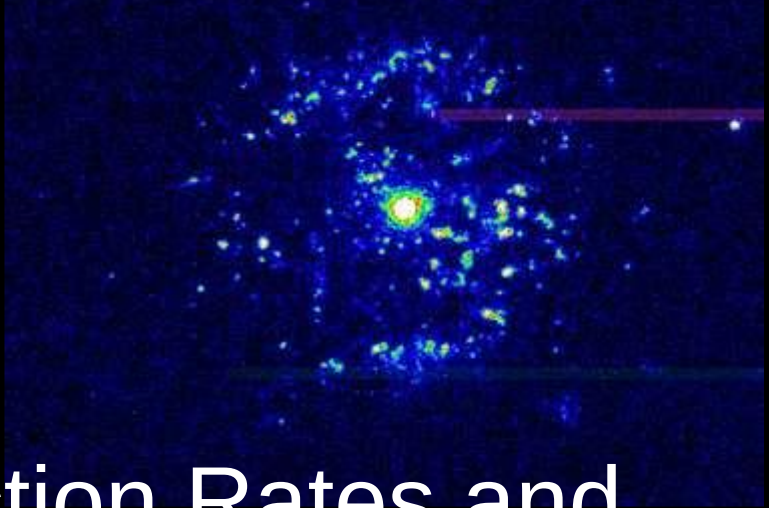
Nova Cygni

Nova T Pyxidis



Novae Reaction Rates and Measurements

Measuring Nuclear Reaction Rates One Step at a Time

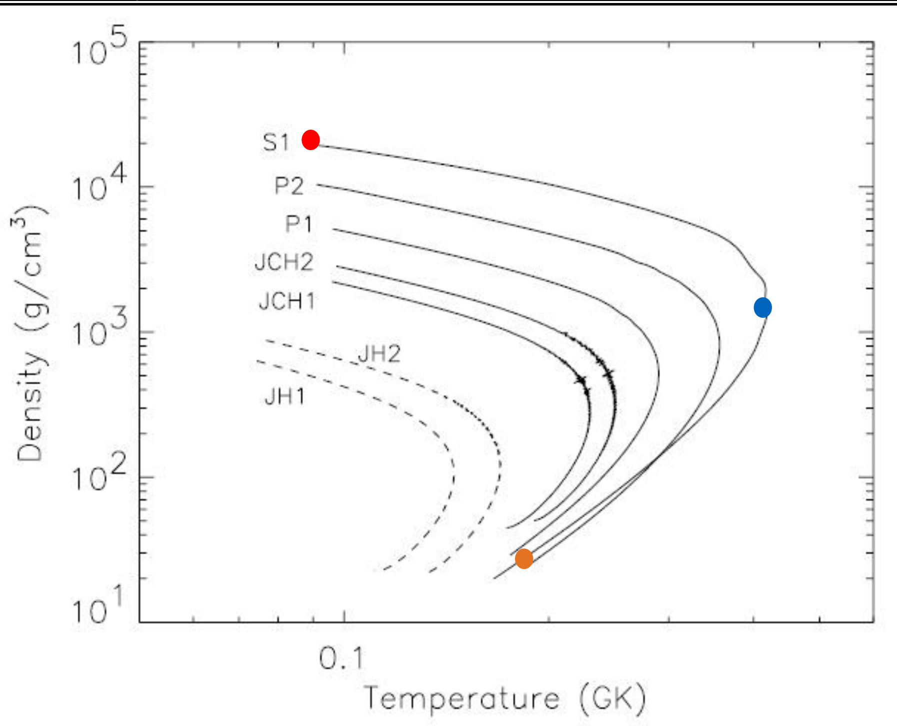
Shawn Bishop, TUM

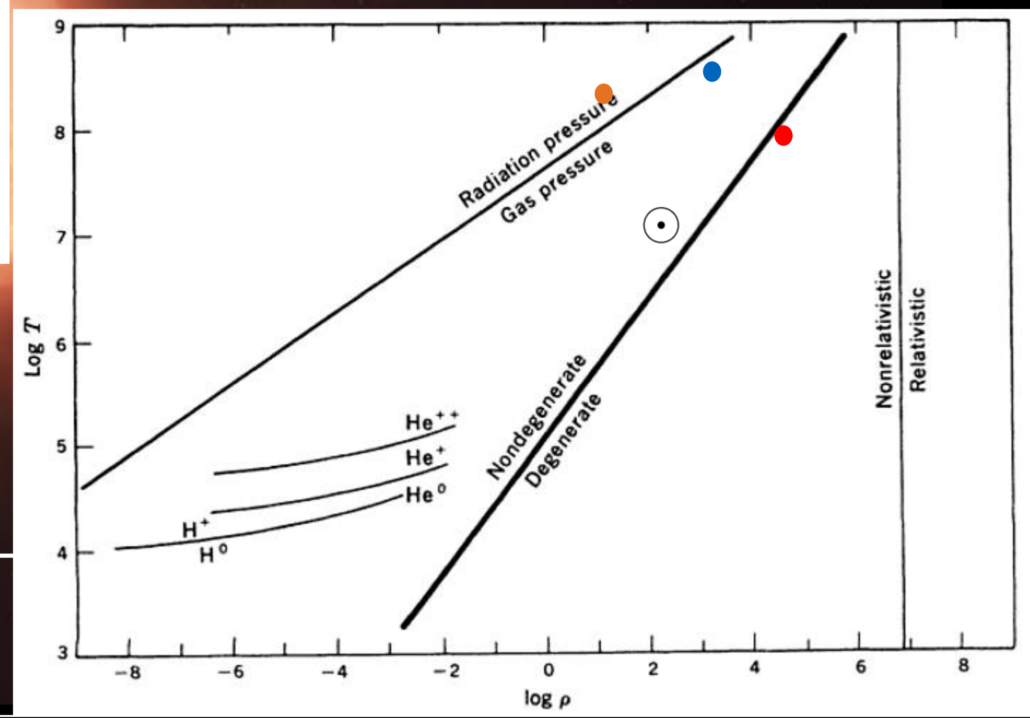
Talk Outline

- Astrophysics Primer
  - Experimental nuclear astrophysics
  - The novae phenomenon
  - Reaction Rates & Measurements
- Facilities at MLL
  - Mapping Explosive Rates: Q3D Spectrometer
  - Doppler Lifetime Station
- Search for Supernova Signal in the Fossil Record
  - Intersection of astrophysics, nuclear physics techniques, geophysics & microbiology
- Summary

We are star-stuff. -- Carl Sagan

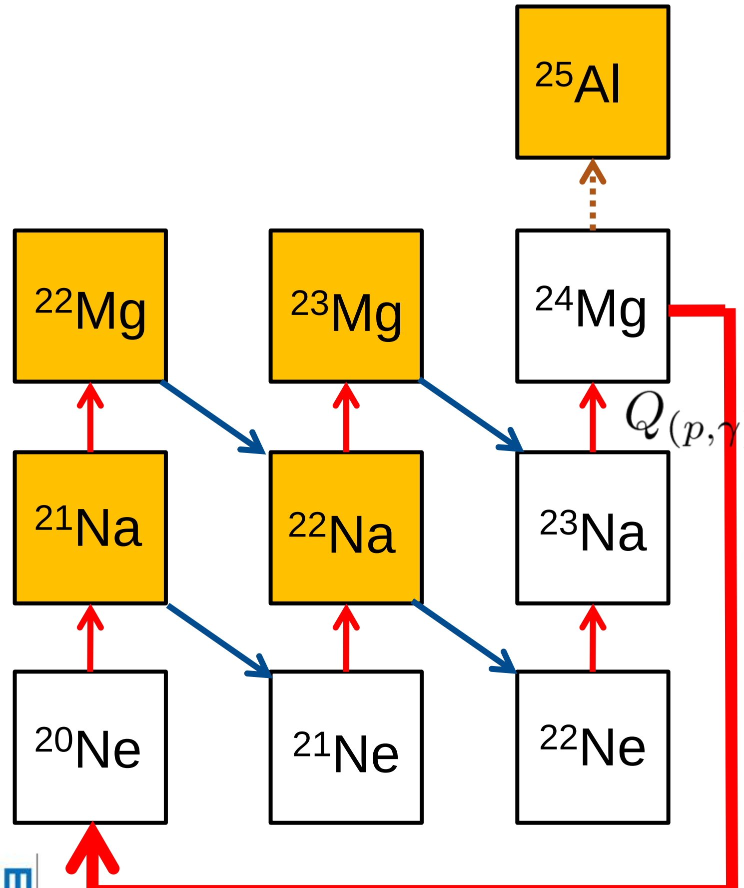
ASTROPHYSICS PRIMER



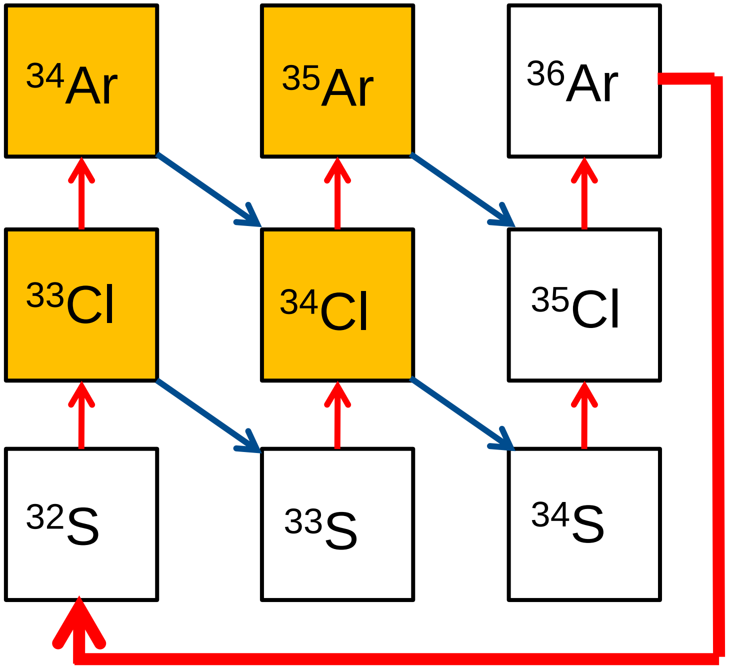


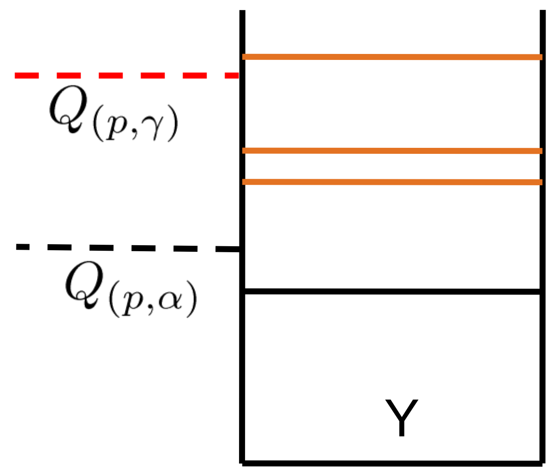
Transfer of H

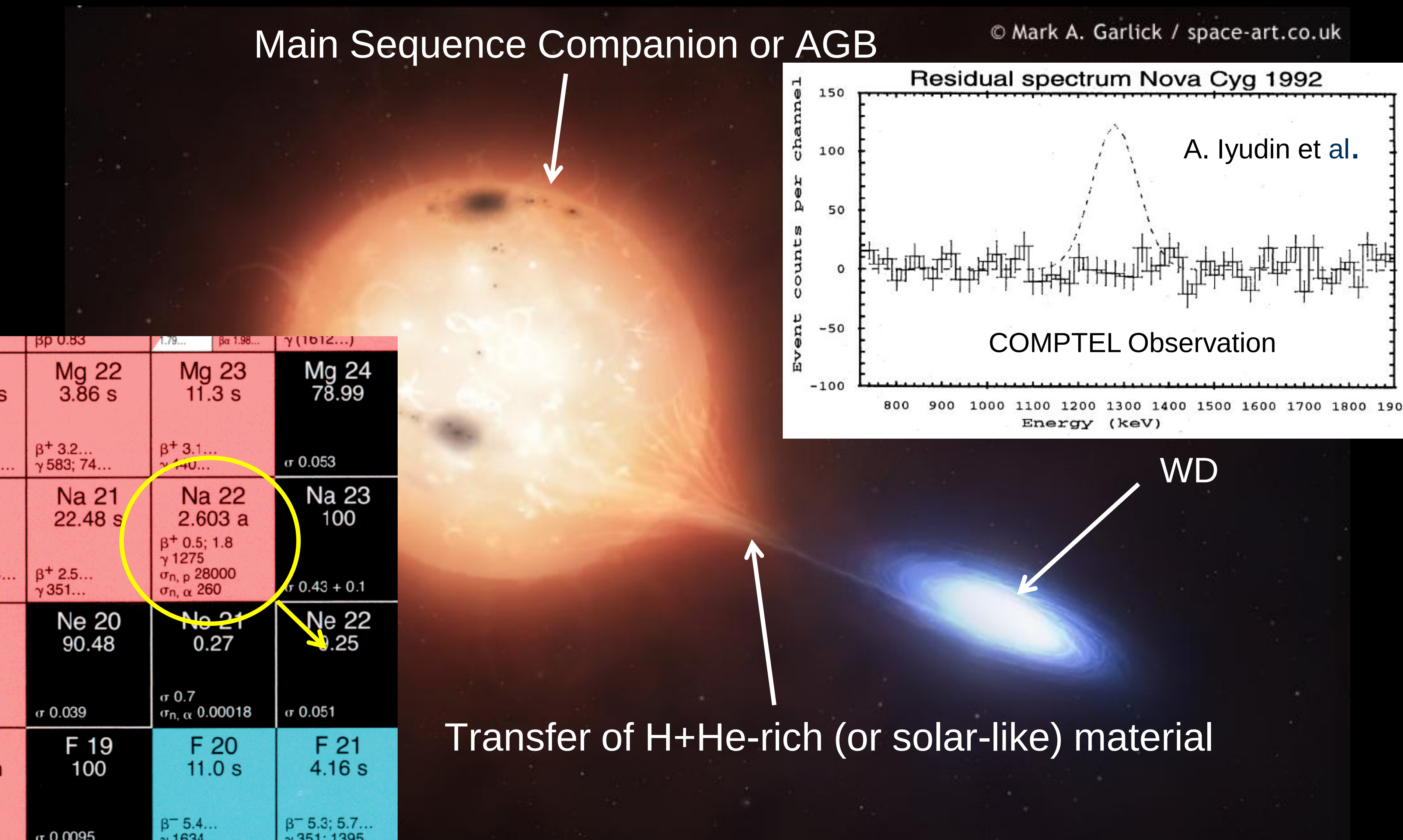
ONe-Nova Burning Cycles



$$Q_{(p,\gamma)} > Q_{(p,\alpha)}$$






Main Sequence Companion or AGB
© Mark A. Garlick / space-art.co.uk
Residual spectrum Nova Cyg 1992
A. Iyudin et al.
COMPTEL Observation
Event counts per channel
150
100
50
0
-50
-100
800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900
Energy (keV)
WD
Mg 22
3.86 s
β+ 3.2…
γ 583; 74…
Mg 23
11.3 s
β+ 3.1…
Mg 24
78.99
σ 0.053
Na 21
22.48 s
β+ 2.5…
γ 351…
Na 22
2.603 a
β+ 0.5; 1.8
γ 1275
σn, p 28000
σn, α 260
Na 23
100
σ 0.43 + 0.1
Ne 20
90.48
σ 0.039
Ne 21
0.27
σ 0.7
σn, α 0.00018
Ne 22
σ 0.051
F 19
100
σ 0.0095
F 20
11.0 s
β− 5.4…
γ 1634…
F 21
4.16 s
β− 5.3; 5.7…
γ 351; 1395…
Transfer of H+He-rich (or solar-like) material

A Recent Surprise from Nova Cas. 1995

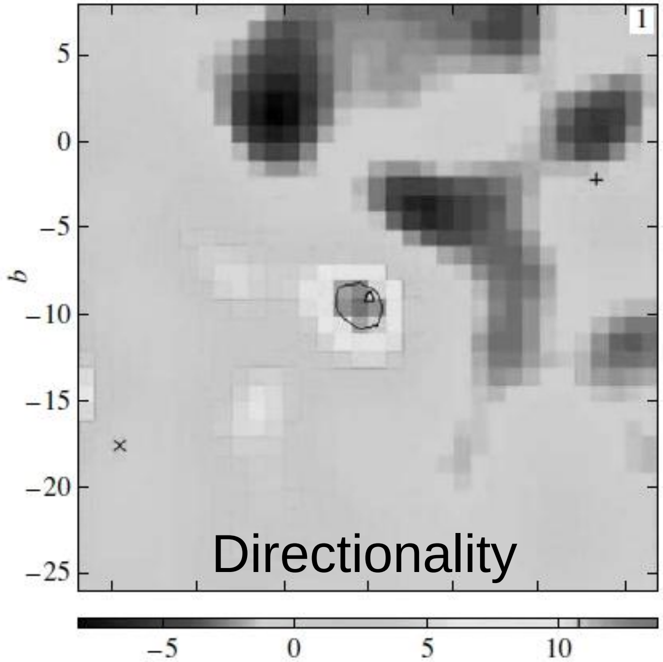
ISSN 1063-7729, Astronomy Reports, 2010, Vol. 54, No. 7, pp. 611–619. © Pleiades Publishing, Ltd., 2010.
Original Russian Text © A.F. Iyudin, 2010, published in Astronomicheskii Zhurnal, 2010, Vol. 87, No. 7, pp. 667–676.

