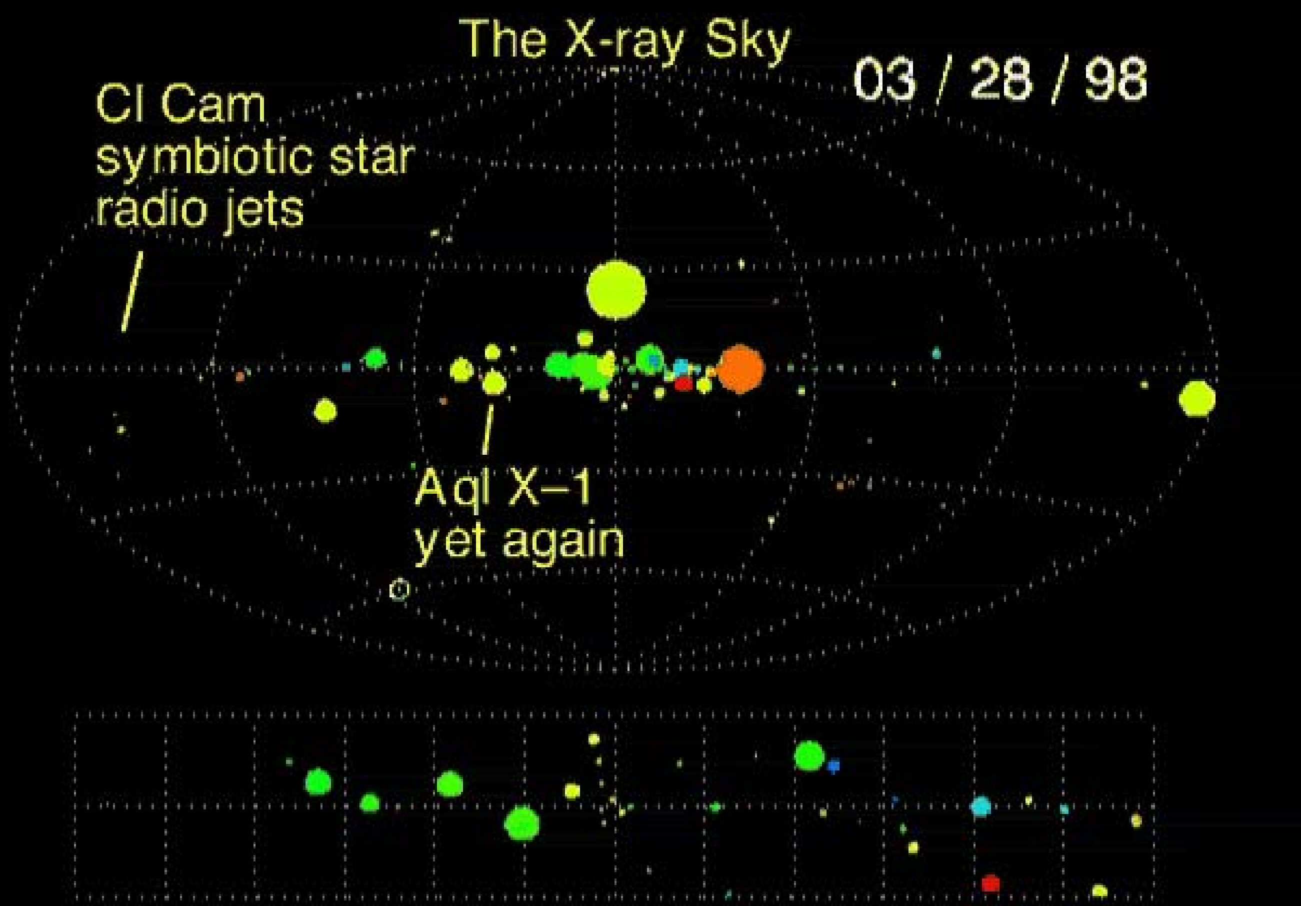
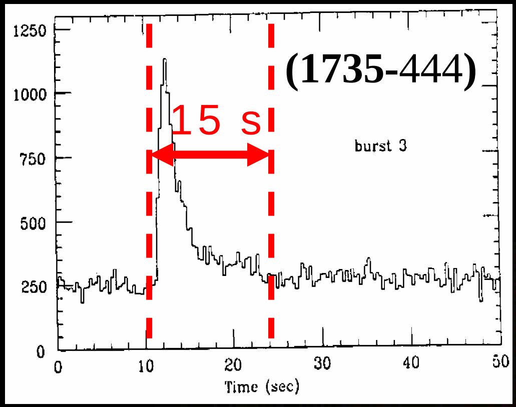
The fate of matter on accreting neutron stars

H. Schatz, MSU, NSCL & Joint Institute for Nuclear Astrophysics

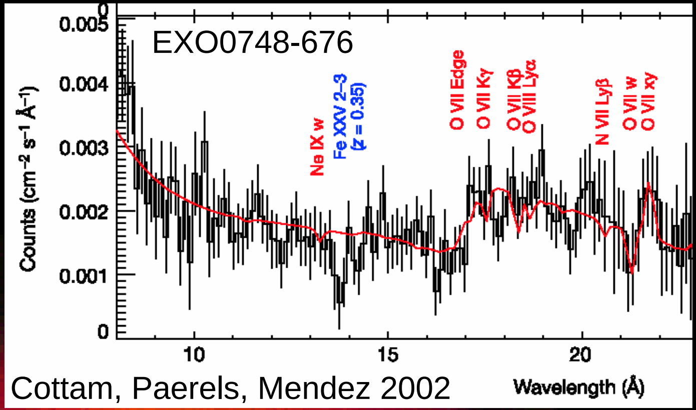


D.A. Smith, M. Muno, A.M. Levine, R. Remillard, H. Bradt 2002 (RXTE All Sky Monitor)

