Nuclear Fireworks in Stars via the Breakout from the CNO Cycle

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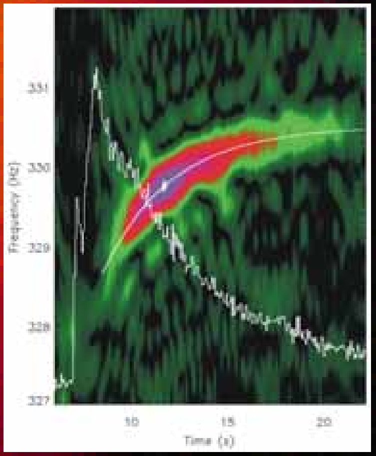

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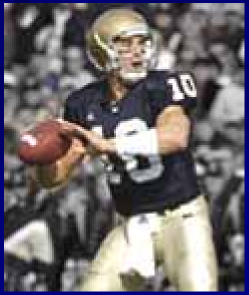
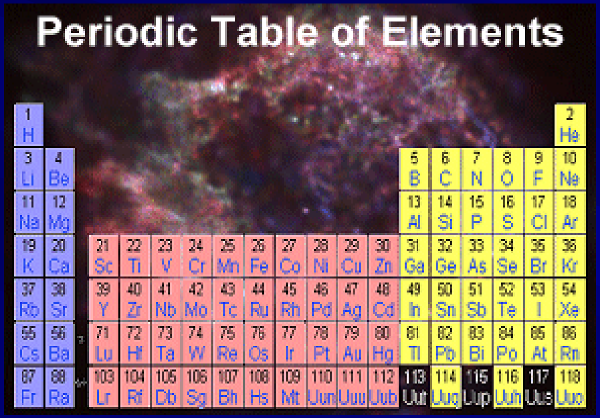
Outline

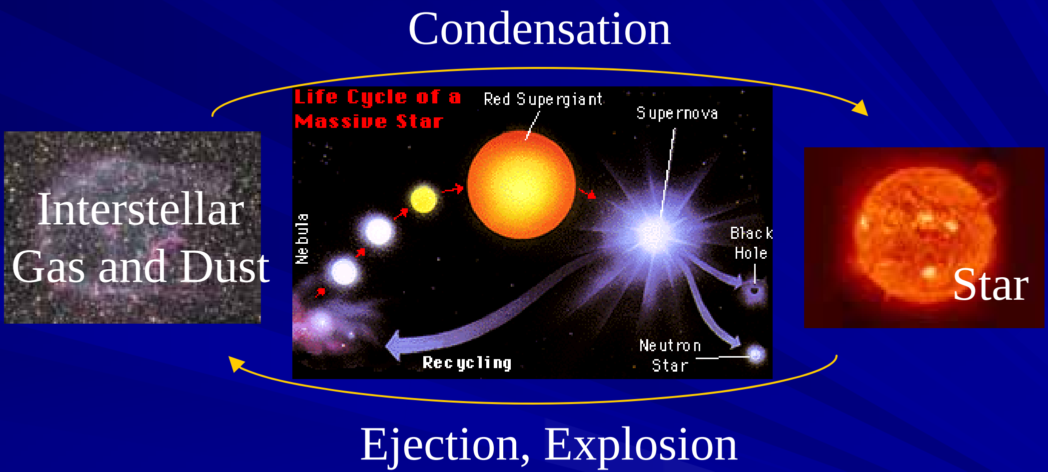
- Introduction
  - Accreting compact stars
  - CNO cycles and breakout
- X-ray Bursts and its thermonuclear origin
  - How $^{15}O(\alpha,\gamma)$ is critical to X-ray bursts?
- How do nuclear physicists measure the reaction rates?
- Current progress in the $^{15}O(\alpha,\gamma)$ reaction rate
- Our new measurements at Notre Dame
- Conclusion and outlook

Introduction

- ♫ We are stardust
- ♫ Billion year old carbon
- ♫ We are **golden**

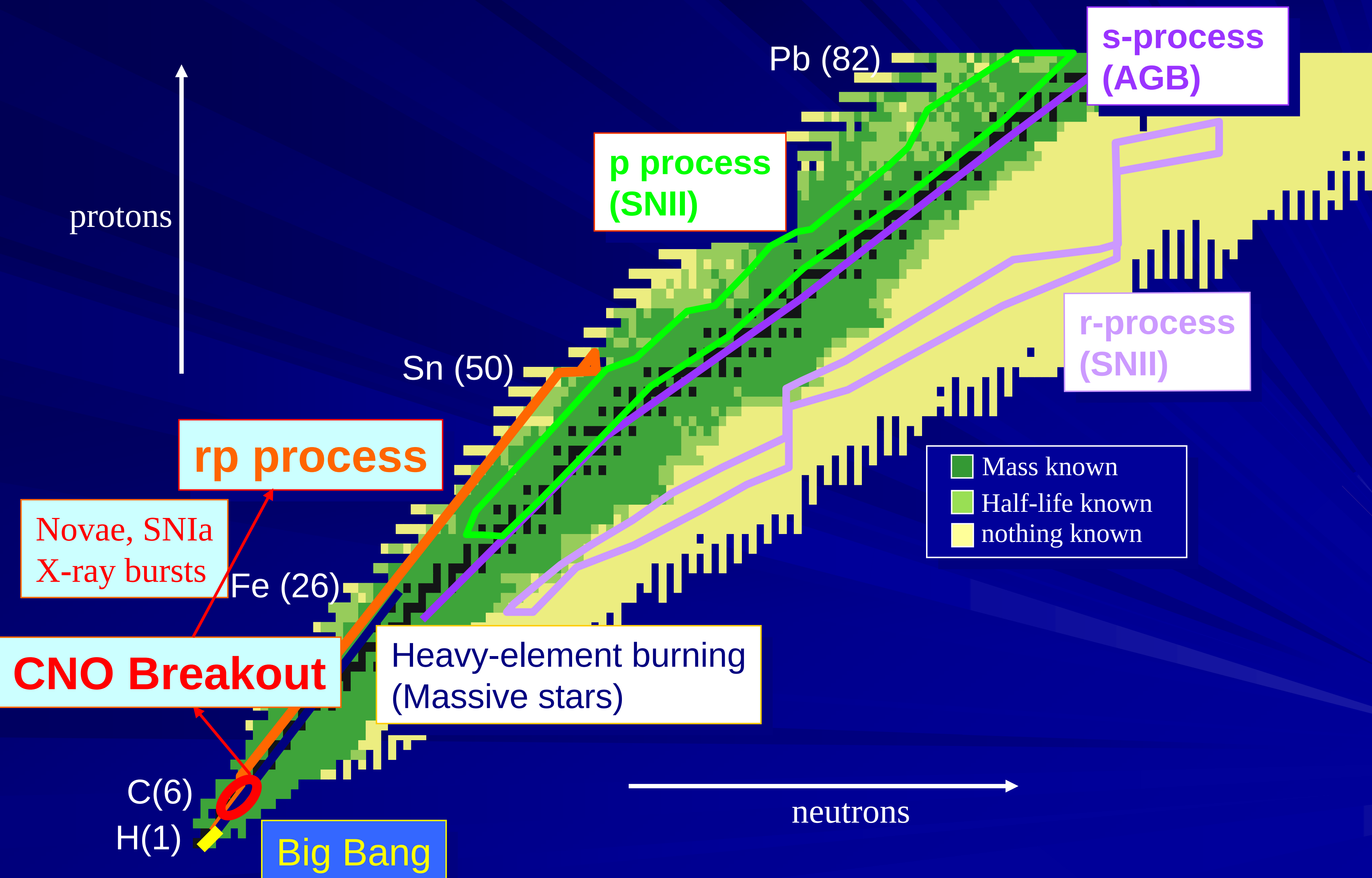




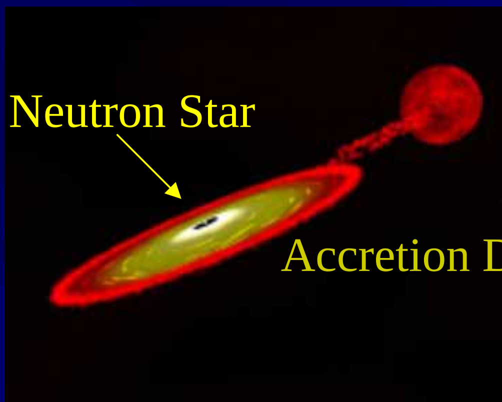


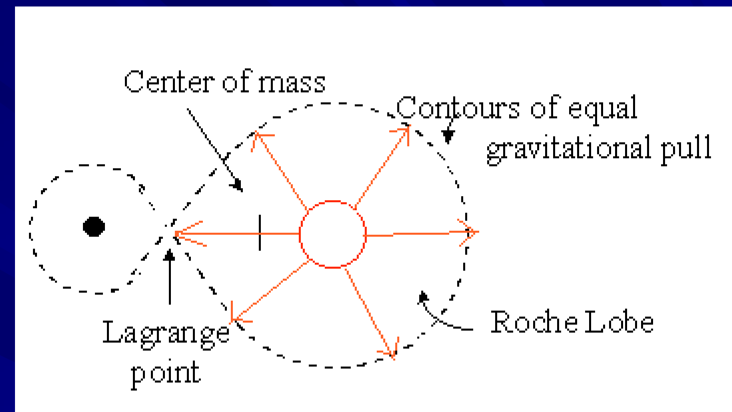
- Big Bang only creates light elements from H, He up to Li
- Heavier elements are synthesized in the stars through nuclear reaction sequences
- These reactions also power the stars and determine the time scale of star evolution
- Nuclear physics under extreme conditions

Nuclear Processes in Stars



Accreting Compact Stars

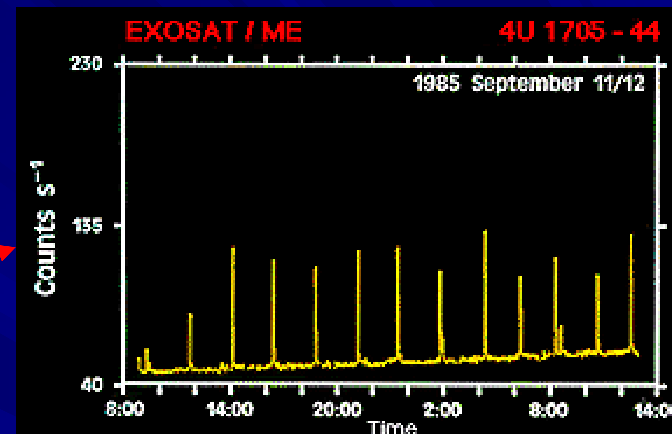


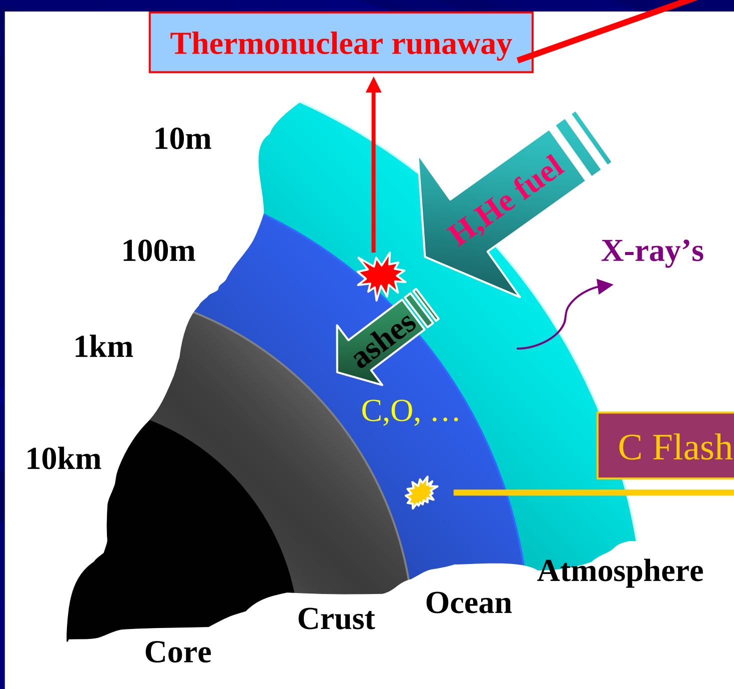


- Accreting White Dwarfs
  - Novae: 10^45 ergs
  - Supernovae Ia – standard candles: 10^51 ergs
- Accreting Neutron Stars / Black Holes
  - X-ray Binaries → some produce X-ray bursts: 10^39 ergs

