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

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Wanpeng Tan
University of Notre Dame

A NEW ESTIMATE OF THE $^{19}Ne(p,\gamma)^{20}Na$ AND $^{15}O(\alpha,\gamma)^{19}Ne$ REACTION RATES AT STELLAR ENERGIES

K. LANGANKE,[1] M. WIESCHER,[2] AND W. A. FOWLER
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena
AND
J. GÖRRES
Department of Physics, University of Pennsylvania, Philadelphia
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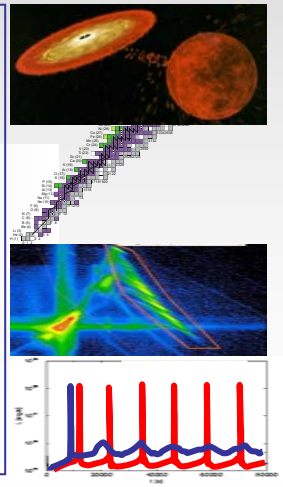
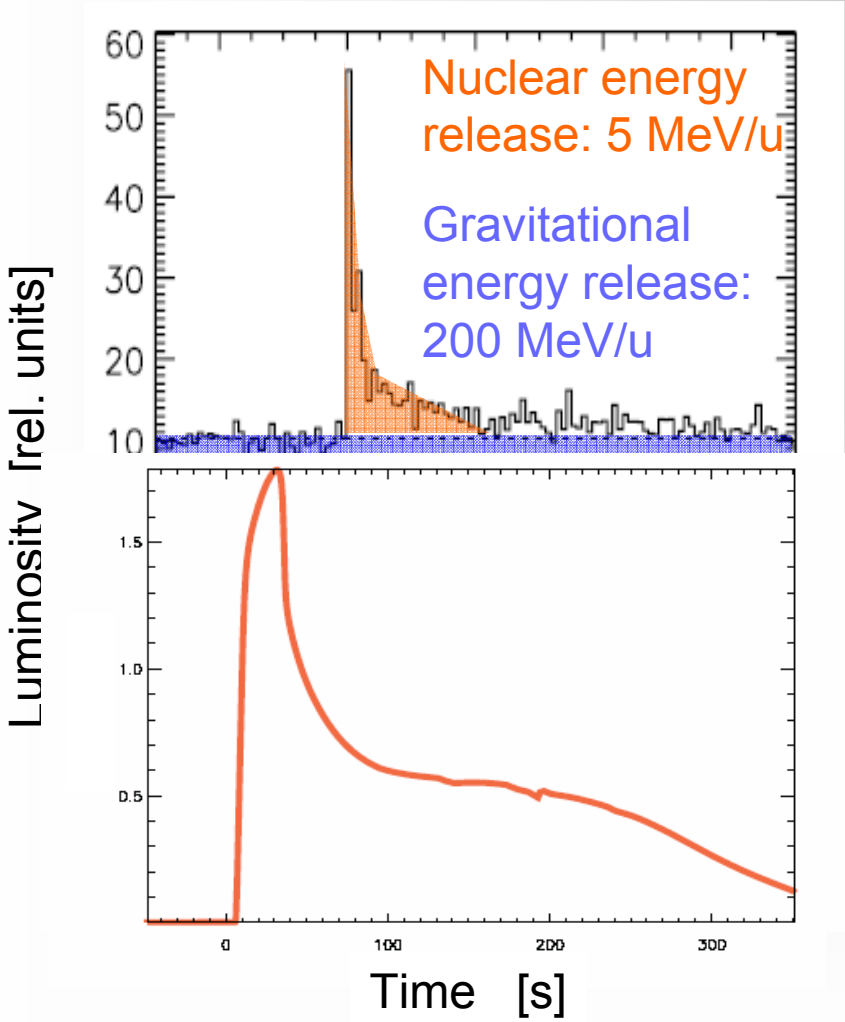
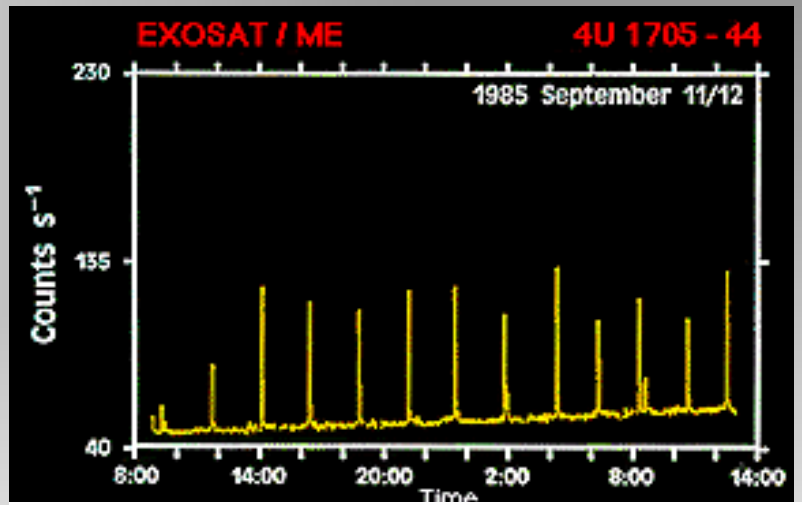
- $^{15}O(\alpha,\gamma)^{19}Ne$ as the trigger of X-ray bursts
- The present uncertainties in $^{15}O(\alpha,\gamma)^{19}Ne$
- The experiment & new results for $^{15}O(\alpha,\gamma)^{19}Ne$
- Interpretation & Implication

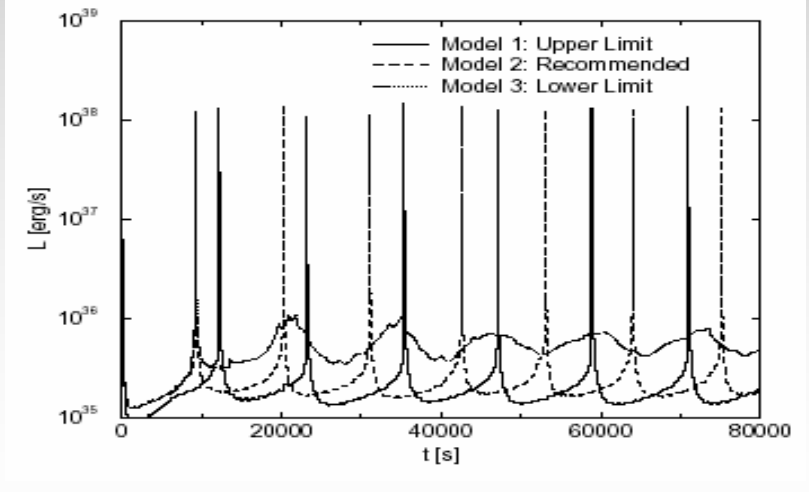


X-Ray Bursts as Nuclear Laboratory



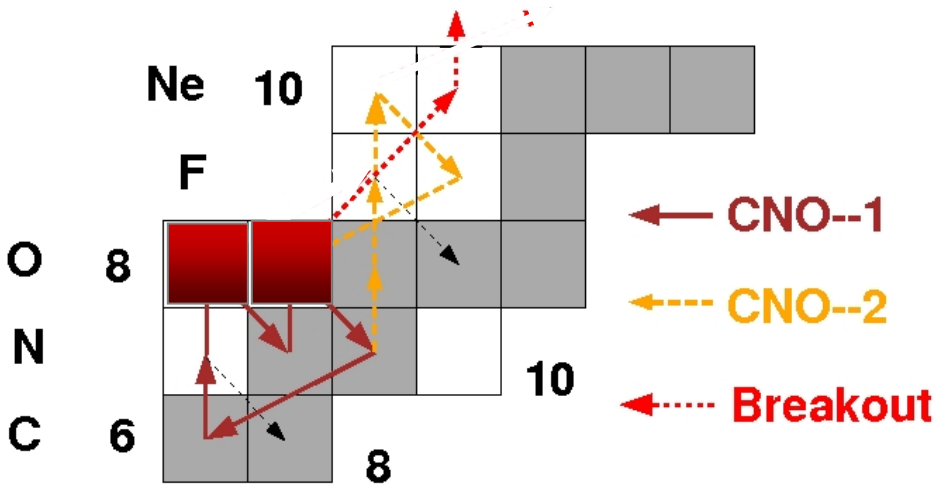
Woosley et al. ApJ (2005)