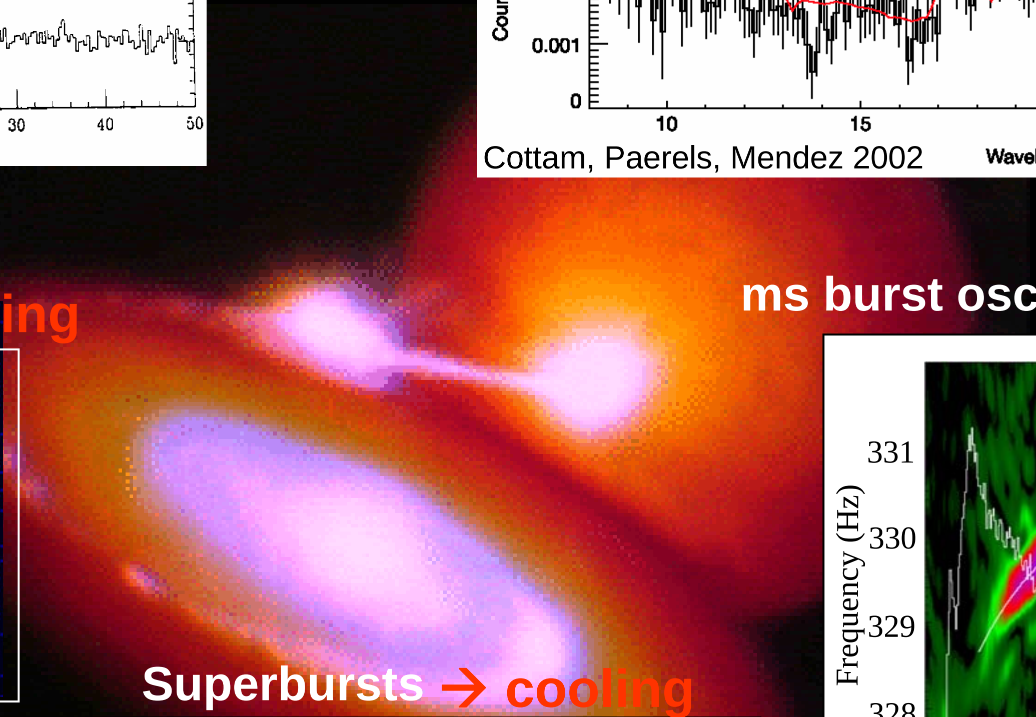
X-ray bursts → cooling



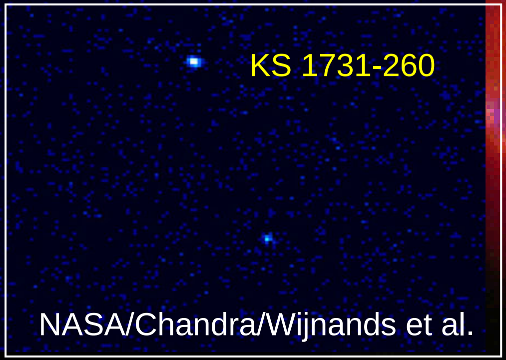
Lines during bursts → M,R



Cottam, Paerels, Mendez 2002

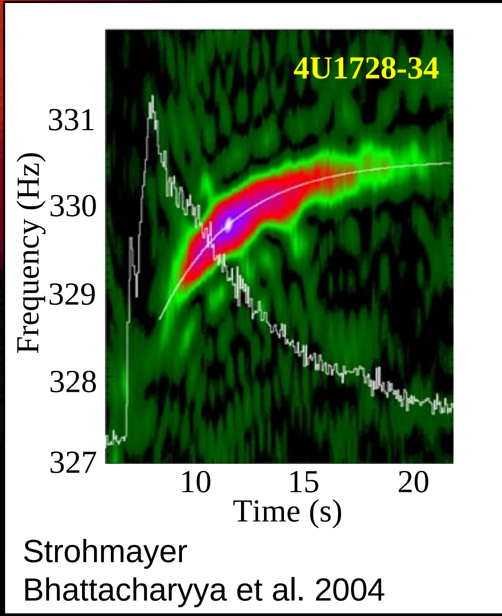


Off-state Lum. → cooling



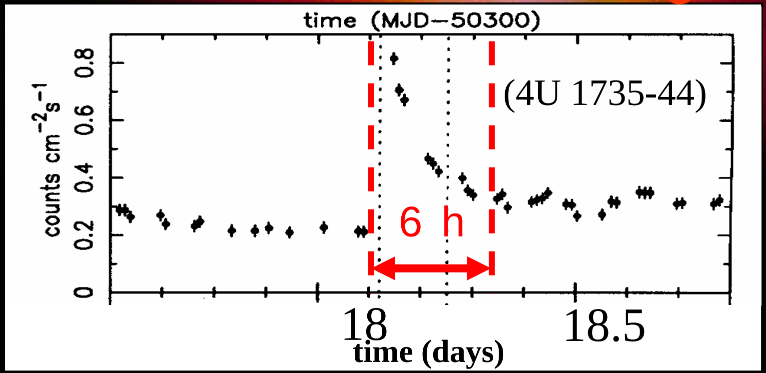
NASA/Chandra/Wijnands et al.

ms burst oscillations → M,R



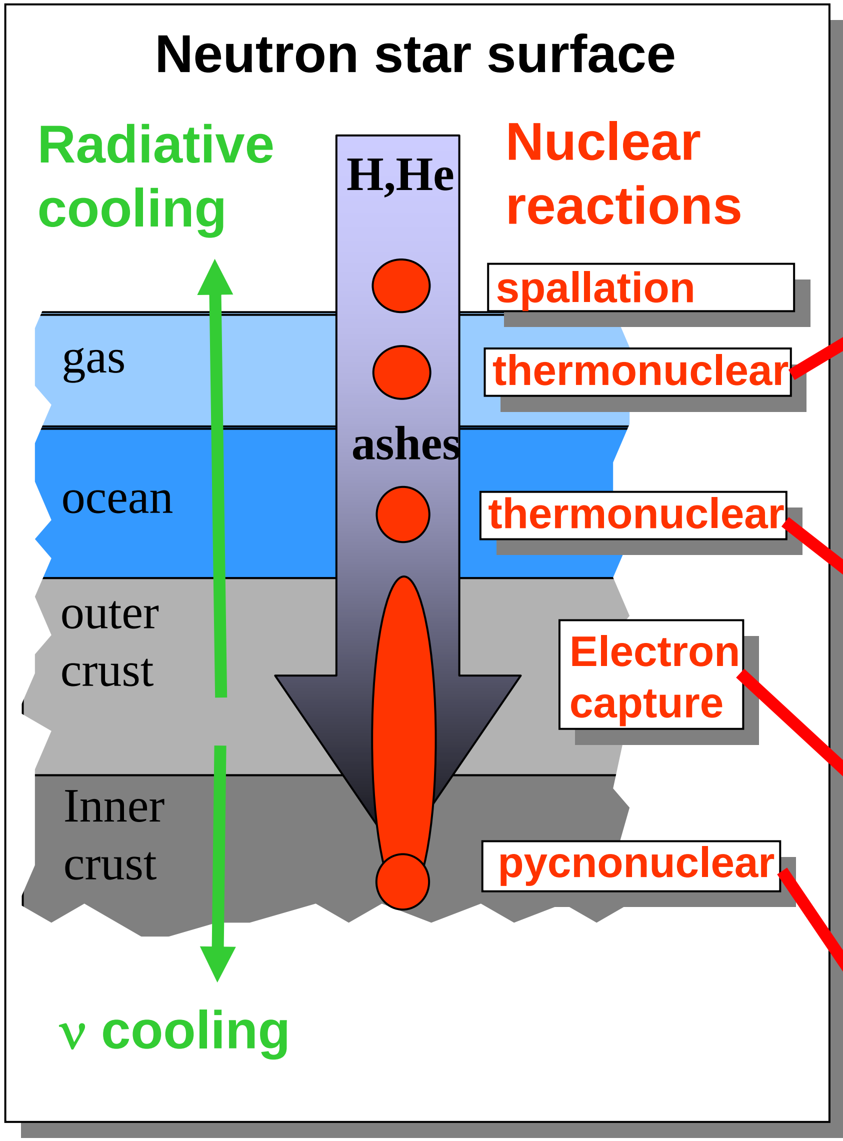
Strohmayer
Bhattacharyya et al. 2004

Superbursts → cooling



Major driver are new observations – “renaissance of X-ray astronomy”

JINA multi-institutional, multidisciplinary effort on X-ray binaries



rp-process experiments
(ANL, Notre Dame, NSCL, …)

Burst modeling, sensitivity studies
(LANL, Notre Dame, NSCL)

Burst physics:

- ejection of material (NSCL, UCSB/KITP)
- sedimentation (Chicago, NSCL)
- pulsations (UCSB/KITP)

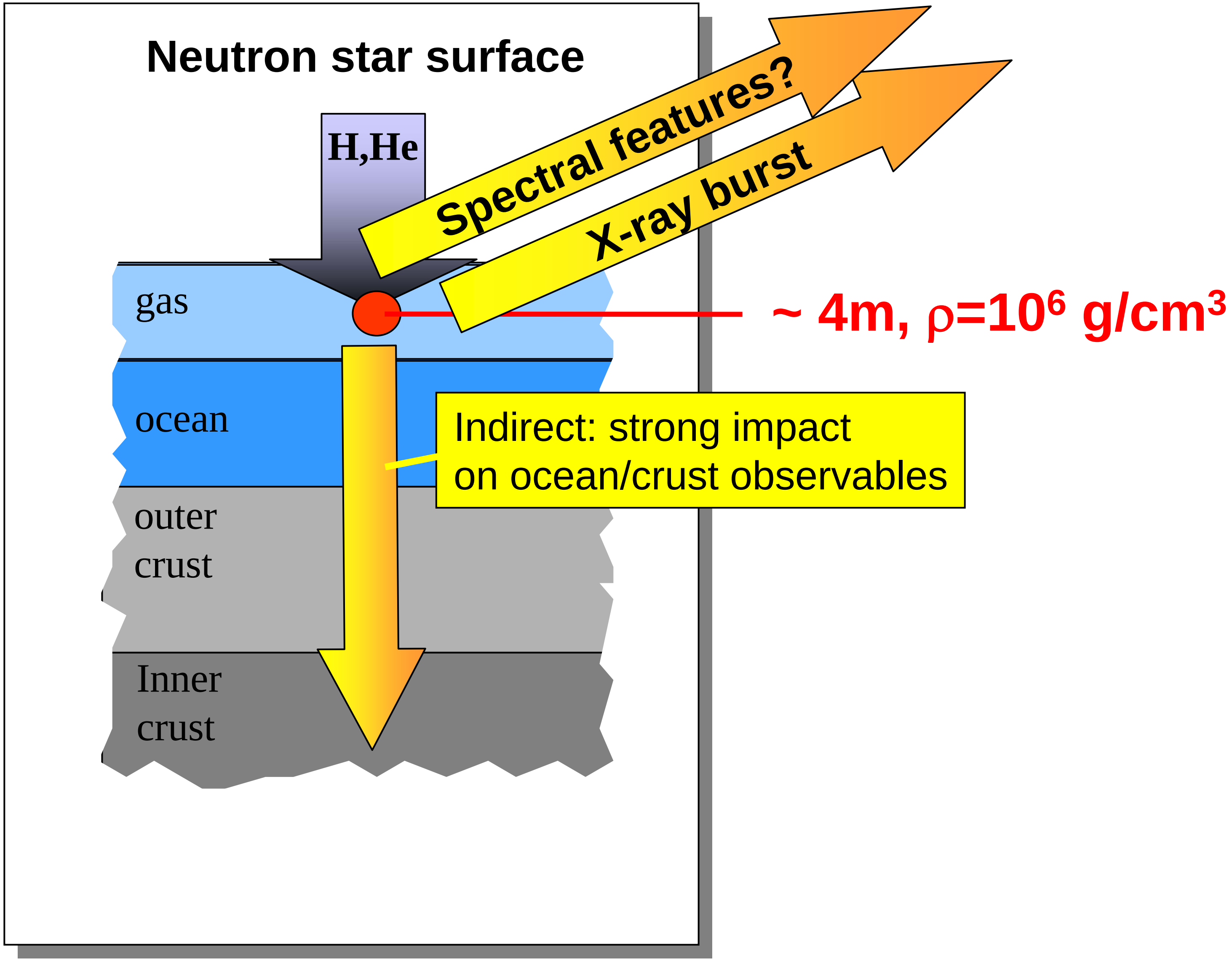
rp-process nuclear theory (NSCL)
Rp-process reaction rate data base