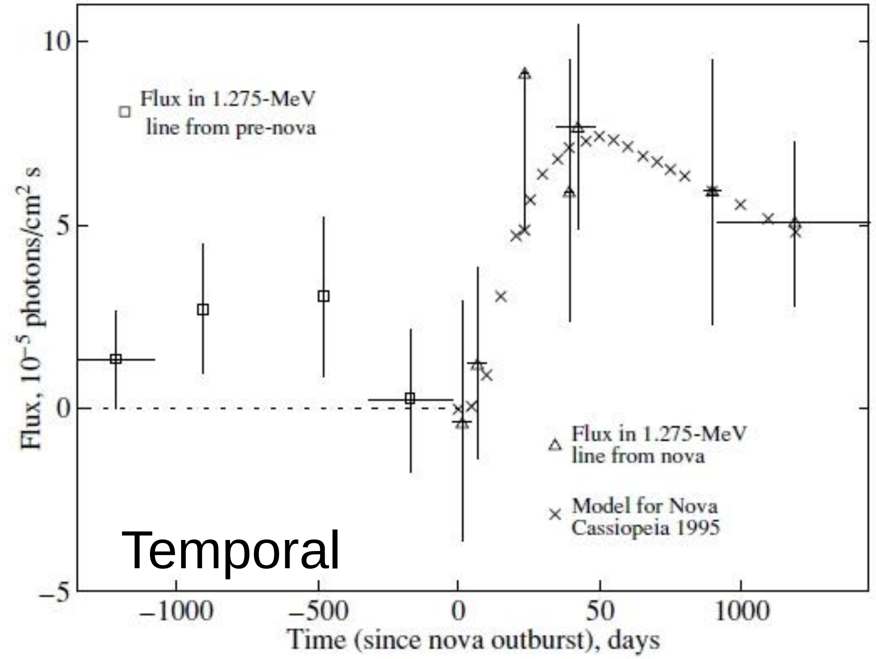
Observation of Line Emission of the Isotope ^{22}Na from a Classical Nova

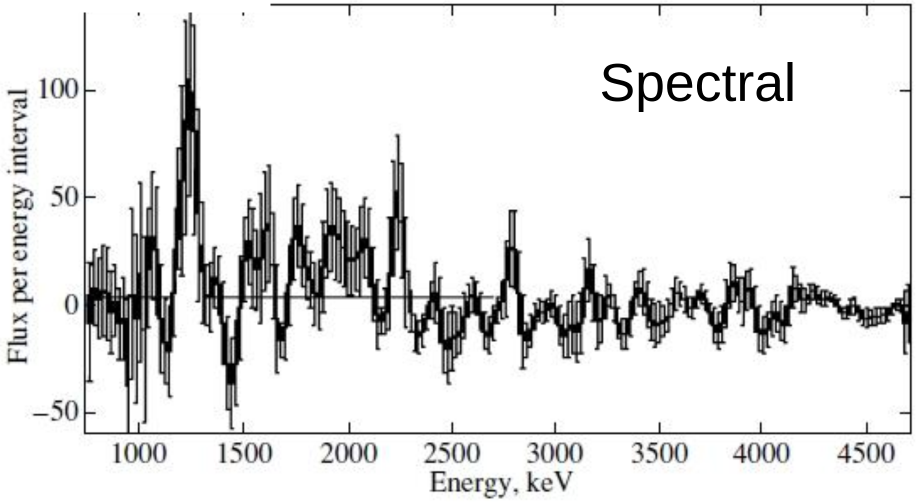
A. F. Iyudin

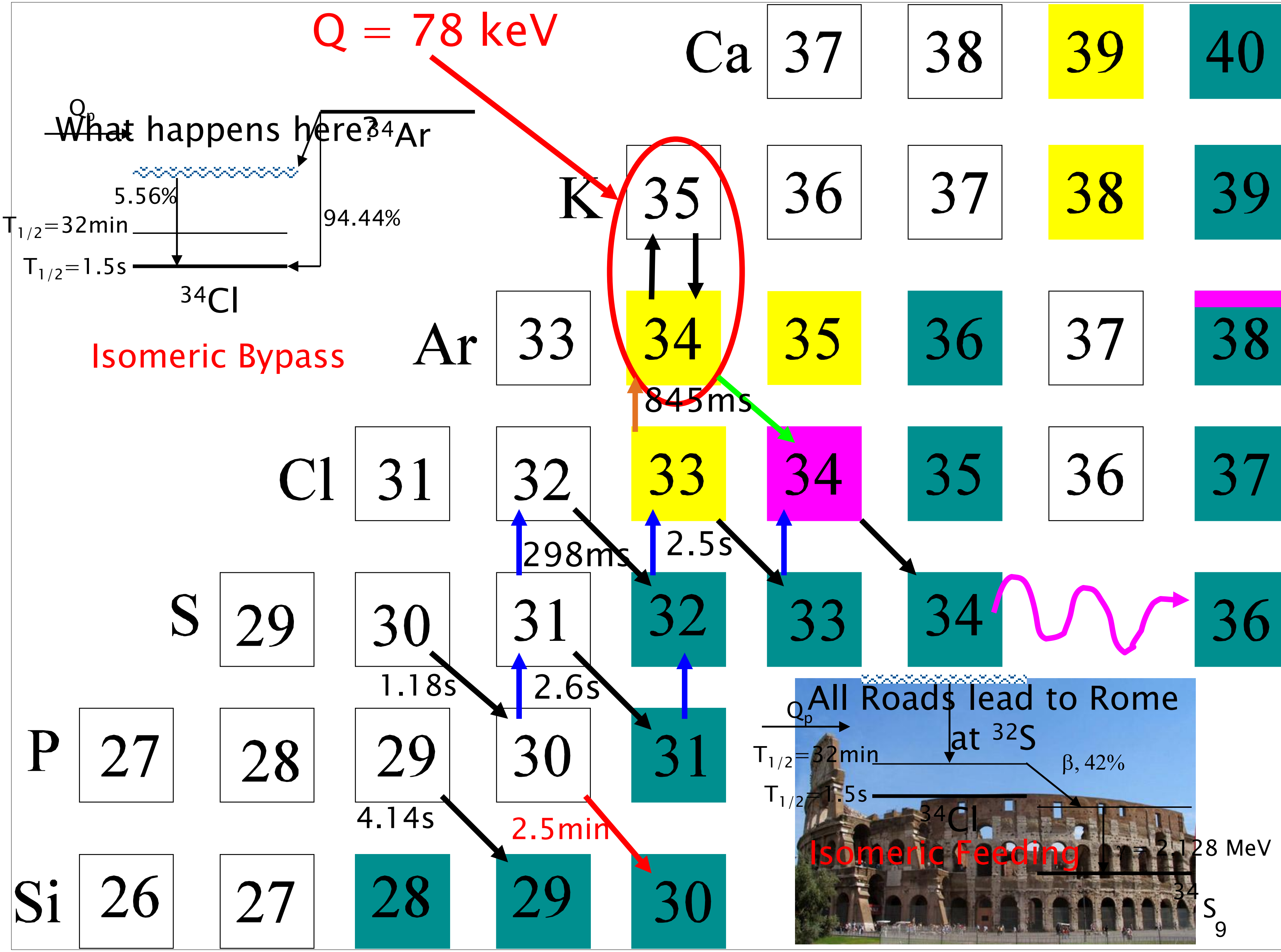
D.V. Skobel'tsin Nuclear Physics Research Institute,
M.V. Lomonosov Moscow State University, Moscow, Russia

Received August 26, 2009; in final form, February 5, 2010


1
5
0
−5
−10
−15
−20
−25
b
−5
0
5
10
Directionality

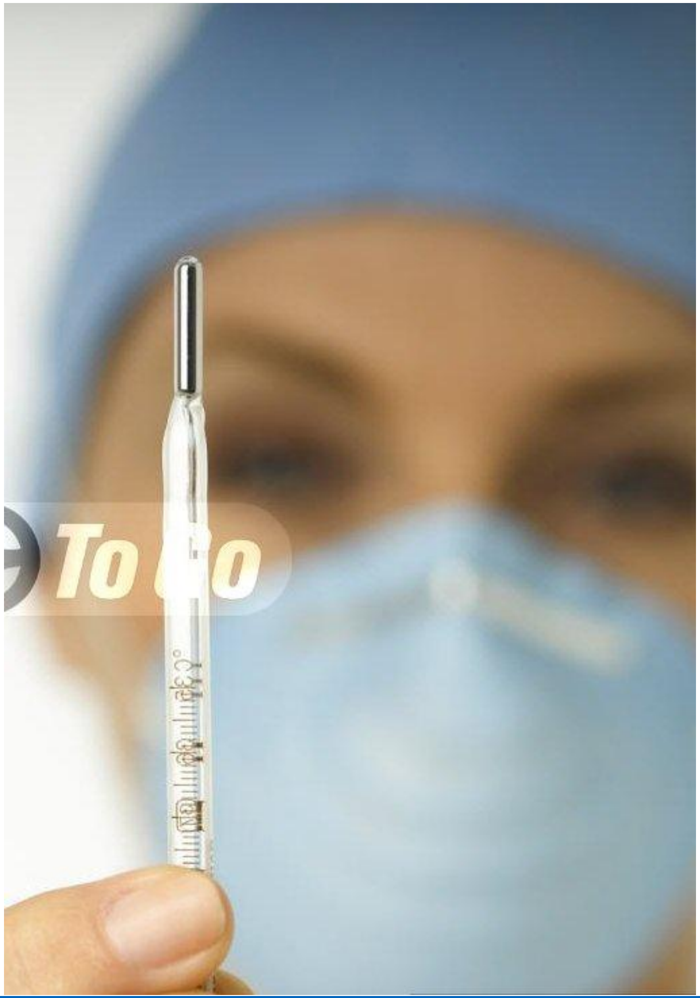

Flux in 1.275-MeV line from pre-nova
Flux in 1.275-MeV line from nova
Model for Nova Cassiopeia 1995
Temporal
Flux, 10^{-5} photons/cm^2 s
Time (since nova outburst), days
10
5
0
−5
−1000
−500
0
50
1000


Spectral
Flux per energy interval
Energy, keV
100
50
0
−50
1000
1500
2000
2500
3000
3500
4000
4500



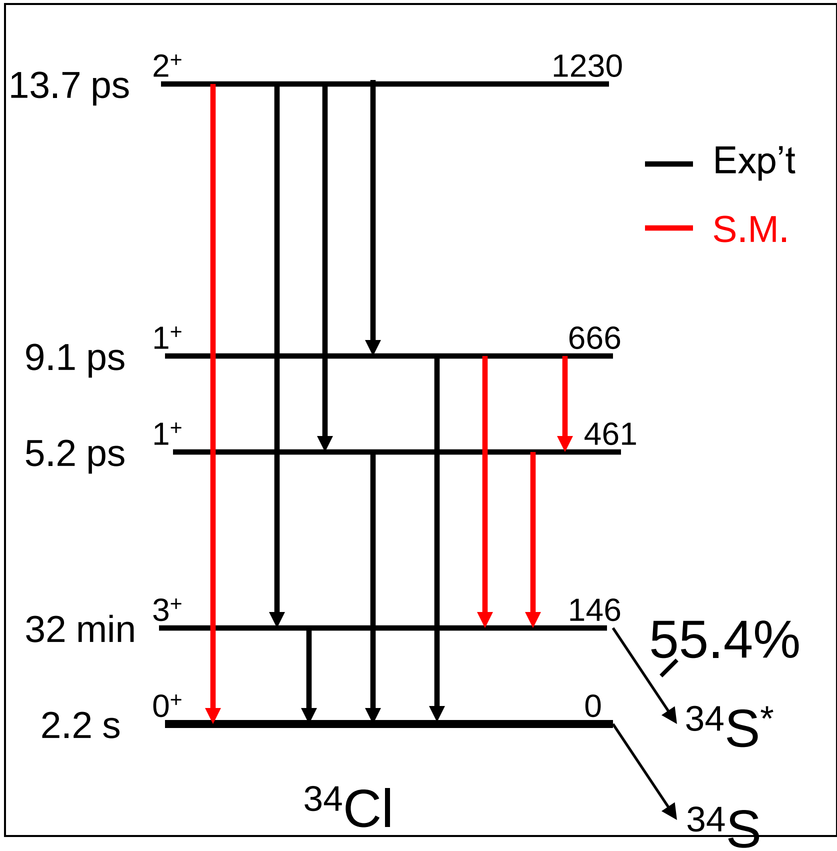
Q = 78 keV
What happens here?
^{34}Ar
Q_p
5.56%
94.44%
$T_{1/2}$=32min
$T_{1/2}$=1.5s
^{34}Cl
Isomeric Bypass
Ca 37 38 39 40
K 35 36 37 38 39
Ar 33 34 35 36 37 38
Cl 31 32 33 34 35 36 37
S 29 30 31 32 33 34 36
P 27 28 29 30 31
Si 26 27 28 29 30
845ms
298ms
2.5s
1.18s
2.6s
4.14s
2.5min
All Roads lead to Rome at ^{32}S
β, 42%
2.128 MeV
Isomeric Feeding
^{34}S

A Thermonuclear Thermometer….