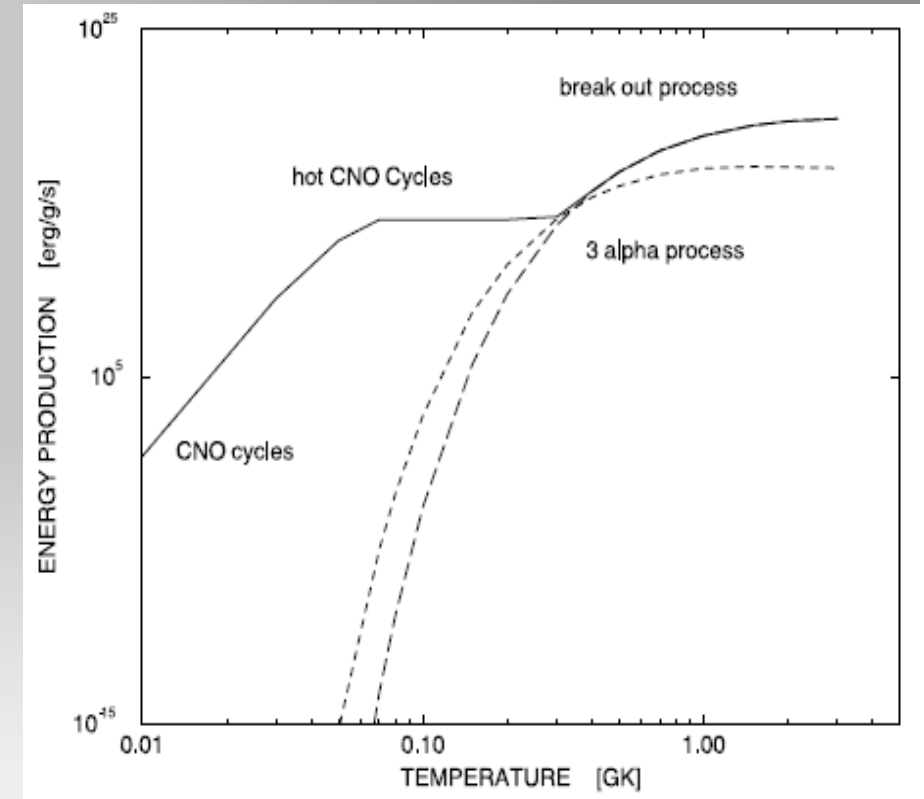


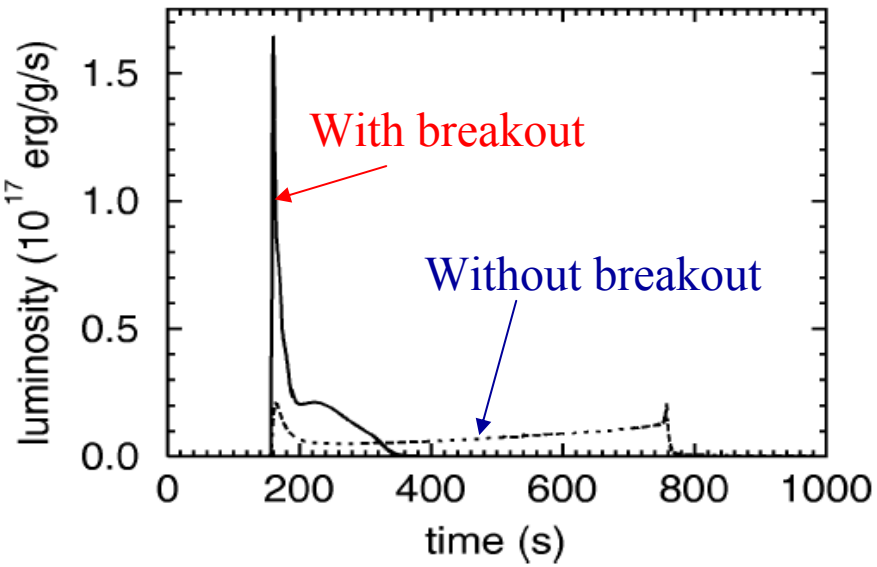


Fisker et al., astro-ph/0410561 (2005)

The Trigger of the Bursts



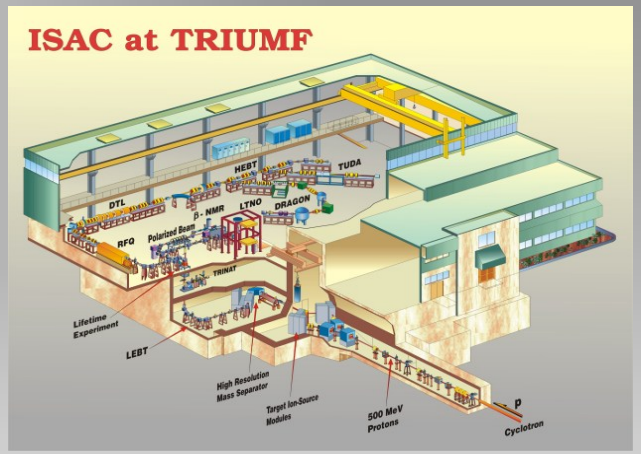


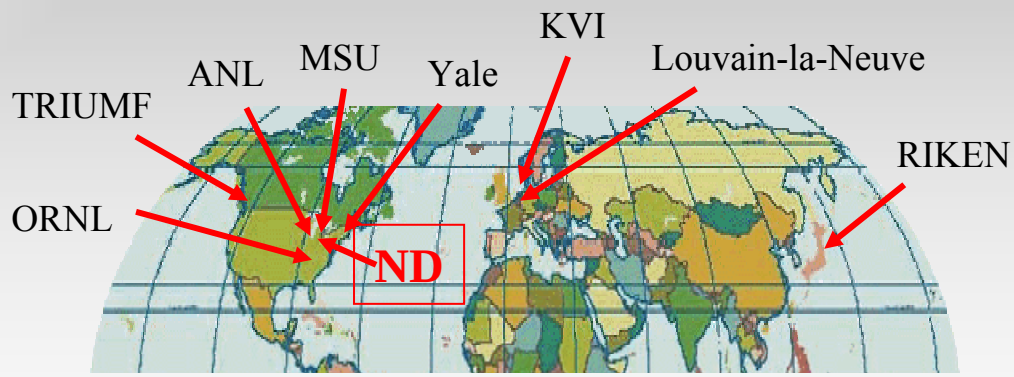


Burst is triggered by $^{15}O(\alpha,\gamma)^{19}Ne$ and by generating additional CNO fuel via the triple α process!

Many proposals and attempts to study $^{15}O(\alpha,\gamma)^{19}Ne$ by direct & indirect approach

- Direct measurement is difficult!
  - An intense (10^{11} /s) radioactive ^{15}O beam gives a count rate of <1/hr (estimated at ISAC, TRIUMF, 10^{9}/s achieved at Louvain la Neuve)





- Indirect method has been approached many times!
  - Populate α-unbound states in ^{19}Ne
  - Measure lifetimes or gamma widths — $^{17}O(^{3}He,n\text{-}\gamma)^{19}Ne$
  - Measure α-decay branching ratios B_{α} — $^{19}F(^{3}He,t\text{-}\alpha)^{19}Ne$