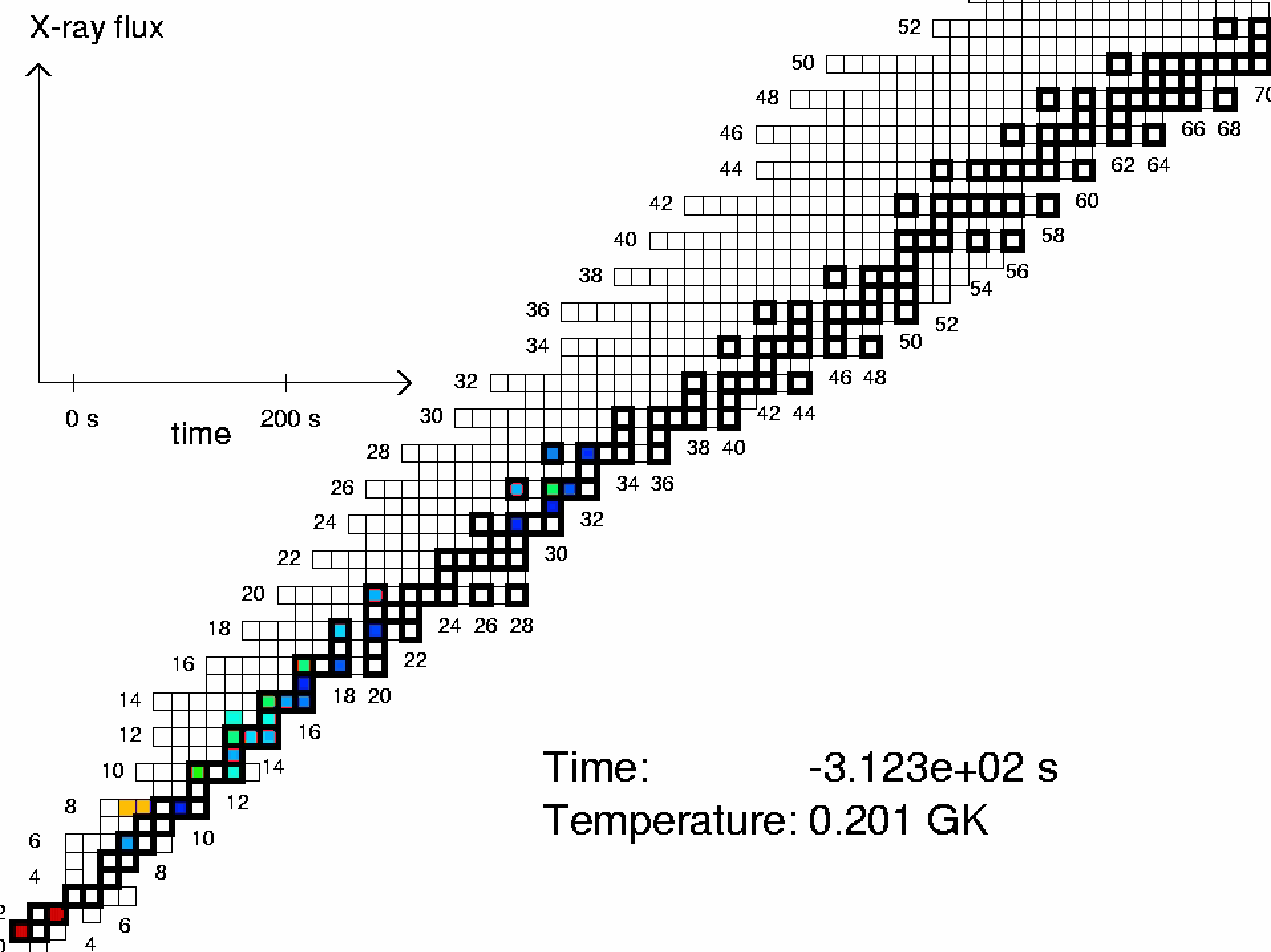
Superburst ignition as probe (NSCL)

Crust experiments (= r-process) (NSCL)
Crust modeling
(LANL, Mainz, ND, NSCL, UCSB/KITP)
EC rates (GSI, LANL, NSCL)

Pycnonuclear fusion (GSI,ND,NSCL)

Step 1: Thermonuclear burning in atmosphere



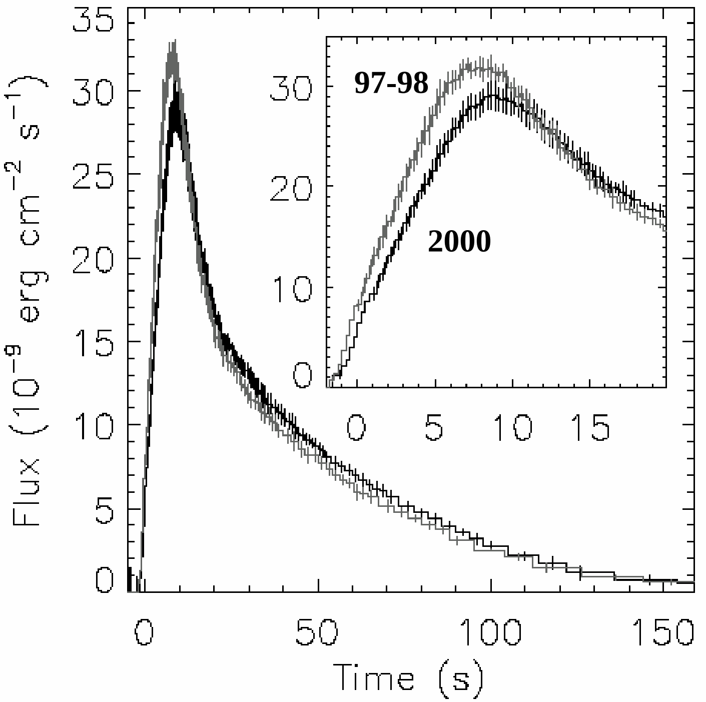


X-ray flux
0 s
time
200 s
Time: -3.123e+02 s
Temperature: 0.201 GK

X-ray burst observations

Precision X-ray observations

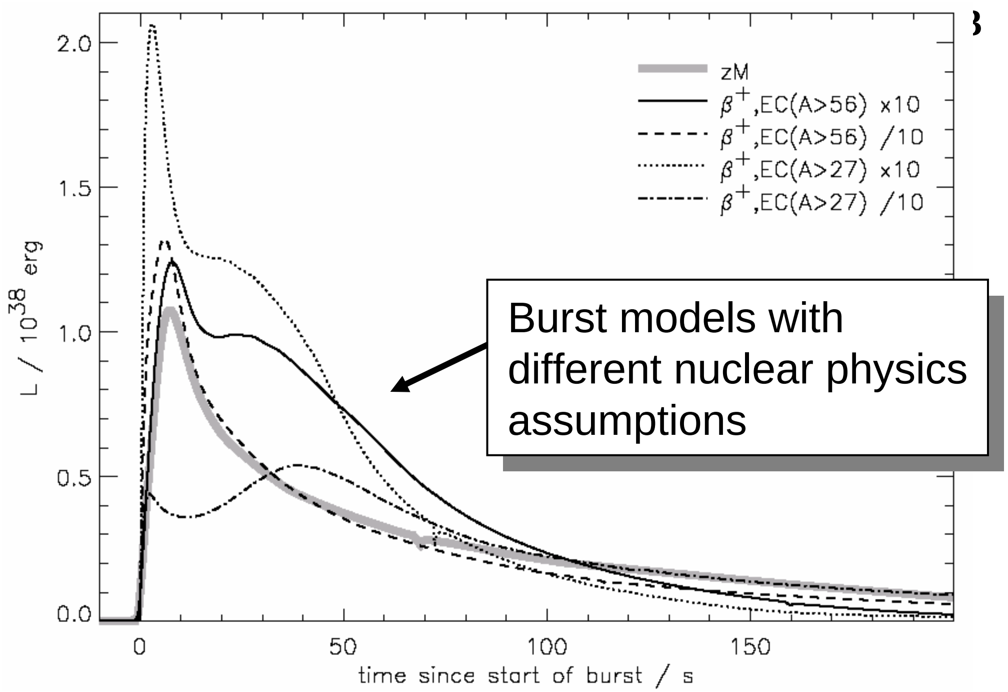
(NASA's RXTE)



→ GS 1826-24 burst shape changes !