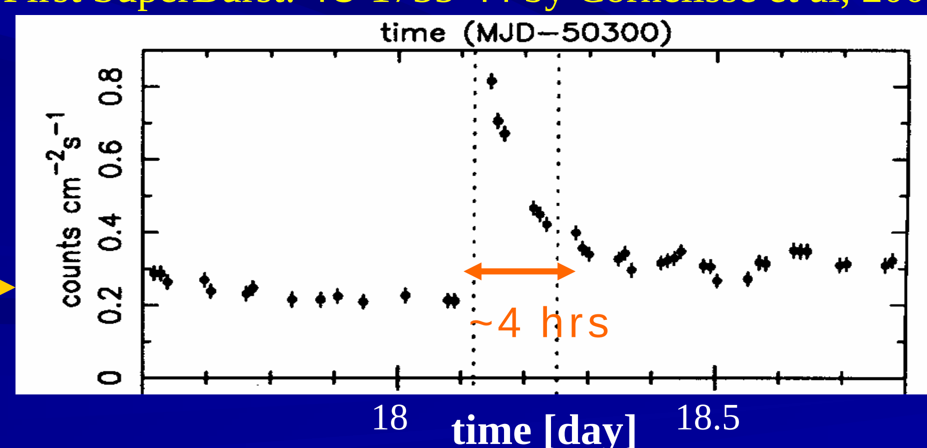
X-ray Bursts

- First **X-ray burst**: 3U 1820-30 by Grindlay et al, 1976
- Type I X-ray bursts: 10-100s, 10^{39} erg
  - Thermonuclear runaways from accreting neutron star of a close binary system
- Superbursts: 1000x stronger and longer

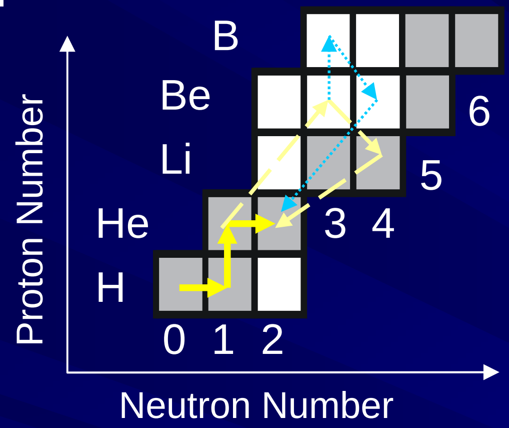


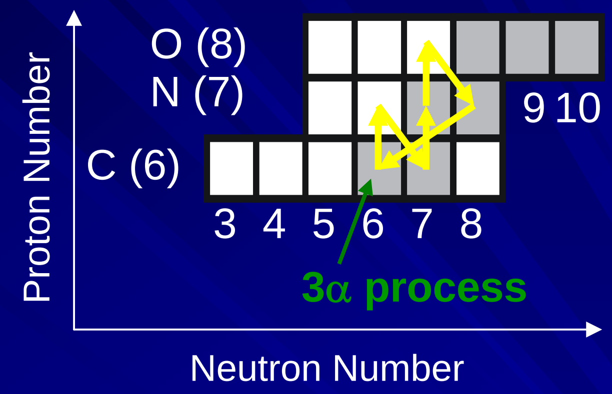


First SuperBurst: 4U 1735-44 by Cornelisse et al, 2000



Hydrogen Burning

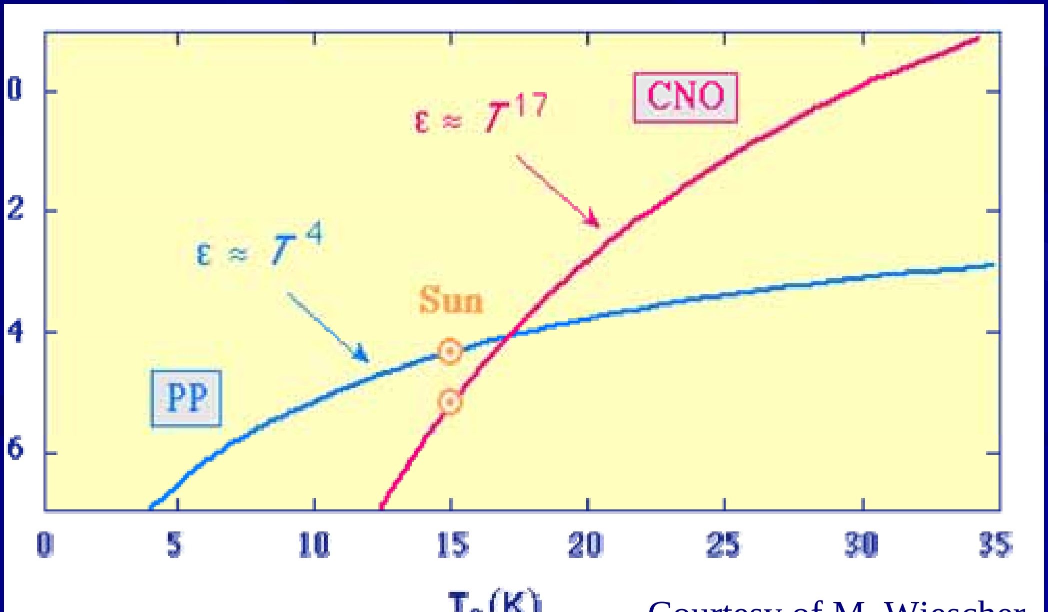




- pp-chains

$$4p \longrightarrow {}^{4}He + 2e^{+} + 2\nu_e + 26.7\text{MeV}$$

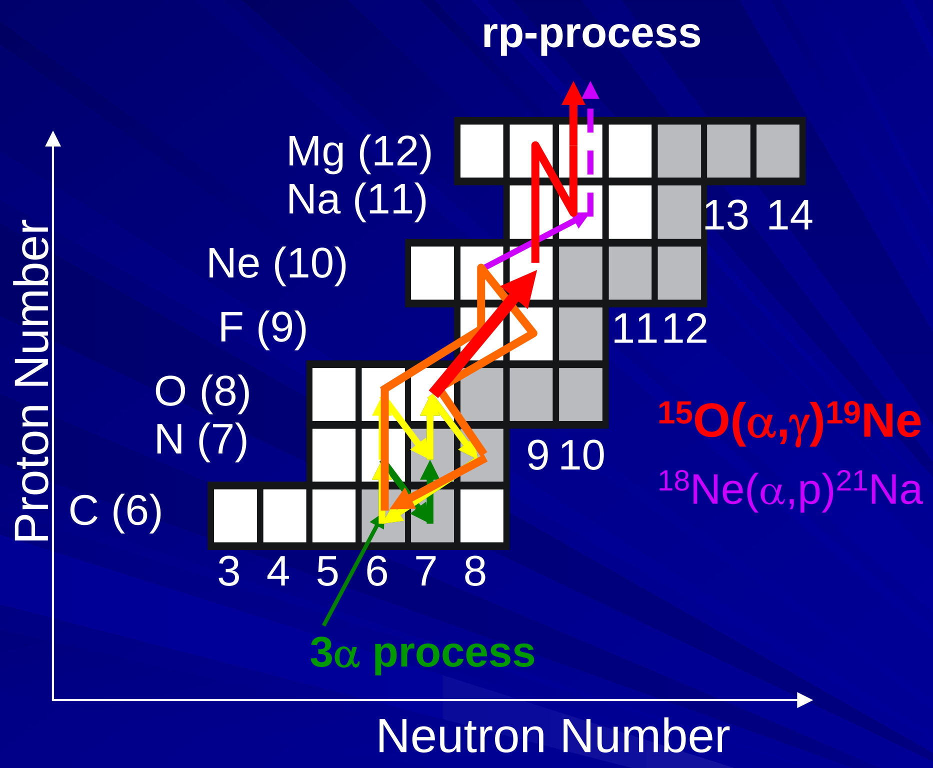
- CNO cycle
  - C,N,O serve as catalysts



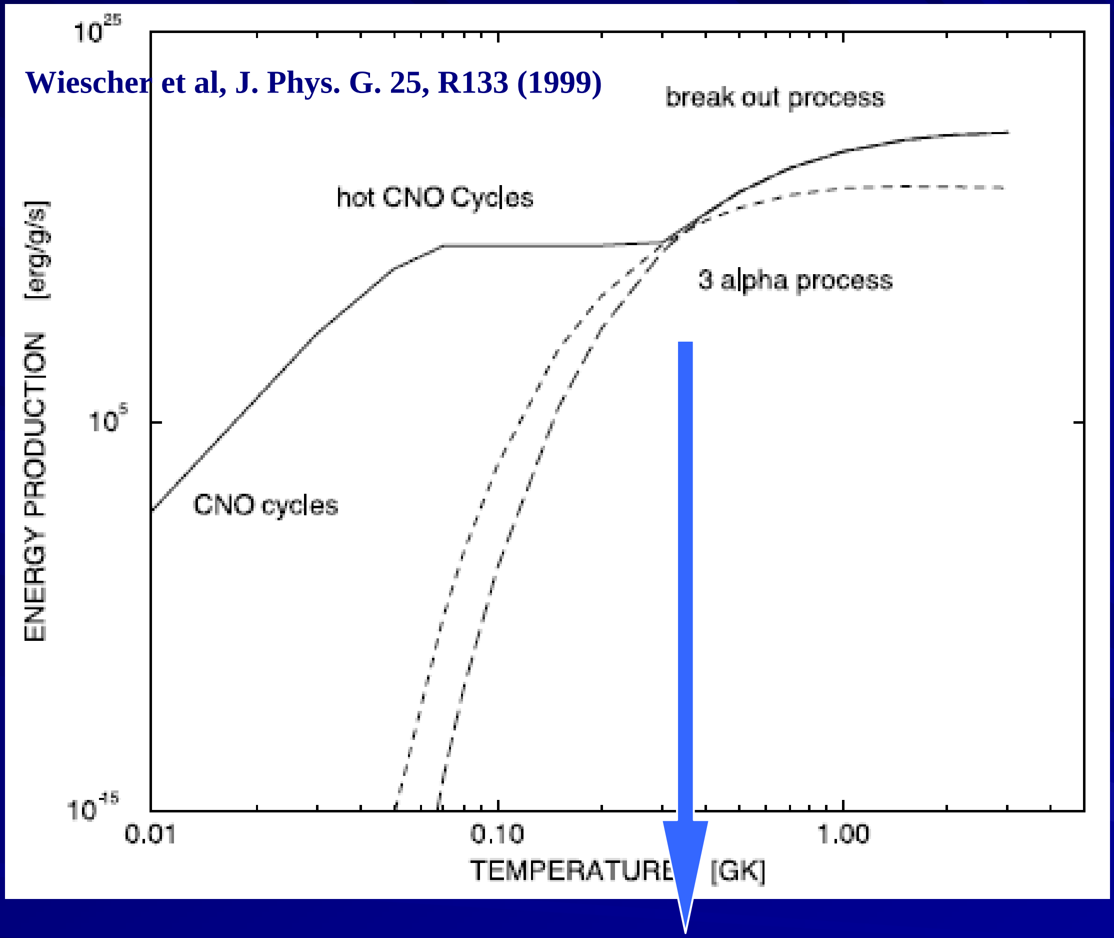
Courtesy of M. Wiescher

Hot CNO cycles and Breakout

- T_9<0.08 "Cold" CNO cycle
- T_9~0.08-0.1 Hot CNO cycle
- T_9~0.1-0.3 Very Hot CNO cycle
- Breakout:
  - **$^{15}O(\alpha,\gamma)^{19}Ne$ T_9>0.3**
  - $^{18}Ne(\alpha,p)^{21}Na$ T_9>0.6



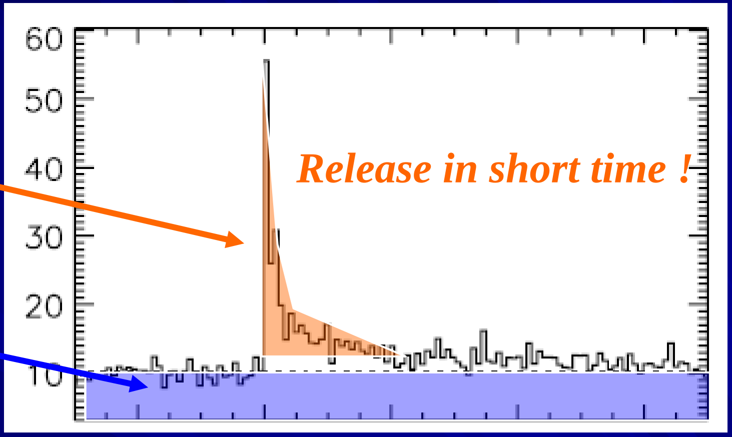
Energy Production of CNO cycles



Explosive burning enviroments:
Novae, Supernovae Ia, X-ray bursts

Why is the $^{15}O(\alpha, \gamma)$ breakout important?