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

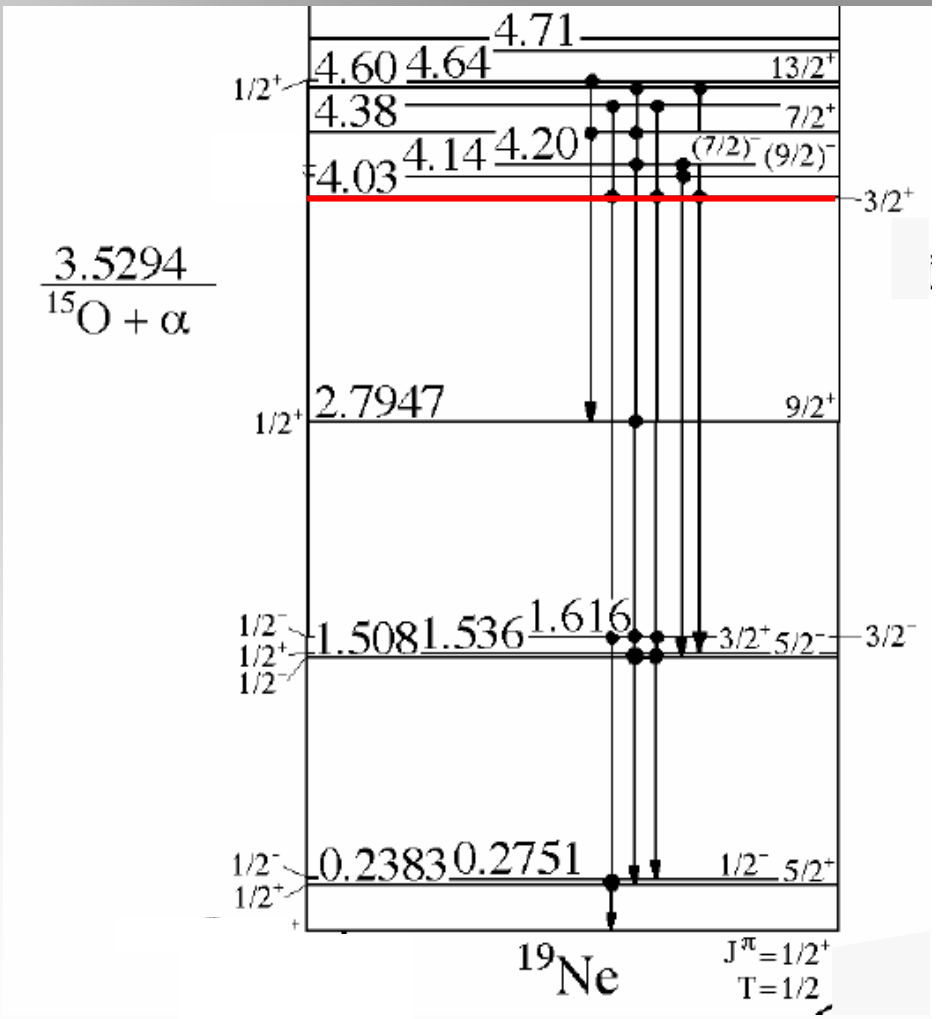
- Reaction Rate

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

determined by resonance energy E_R and strength $\omega\gamma$

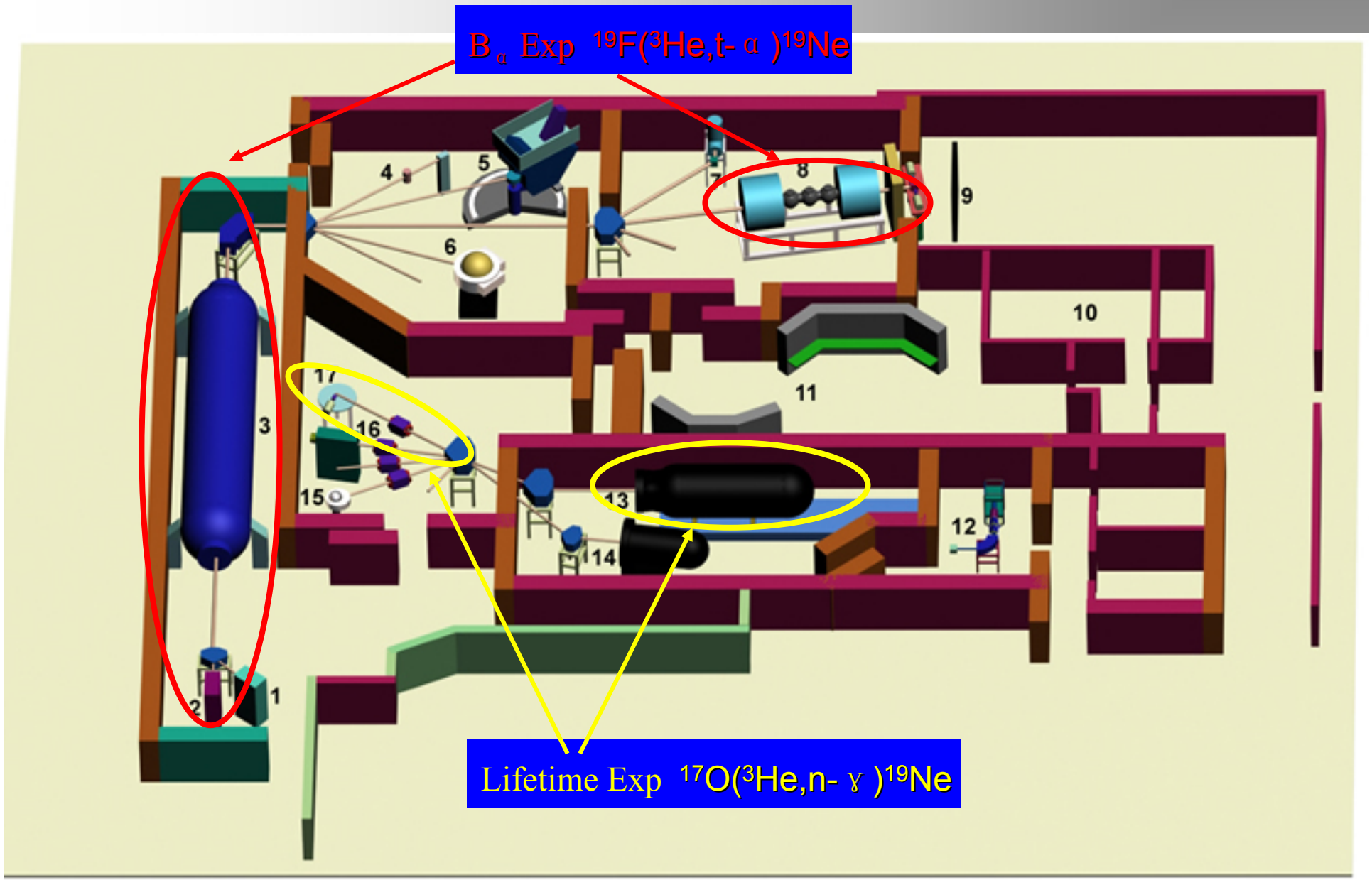
where $$\omega\gamma = \frac{2J_R + 1}{(2J_P + 1)(2J_T + 1)} B_\alpha \Gamma_\gamma$$

- Three measurable quantities characterize the resonance strength: J^π, Γ_γ, and $B_\alpha = \Gamma_\alpha / \Gamma_{tot}$



Single resonance contribution!

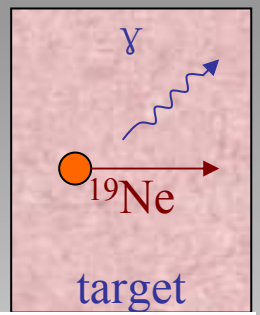
Lab Layout at Notre Dame



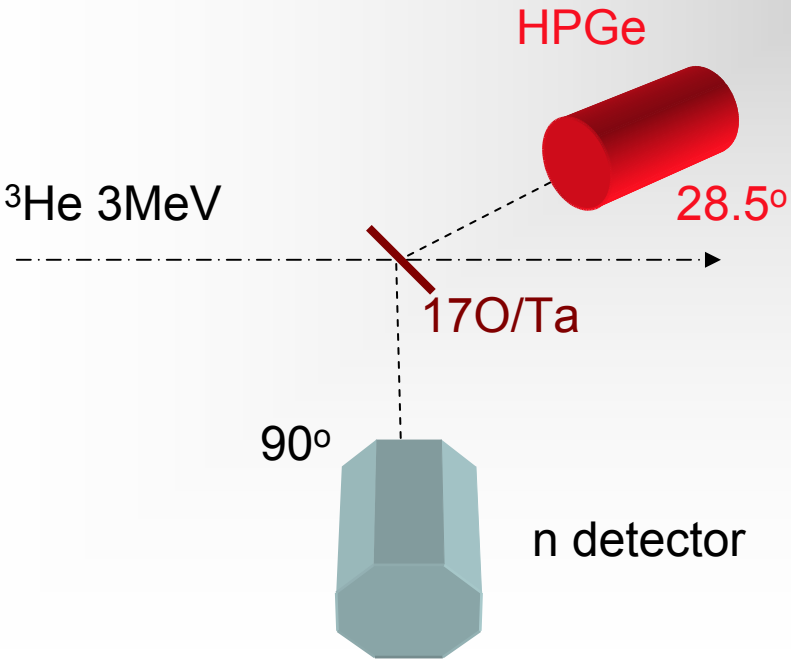
Lifetime measurement using the Doppler-Shift Attenuation Method

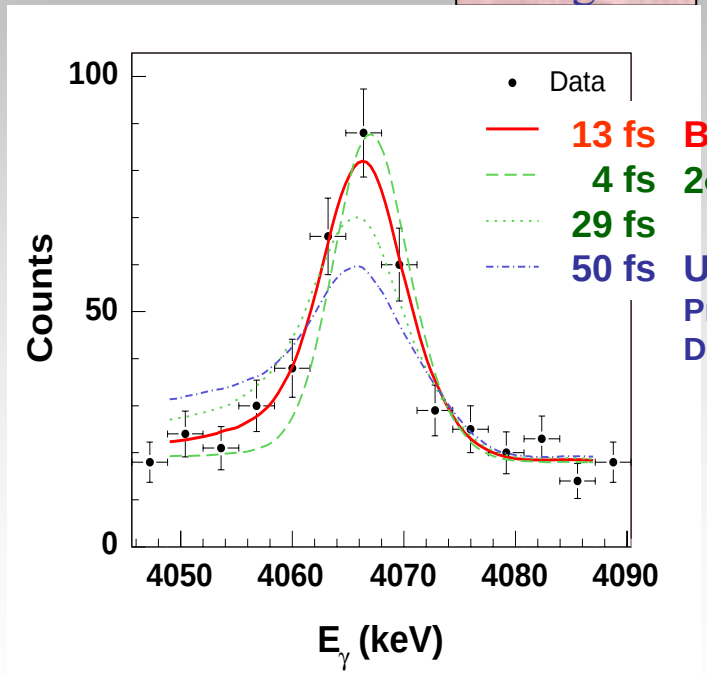
- Measure lifetime to obtain decay width $\Gamma = \hbar / \tau$

