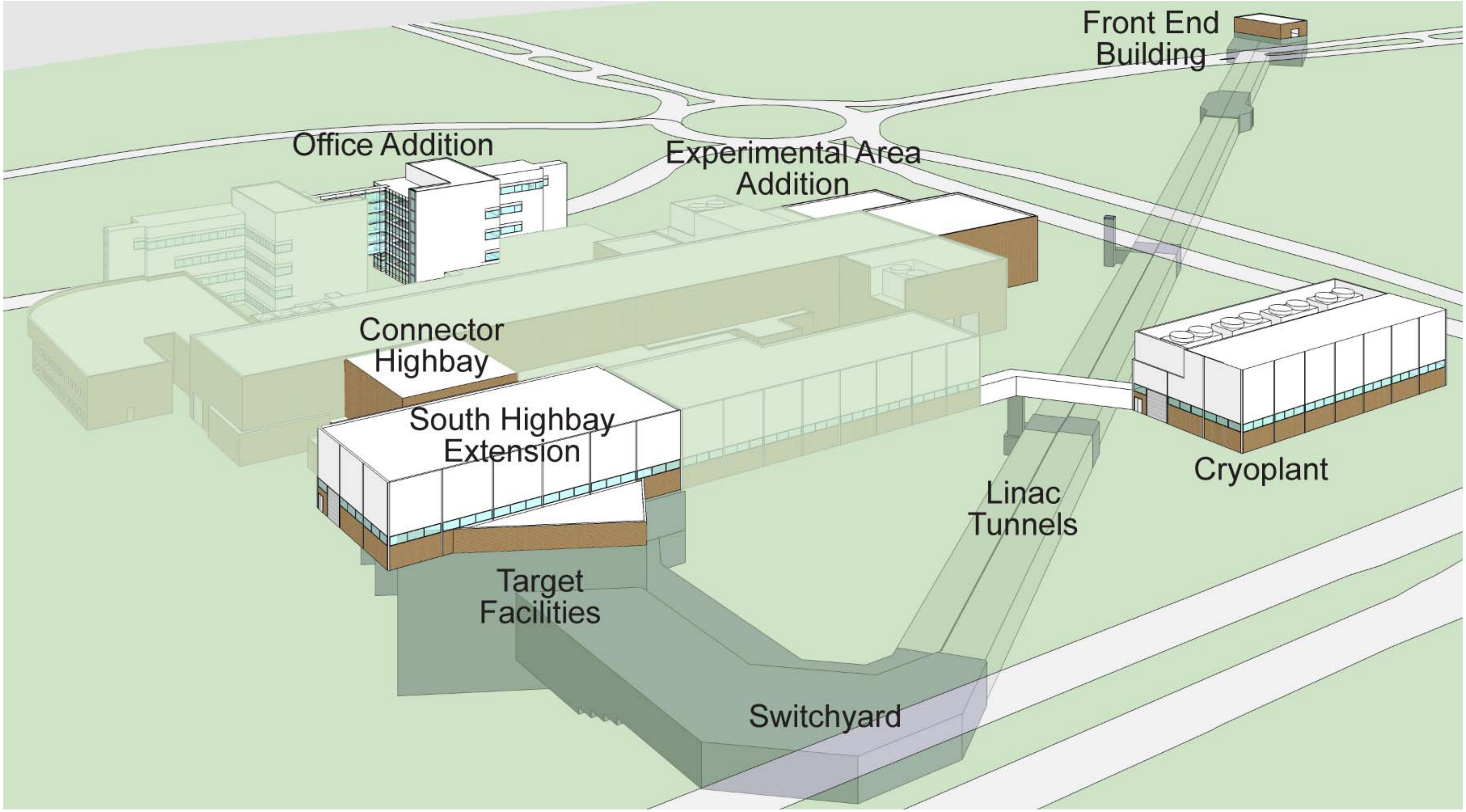
and p-process …

Up to here:
For indirect measurements: many
For direct measurements: some important rates

Capabilities:

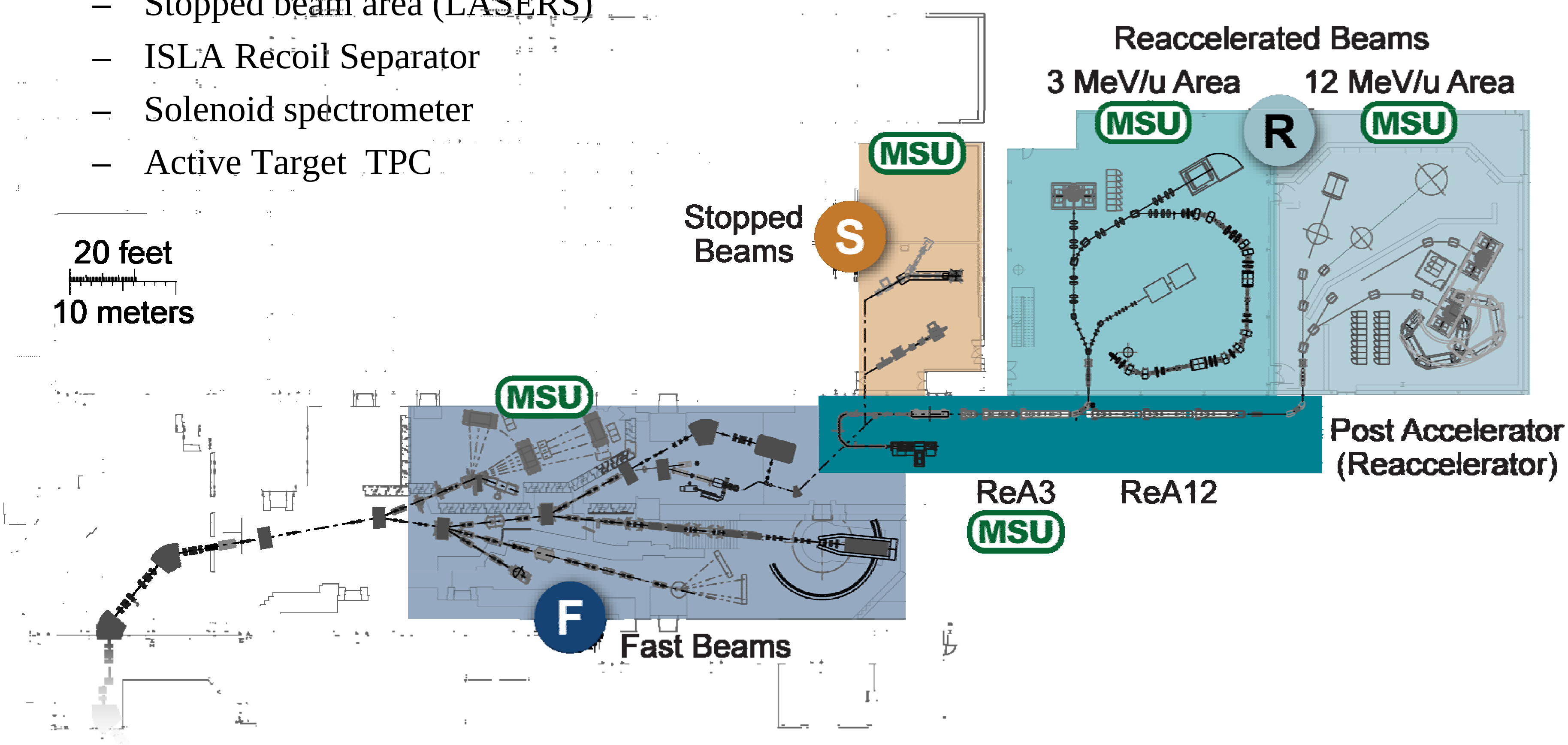
- sufficient beam intensities for many important measurements
- all beams available once system commissioned
- probably very good beam purity
- none of the measurements identified can be performed at another facility as of now