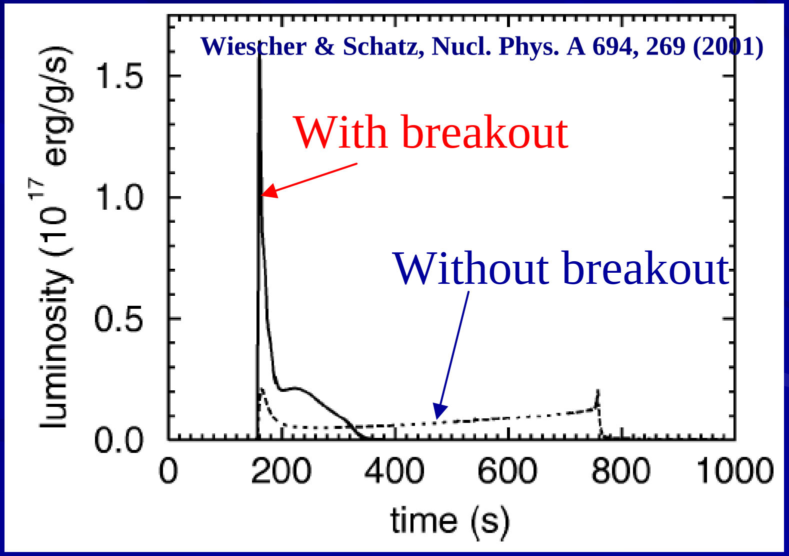
Light curve of a typical XRB



Nuclear Energy Release: ~ 5MeV/u

Gravitation Energy Release: GMm_u/R ~ 200 MeV/u

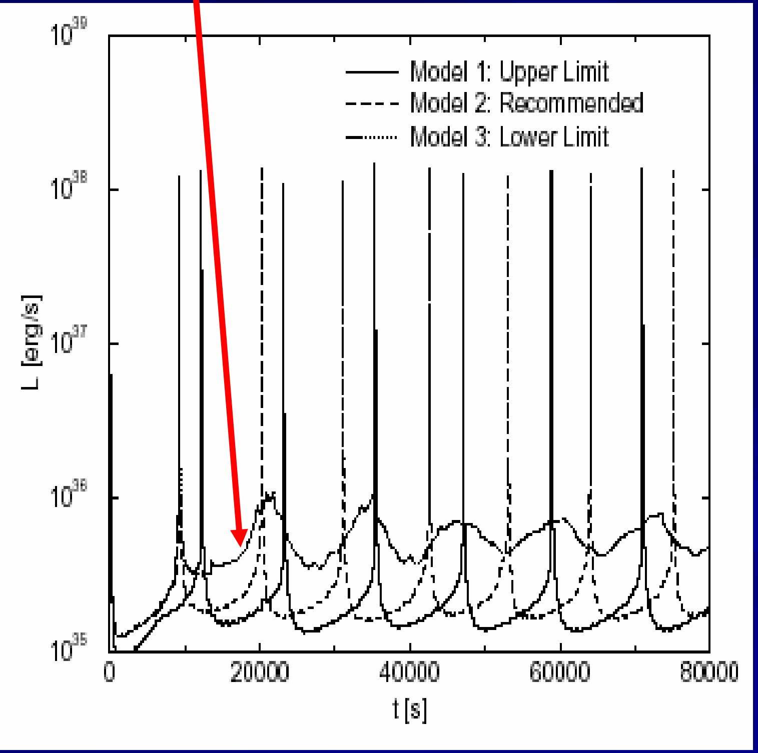
- $^{15}O(\alpha,\gamma)^{19}Ne$ is critical to break out CNO cycles and trigger rp-process
  - Energy production
  - Nucleosynthesis
- It is very sensitive to the burst amplitude



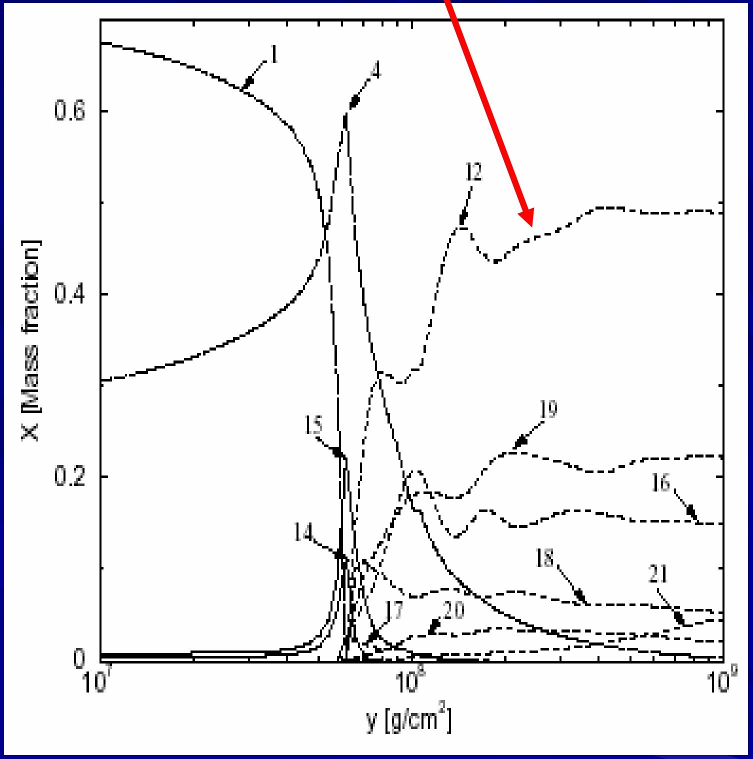
$^{15}O(\alpha,\gamma)$ and X-ray Superbursts

Fisker et al., astro-ph/0410561 (2005)

Low reaction rate quenches bursts

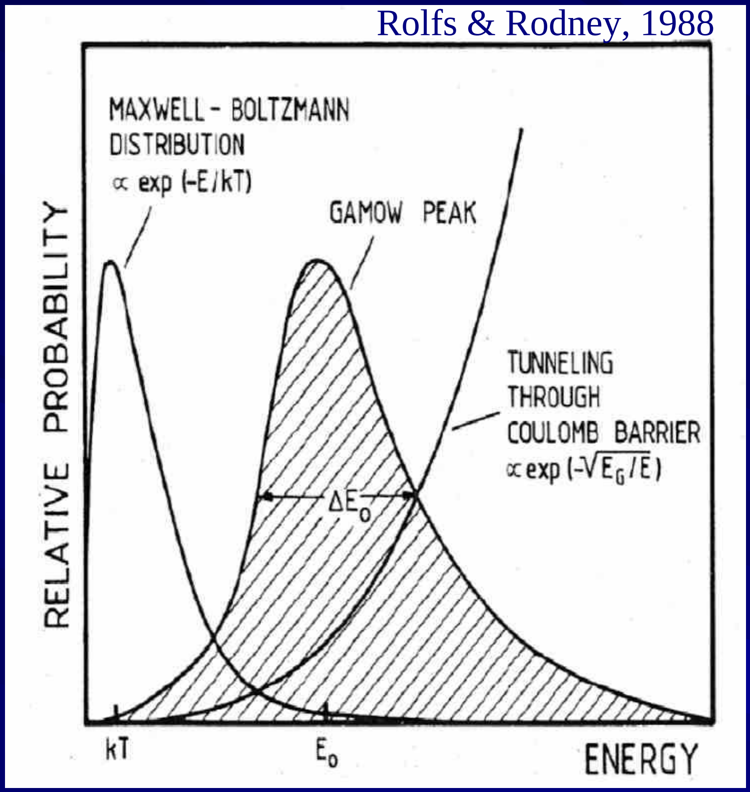


Carbon buildup for superbursts



- This reaction is critical for the burst behavior of XRB's
- Superburst theory needs C-rich ashes which are very sensitive to this reaction rate

Gamow Window & Reaction Rate



T~10^7-10^9K <===> kT=1-100 keV

- Direct measurement
  - Low energy beam to reach Gamow window
  - Intense beam to make up for the small cross section
- Indirect method
  - Resonances in the Gamow window
  - Reaction rate:

$$N_A < \sigma v > \propto T^{-3/2} \, \omega\gamma \, e^{-E_R/kT}$$

$$\text{where} \quad \omega\gamma = \frac{2J_R+1}{(2J_P+1)(2J_T+1)} B_\alpha \Gamma_\gamma$$

Gamow window for $^{15}O(\alpha,\gamma)^{19}Ne$ at T_9=0.3: ~ 500 keV with a width of ~250 keV

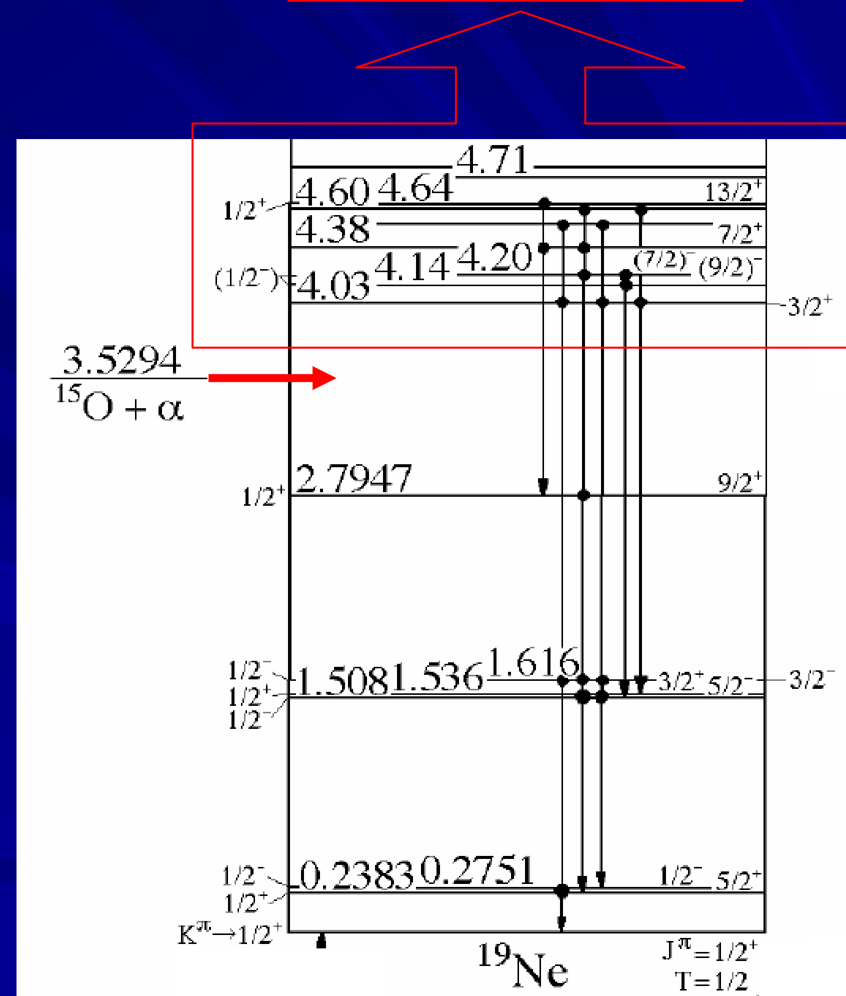
Quantities to measure: E_R, Γ_γ, B_α besides J

Reaction Rate of $^{15}O(\alpha,\gamma)^{19}Ne$

- Direct capture contribution is negligible at $T_9>0.1$
- 4.03 MeV level dominates the rate at temperatures $T_9 < 0.6$
  - Right within Gamow window
  - Very small B_α
  - Only upper/lower limits on lifetime/gamma width
- Γ_γ of α-unbound states of ^{19}Ne are unmeasured

The rate is based on the information from analog states in ^{19}F and theoretical calculations

α-unbound states



What have experimentalists been doing?