$$E_\gamma = E_{\gamma_0}(1 + F(\tau)\beta\cos\theta)$$



- Full line shape analysis



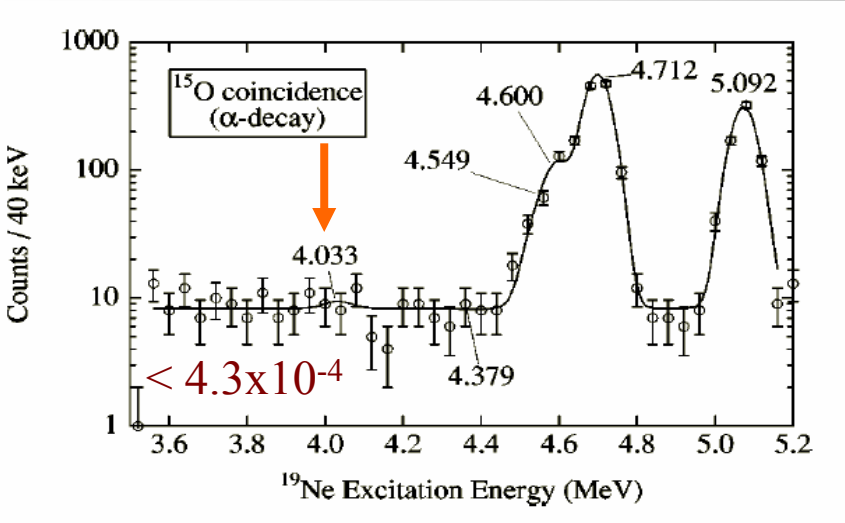


Measured lifetime $\tau = 13 \pm {}^{9}_{6}$ fs or $\Gamma = 51 \pm {}^{43}_{21}$ meV

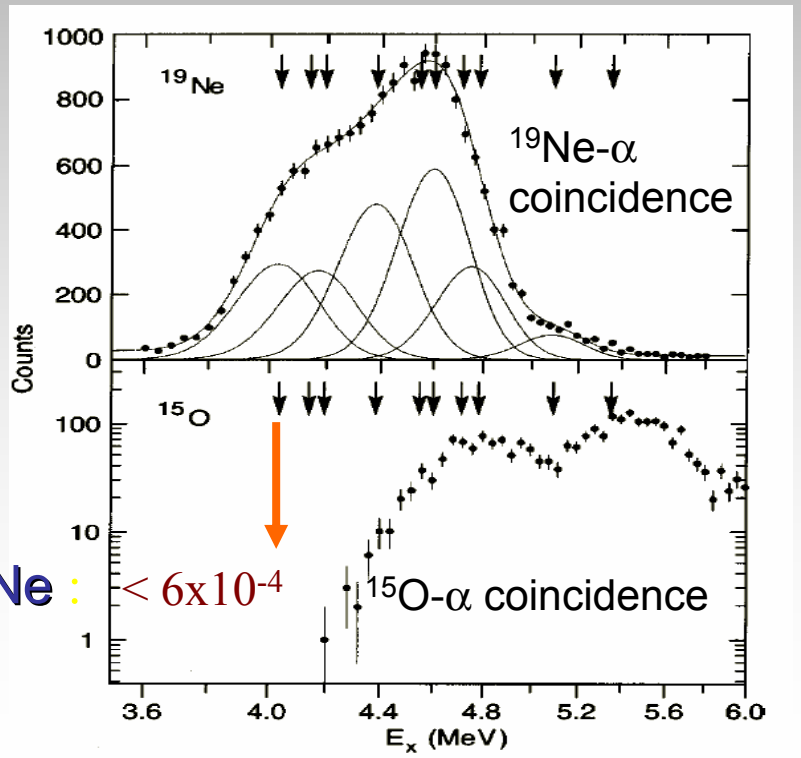
Alpha-decay branching ratios

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

Davids et al, 2003 at KVI $^{1}H(^{21}Ne,^{3}H)^{19}Ne^*$



Rehm et al, 2003 at ANL $^{3}He(^{20}Ne,\alpha)^{19}Ne^*$

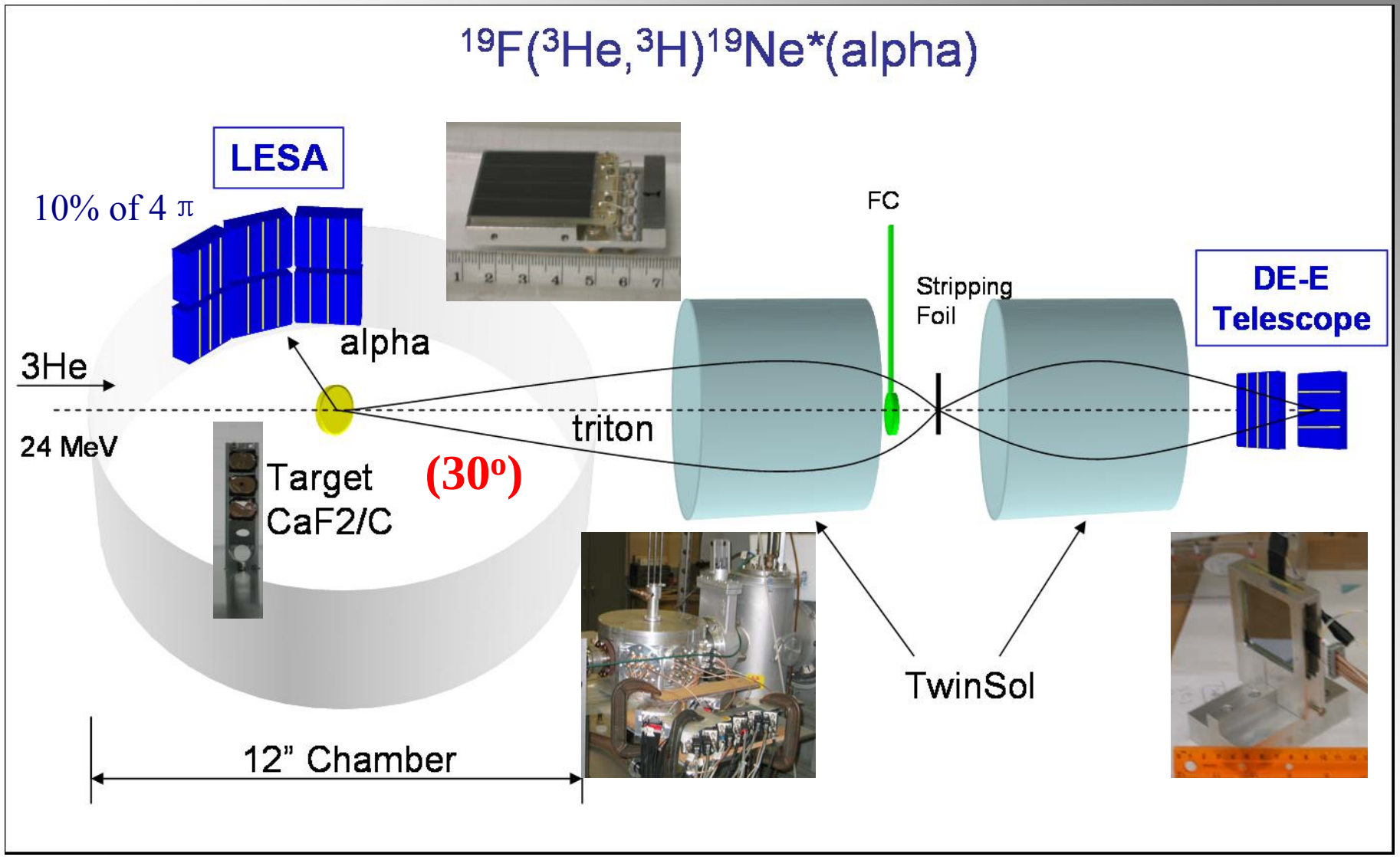


Challenges for our experiment $^{19}F(^{3}He,t\text{-}\alpha)^{19}Ne$:

High statistics for coincidences

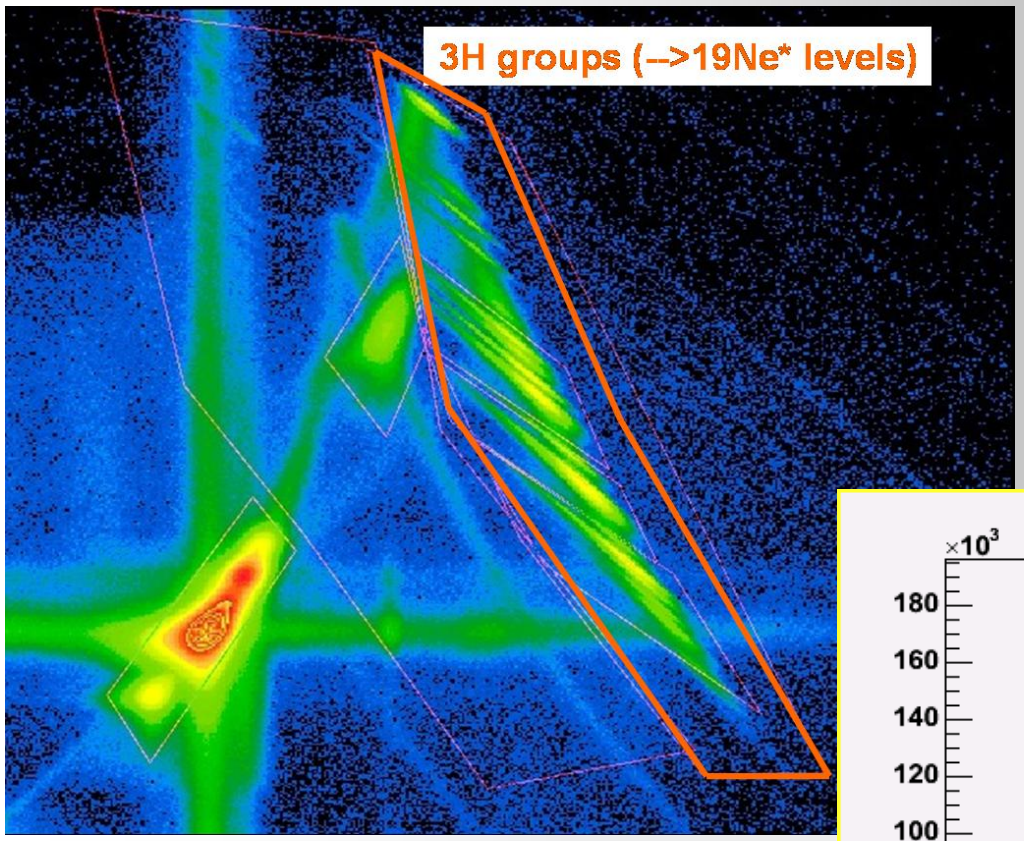
Detect low energy alpha's about 200-500keV

Experimental Setup



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

one million of ^{3}H populating 4.03 MeV State

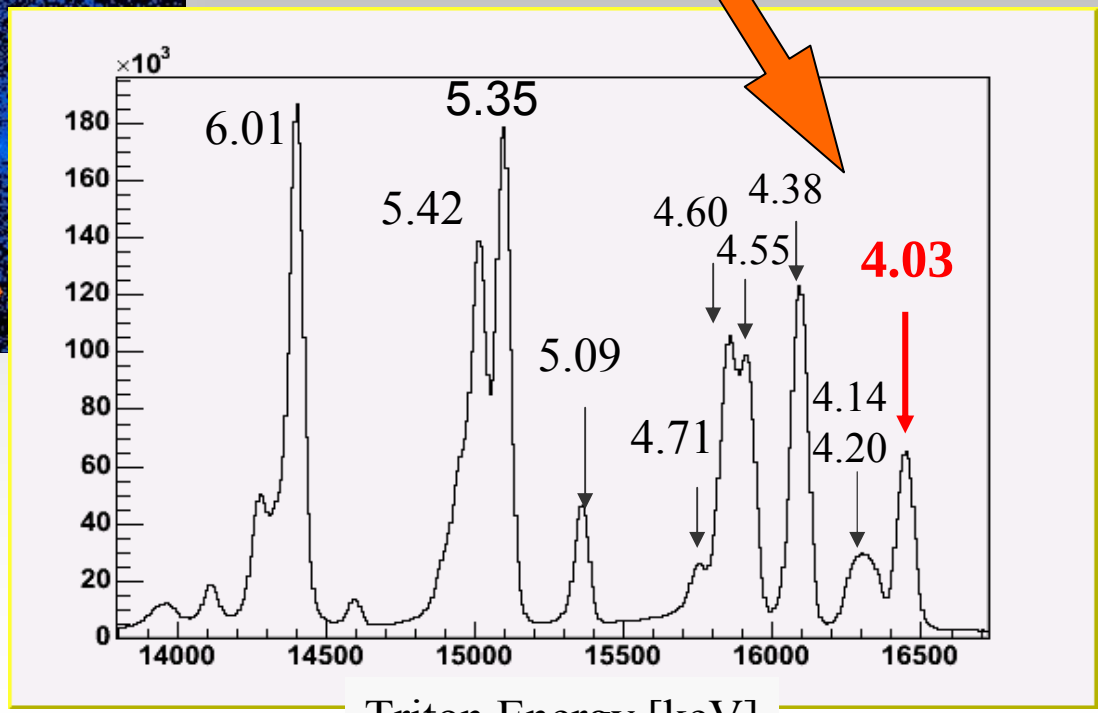


… to reach the sensitivity of 10^{-4} in B_α

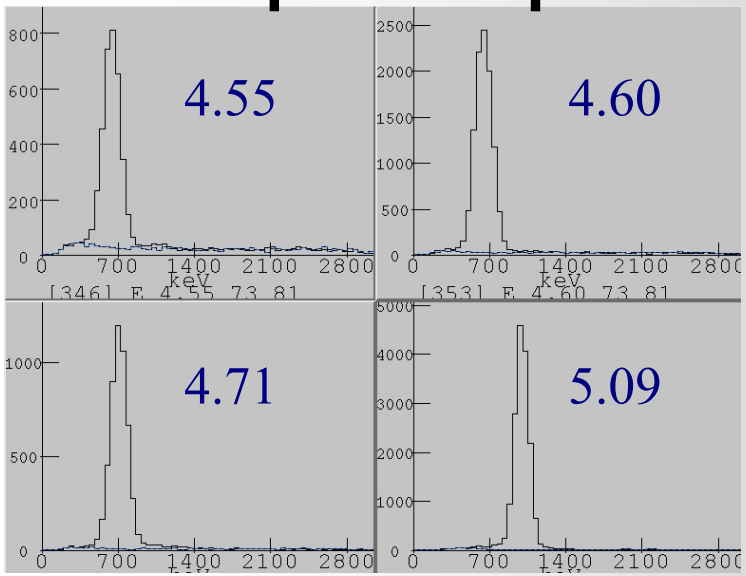
... after two weeks

E

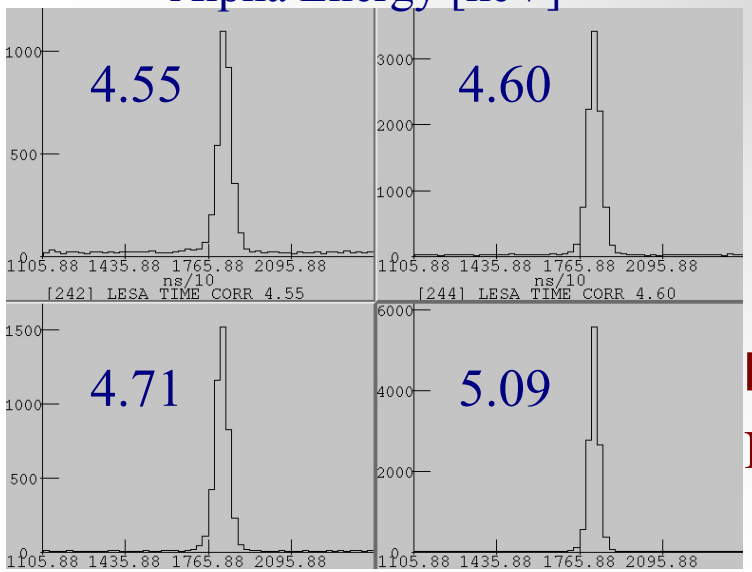
dE



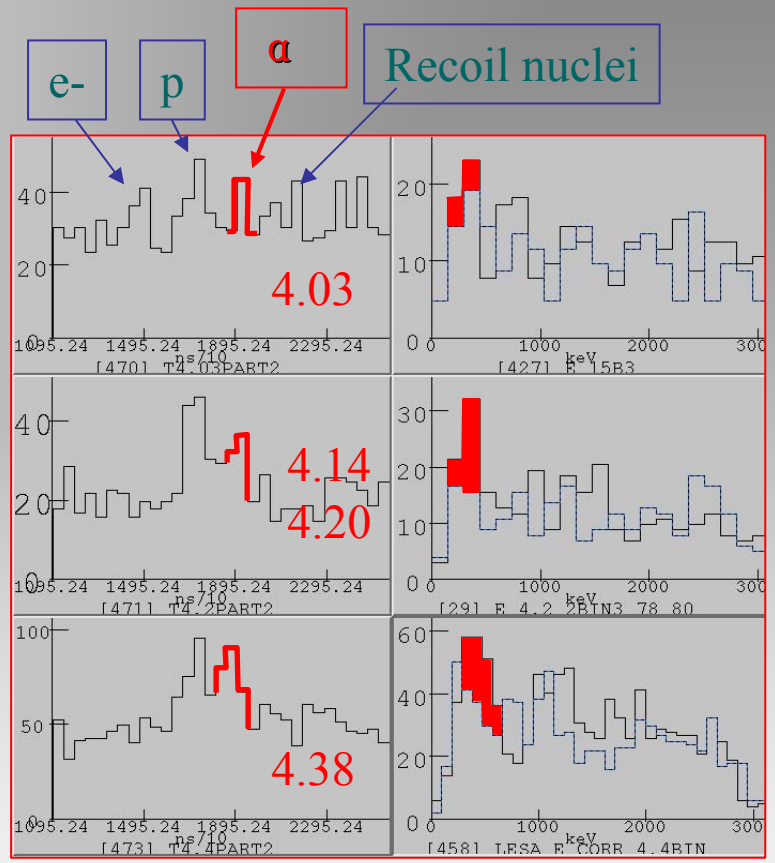
Alpha spectra from $^{19}Ne^*$ decay



Alpha Energy [keV]