^{34m}Cl: A Thermonuclear Thermometer

- 3^+ isomeric state gives rise to 2.12 MeV γ-line $\approx$ 42% per β decay
- Connected directly to ground by M3 transition (45.6% of the time)
- Radiation field can also connect isomeric state to ground state by induced transitions into higher states
  - If this is large enough, lifetime will be reduced from 32 min.
- System of coupled differential equations has been solved



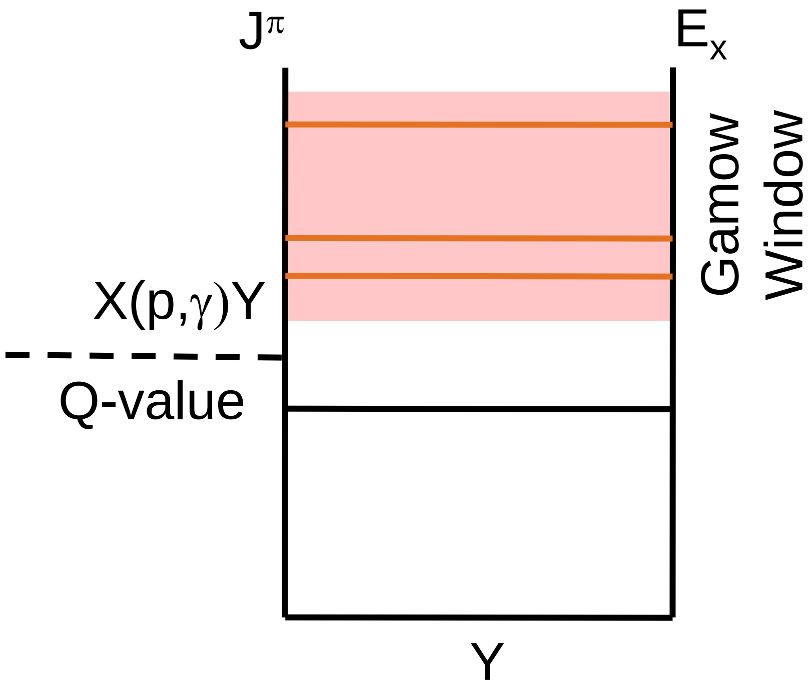
Coc et al., PRC61 (1999)

Some Key Nuclear Reactions

- ^{34m}Cl is a “last chance” γ-emitter for novae nucleosynthesis
  - Bypassed: ^{33}Cl(p,γ)^{34}Ar
  - Produced: ^{33}S(p,γ)^{34m}Cl
  - Destroyed: ^{34m}Cl(p,γ)^{35}Ar
- Excited states need to be “mapped out”
  - Energy, width, branching ratio, spin
- Equipment and Instruments
  - Q3D spectrometer
  - 95% hpGe detector (Canberra)
  - Si-detector charged particle telescopes (Micron UK)

What Needs to be Measured to Determine the Rates

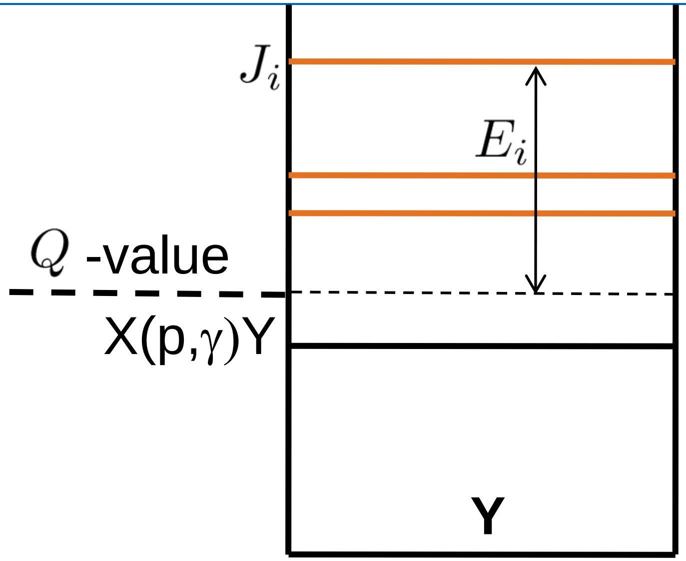
- Rates in explosive h-burning dominated by resonant proton-capture into excited states
- Properties of these states uniquely determine explosive X(p,γ)Y reaction rates
- Nuclear properties required:
  - Spin
  - Excitation energy
  - Lifetime
  - Proton and/or γ partial decay-widths
- Goal: Build facilities at MLL to accomplish these



X(p,γ)Y Resonant Reaction Rate

$$\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} (kT)^{-3/2} \int_0^\infty E\,\sigma(E) e^{-\frac{E}{kT}}\, dE$$

$$\sigma(E) = \frac{\hbar^2}{\mu E} \frac{2J_r + 1}{(2J_p + 1)(2J_X + 1)} \frac{\Gamma_p \Gamma_\gamma}{(E - E_r) + \Gamma^2/4}$$



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

resonance strength

$$\omega\gamma = \frac{2J_i + 1}{(2J_p + 1)(2J_X + 1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma_p + \Gamma_\gamma} = g(1 - B_p) B_p \frac{\hbar}{\tau}$$

→ Key quantity

μ - reduced mass
J_i, J_p, J_X – Spins of: resonance state/ projectile/ target
T – temperature
E_i – energy of state relative to Q
Γ_p, Γ_γ – partial width of p- / γ- decay
$B_p = \Gamma_p / \Gamma$ – branching ratio

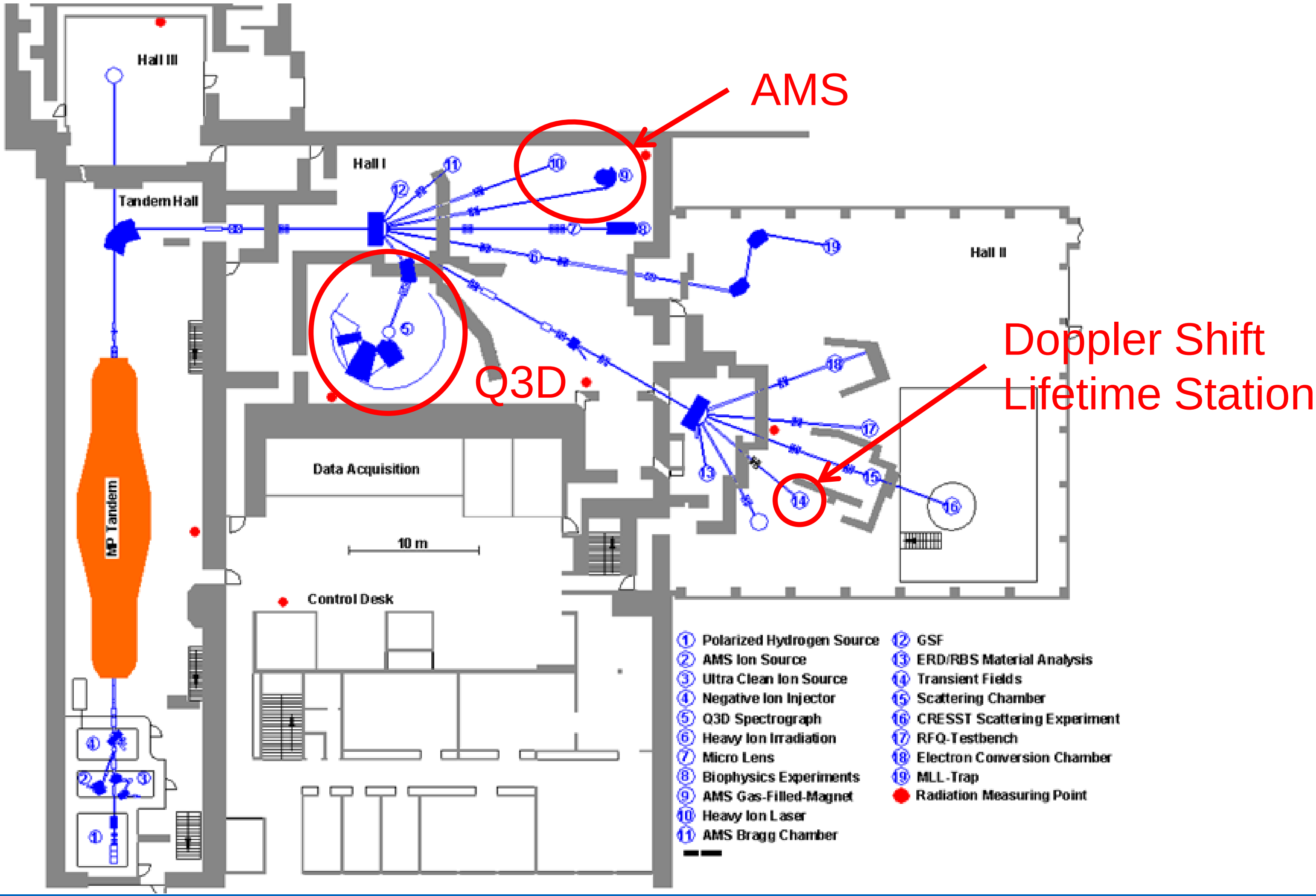
Measuring Astrophysical Rates one Step at a Time

FACILITIES

MLL Overview

- 14 MV Terminal voltage
- Pulsed beam
  - 200 ns between pulses
  - Pulse width ~ 1 ns
- Cesium sputtering ion source
  - Negative ion beams
  - No Nobel gas ion beams (except $^{3,4}He$)
- Isobaric separation at $90°$ bending magnet

Accelerator Laboratory: Overview

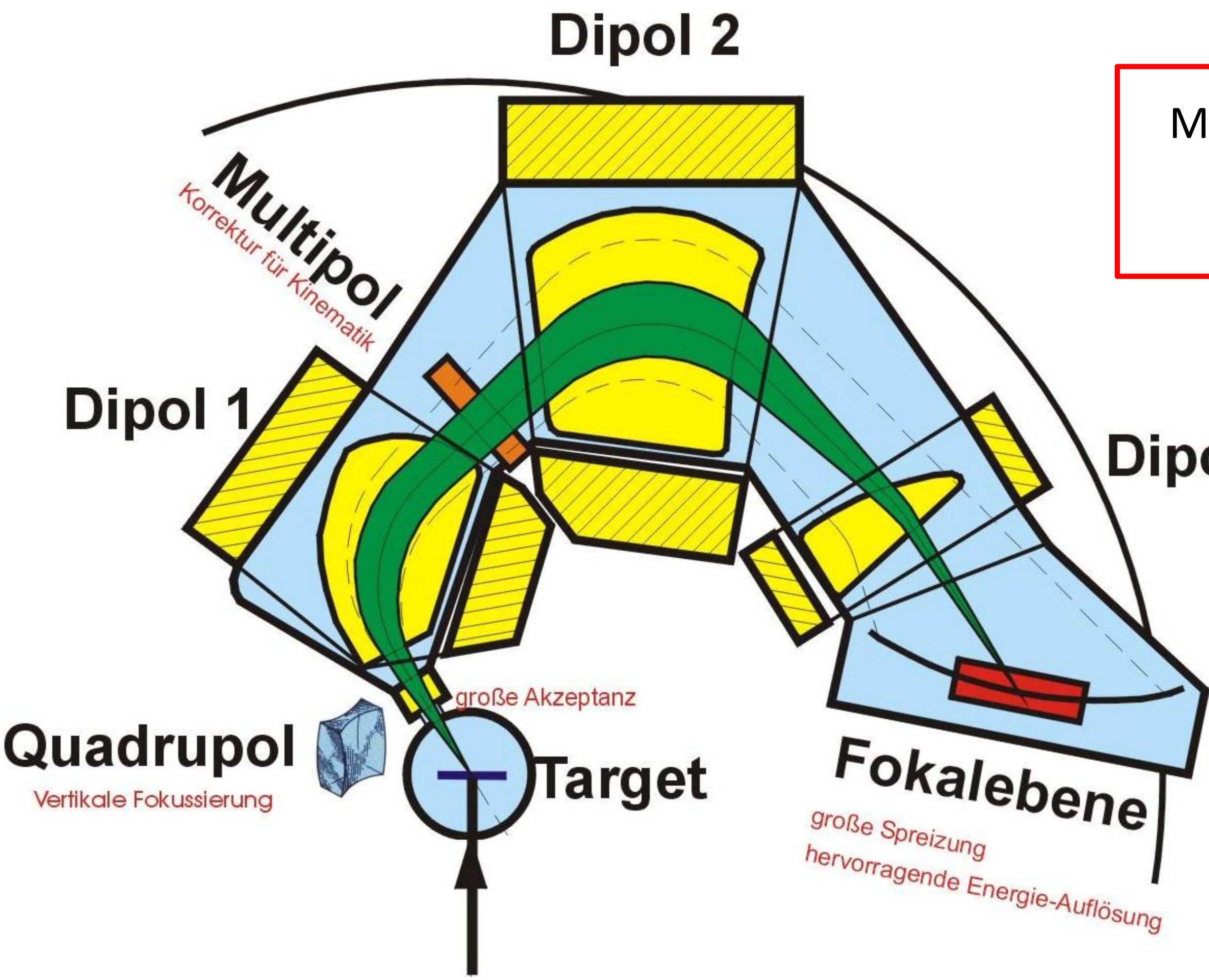


$$\langle \sigma v \rangle = \left(\frac{2\pi}{\mu k T}\right)^{3/2} \hbar^2 \sum_i \omega\gamma_i e^{-\frac{E_i}{kT}}$$

- Extracting $\exp(-E_i/kT)$

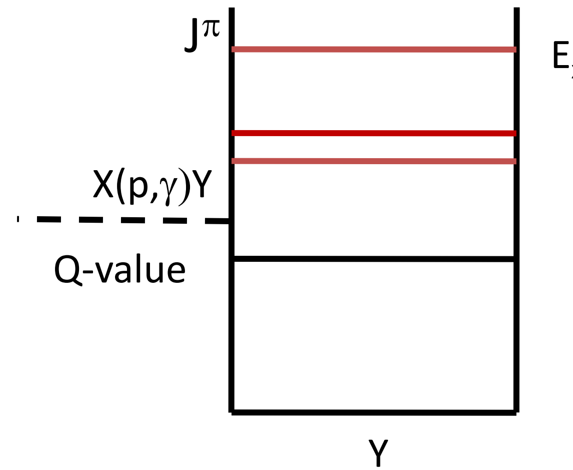
MAPPING EXPLOSIVE REACTION RATES: THE Q3D

Q3D High Resolution Spectrograph at TUM



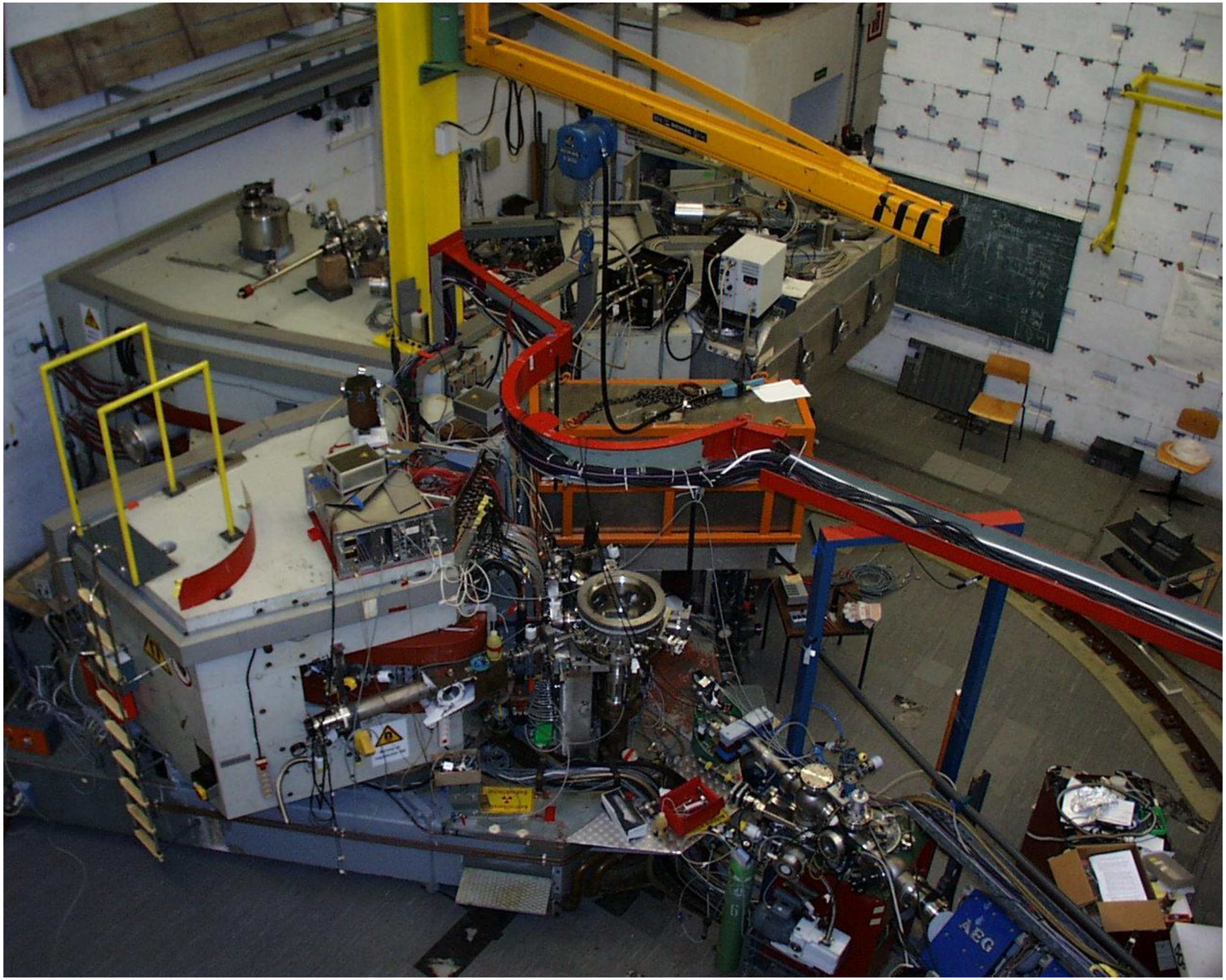
Momentum resolution:

$$\Delta p/p \approx 10^{-4}$$



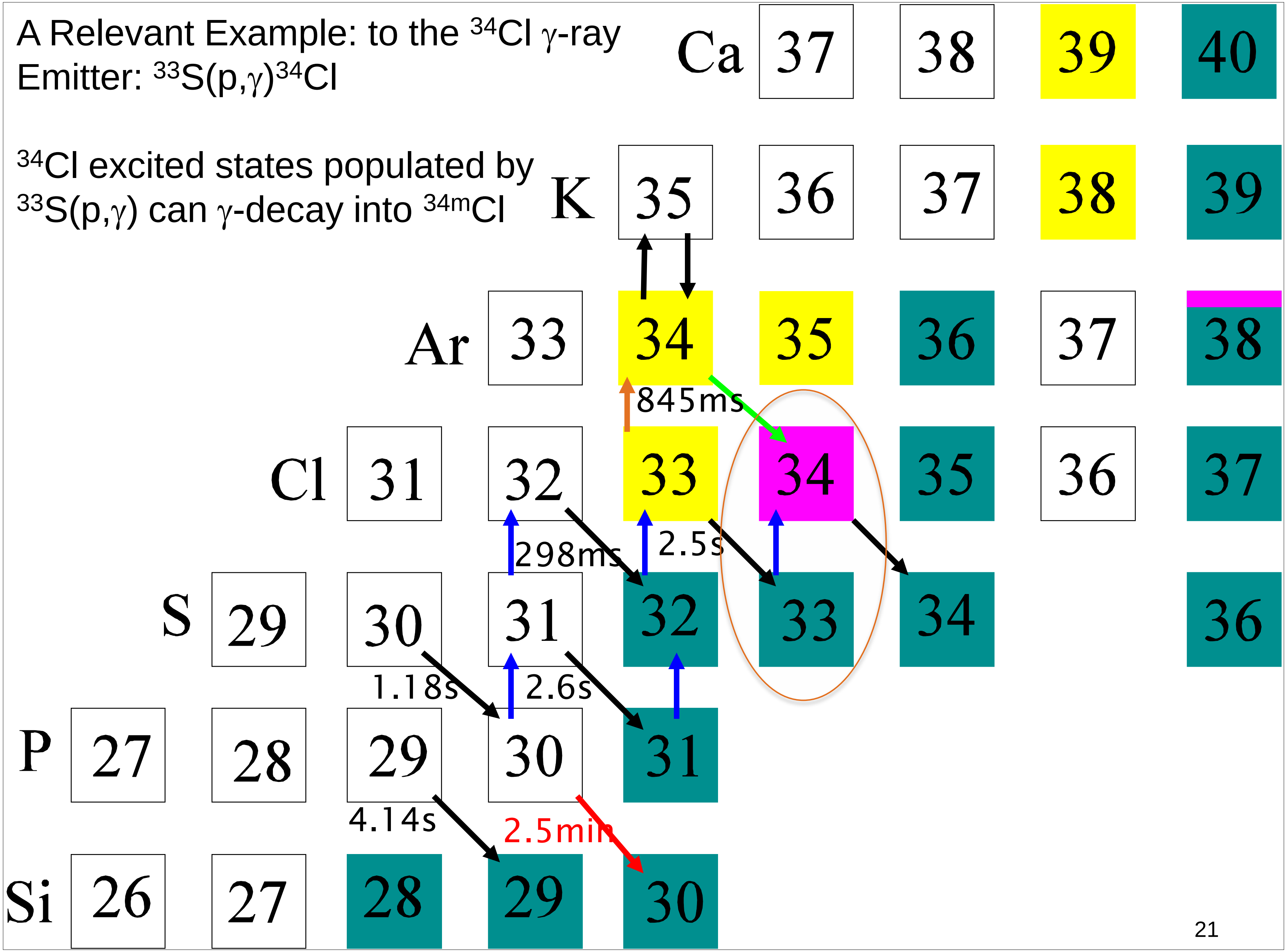
Used to search for, and study, excited states of nuclei by populating those states using one-step transfer reactions: X(^{3}He,t)Y, as an example

Position of triton along Focal Plane is a measure of the excitation energy.

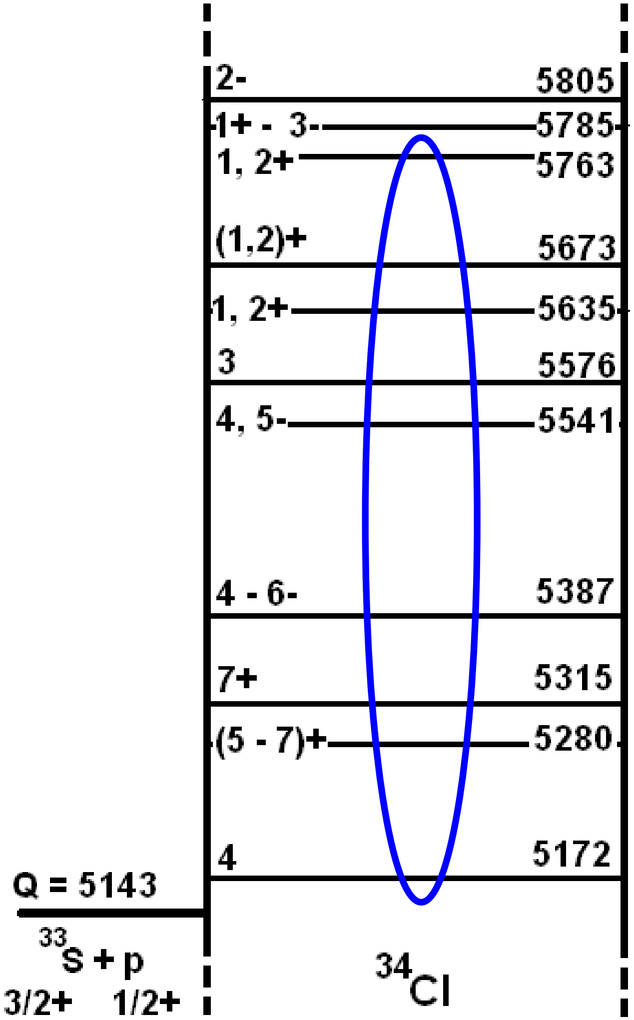


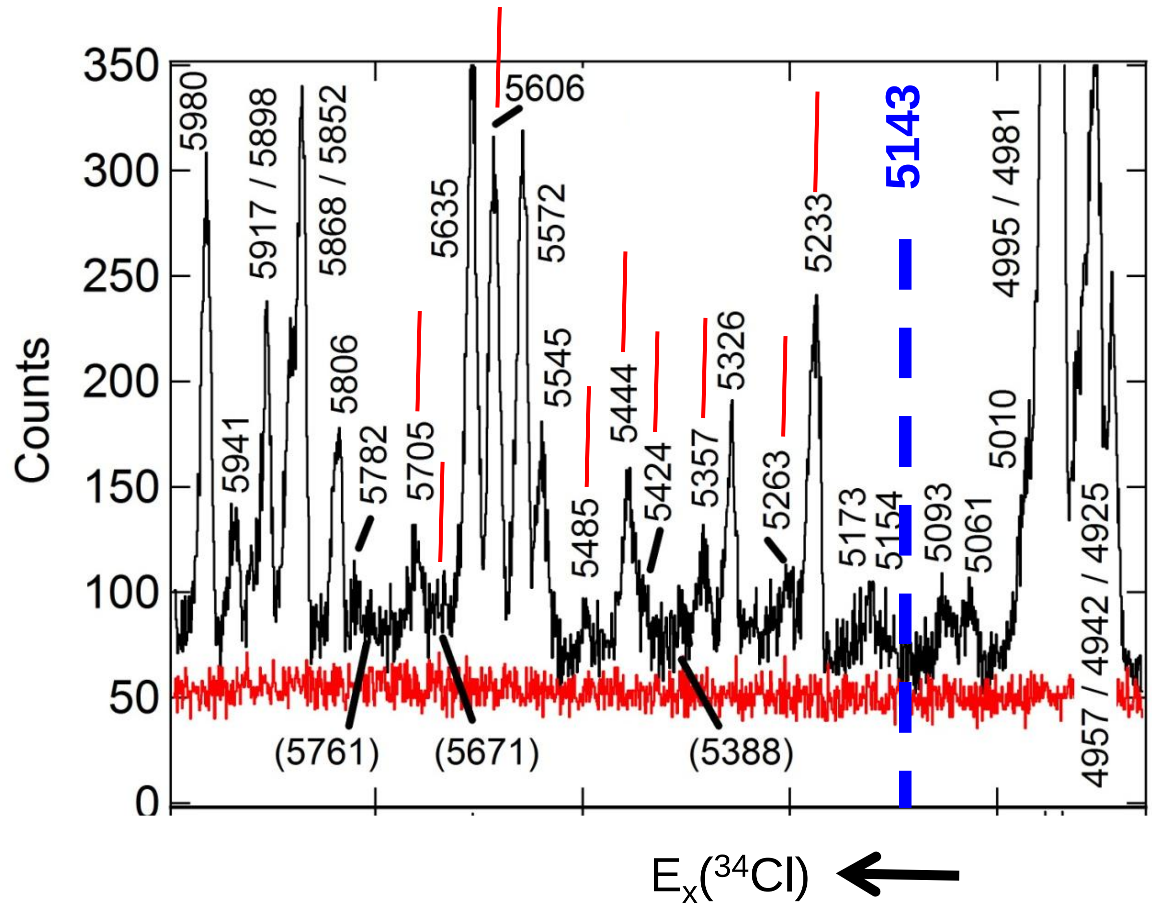
A Relevant Example: to the ^{34}Cl γ-ray Emitter: ^{33}S(p,γ)^{34}Cl

^{34}Cl excited states populated by ^{33}S(p,γ) can γ-decay into ^{34m}Cl



$^{34}S(^{3}He,t)^{34}Cl$, E_{He} = 25 MeV, θ = 15°





Parikh et al. PRC (2009)

$$\langle \sigma v \rangle = \left(\frac{2\pi}{\mu k T} \right)^{3/2} \hbar^2 \sum_i \omega\gamma_i e^{-\frac{E_i}{kT}}$$

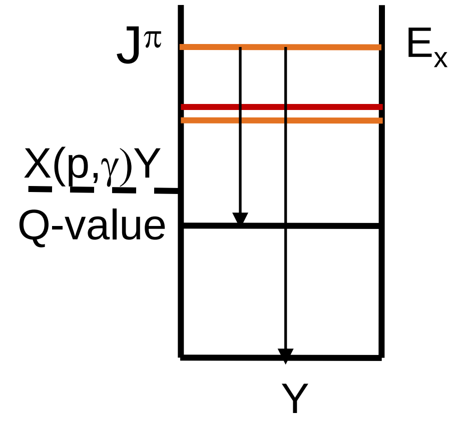
$$\omega\gamma = \frac{2J_i + 1}{(2J_p + 1)(2J_X + 1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma_p + \Gamma_\gamma} = g(1 - B_p) B_p \frac{\hbar}{\tau}$$

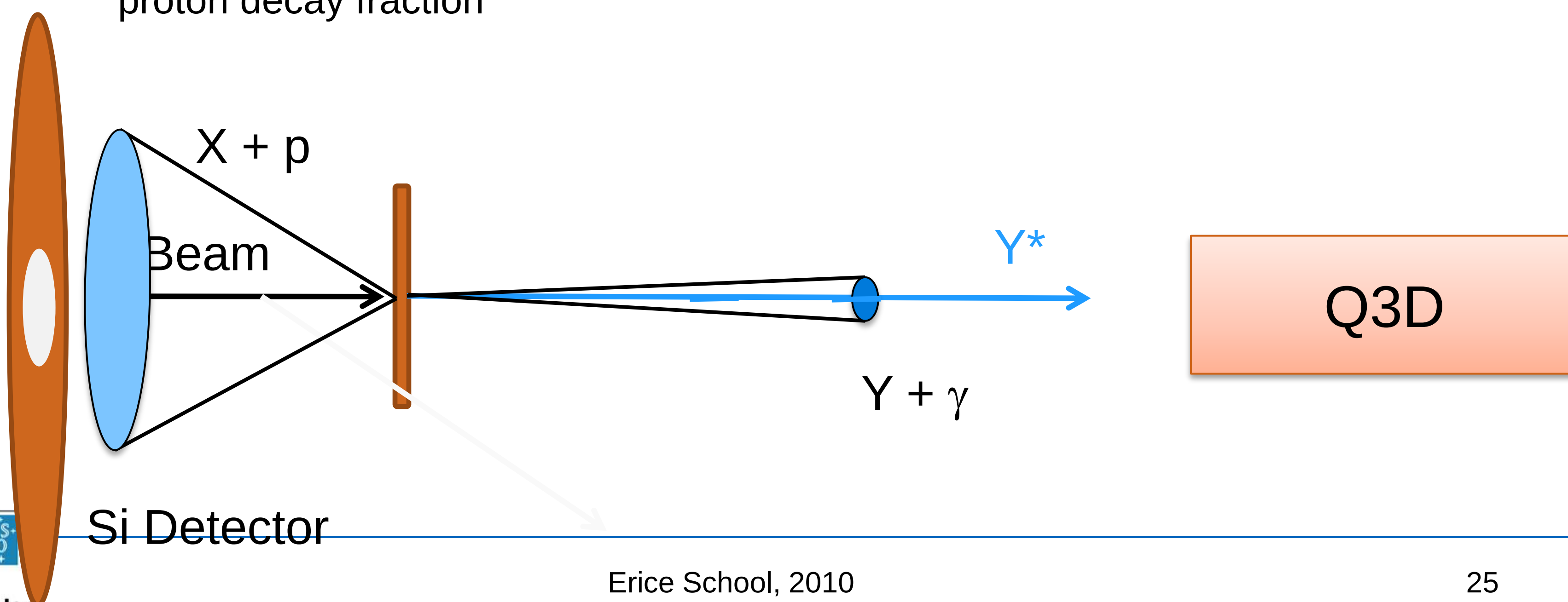
- Extracting B_p

MAPPING EXPLOSIVE REACTION RATES: THE Q3D

- Transfer reaction populates astrophysical state
- Product Y^* will either:
  - gamma-decay
  - proton-decay
- Decay cone for γ-decay is small
  - Detection of Y with Q3D, reconstruct kinematics, determine fraction of γ-decays
- Decay cone for proton decay large
  - Detect X and p together with Si, determine proton decay fraction