Experimental endeavor for $^{15}O(\alpha,\gamma)^{19}Ne$

- Direct measurement?

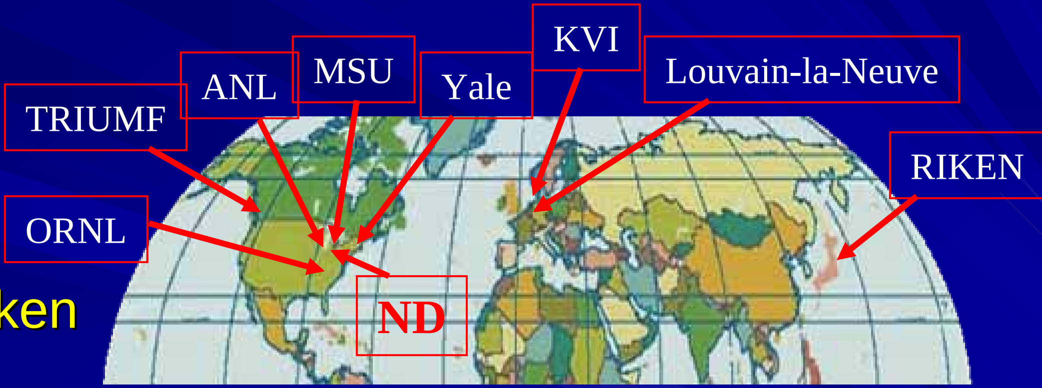
  Not likely now:

  – An intense (10^{11} /s) radioactive ^{15}O beam gives a count rate of <1/hr (estimated at ISAC, TRIUMF)

- Indirect method?

  Yes,

  many attempts have been taken

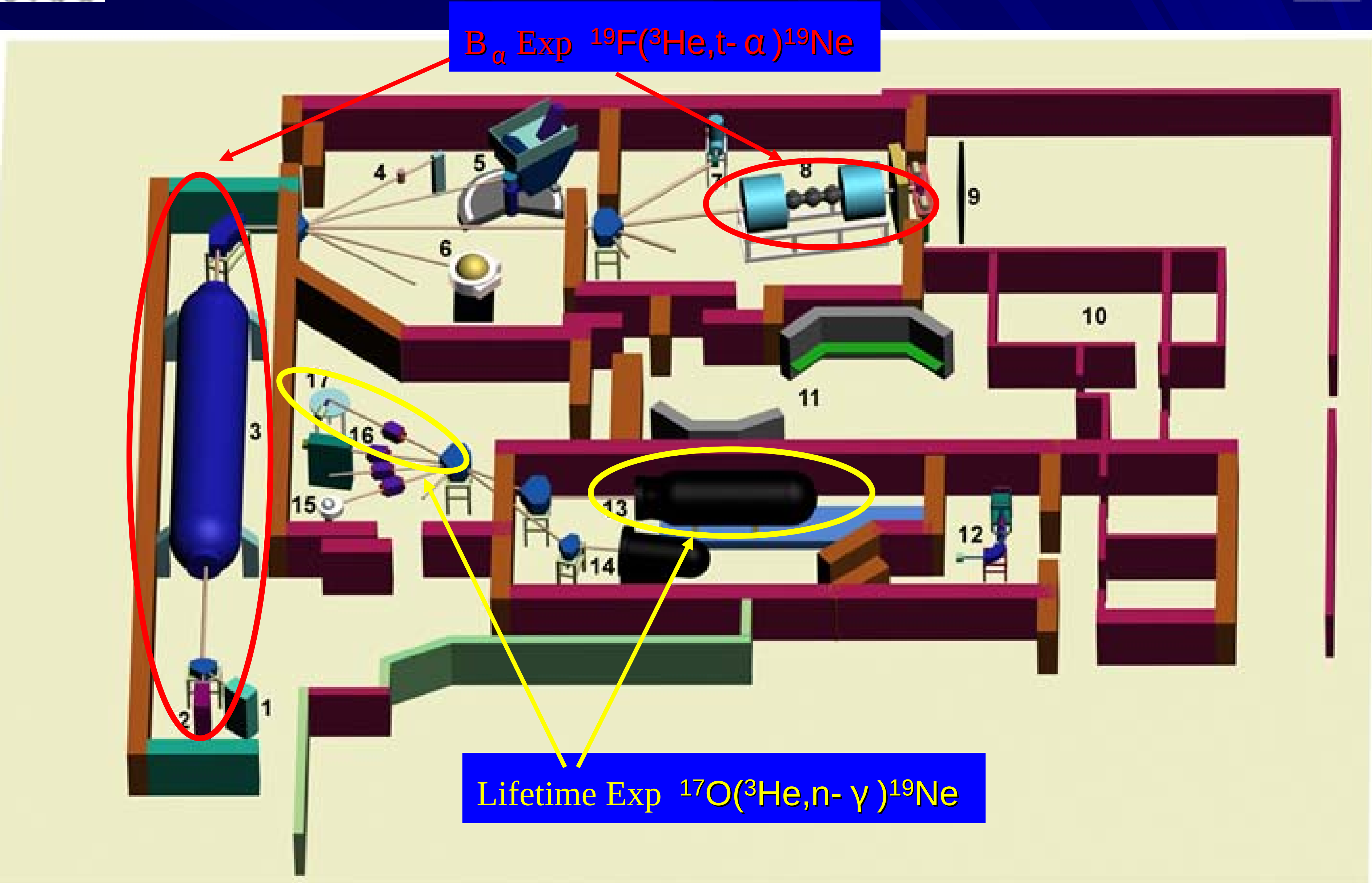


– Populate α-unbound states in ^{19}Ne

– Measure lifetimes or gamma widths — $^{17}O(^3He,n\text{-}\gamma)^{19}Ne$

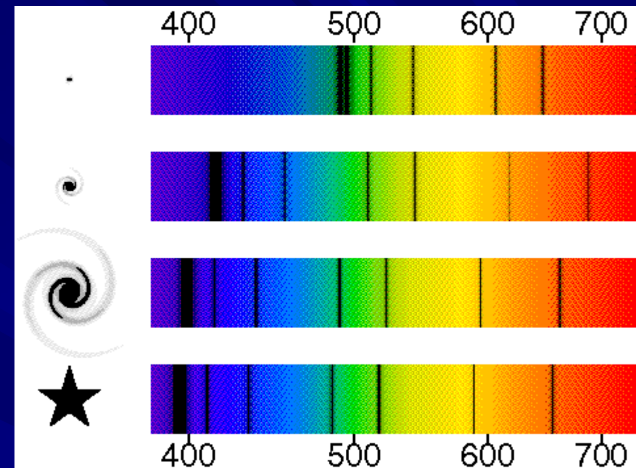
– Measure α-decay branching ratios B_α — $^{19}F(^3He,t\text{-}\alpha)^{19}Ne$

Lab Layout at Notre Dame



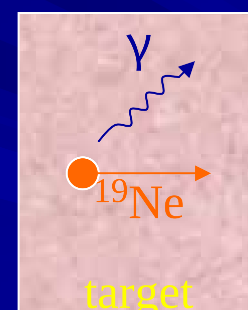
Doppler-Shift Attenuation Method (DSAM)

- Doppler shift



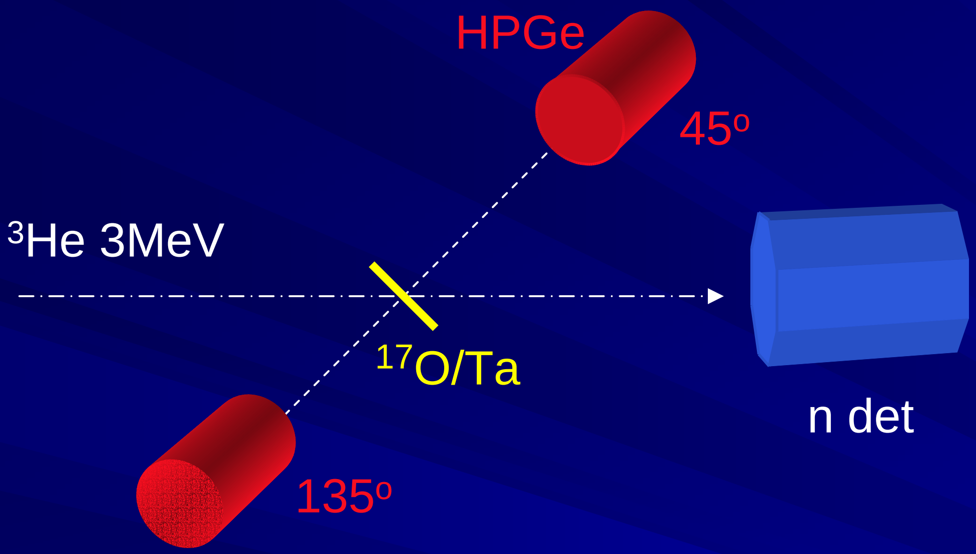
- ‘Attenuated’ Doppler Shift

$$E\gamma = E\gamma_0 (1 + F(\tau)\beta \cos\theta)$$



- Measure lifetime to obtain decay width $\Gamma = \hbar / \tau$

$^{17}O(^{3}He,n\text{-}\gamma)^{19}Ne$ Experiment

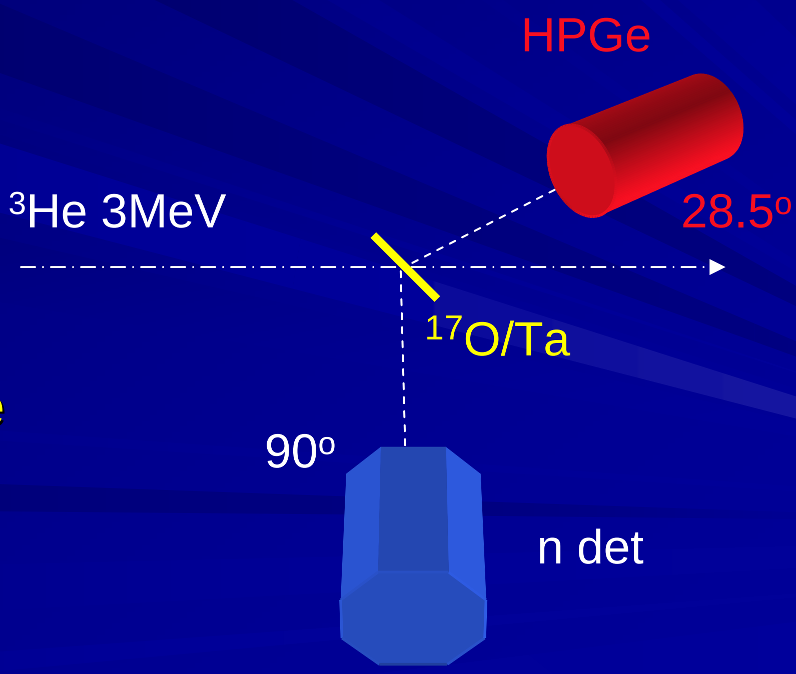


- Doppler shifts and geometry uncertainty are cancelled.