Alpha Time



Time Energy

$B_\alpha = 2.9 \pm 2.1 \cdot 10^{-4}$ ($<4.3 \cdot 10^{-4}$, Davids et al 2003)

$\Gamma = 51 \pm {}^{43}_{21}$ meV

$\Rightarrow \omega\gamma = 30 \pm {}^{44}_{15}$ μeV

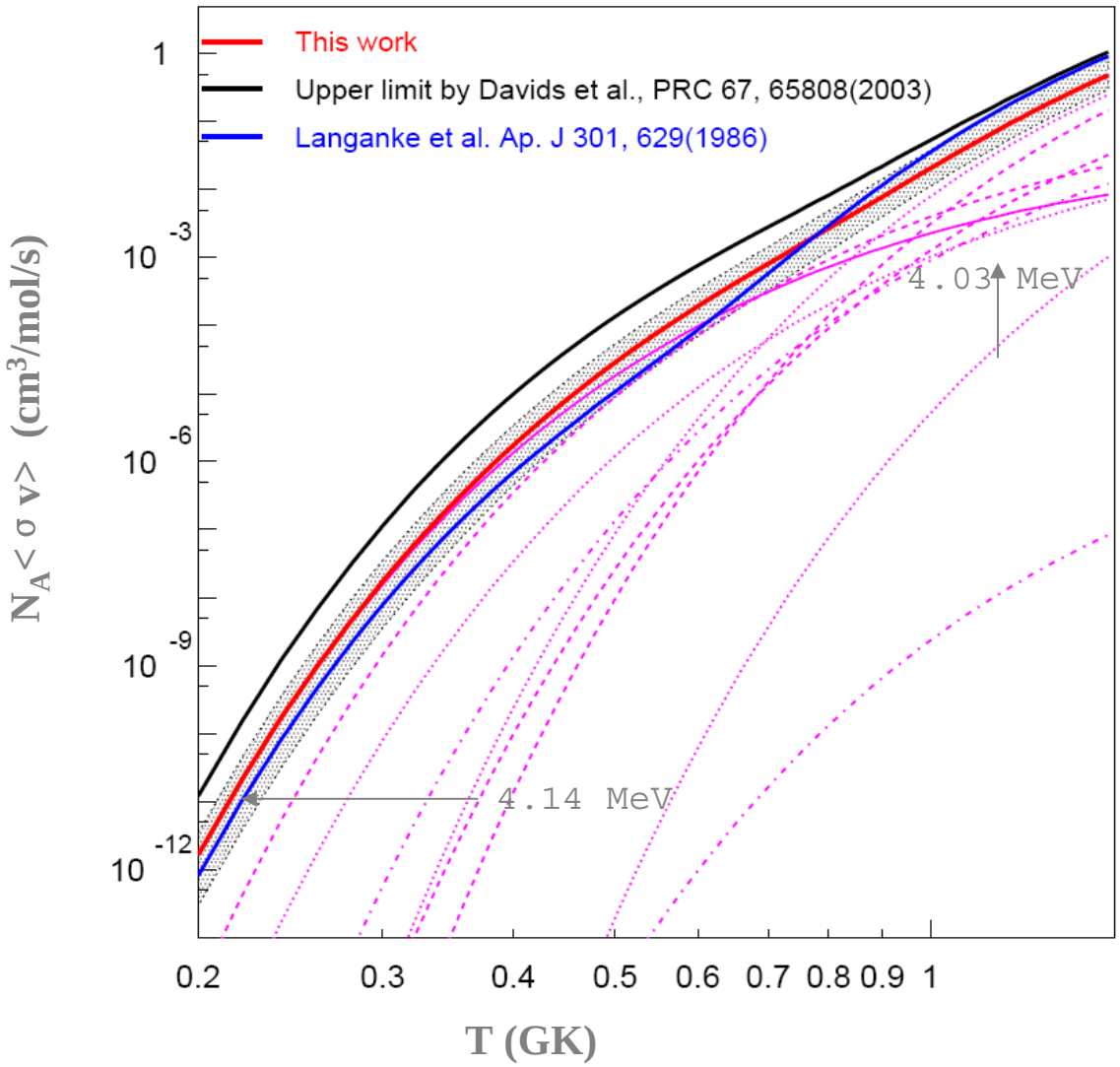
Results of α -decay Branching Ratios

Ex [MeV]	Magnus90	RIKEN	Laird02	Rehm03	Davids03	Visser04	This work
4.03		<0.03	<0.01	$<6\times10^{-4}$	$<4.3\times10^{-4}$		$2.9\pm2.1\times10^{-4}$?
4.14 4.20			<0.01				$1.2\pm0.5\times10^{-3}$
4.38	0.044±0.032	<0.04		$16\pm5\times10^{-3}$	$<3.9\times10^{-3}$	(>0.0027)	$1.2\pm0.3\times10^{-3}$
4.55	0.07±0.03	$0.09^{+0.04}_{-0.02}$	0.32±0.03		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±0.04	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

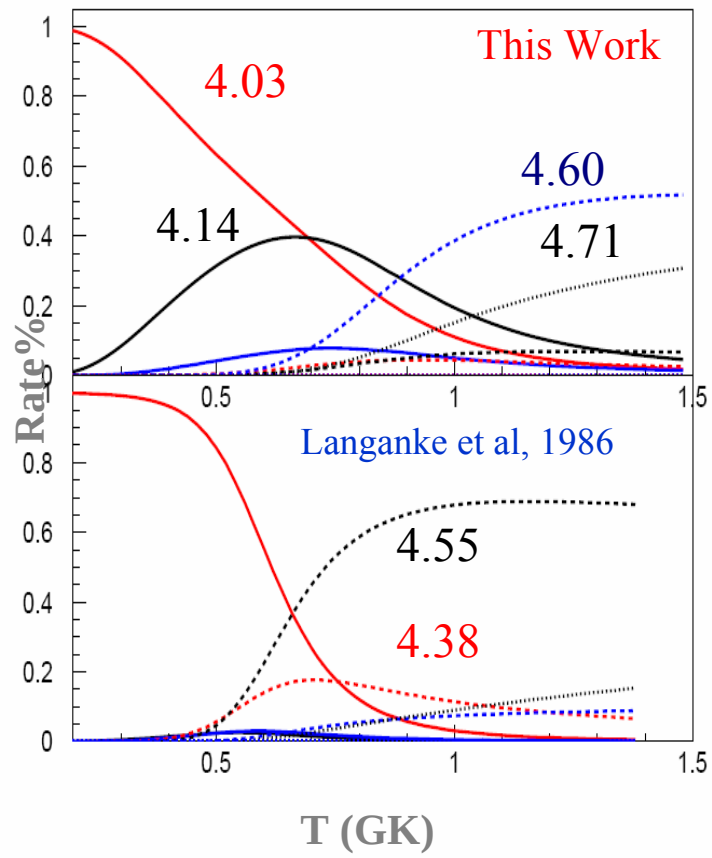
Preliminary

- 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)