Transfer reaction in inverse kinematics



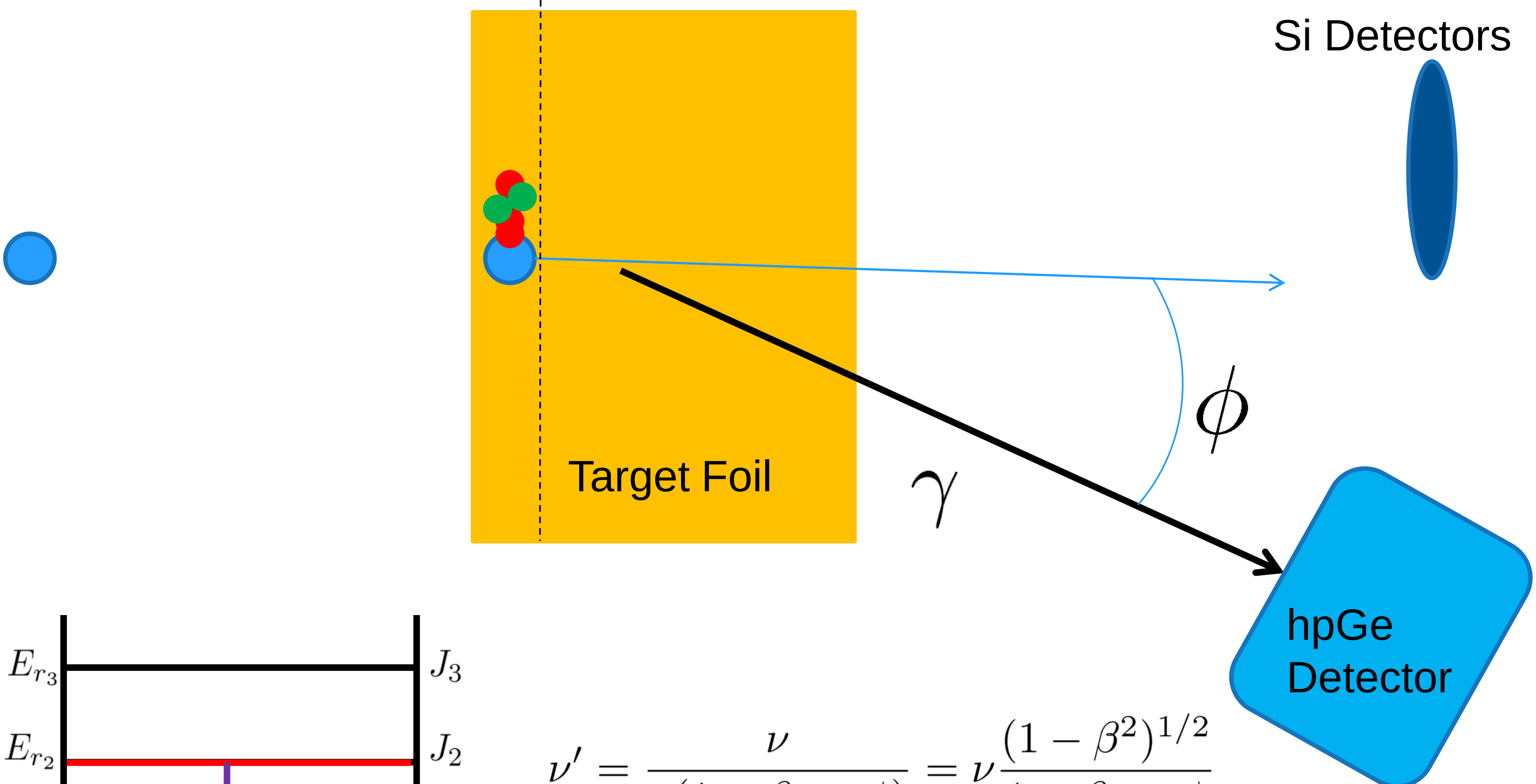


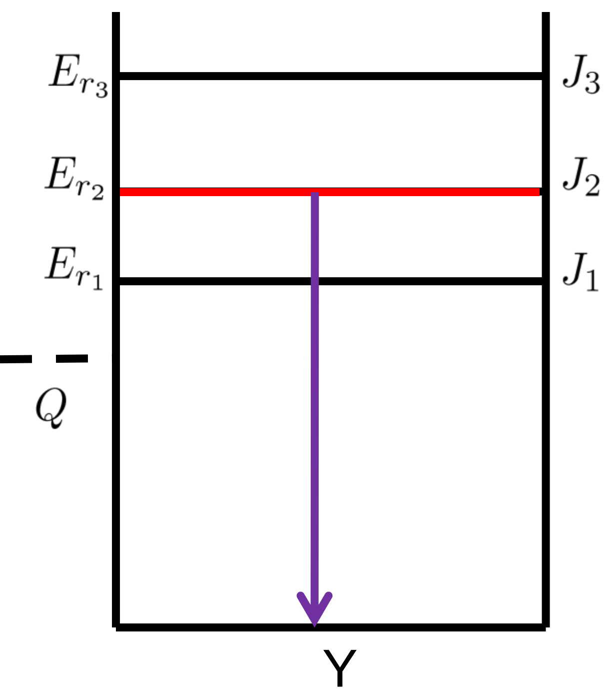
$$\omega\gamma = \frac{2J_i + 1}{(2J_p + 1)(2J_X + 1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma_p + \Gamma_\gamma} = g(1 - B_p)B_p \frac{\hbar}{\tau}$$

$$B_p = \Gamma_p / (\Gamma_p + \Gamma_\gamma)$$

Extracting the $\hbar/\tau$ term

DOPPLER LIFETIME STATION



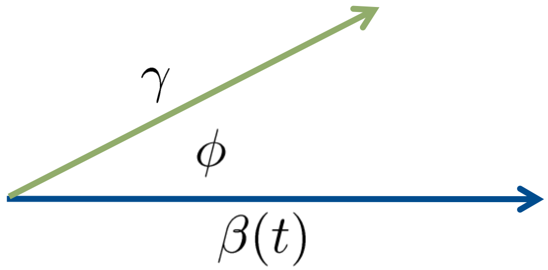


$$\nu' = \frac{\nu}{\gamma(1-\beta\cos\phi)} = \nu\frac{(1-\beta^2)^{1/2}}{1-\beta\cos\phi}$$

$$\Rightarrow E'_\gamma = E_\gamma\frac{(1-\beta^2)^{1/2}}{1-\beta\cos\phi}$$

$$\approx E_\gamma(1-1/2\beta^2+\ldots)(1+\beta\cos\phi+\ldots)$$

$$\approx E_\gamma(1+\beta\cos\phi)$$



$$E_\gamma = E_0 (1 + \beta_t \cos\phi)$$

$$\Rightarrow \frac{E_\gamma - E_0}{E_0} = \beta_t \cos\phi = V_t$$

Measurement of the Doppler shifted gamma yields velocity distribution of nucleus at instant of decay.

Decay probability in $[t, t+dt]$:

$$P_\gamma dt = \frac{1}{\tau} \exp\left(-t/\tau\right) dt$$

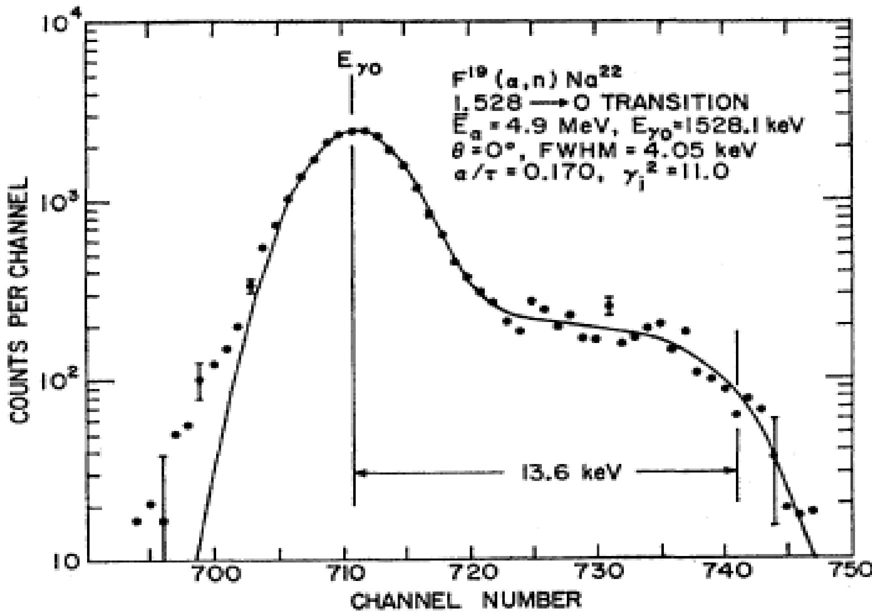
Fraction of N total nuclei that decay with velocity in [β(t) cos ϕ, β(t + dt) cos ϕ]:

$$F(\tau)dt = V_t \frac{1}{\tau} \exp\left(-t/\tau\right) dt$$

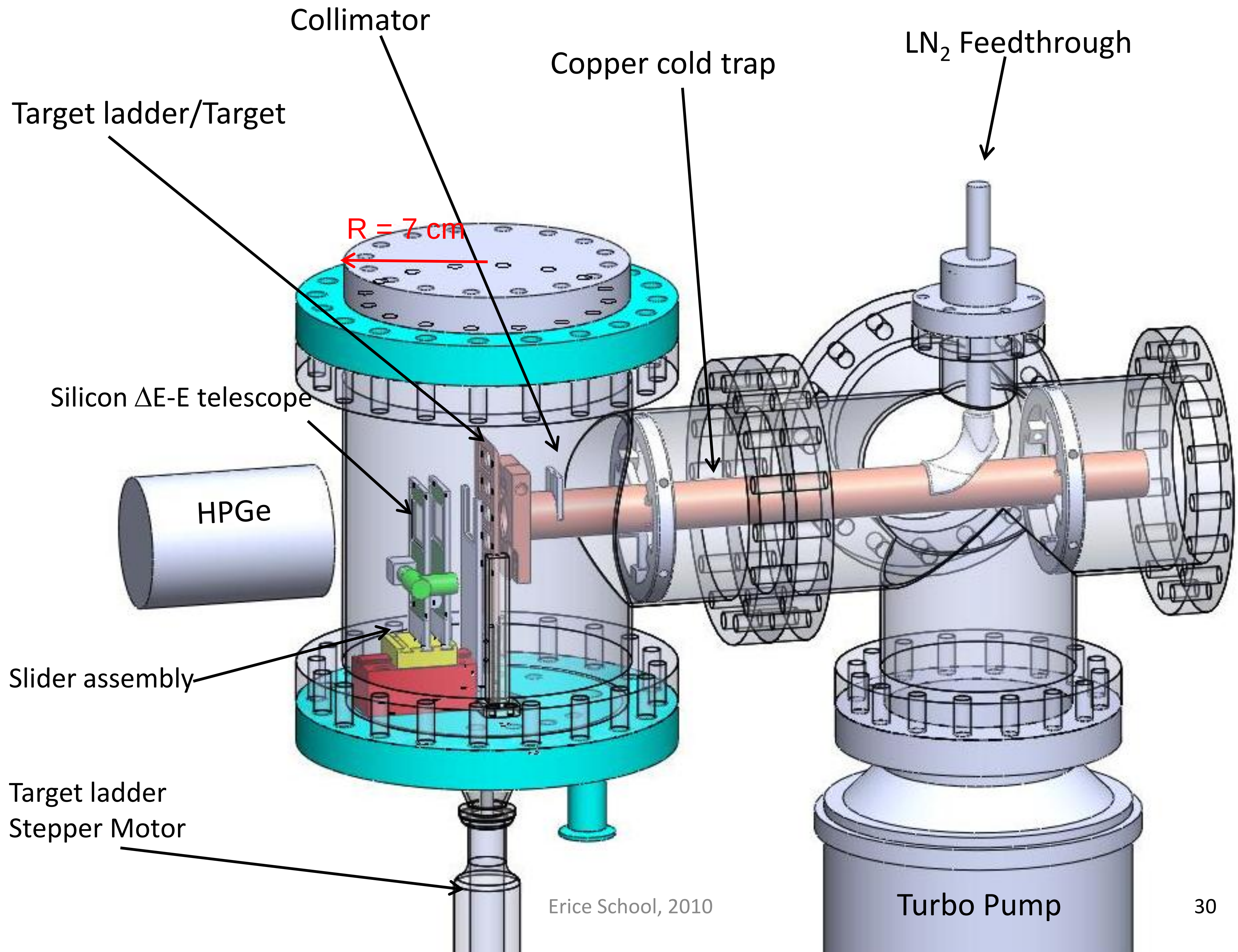
Velocity distribution formed by an ensemble of N decaying particles:

$$F(\tau) = N \int_0^\infty \beta_t P_\gamma \cos\phi \, dt = \frac{N}{\tau} \int_0^\infty \beta_t \exp\left(-t/\tau\right) \cos\phi \, dt$$

$$E_\gamma = E_0 (1 + F(\tau) \beta_0 \cos\phi)$$

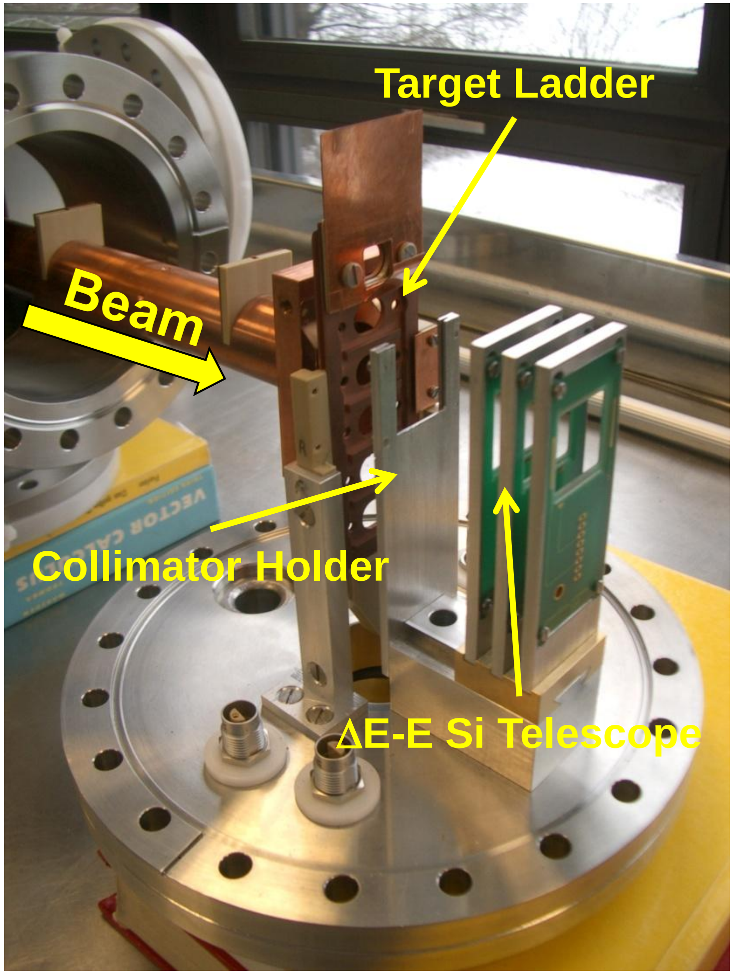


E.K.Warburten et al.
Phys. Rev. 160, 938 - 963 (1967)

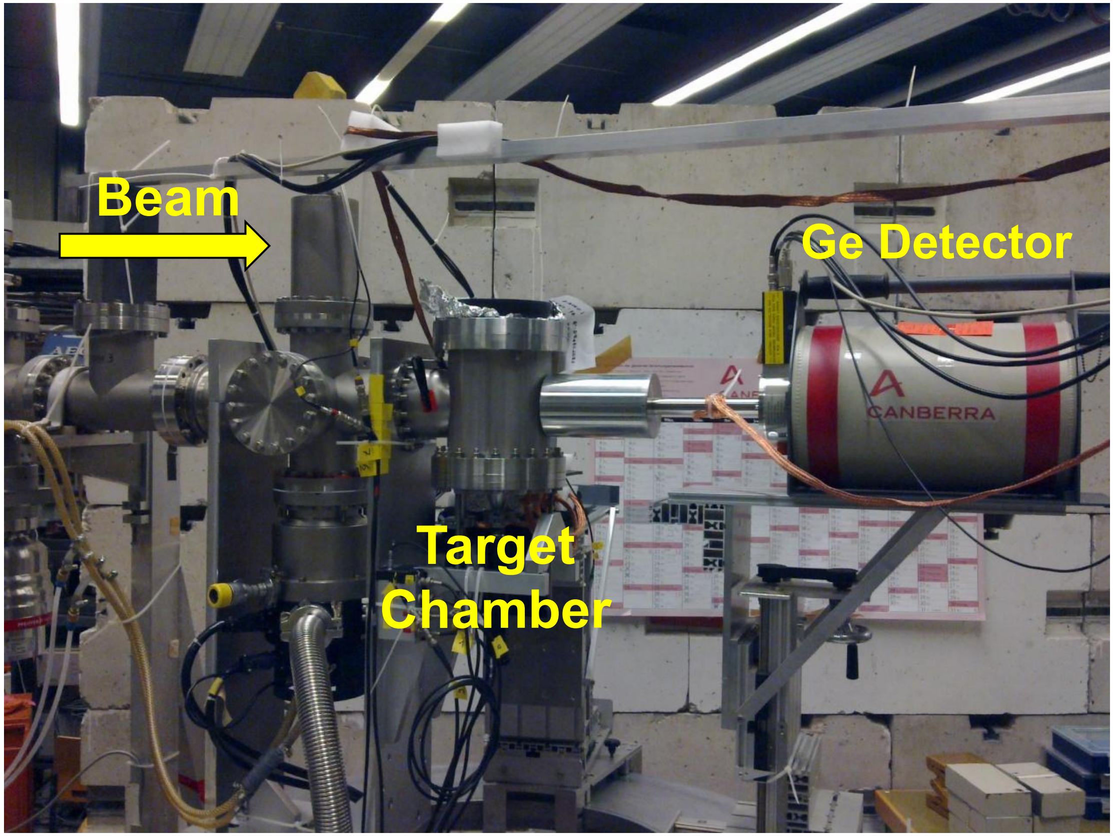


Collimator
LN$_2$ Feedthrough
Copper cold trap
Target ladder/Target
R = 7 cm
Silicon ΔE-E telescope
HPGe
Slider assembly
Target ladder
Stepper Motor
Turbo Pump