(Galloway 2003 astro/ph 0308122)

Uncertain models due to nuclear physics

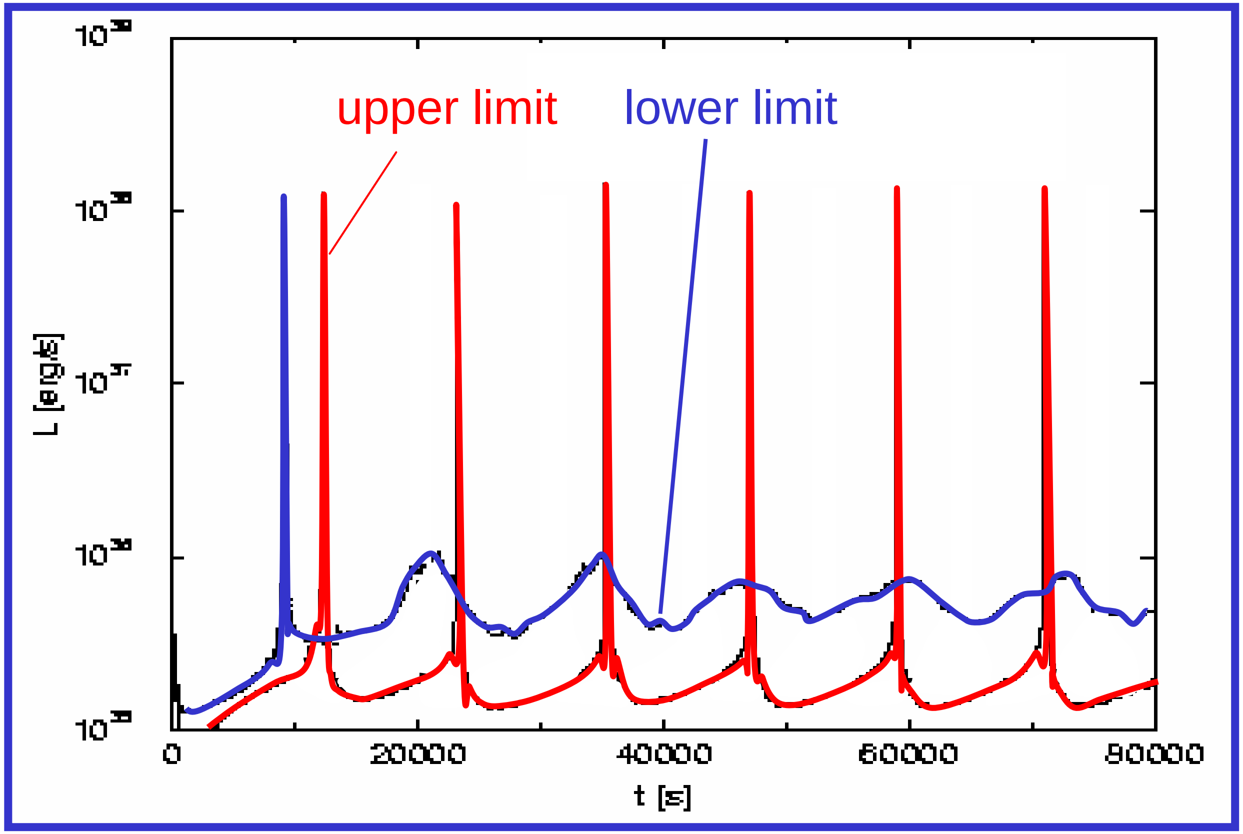


Woosley et al. 2003 astro/ph 0307425

- Need much more precise nuclear data to make full use of high quality observational data

Importance of reaction rates - $^{15}O(\alpha,\gamma)$

X-ray bursting behavior for different $^{15}O(\alpha,\gamma)$ reaction rate



JINA 1-zone X-ray burst model by Fisker et al. 2004

$\Gamma\alpha$ (4.033 MeV state): 345neV – 130 μeV

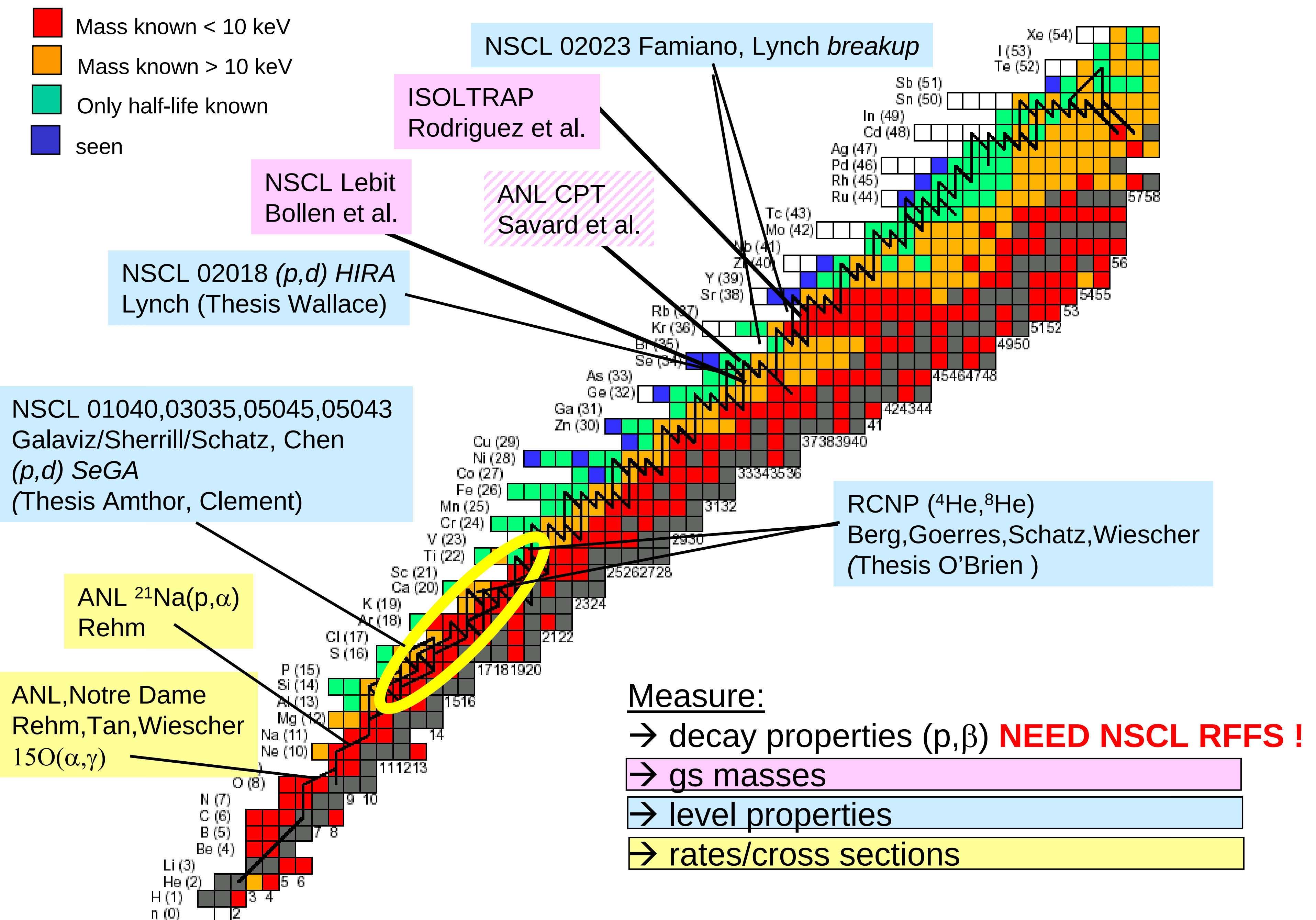
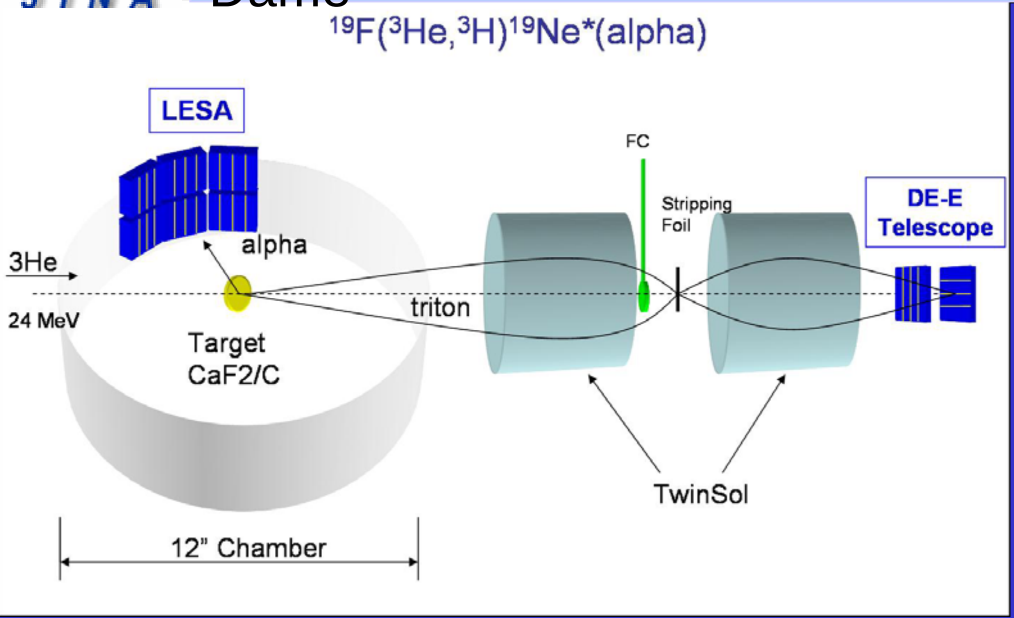