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

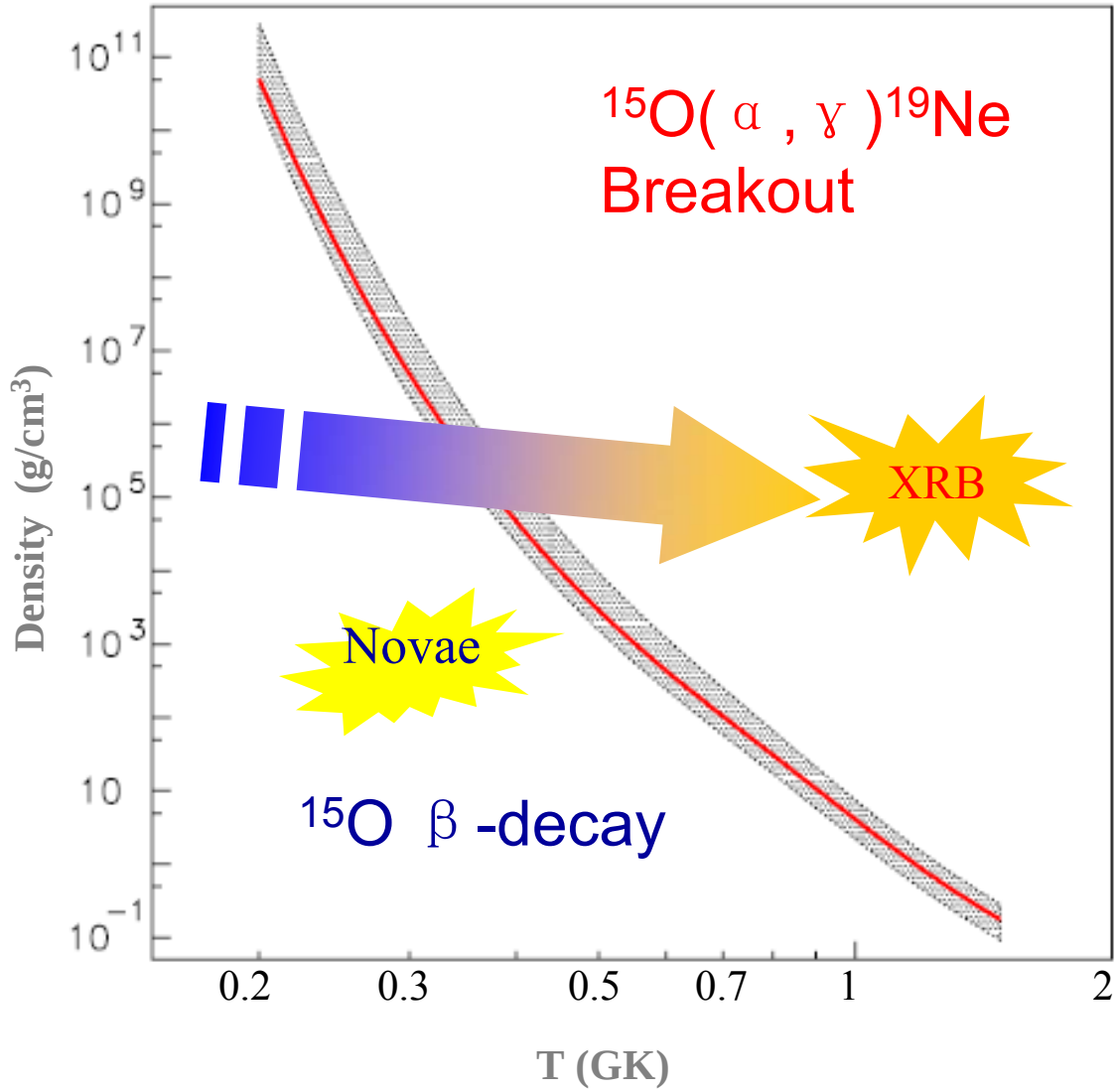


Differences in detail



- More work needed for the near-threshold states

Competition between breakout & β-decay

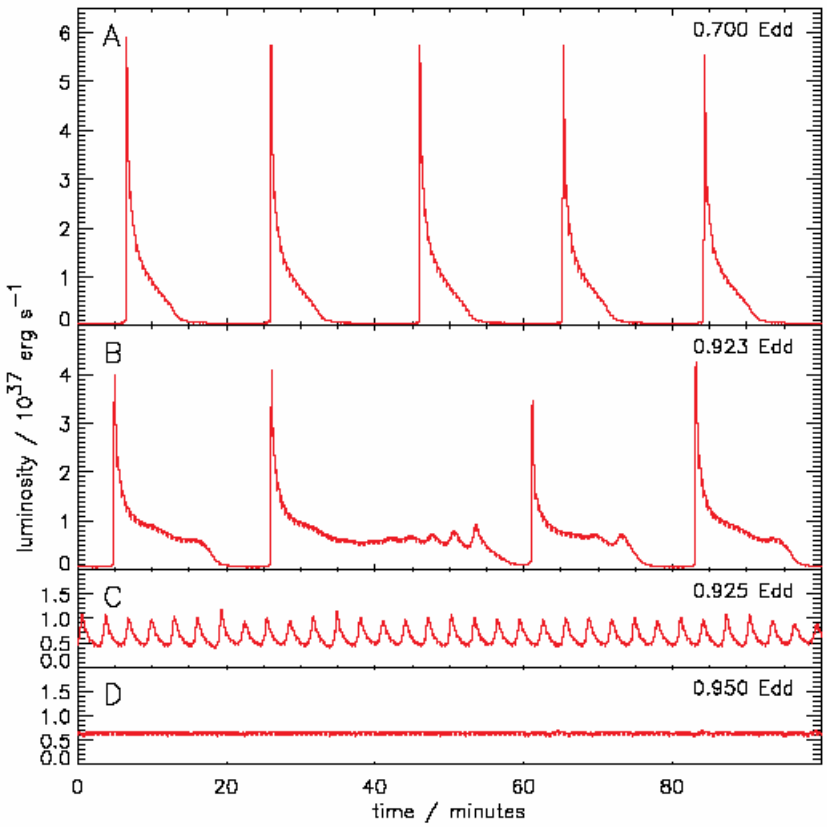


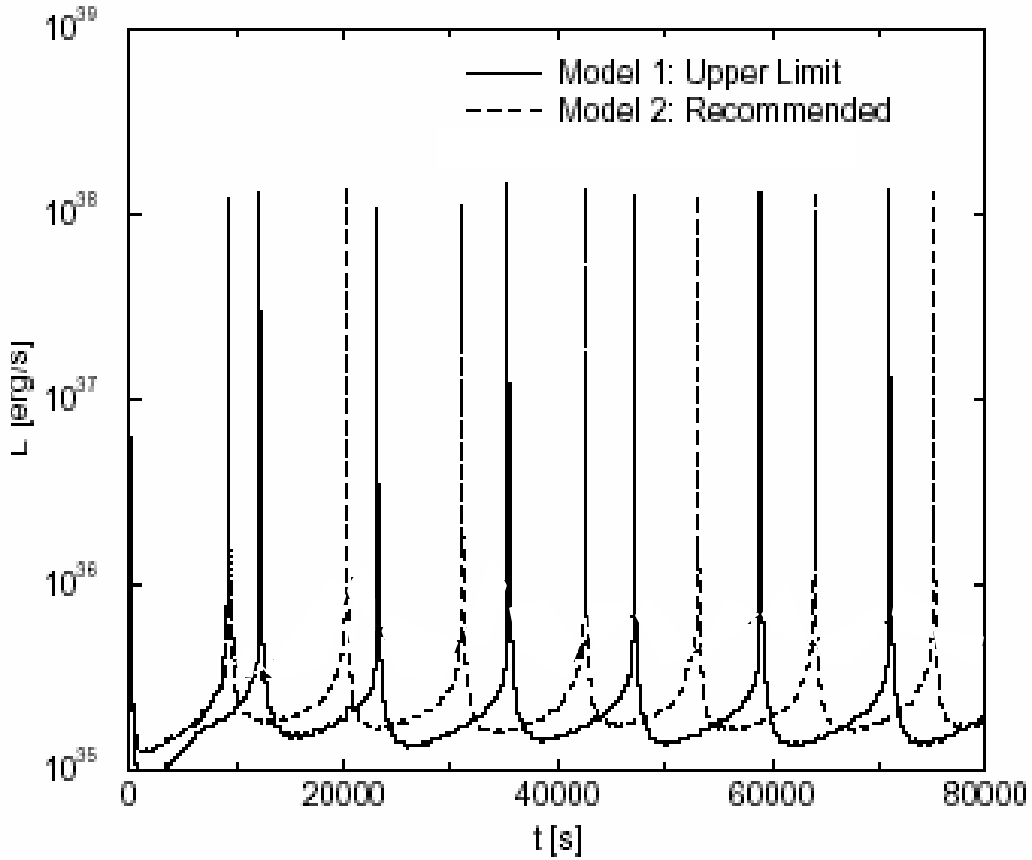
- ^{15}O β -decay $t_{1/2}$=122s
  X_α =0.27

The $^{15}O(\alpha,\gamma)$ breakout reaction rate plays a critical role in the ignition phase of the X-ray burst!

Accretion Rate Dependence for XRB

Steady state surface burning predicted for low accretion rates!