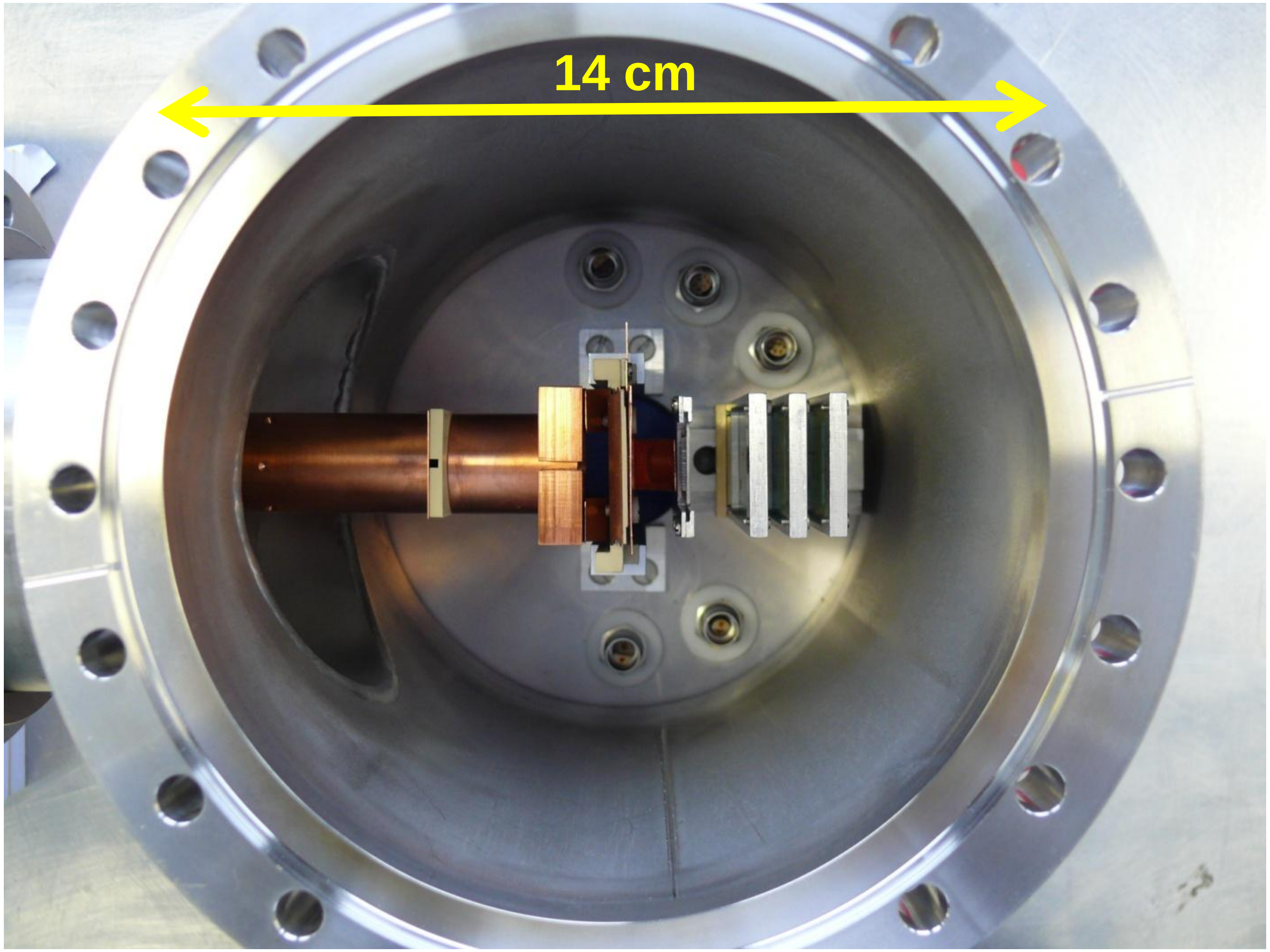
Target Chamber Innards



Installation on MLL Beamline

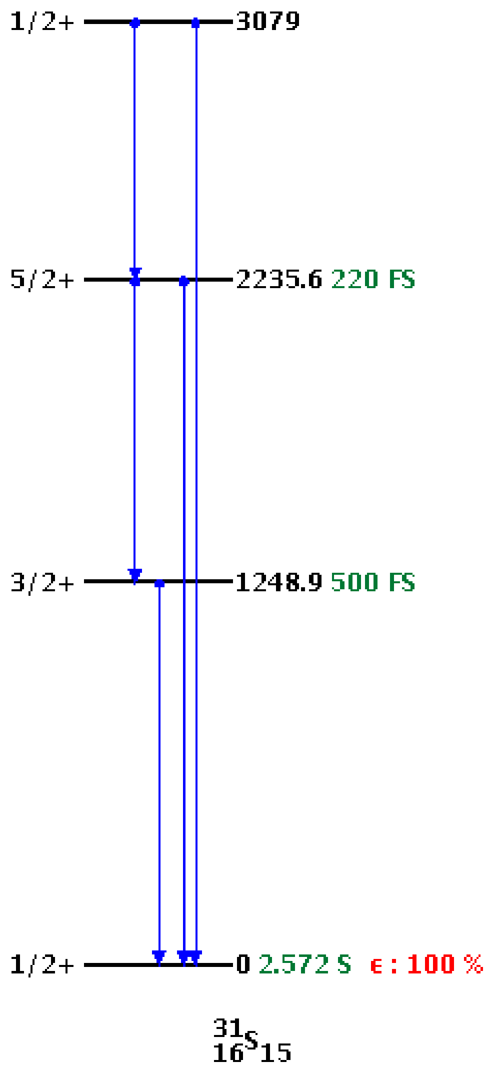


Doppler Shift Station: Target Chamber

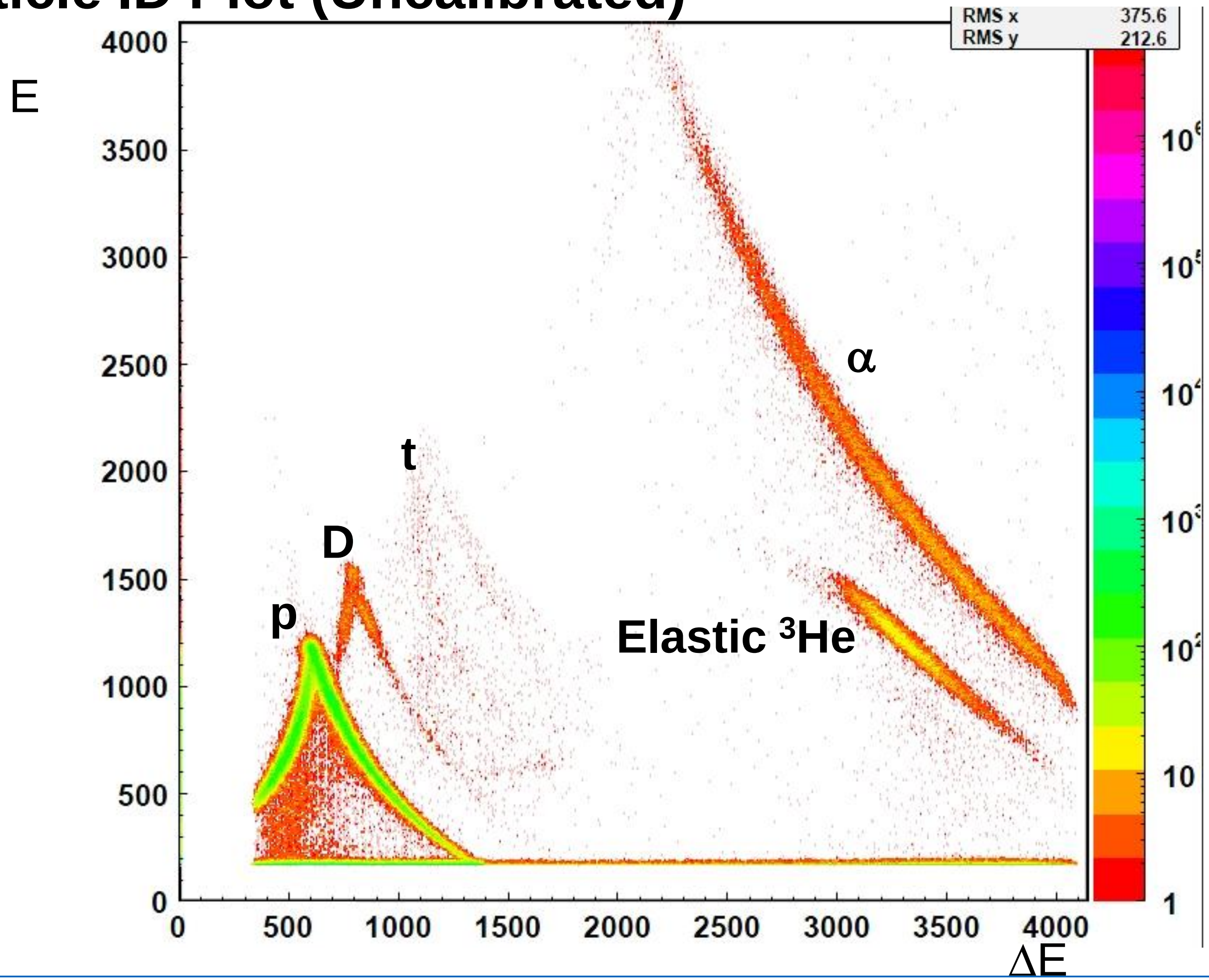


Commissioning (two weeks ago)

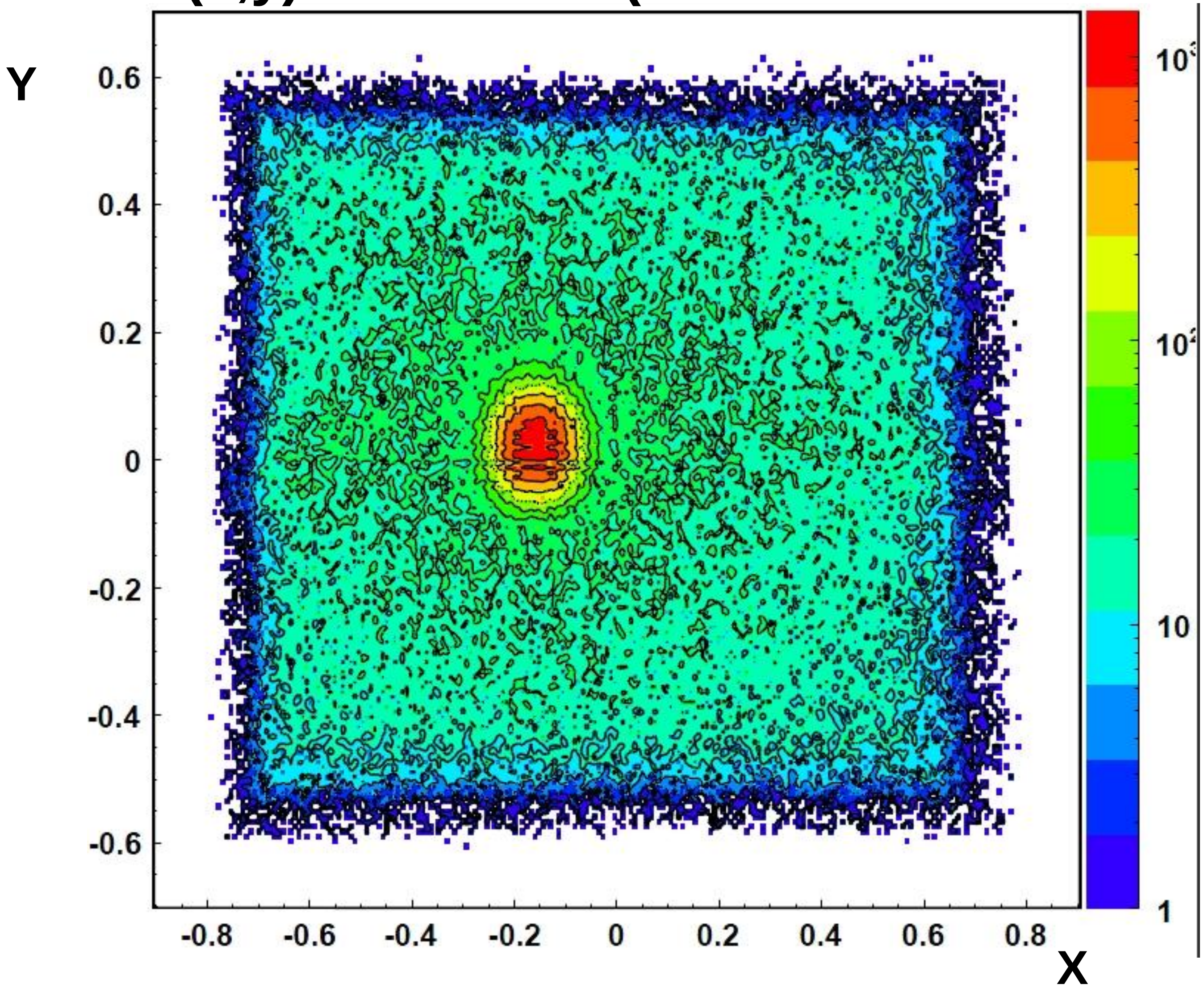
- Chose the $^{32}S(^{3}He,\alpha)^{31}S$ reaction
  - 1st and 2nd excited states previously observed
  - Lifetimes known
- Energy spacing large
  - Gammas easily distinguishable
  - Alpha particles well-separated kinematically
- ^{32}S beam energy: 80 MeV
- Target:
  - Au foil, 15 micron thick
  - 1st 0.5 micron implanted with ^{3}He at FZD
- Analysis presently underway



Particle ID Plot (Uncalibrated)



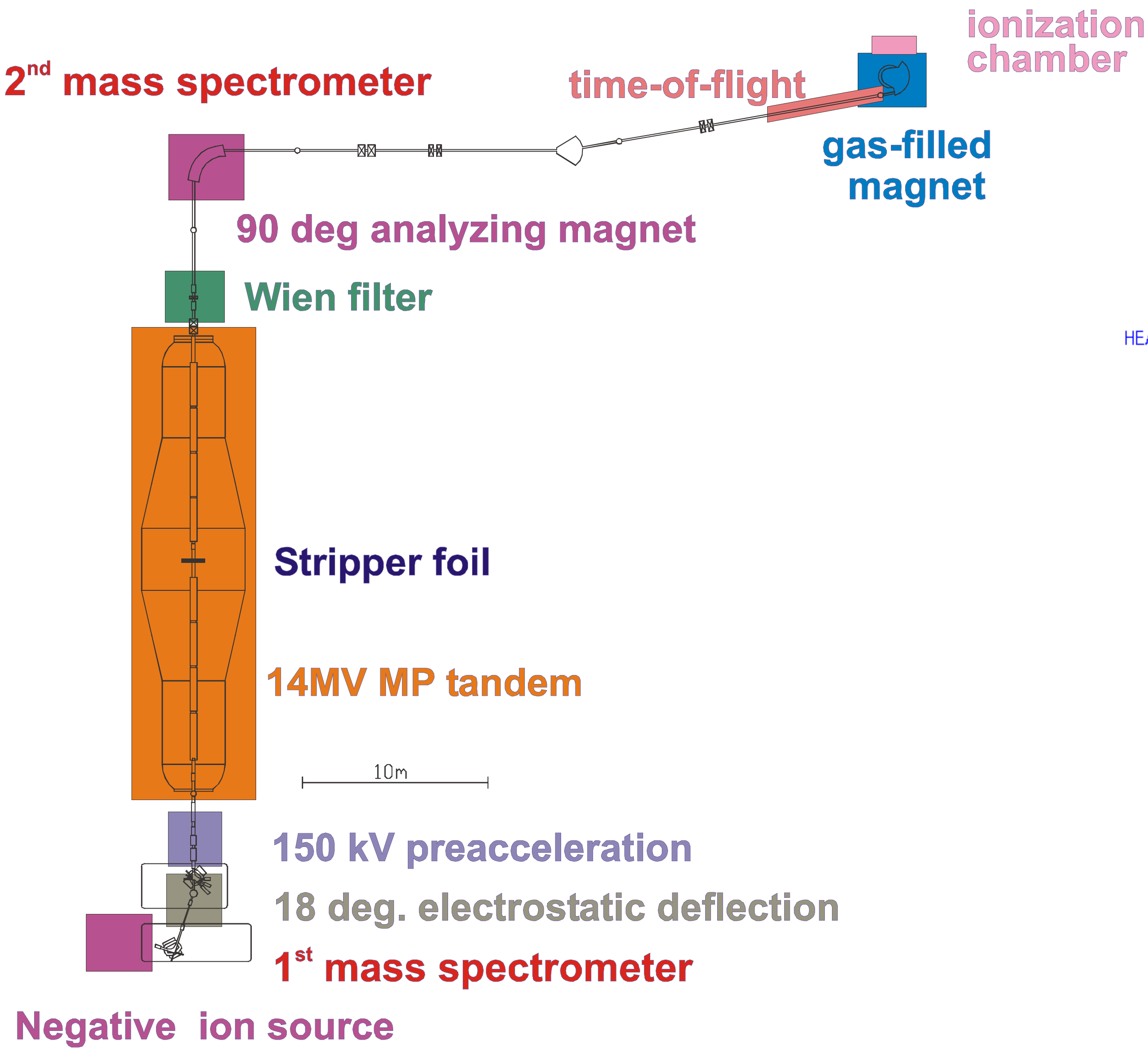
Si-Detector (x,y) Hit Pattern (Raw and Uncalibrated)