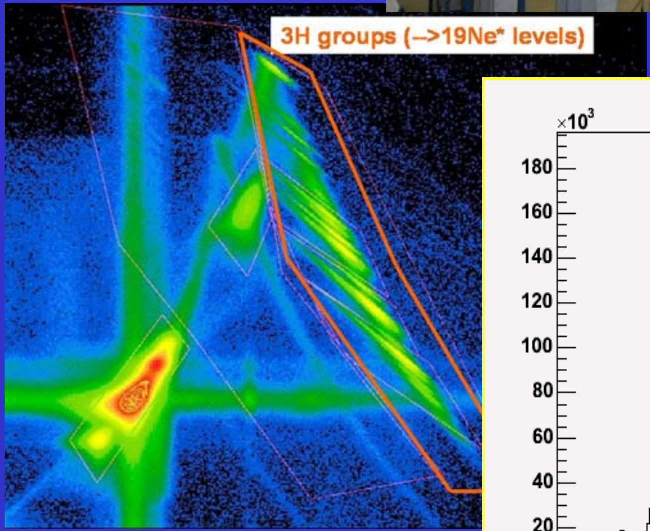
Figure: Schatz&Rehm, Nucl. Phys. A, to be published

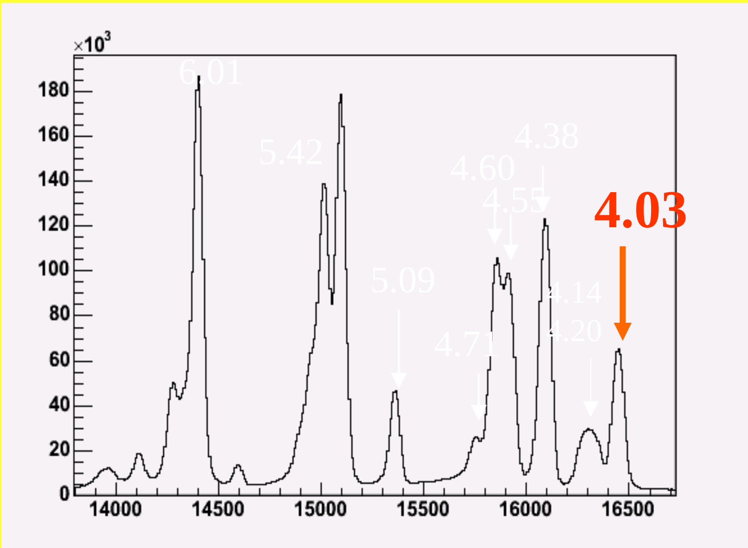
$^{15}O(\alpha,\gamma)$ Γ_α/Γ measurements using LESA and TWINSOL @ Notre Dame



Tan et al.

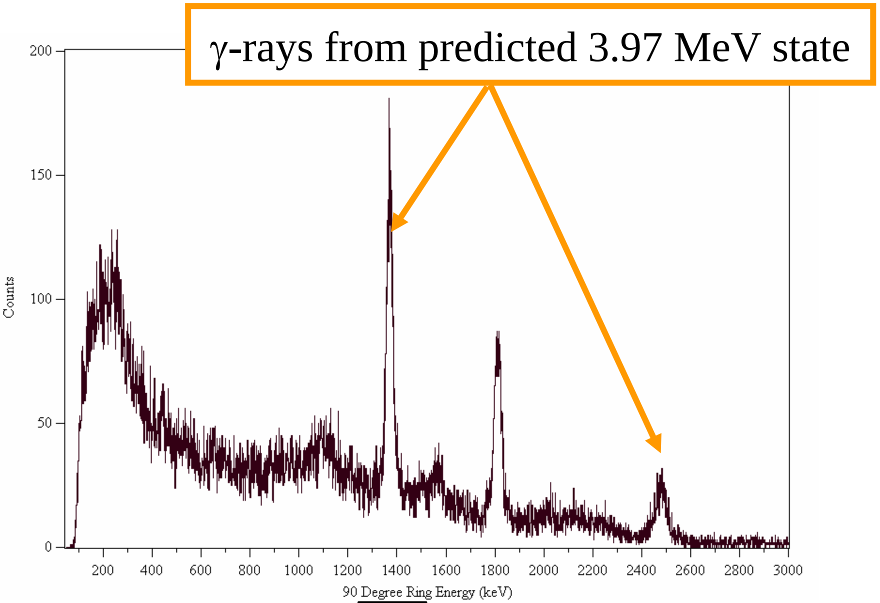
- **Dominant 4.03-MeV level**
  - **JINA ND: $\Gamma=51\pm^{43}_{21}$ meV**
  - **$\Gamma_\alpha/\Gamma<4.3\times10^{-4}$ by Davids et al, PRC2003**
- **Large statistics ensure the sensitivity of $\Gamma_\alpha/\Gamma\sim10^{-4}$**
- **~1,000,000 events recorded for the 4.03-MeV state**
- **Preliminary result:**
  $\Gamma_\alpha/\Gamma=(2.9 \pm 2.1)\times10^{-4}$





NSCL Experiments: New ^{32}Cl(p,g)^{33}Ar rate

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



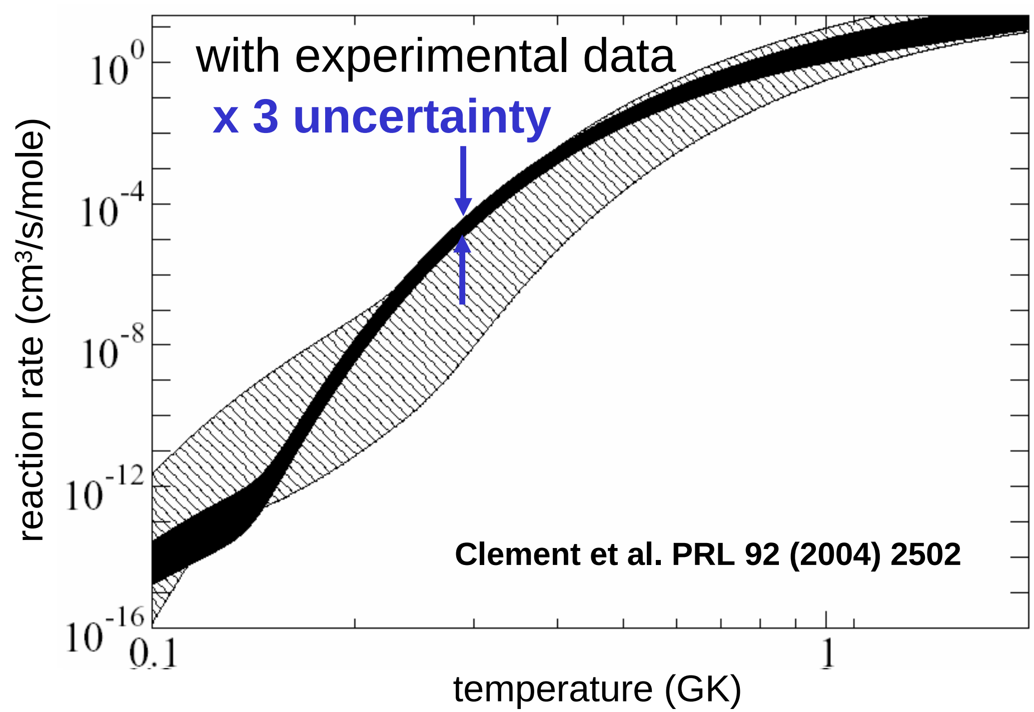
^{33}Ar level energies measured:

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

JINA faculty:
Sherrill, Schatz
Thesis: R.R.C. Clement

Use ^{34}Ar(p,d)^{33}Ar* → ^{33}Ar + γ

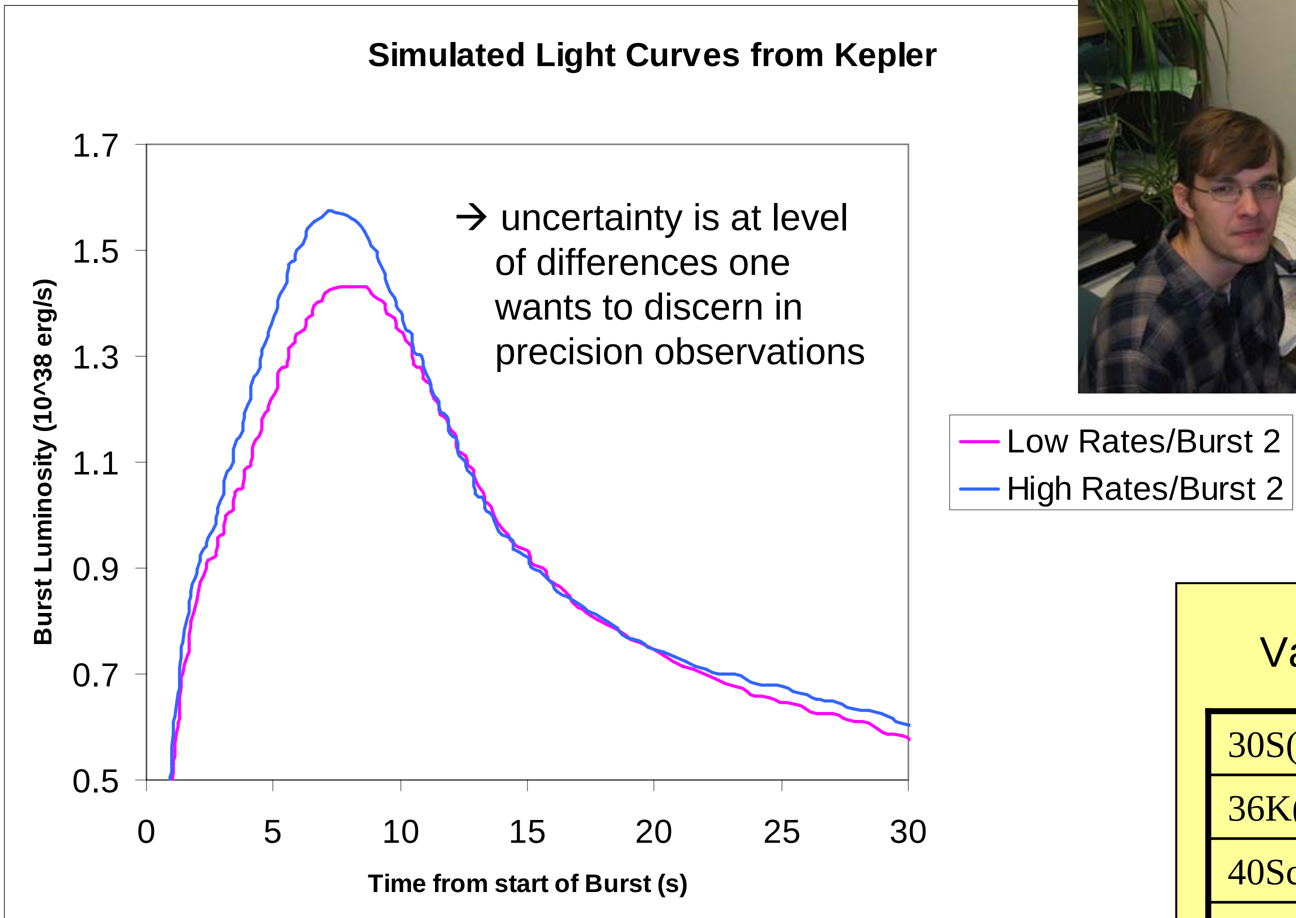
stellar reaction rate



- sometimes only choice (here !)
- first major step for accurate rates
- guide direct measurements if needed
  - reliable analysis of important rates
  - location of resonances

JINA Grad Student project: X-ray burst sensitivity to reaction rates

Summer research project of graduate student Matt Amthor at LANL (A. Heger) prior to his NSCL thesis experiment to determine rp-process reaction rates



Vary by factor 100

30S(p,g)*	31Cl
36K(p,g)**	37Ca
40Sc(p,g)	41Ti
46Cr(p,g)	47Mn

M. Amthor, A. Heger, H. Schatz, B. Sherrill

Theoretical burst projects– connecting nuclear physics and astrophysics

Abundance signatures – non solar O/Ne ratios towards some XRBs

- Ejection of burst ashes into space (UCSB,MSU) **Weinberg et al. Ap.J. 639 (2006) 1018**

Discovery of a spectral line – what does it tell us about the NS ?

- Spectral line formation and lineshape for EXO 0748-676 and beyond (UCSB) **Chang et al. ApJ 636 (2006) 117, Chang et al. ApJ 629 (2005) 998**

Origin of burst oscillations

- Burst oscillations due to surface modes (UCSB)

Piro & Bildsten ApJ 619 (2005)1063, Apj 629(2005)438, ApJ638(2006)968

Burst behavior as a function of parameters (accretion rate, …)

- Sedimentation (MSU,Chicago) **Brown,Peng@Truran ApJ, submitted**

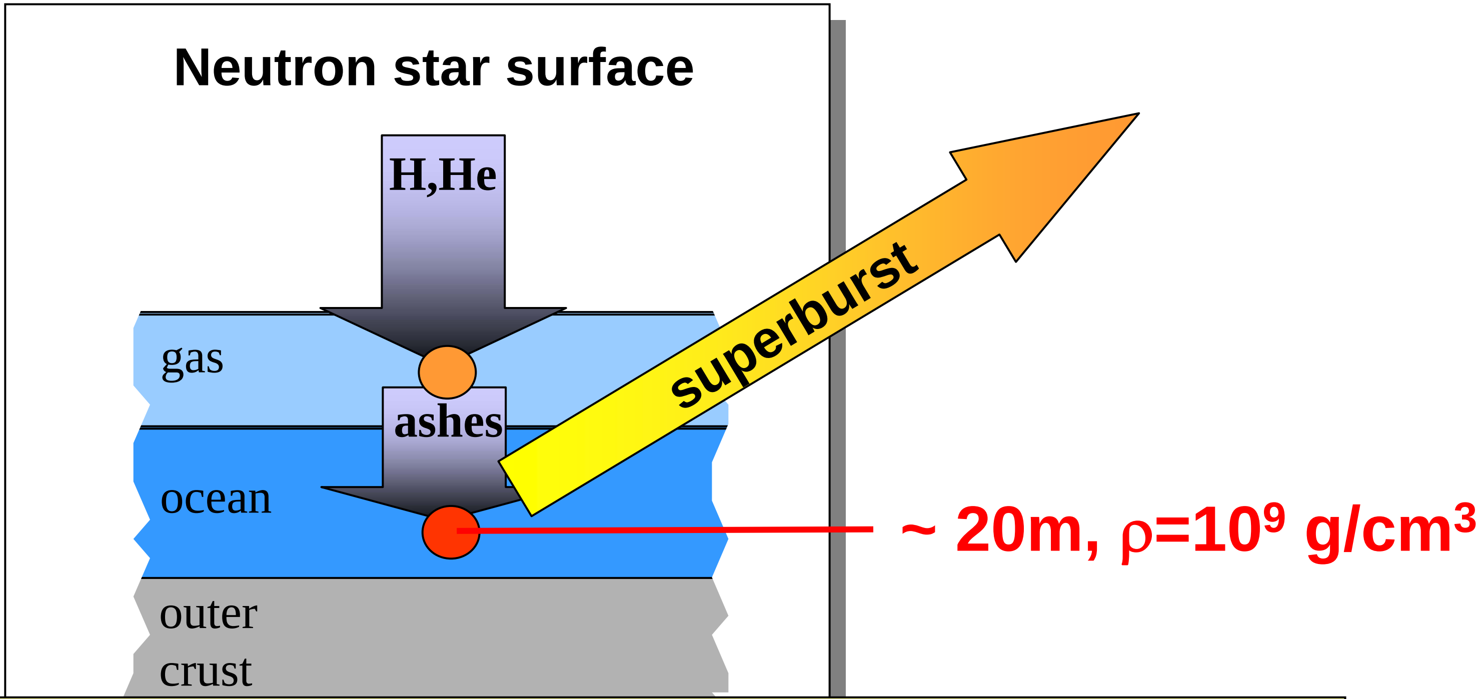
→ JINA grad. Student Peng visited LANL summer 2006 to implement sedimentation in Kepler code

- 1D Burst modeling: Sensitivity and systematic behavior (ND,MSU,LANL)