Overview of the FRIB Layout



ReA12 and Experimental Areas

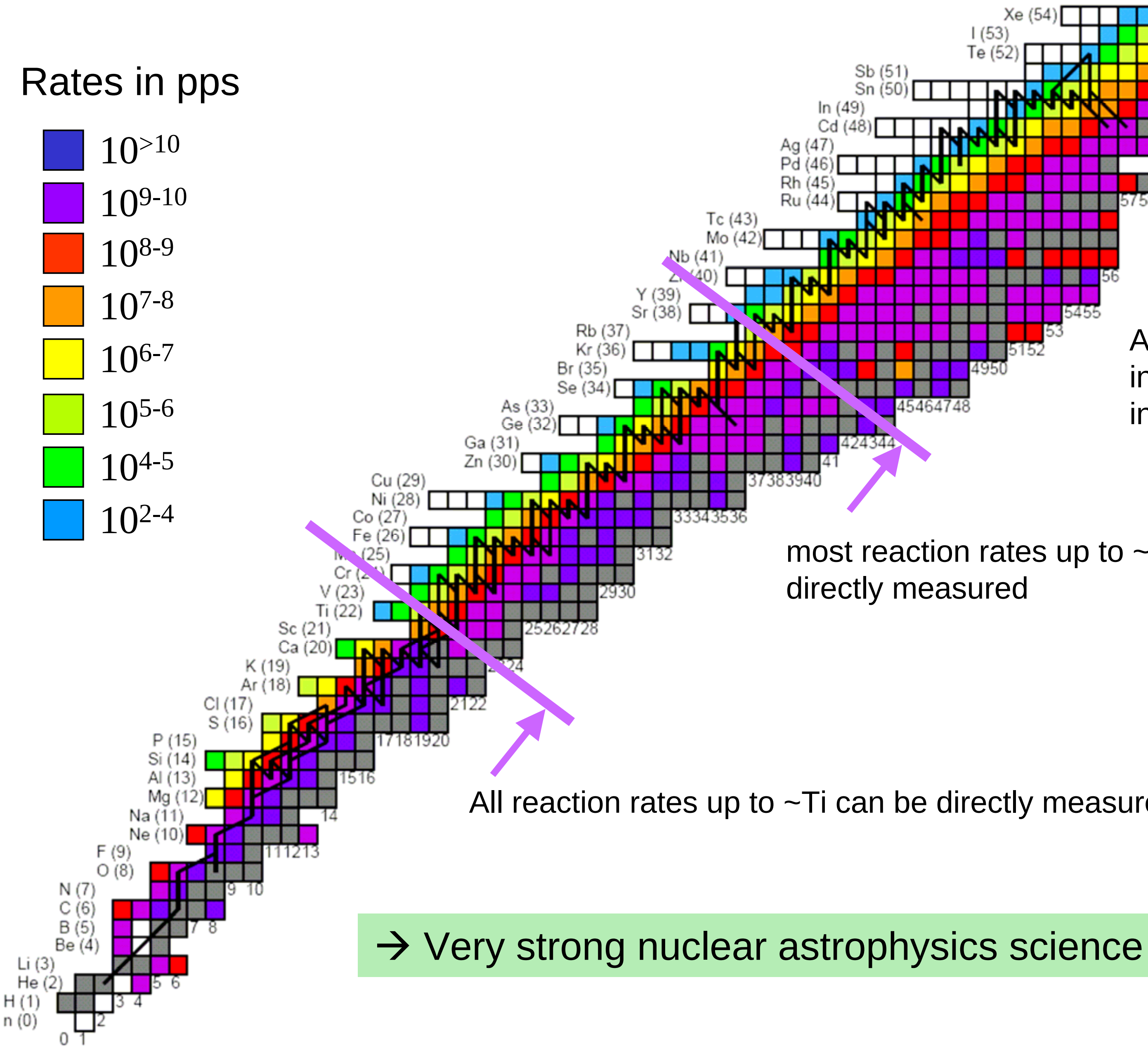
- A full suite of experimental equipment will be available for fast, stopped and reaccelerated beams
- New equipment
  - Stopped beam area (LASERS)
  - ISLA Recoil Separator
  - Solenoid spectrometer
  - Active Target TPC



Science with reaccelerated beams at FRIB

Rates in pps

- $10^{>10}$
- 10^{9-10}
- 10^{8-9}
- 10^{7-8}
- 10^{6-7}
- 10^{5-6}
- 10^{4-5}
- 10^{2-4}



Direct measurements for many (α,γ) reactions in p-process

All reaction rates can be indirectly measured including ^{72}Kr waiting point

most reaction rates up to ~Sr can be directly measured

All reaction rates up to ~Ti can be directly measured

→ Very strong nuclear astrophysics science case