Looking into the Past

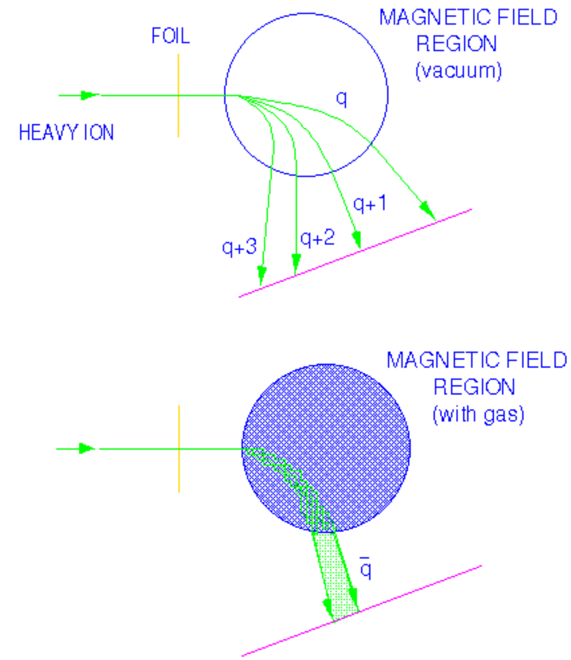
ACCELERATOR MASS SPECTROMETRY

Accelerator Mass Spectroscopy at TUM



magnetic rigidity

$$B\rho = \frac{Mv}{q}$$

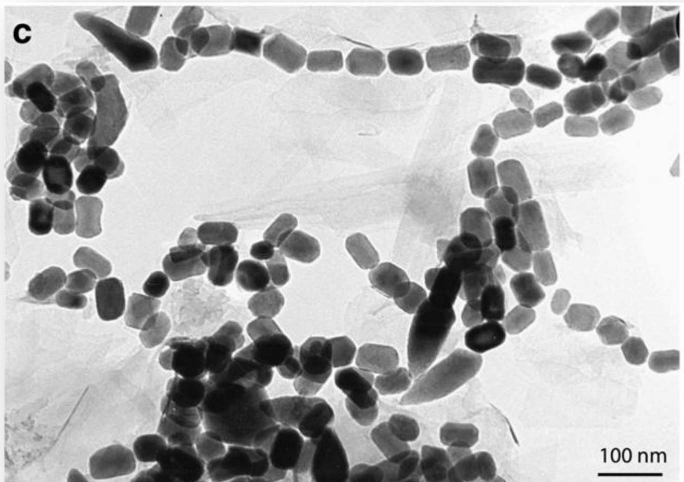


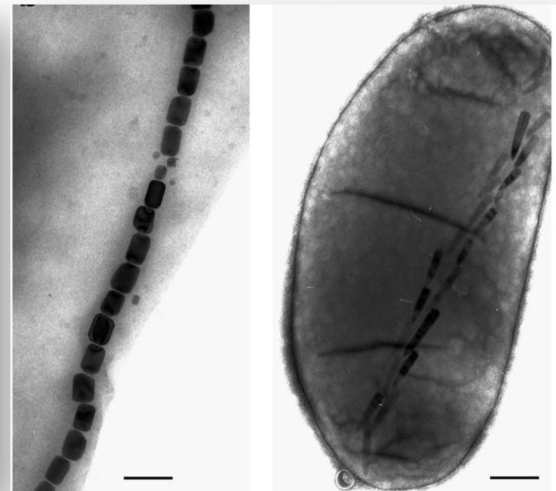
in a gas-filled magnet

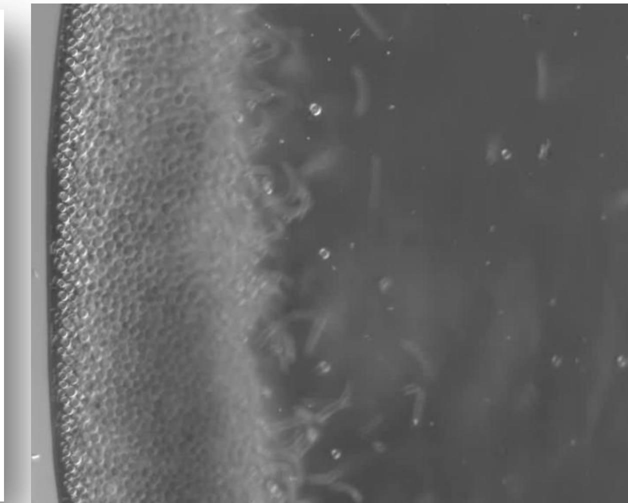
$$\langle q \rangle \propto v Z^{0.4}$$

$$B\rho \propto \frac{M}{Z^{0.4}}$$

150 My BP

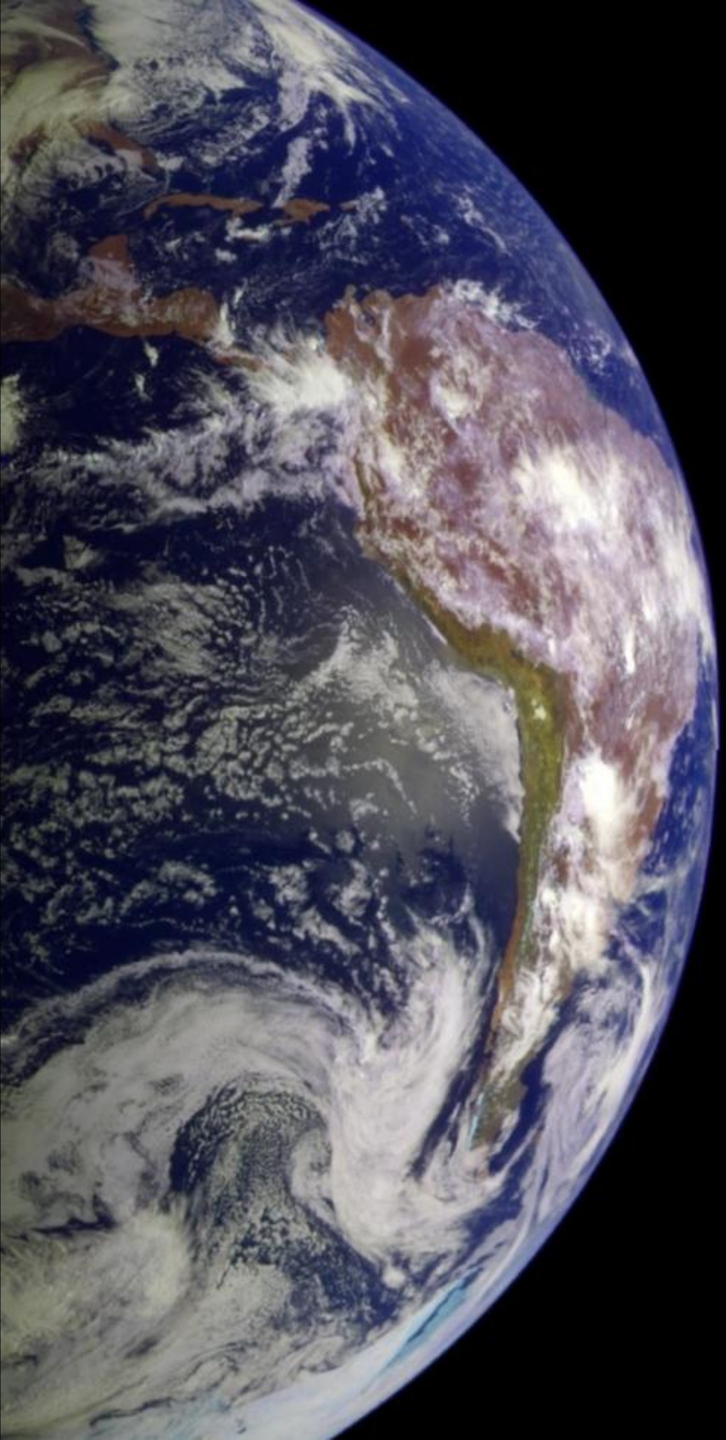


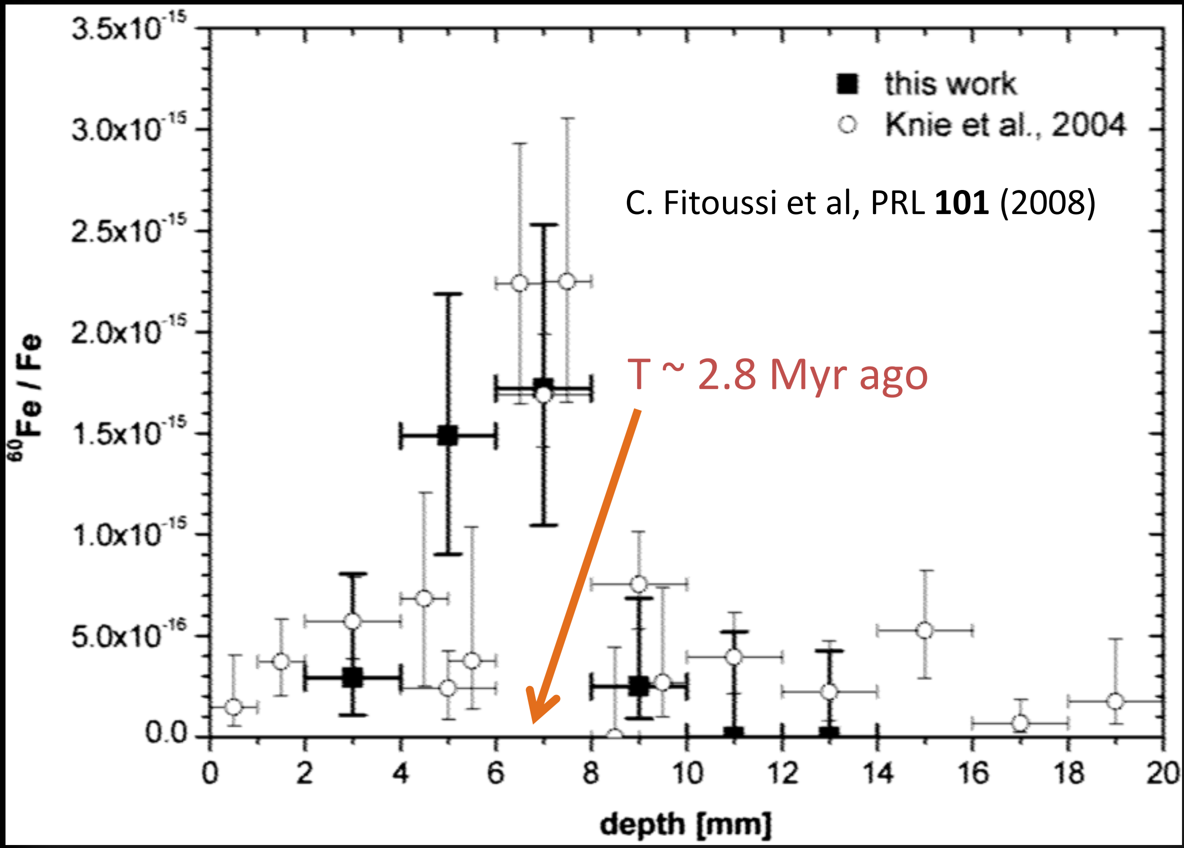




- The dead don’t talk, but perhaps they have left us a message

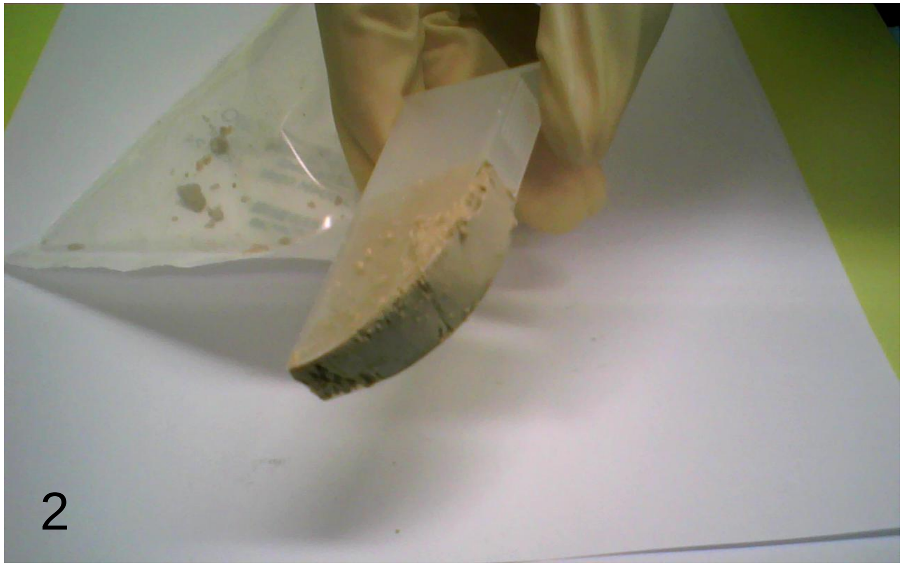
BIOGENIC RECORD OF A SUPERNOVA?