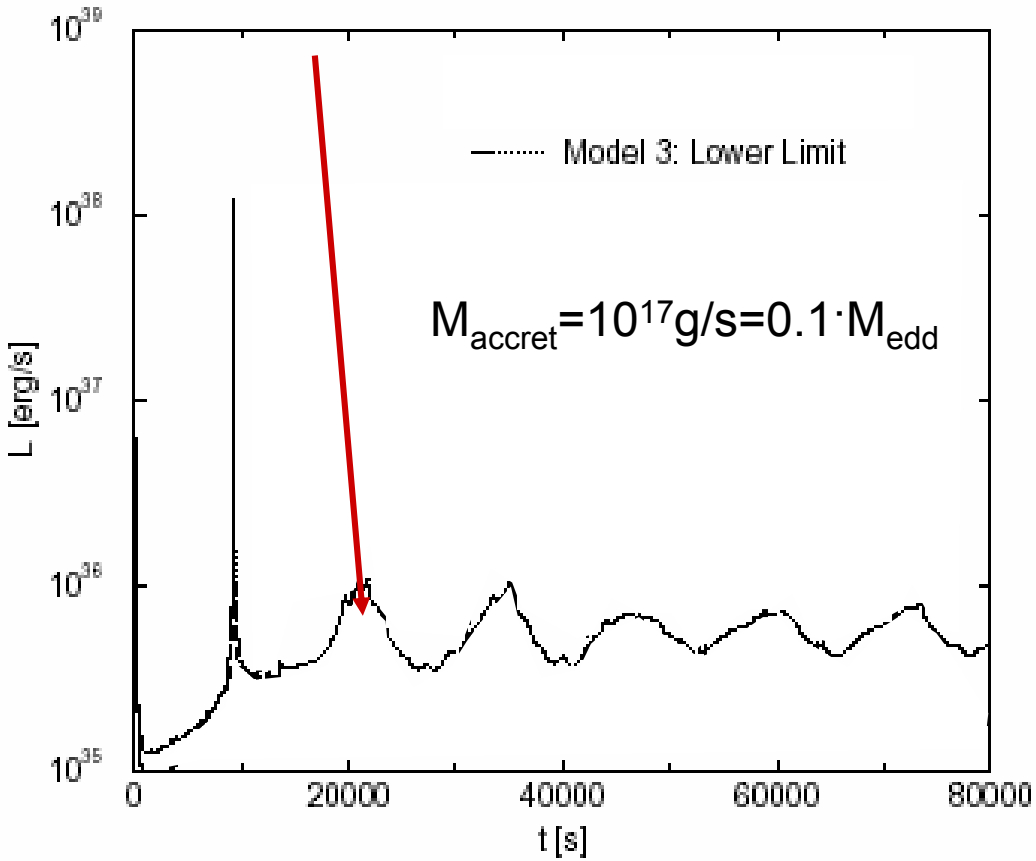


$M_{accret}=10^{17}$g/s$=0.1\cdot M_{edd}$

$^{15}O(\alpha,\gamma)$ Rate & Burst Structure

Low reaction rate quenches bursts

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



High rate ⇒ break-out
⇒ H-burning by rp-process

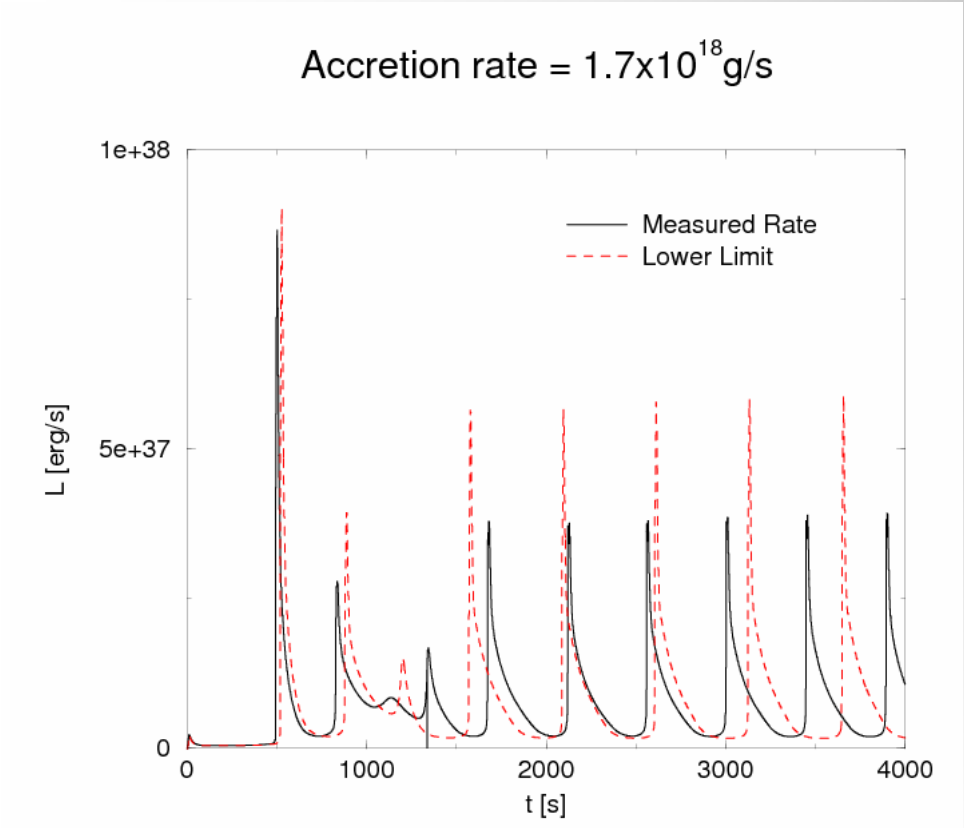
Low rate ⇒ He-depletion & HCNO

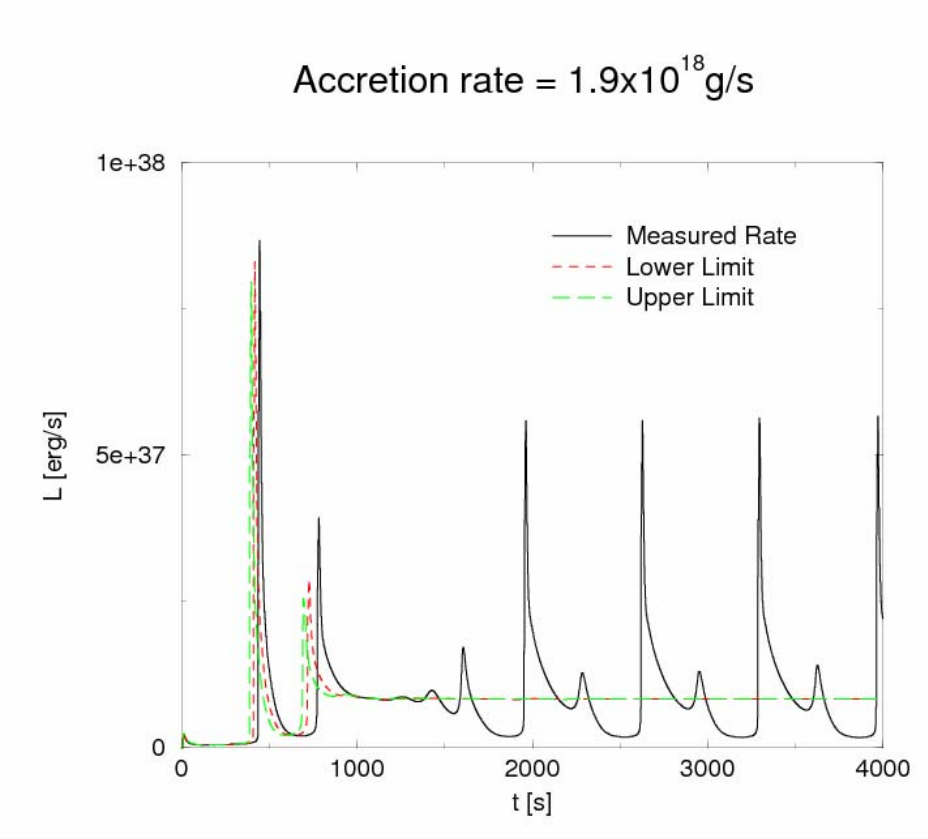
⇒ H-burning by 3α fueled HCNO cycle

New lower (1σ) limits ⇒ defines accretion rate limit for bursts!

New limit of sensitivity for nuclear signatures has been reached!

Present Speculation

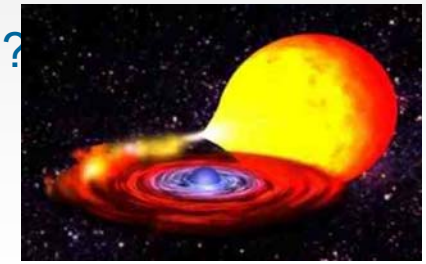




Fisker et al. in preparation

Conclusion

- The reaction rate of $^{15}O(\alpha, \gamma)^{19}Ne$ has been determined by determining the lifetimes and branching ratios of α-unbound states in ^{19}Ne
- The results seem to provide more stringent limits on the burst behavior of accreting neutron stars.
- The results will be used to constrain other X-ray burst model parameters such as accretion rate, ignition conditions ...
- Future steps towards improvement requires
  - Precise measurement for the near threshold states (4.03, 4.14, & 4.20) in ^{19}Ne
  - Direct measurement with intense radioactive beams?



Acknowledgements

Collaborators:

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University of Notre Dame