Multi-D simulation of accretion flows

- Initially for white dwarfs (ND) **Fisker&Balsara ApJ635(2005)69**

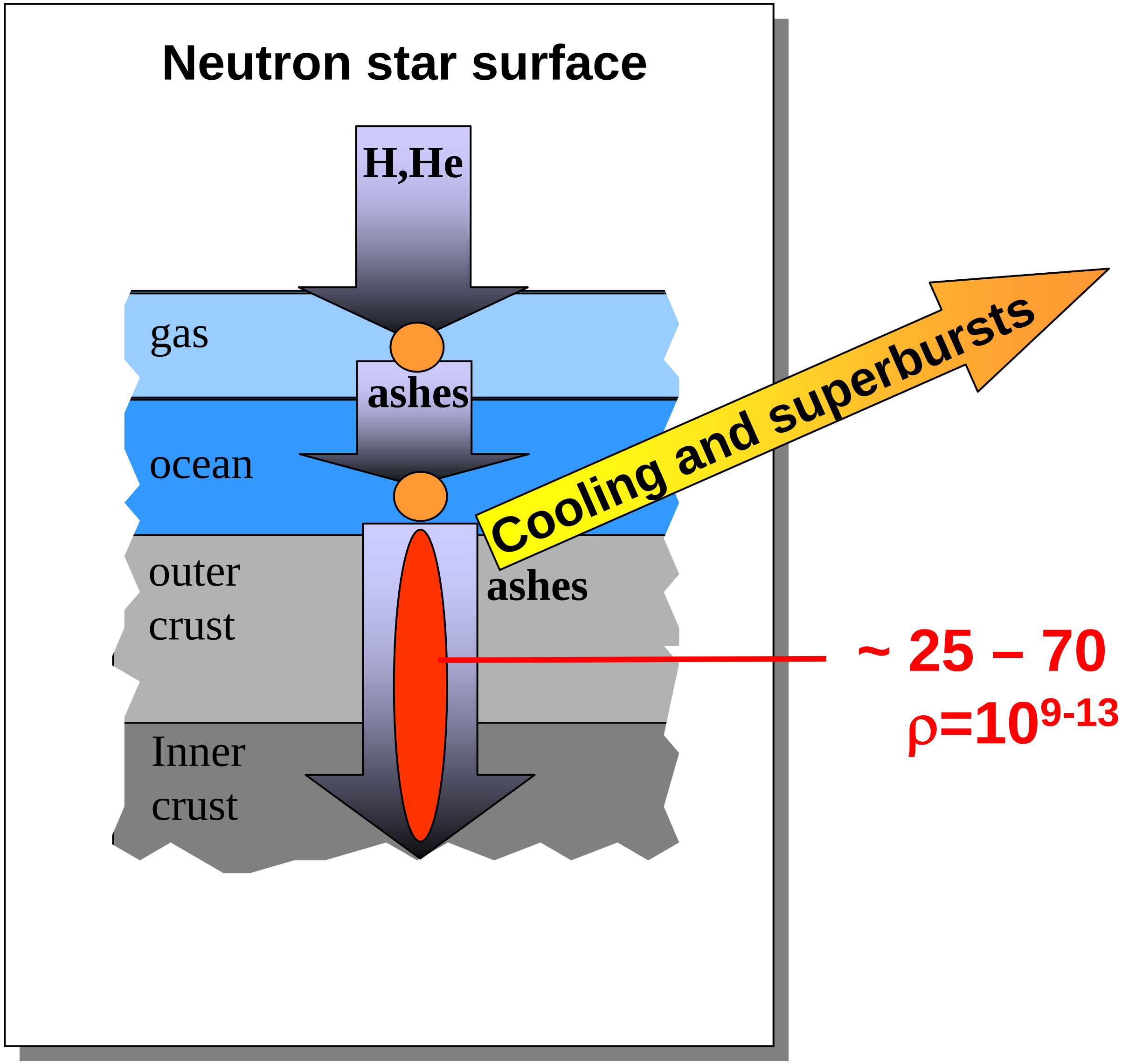
Step 2: Deep ocean burning: Superbursts



Superbursts

- Superbursts as probe for NS cooling (Brown 2005)
  → PROBLEM: recurrence times too long
  Strange matter stars ? (Page & Cumming 2005)
  Or deep heating underestimated ?

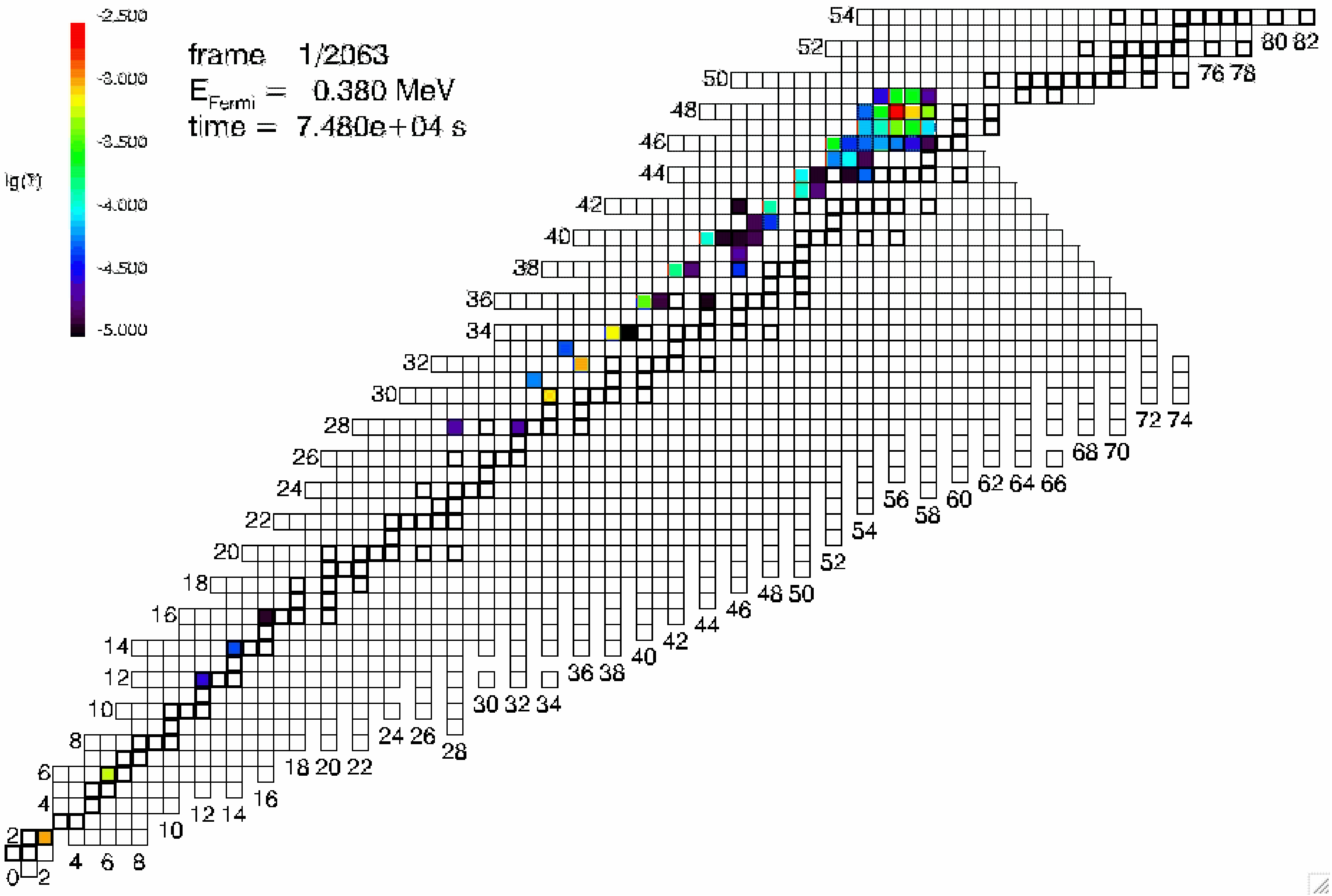
Crust burning



~ 25 – 70 m

ρ=10$^{9\text{-}13}$ g/cm^3

Preliminary results: crust processes (calculation by JINA postdoc S. Gupta)



How does this process continue at greater depth ?