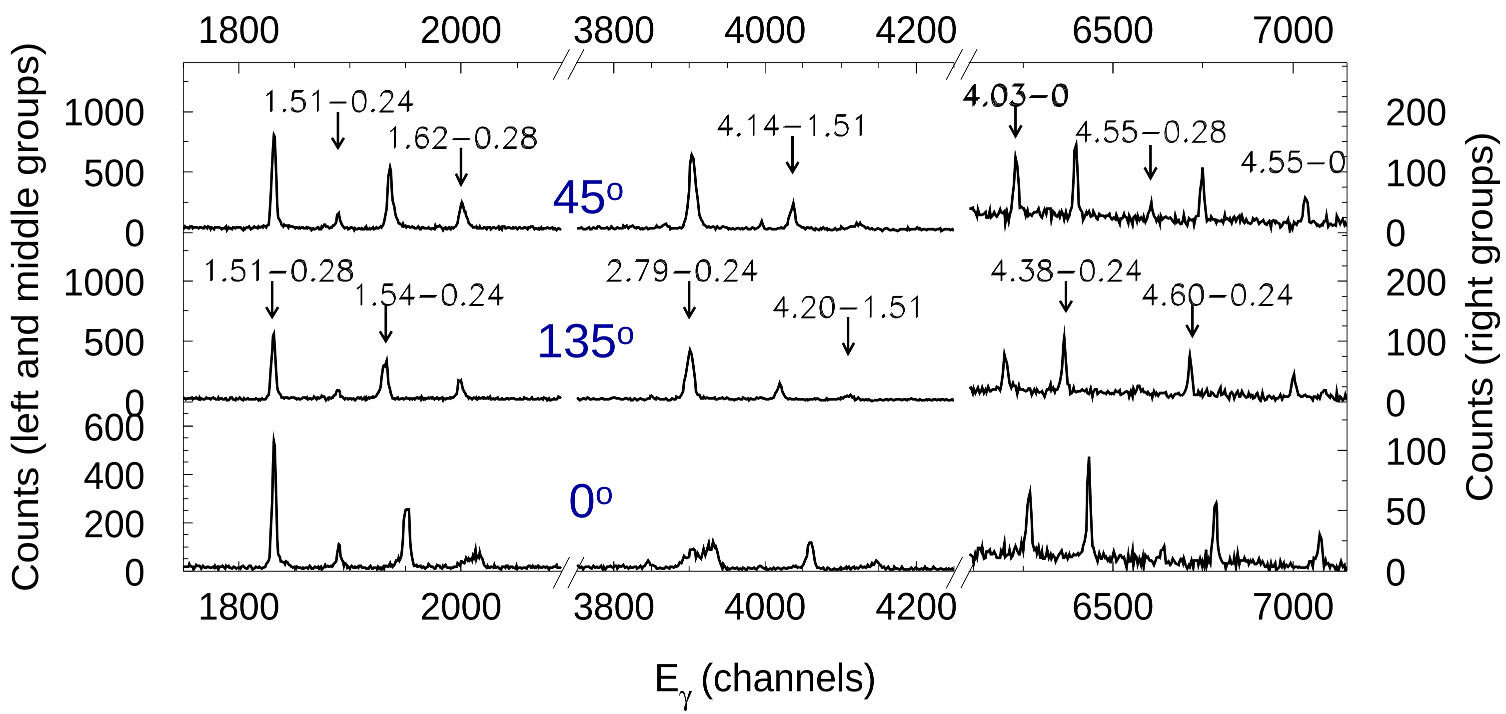
  => energy measurement

- maximize Doppler shift of gamma energies by measuring gammas emitted along the same direction as ^{19}Ne travels.

  => lifetime measurement

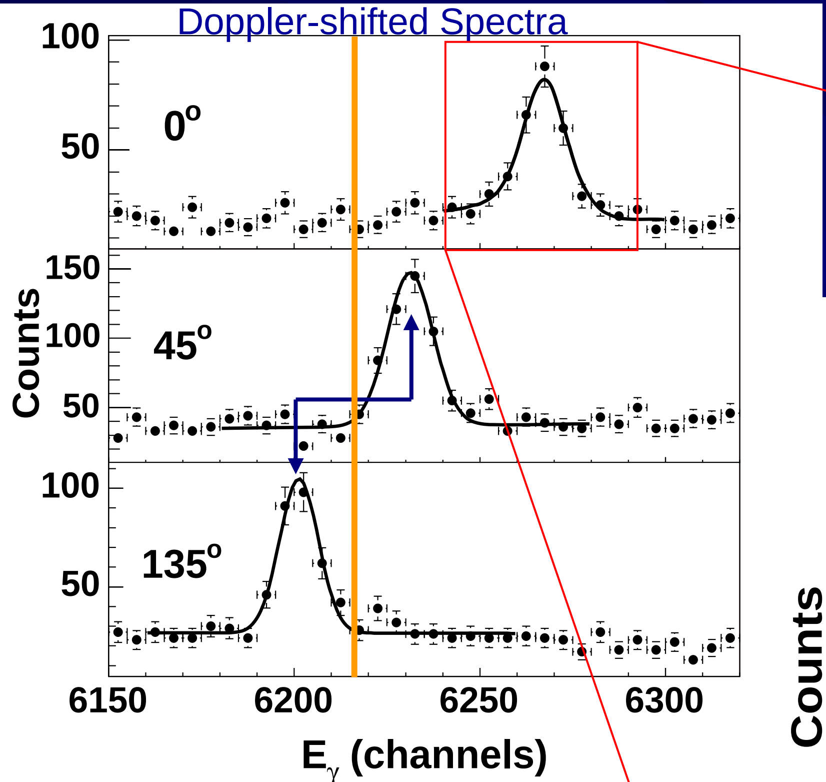


^{19}Ne related gamma spectra in coincidence with neutrons



- Gamma peaks are not only shifted but also broadened.
- Simple DSAM approach is insufficient to study more complicated shapes
- Full line-shape analysis is necessary for precise measurements
  - Details of the peak shape, especially for double peak structure and tailing effects
  - Dealing with the feeding from higher lying states

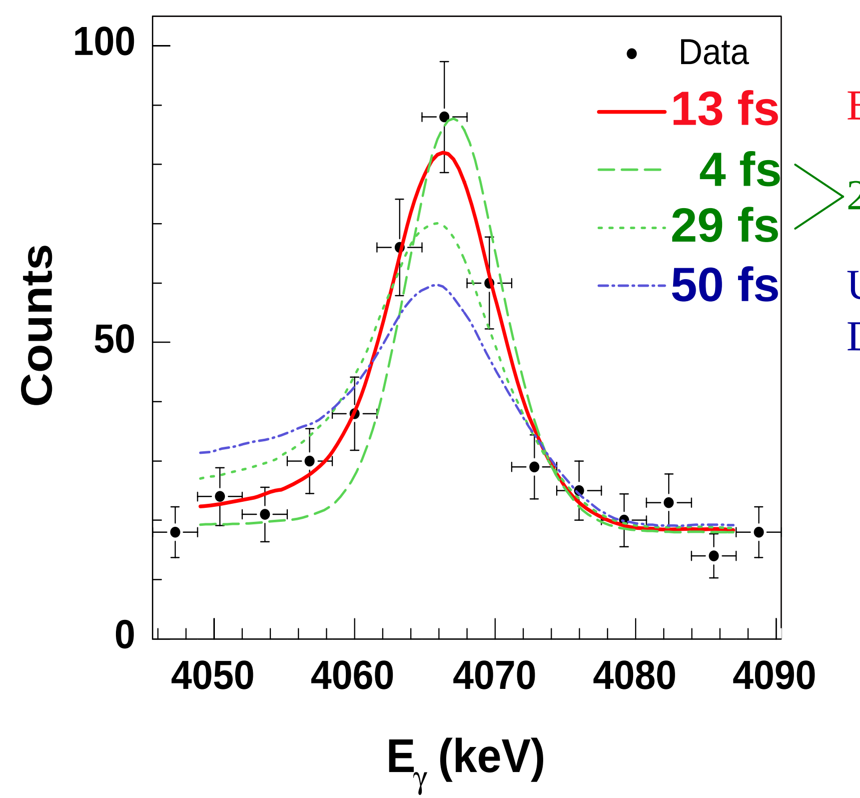
Lifetime of the 4.03-MeV state



Measured lifetime $\tau = 13^{+9}_{-6}$ fs
or $\Gamma = 51^{+43}_{-21}$ meV

Unshifted

Ex = 4034.5±0.8 keV

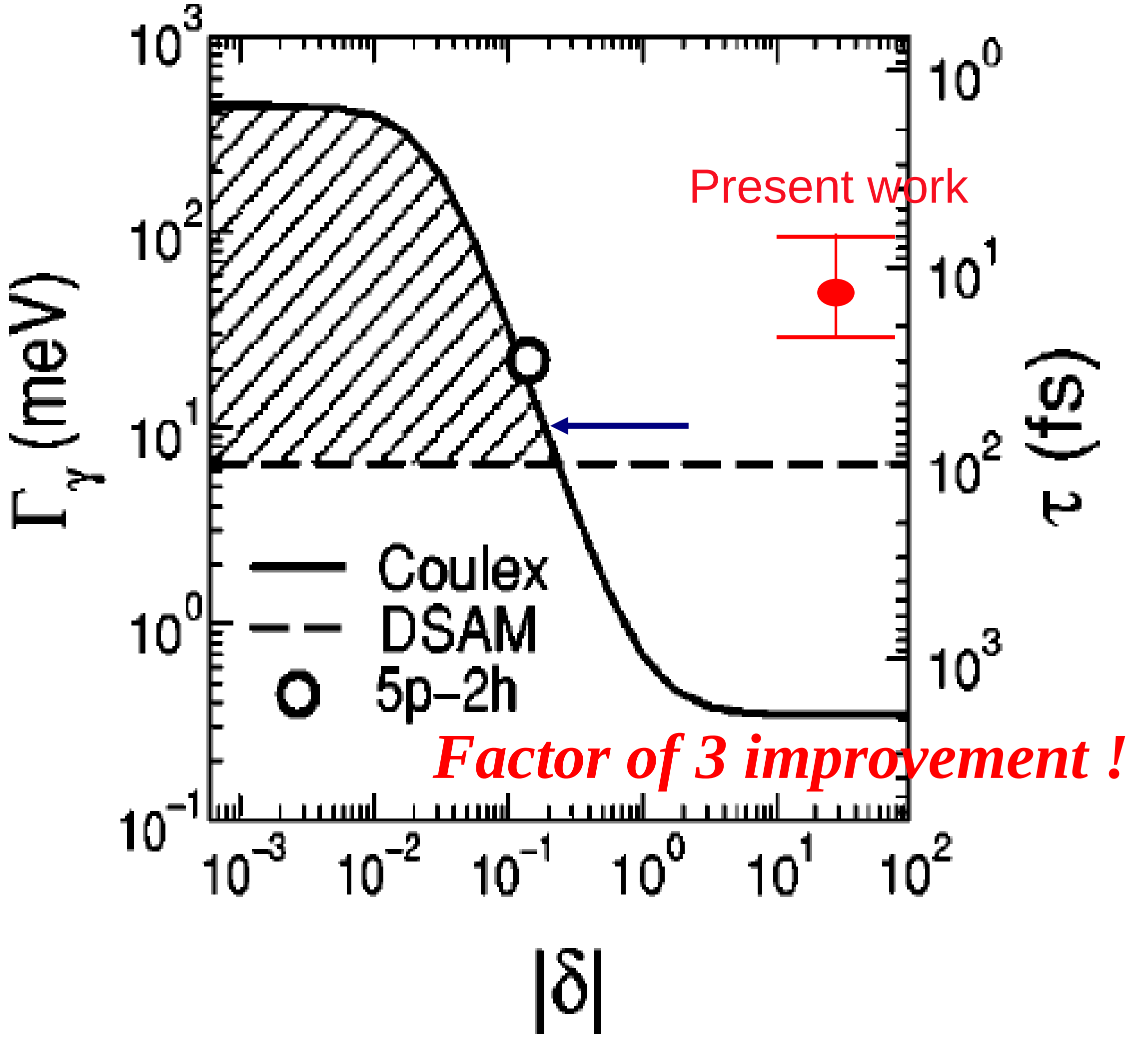


Best Geant4 fit

2 σ uncertainties

Upper limit by Davidson et al

Hackman et al, Phys. Rev.C 61, 052801R(2000)



Summary of Lifetime Results

Compilation (TUNL)			Present work	
E* [keV]	J^{π}	τ_m [fs]	E*[keV]	τ_m[fs]
4032.9±2.4	3/2+	<50	4034.5±0.8	13^{+9}_{-6}
4140±4	(9/2)-*	<300	4143.5±0.6	18^{+2}_{-3}
4197.1±2.4	(7/2)-*	<350	4200.3±1.1	43^{+12}_{-9}
4379.1±2.2	7/2+	<120	4377.8±0.6	5^{+3}_{-2}
4549±4	(1/2,3/2)-	<80	4547.7±1.0	15^{+11}_{-5}
4600±4	(5/2+)	<160	4601.8±0.8	7^{+5}_{-4}
4635±4	13/2+	>1x10^3	4634.0±0.9	>1x10^3