3.5x10^-15
3.0x10^-15
2.5x10^-15
2.0x10^-15
1.5x10^-15
1.0x10^-15
5.0x10^-16
0.0
^{60}Fe / Fe
0 2 4 6 8 10 12 14 16 18 20
depth [mm]
this work
Knie et al., 2004
C. Fitoussi et al, PRL **101** (2008)
T ~ 2.8 Myr ago

Ocean Drill Core Samples



Fe Concentration in Drill Core

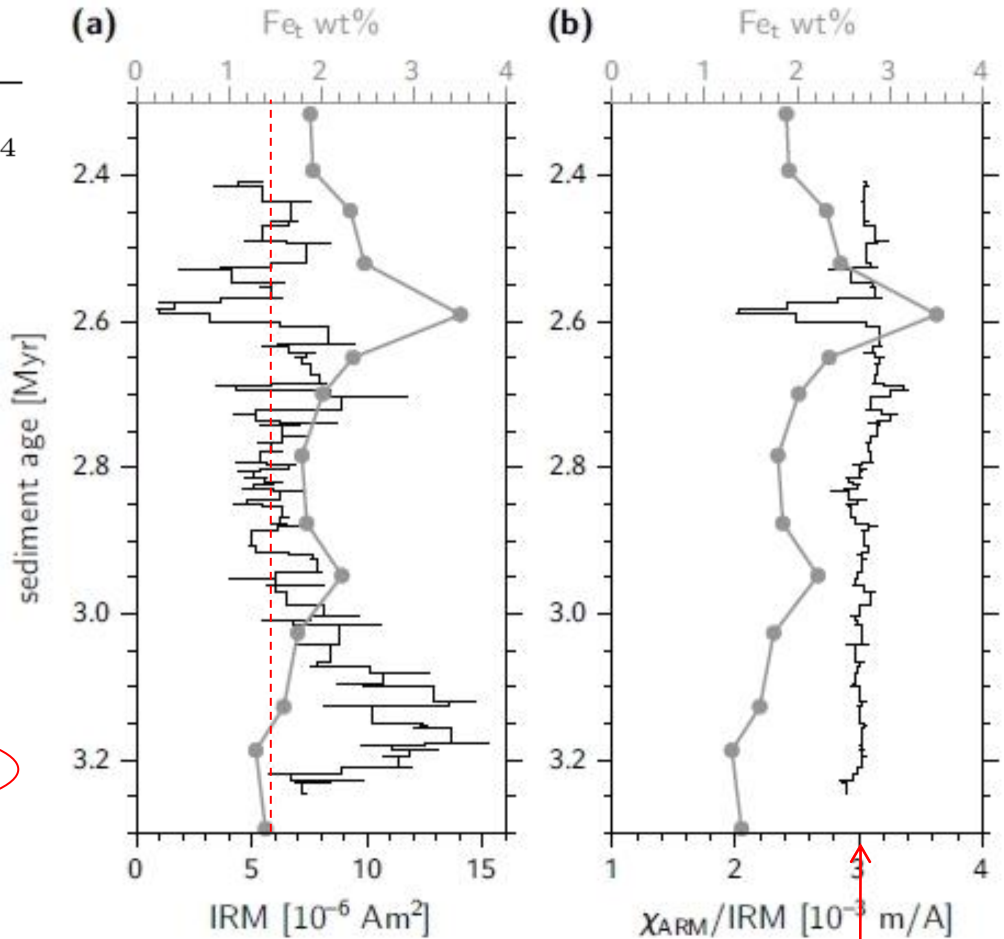
Fe concentration: $c_{\mathrm{Fe}} = \frac{2m_{\mathrm{rs}}}{w\mu_s}\frac{M_{\mathrm{Fe}}}{M_{\mathrm{Fe_3O_4}}}$

w = sample mass (~ 5 g)
μ_s = <sample magnetic moment>(~ 6 Am^2)
m_{rs} = saturation magnetization (92 Am^2/kg)

Primary Fe minerals: $\chi_{\mathrm{ARM}}/\mathrm{IRM} < 2\times10^{-4}\,\mathrm{m/A}$

Dispersed magnetite: $\chi_{\mathrm{ARM}}/\mathrm{IRM} > 10^{-3}\,\mathrm{m/A}$

Intact M-somes: $\chi_{\mathrm{ARM}}/\mathrm{IRM} \approx 3^{+2}_{-1}\times10^{-3}\,\mathrm{m/A}$



LMU Excellence Cluster Universe

Estimate of ^{60}Fe in the Magnetofossils

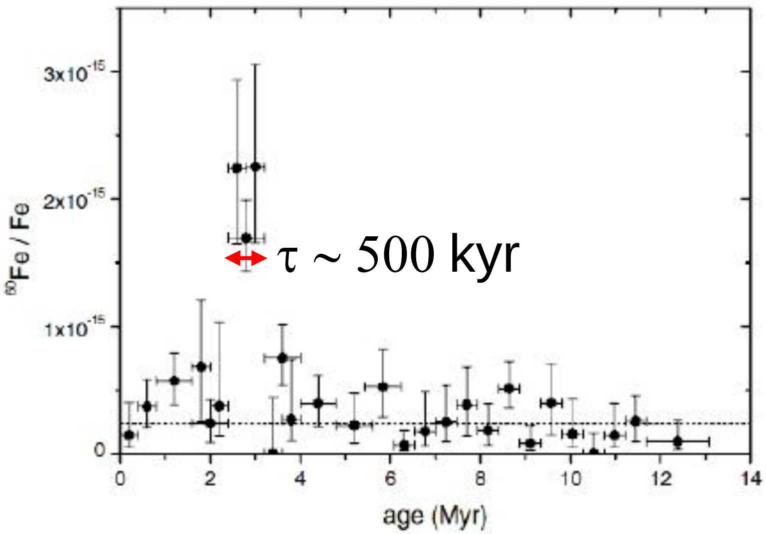
Atom flux of iron from bacteria growth and sedimentation rate:

$$\Phi_{\mathrm{Fe}} = c_{\mathrm{Fe}} \frac{N_A}{M_{\mathrm{Fe}}} \rho \frac{dh}{dt}$$

Atom flux of ^{60}Fe: $\Phi_{60} = \frac{\phi_{60}}{\tau}$; ϕ_{60} = 3.8 x 10^8 atom/cm^2 [Knie et al., PRL (2004)]

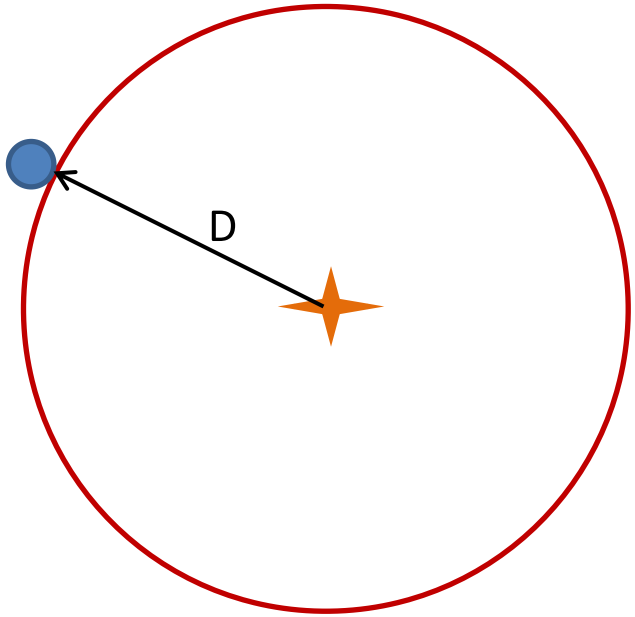
Ratio of fluxes gives atom ratios:

	^{60}Fe/Fe		
	$\tau = 250$ kyr	$\tau = 500$ kyr	$\tau = 750$ kyr
ϕ_{60}	1.8×10^{-12}	9.0×10^{-13}	6.0×10^{-13}
$0.006\times\phi_{60}$	1.1×10^{-14}	5.4×10^{-15}	3.6×10^{-15}



Amount of drill core: 100 – 200 grams; → approx. 2 – 4 mg magnetite

Earth: A SN Yield Detector



• Particle Flux of isotope "i" at radius D without decay: $$F_i = \frac{M_i}{4\pi A_i D^2} N_A$$

• Cross sectional area of Earth intercepting SN debris: $$A_{int} = \pi R_e^2$$

• This debris deposited on Earth uniformly, over an area of: $$A_e = 4\pi R_e^2$$

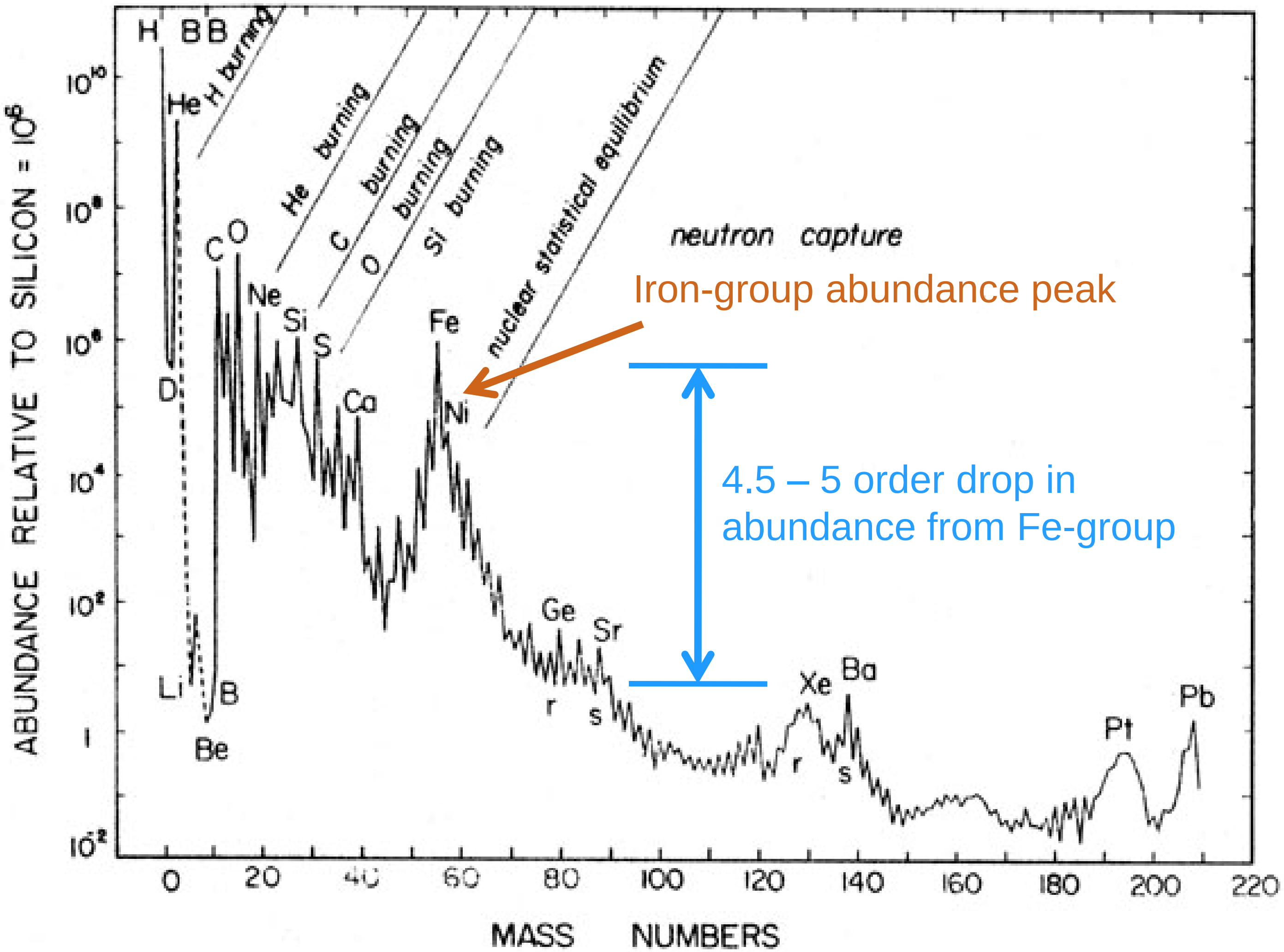
Number of atoms "i" deposited in uniform layer on Earth's surface (now include decay) after a time T since SN occurred:

$$N_i = \frac{F_i A_{int}}{A_e} e^{-\lambda_i T} = \frac{F_i}{4} e^{-\lambda_i T}$$

Ratio of any two radio-nuclides: $$R = \frac{N_i}{N_j} = \frac{M_i}{M_j} \frac{A_j}{A_i} \exp\left[(\lambda_j - \lambda_i) T\right]$$

Independent of unknown distance D!

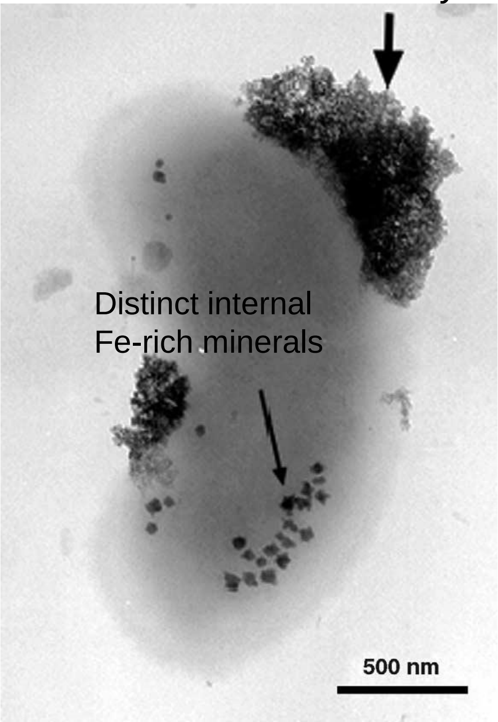
The Problem of AMS Detection Beyond Iron



Could These be the Result of Microbial Activity?

Banded Iron Formation

External ferrihydrite (rust)



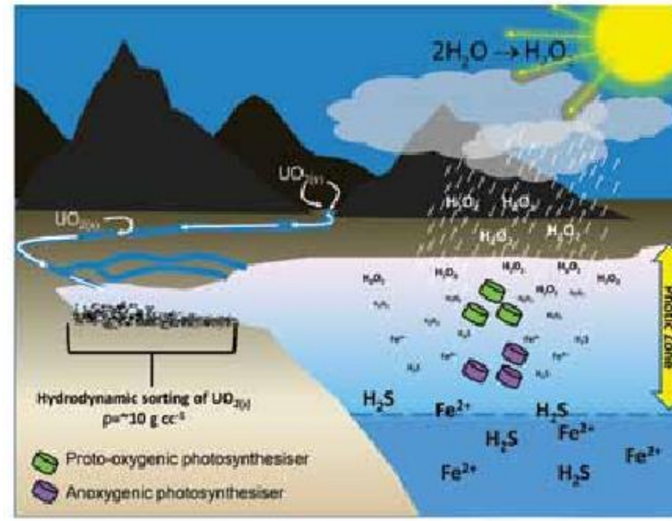
Summary

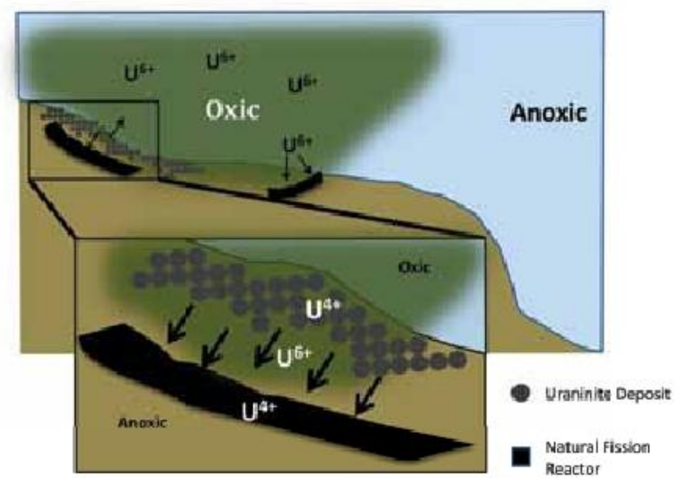
- Astrophysics program at TUM underway
- Objective: Properties of nuclear states for nova
- Status of program
  - Q3D spectrograph for measuring/searching out excited states
  - Doppler lifetime station commissioning underway
  - Arrival of neutron detector in July to extend Doppler station to transfer reaction channels with neutron ejectiles
    - Try to utilize pulsed-beam feature of MLL Tandem
    - Another PhD student required (know any candidates?)
- Supernova search in microfossils
  - Initial phases of project underway (another PhD project)
  - Manuscript presently under peer review: *Icarus*

EXTRA SLIDES

Bacteria and Archean Nuclear Reactors

- Connected to when bacterial life evolved to cope with increasingly richer O_2 atmosphere
  - Ca. 3 Gyr before present
- Erosion carries UO_2 to into shallow basins
- Photosynthesis of newly evolving bacteria produces O_2 in shallow water, bringing U^{6+} into purely dissolved form in water column
- Water motion/currents carry U^{6+} out of O_2-rich water
  - Redox boundary changes $U^{6+} \rightarrow U^{4+}$
  - U^{4+} is precipitated out of solution at the oxic-anoxic boundary
  - Highly concentrated in small zone
- Possible source of natural nuclear reactor
  - Look for depletions in ^{235}U





If Companion is AGB

- ^{36}S is s-process: not nova
- AGB Star: $^{36}Cl(n,p)^{36}S$
- ^{34}S in nova from ^{34}Cl decay
- Sulfur measurements should be target of grains