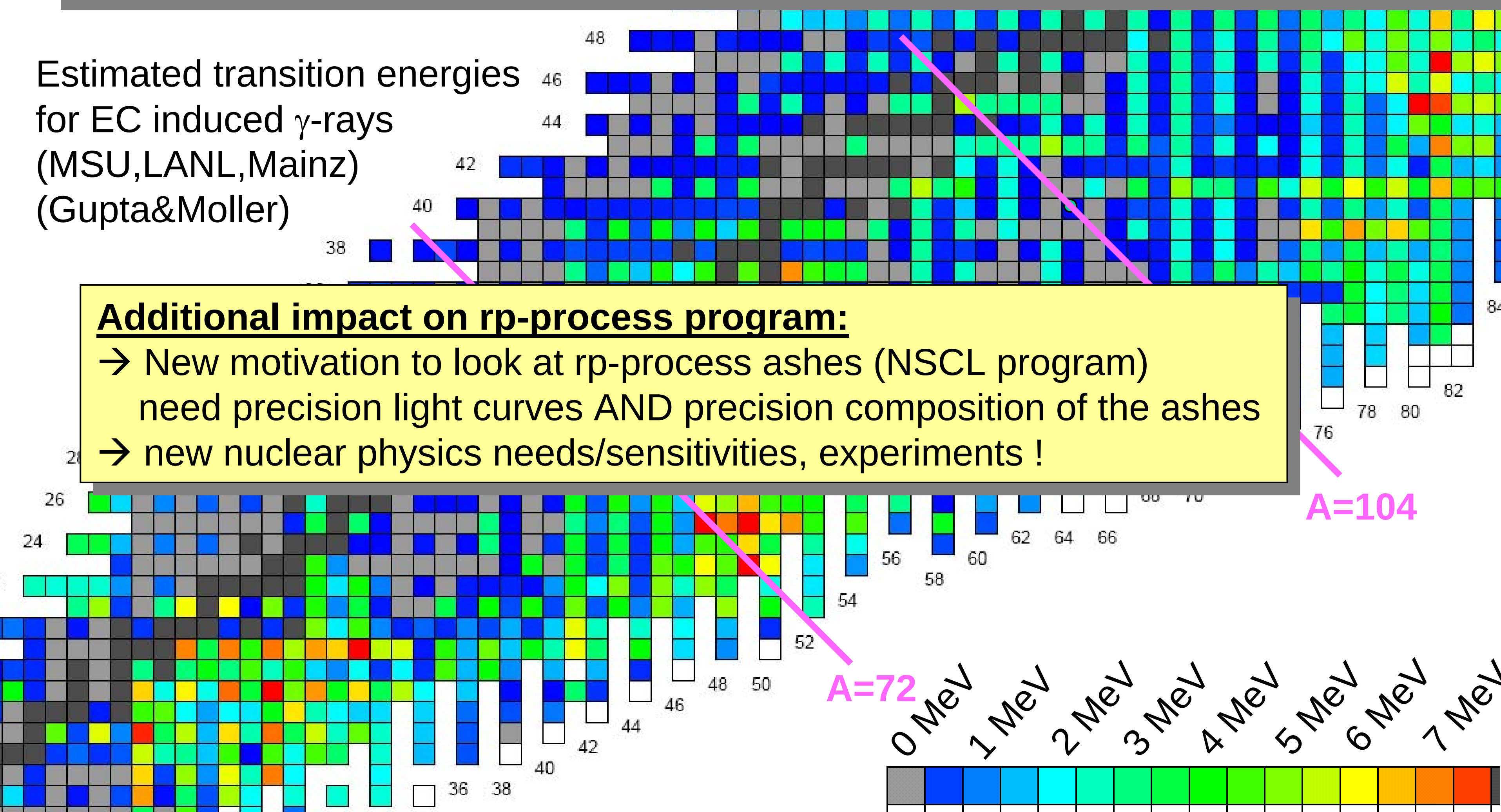
→ Pycnonuclear fusion ? (rates calculated by ND group)

Connection to astrophysics: JINA neutron star crust project

→ New processes identified, more heat released – solution to problem ???

→ Masses and excitation energies determine heat release
possibly within reach at NSCL → experimental program

Estimated transition energies for EC induced γ-rays
(MSU,LANL,Mainz)
(Gupta&Moller)



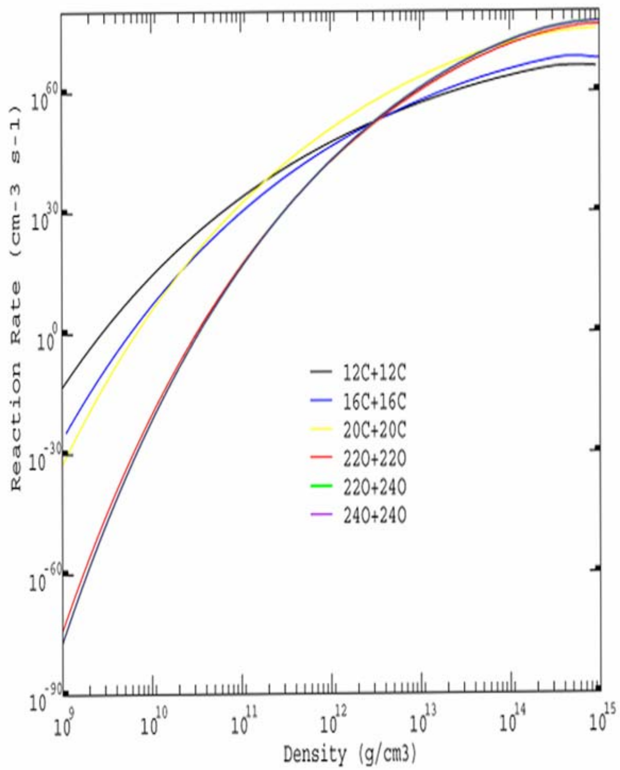
Additional impact on rp-process program:

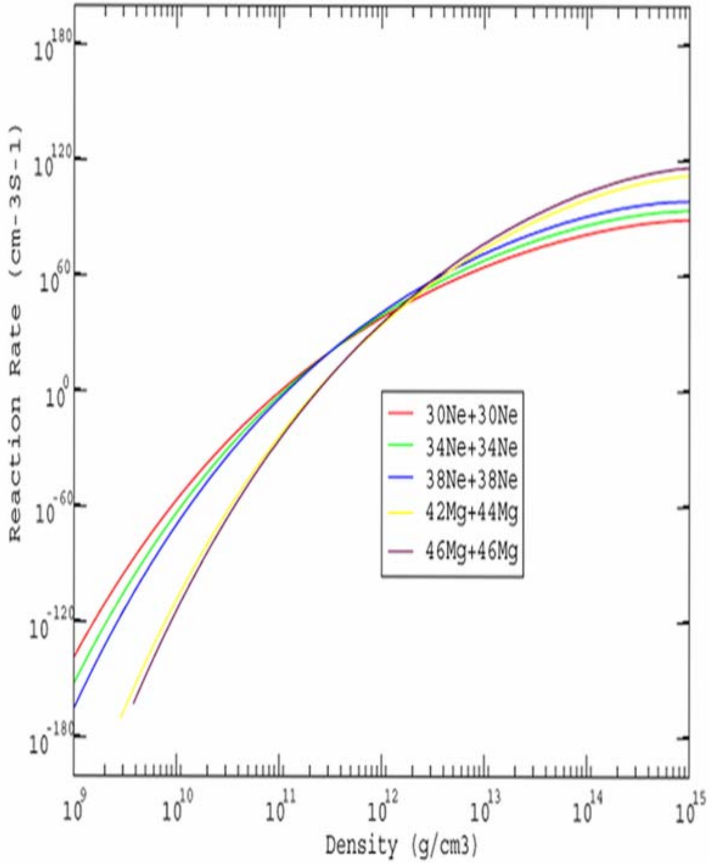
→ New motivation to look at rp-process ashes (NSCL program)
need precision light curves AND precision composition of the ashes

→ new nuclear physics needs/sensitivities, experiments !

Pycnonuclear fusion reaction rates

M. Beard, L. Gasques, M. Wiescher, D. Yakovlev (Notre Dame/St. Petersburg)





The rates involving isotopes with identical charge number show only minor differences which are entirely due to the difference in S-factor;

For higher Z-values the rates decrease steeply at density values less than 10^{12} g/cm^3 because of the strong Z-dependence in the pycno equation.

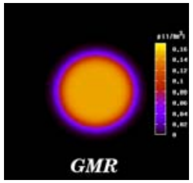
MRC3 focused workshops

Nuclear physics and astrophysics of accreting neutron stars, April 23-24, 2004, Santa Babara, CA

"Overall, I found this one of the most stimulating workshops I have been to. In that sense, the ACP workshop that we are now planning is a spin-off from that ITP workshop." comment by Alex Heger

Symposium on Nuclear EOS used in astrophysical models
Philadelphia, August 25-26, 2004

Workshop on Classical Novae and Type Ia Supernovae May 20-22, 2005, Santa Babara, CA



Workshop on Nuclear Incompressibility
University of Notre Dame
July 14-15, 2005

In Heaven and on Earth 2006 – the Nuclear EOS in Astrophysics Montreal, July 5-7, 2006

Planned: Aspen workshop on the physics of accreting neutron stars

Summary

- Recent observations have revealed many new phenomena
  → unique opportunities to understand these systems
  → and learn about neutron stars in unique environment

- Wide range of nuclear physics needed to understand accreting neutron stars
  - exotic nuclei from p-drip to n-drip
  - EOS

- Concerted effort of wide range of JINA institutions and groups
  → towards a complete model of neutron star crust processes

- Major progress in theory and experiment already

- Immediate JINA Goals:
  → identify underlying nuclear physics (new processes possible)
  → predict new observables for range of system parameters
  → explore sensitivity of observables to nuclear physics
  → understand and interpret observations