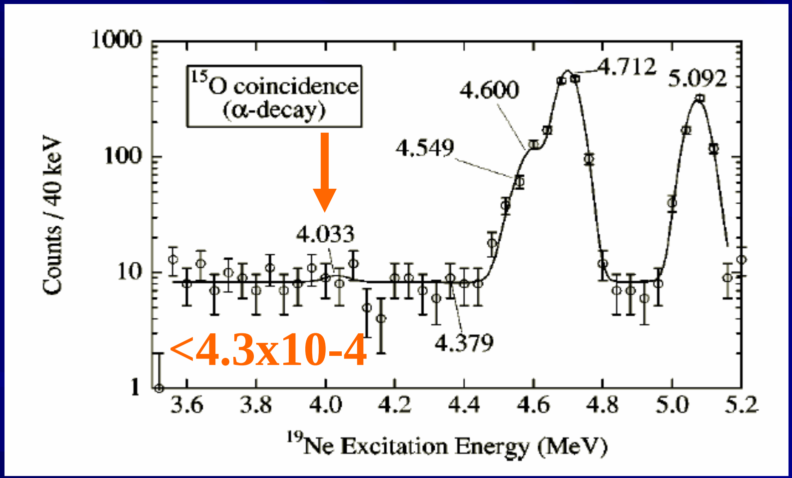
* Our study shows the spin assignments should be exchanged

W.P. Tan et al, Phys. Rev. C72, 041302R (2005)

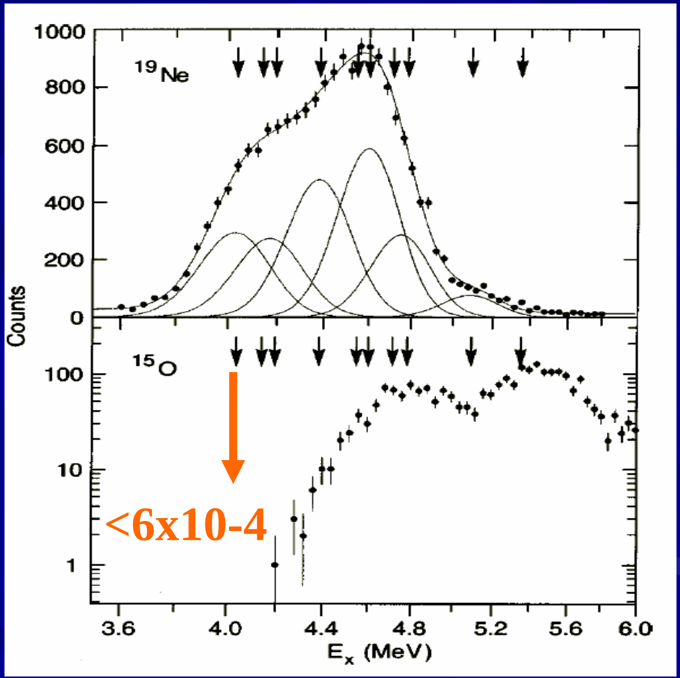
Alpha-decay branching ratios

- Pursued at many places such as Yale, ANL, ORNL, Louvain-la-Neuve, KVI, TRIUMF, and RIKEN
- Dominant resonance of 4.03 MeV state in 19Ne
  - **Its branching ratio $\Gamma_\alpha / \Gamma \sim 10^{-4}$**

Davids et al, 2003 at KVI



Rehm et al, 2003 at ANL

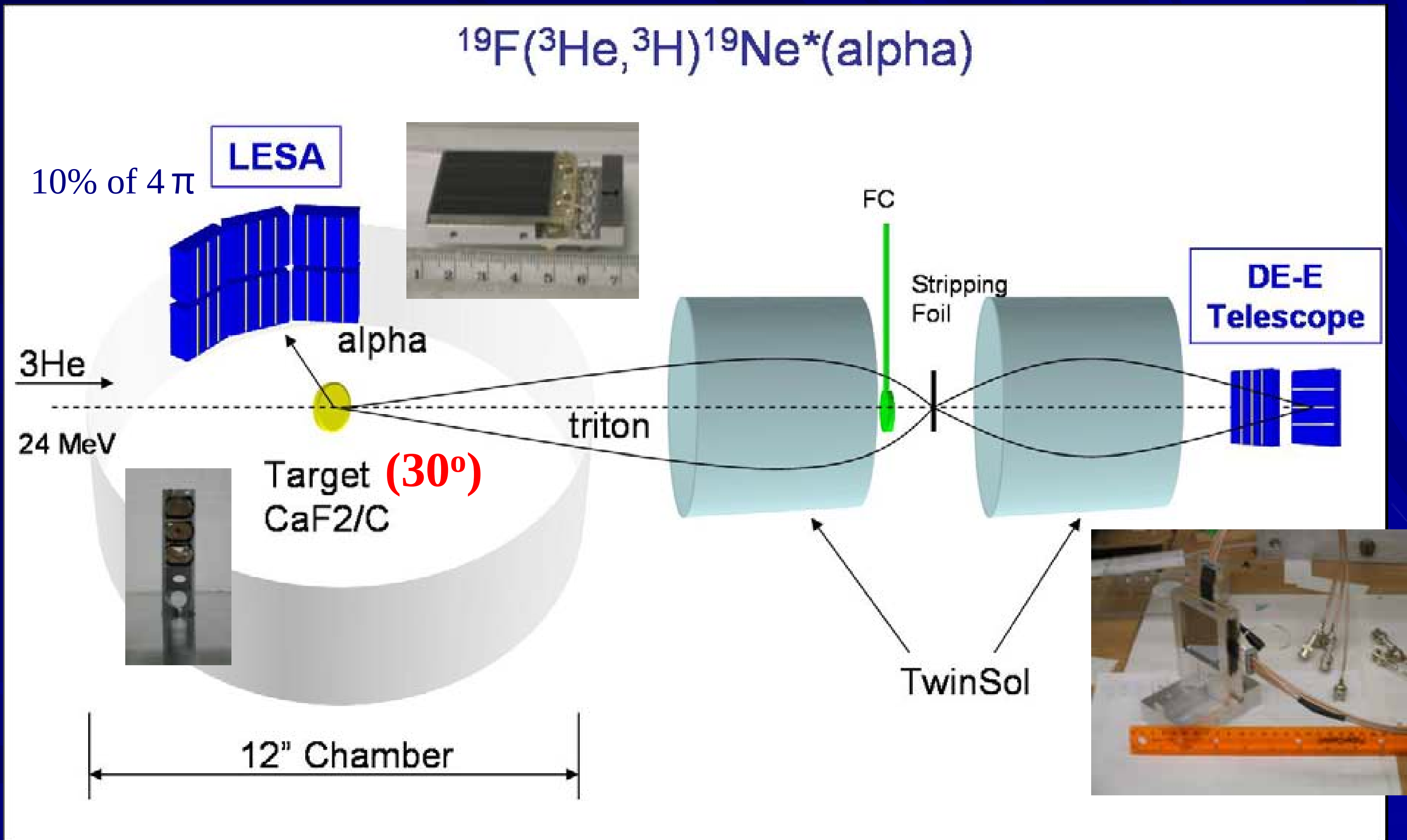


Challenges for our experiment $^{19}F(^{3}He,t-\alpha)^{19}Ne$:

High statistics for coincidences

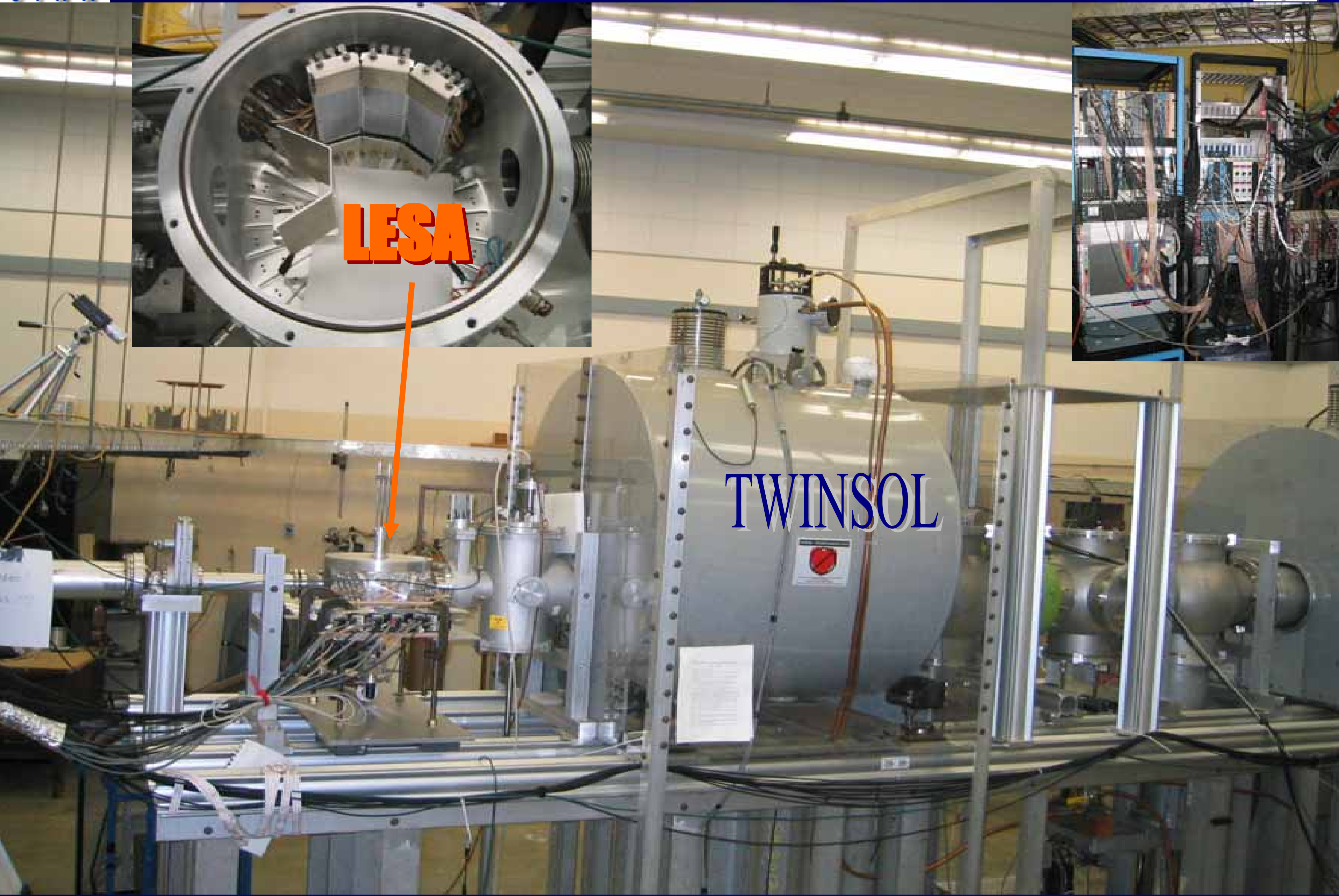
Detect low energy alpha's about 200-500keV

Experimental Setup



- Populate excited states in ^{19}Ne
- 3H-alpha coincidences → alpha-decay branching ratios

Experimental Setup II

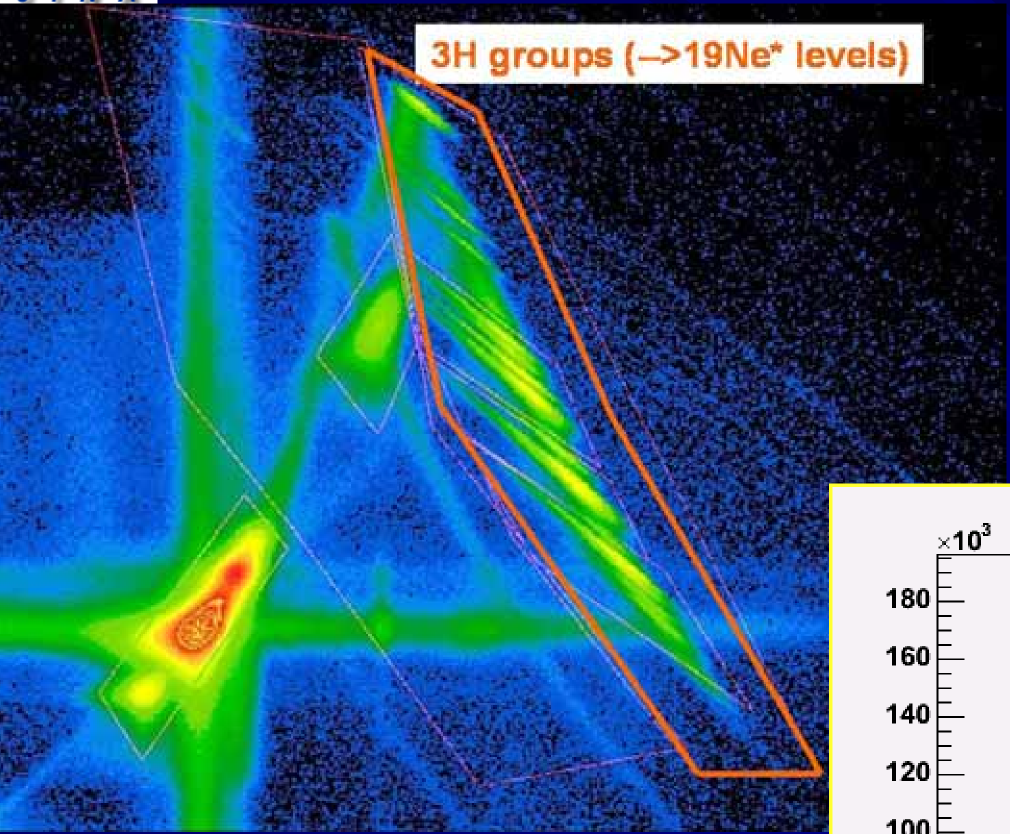


Challenges and Solutions

- Low energy alpha's detection
  - 200-500 keV from the decay of the 4.03 MeV state
  - Thin-window Silicon Detectors: <0.05 μ m, 300 μ m thick (balance between noise deduction and electron energy deposit)
    → threshold ~ 150 keV
  - Time of flight for particle identification

- High statistics for 10^{-4} in B_α
  - Large coverage: LESA for 10% of 4pi
  - Maximize triton detection:
    - TWINSOL acceptance: 2-7.5^o
    - Position sensitive dE-E telescope for tracking: 4x4, 500 μ m thick
  - 30^o target: 40 μ m/cm2→effective thickness doubled (tradeoff between reaction rate and energy loss of alpha's)

A million of ^{3}H detected for 4.03 MeV State

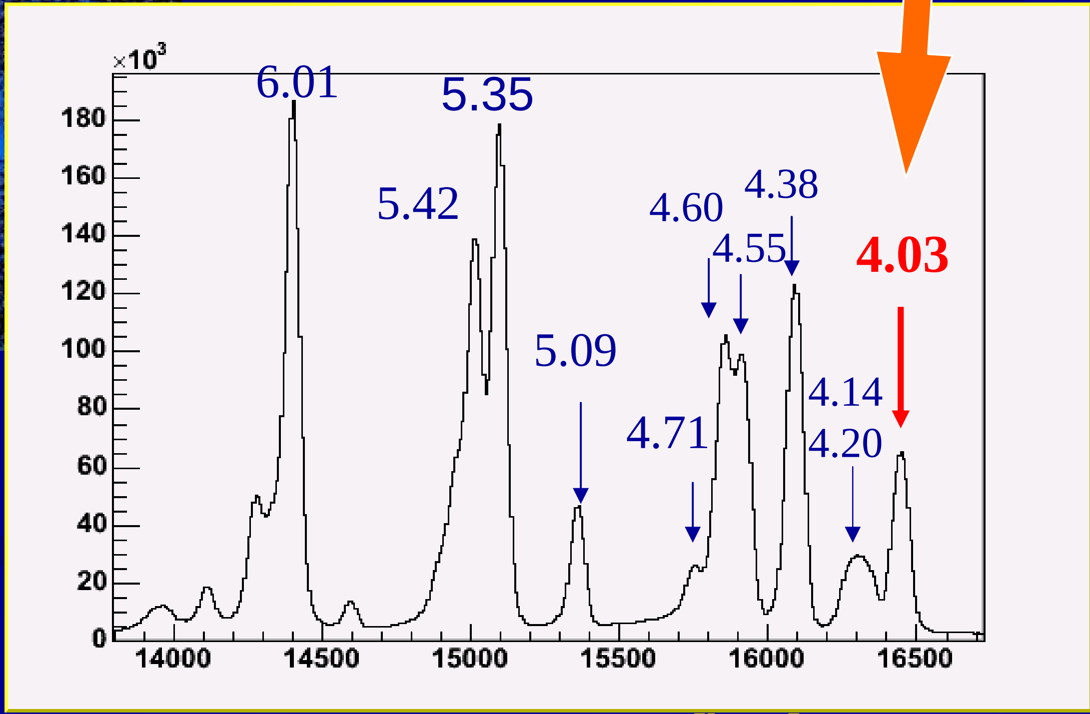


E

dE

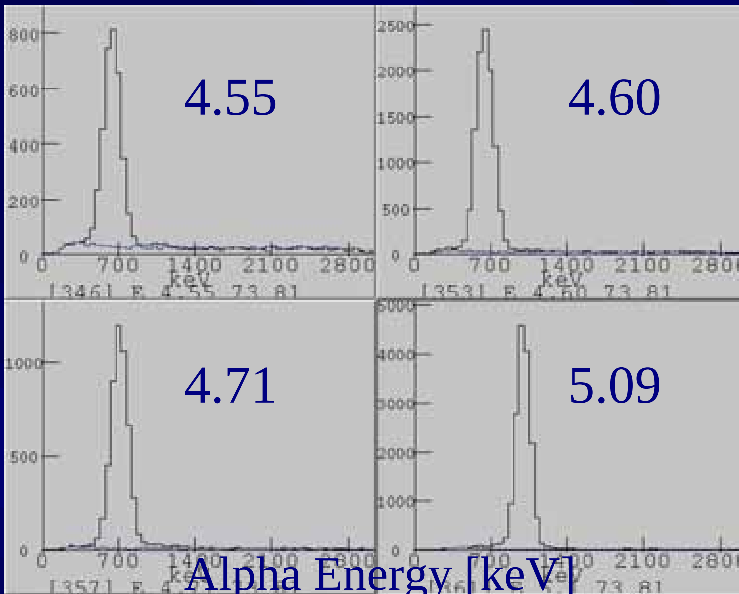
… to reach the sensitivity of 10^{-4} in B_α

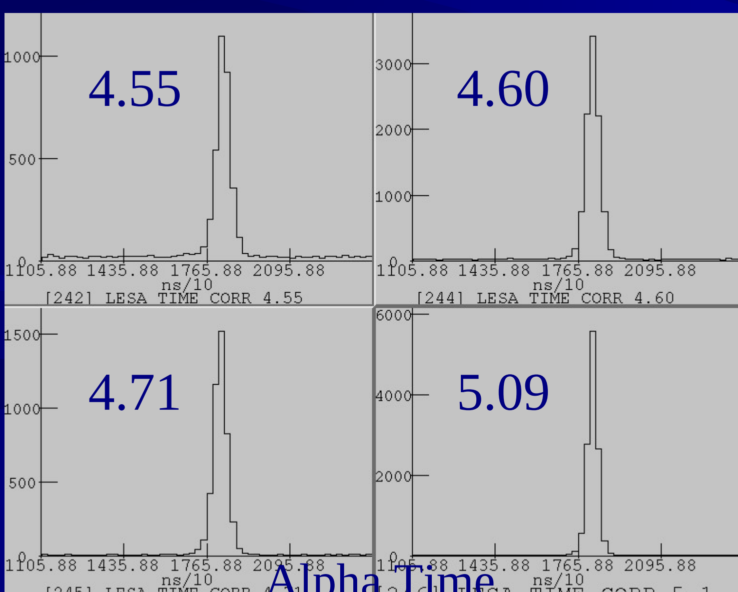
… after two weeks

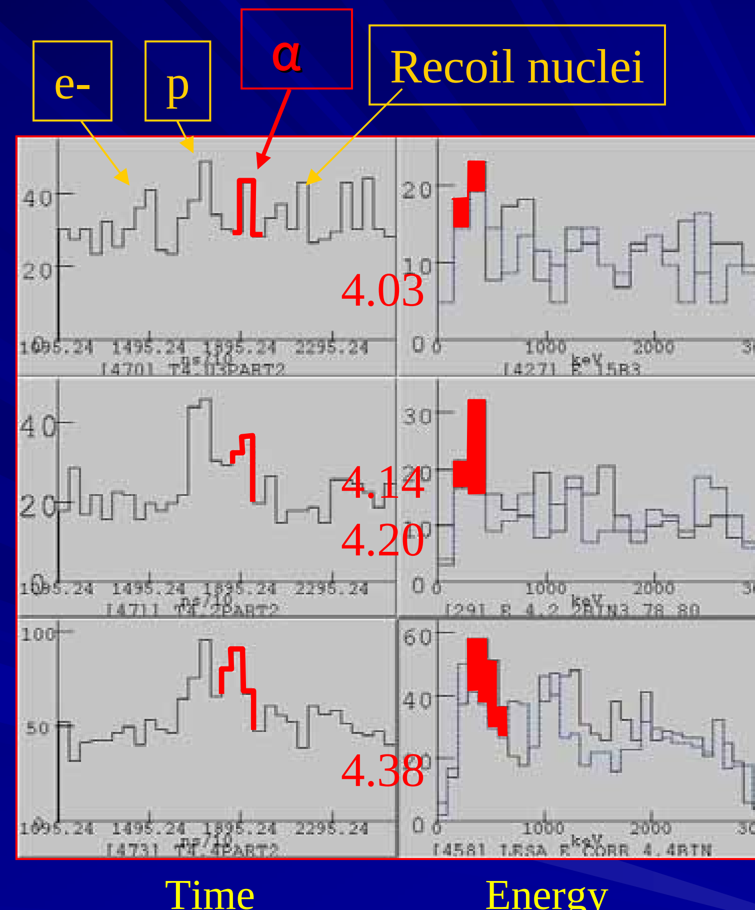


Triton Energy [keV]

Alpha spectra from $^{19}Ne^*$ decay







Preliminary

Results of α-decay Branching Ratios

Ex [MeV]	Magnus90	RIKEN	Laird02	Rehm03	Davids03	Visser04	This work
4.03		<0.03	<0.01	$<6 \times 10^{-4}$	$<4.3 \times 10^{-4}$		$2.9 \pm 2.1 \times 10^{-4}$?
4.14 4.20			<0.01				$1.2 \pm 0.5 \times 10^{-3}$
4.38	0.044 ± 0.032	<0.04		$16 \pm 5 \times 10^{-3}$	$<3.9 \times 10^{-3}$	(>0.0027)	$1.2 \pm 0.3 \times 10^{-3}$
4.55	0.07 ± 0.03	$0.09^{+0.04}_{-0.02}$			0.16 ± 0.04	0.06 ± 0.04	0.07 ± 0.02
4.60	0.25 ± 0.04	$0.29^{+0.06}_{-0.04}$	0.32 ± 0.03		0.32 ± 0.04	0.208 ± 0.026	0.26 ± 0.03
4.71	0.82 ± 0.15	$0.67^{+0.23}_{-0.14}$			0.85 ± 0.04	$0.69^{+0.11}_{-0.14}$	0.80 ± 0.15
5.09	0.90 ± 0.09	$1.11^{+0.17}_{-0.13}$	1.8 ± 0.9	0.8 ± 0.1	0.90 ± 0.06	$0.75^{+0.06}_{-0.07}$	0.87 ± 0.03

- Magnus90: Magnus et al, Nucl. Phys. A 506, 332 (1990)
- RIKEN: private communication from T. Motobayashi
- Laird02: Phys. Rev. C 66, 048801 (2002)
- Rehm03: Phys. Rev. C 67, 065809 (2003)
- Davids03: Phys. Rev. C 67, 012801R (2003)
- Visser04: Phys. Rev. C 69, 048801 (2004)

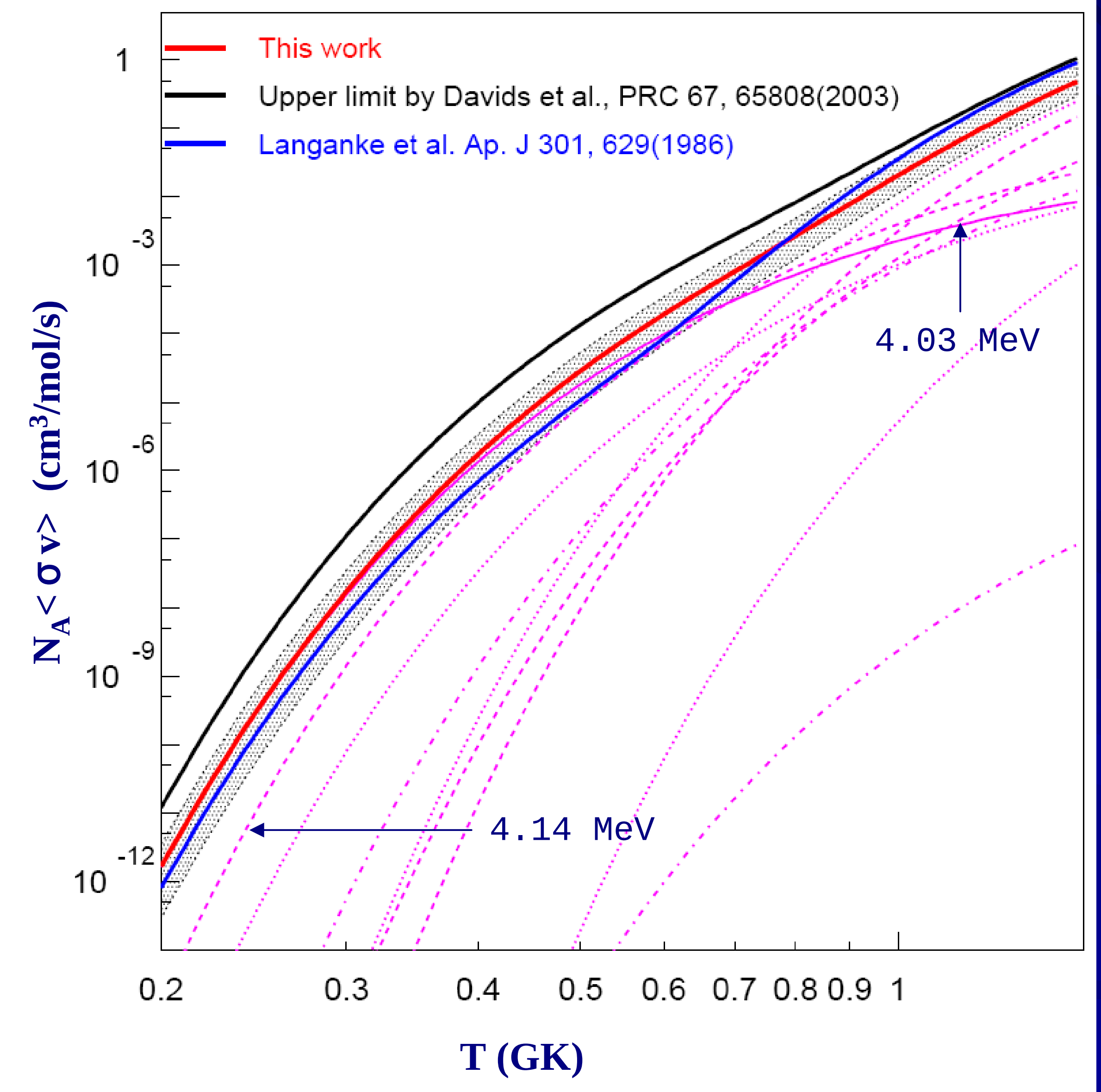
Preliminary

Adopted Level Information

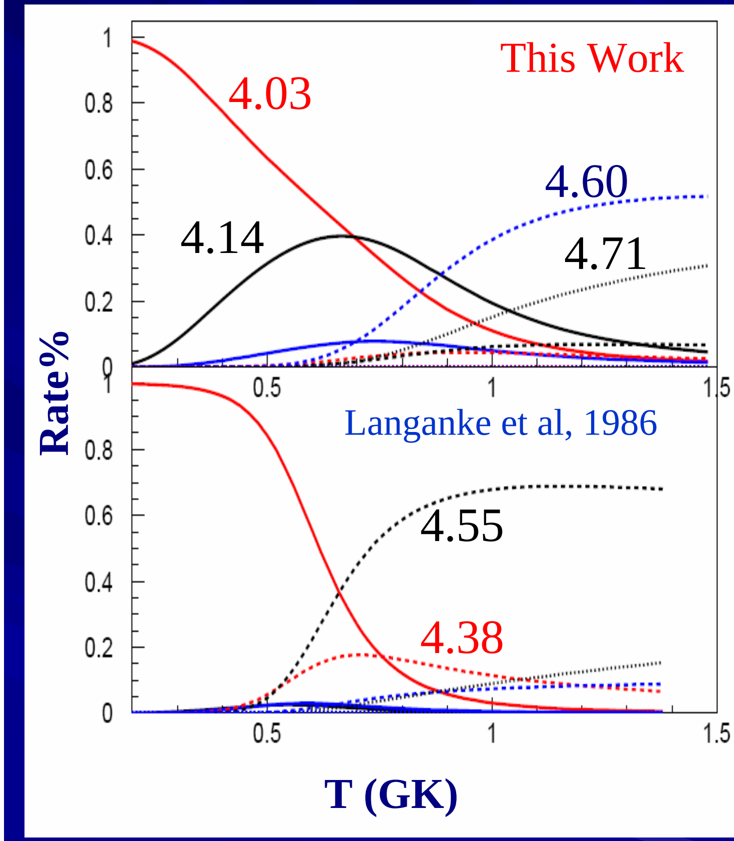
Ex [keV]	J^{π}	τ_m [fs]	Γ_γ [meV]	Γ_α / Γ	$\omega\gamma$ [meV]
4034.5±0.8	3/2+	13^{+9}_{-6}	51^{+43}_{-21}	$2.9\pm2.1\times10^{-4}$	$0.029^{+0.032}_{-0.024}$
4143.5±0.6	7/2-	18^{+2}_{-3}	37^{+7}_{-4}	$1.2\pm0.5\times10^{-3}$	0.18±0.08
4200.3±1.1	9/2-	43^{+12}_{-9}	15^{+4}_{-3}		0.09±0.04
4377.8±0.6	7/2+	5^{+3}_{-2}	130^{+90}_{-50}	$1.2\pm0.3\times10^{-3}$	$0.62^{+0.46}_{-0.28}$
4547.7±1.0	3/2-	15^{+11}_{-5}	44^{+22}_{-18}	0.07±0.02	$6.2^{+3.6}_{-3.1}$
4601.8±0.8	5/2+	7^{+5}_{-4}	94^{+125}_{-39}	0.26±0.03	73^{+97}_{-31}
4634.0±0.9	13/2+	$3.7\pm0.4\times10^{3}$	0.18±0.02	$\sim10^{-5}$	$\sim10^{-5}$
4712±4	5/2-	15.4±3.0	43±7	0.80±0.15	103±26
5092±4	5/2+		5.2±0.9	0.87±0.03	14±3

- **Based on this work**
- Previous exp. work
- Mirror states in 19F
- Theoretical calculations

Reaction Rate of $^{15}O(\alpha,\gamma)^{19}Ne$

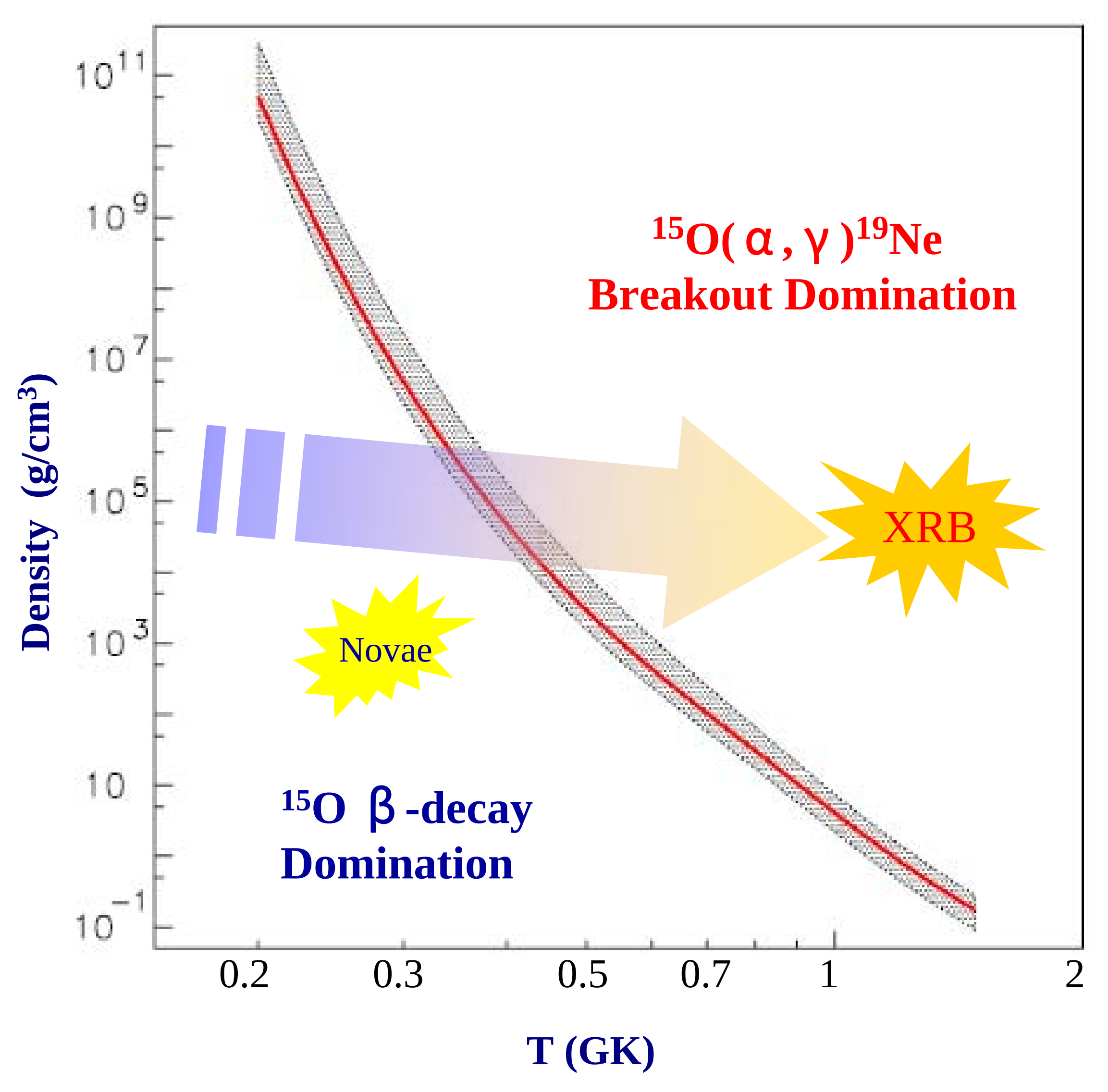


Differences in detail



- More work needed for the near-threshold states

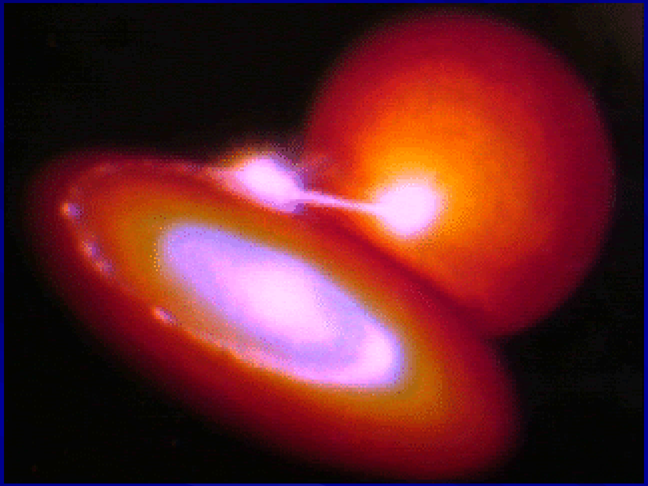
Competition between breakout and β decay



- β -decay $t_{1/2}$=122s
  X_α=0.27
- The breakout reaction rate plays a critical role in the early stage of the bursts

Conclusion

- Critical reaction rate of $^{15}O(\alpha,\gamma)^{19}Ne$ is provided on experimental basis via measurement of lifetimes and branching ratios of the α-unbound states in ^{19}Ne
- Ongoing simulations of X-ray bursts based on the new rate will possibly answer:
  - Can we see the quenching effect with the new rate?
  - What is the accretion rate for marginally stable burning (mHz QPOs)?
  - Where is Carbon from for superbursts?



- Outlook
  - Precise measurement is needed for the near threshold states (4.03, 4.14, and 4.20)
  - Direct measurement requires development of intense radioacive beams in future facilities like

Acknowledgements

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