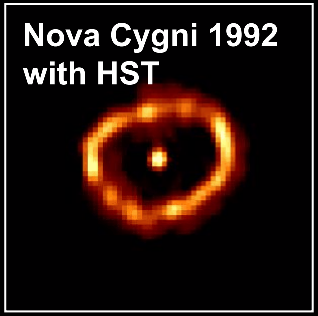
MRC 3

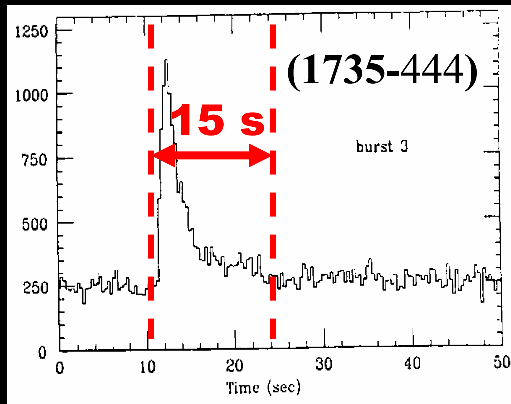
spokesperson: H. Schatz

X-ray binaries
Equation of State

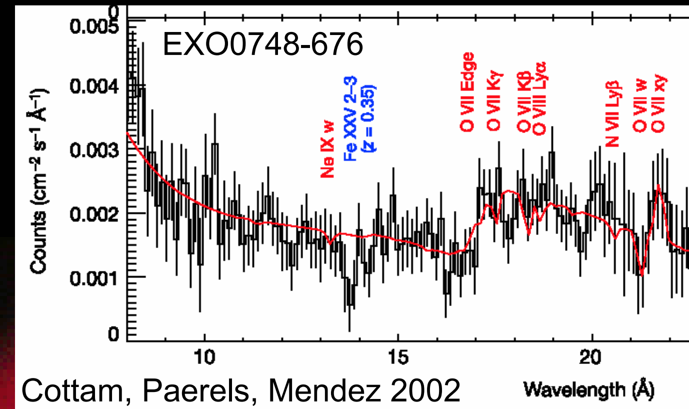


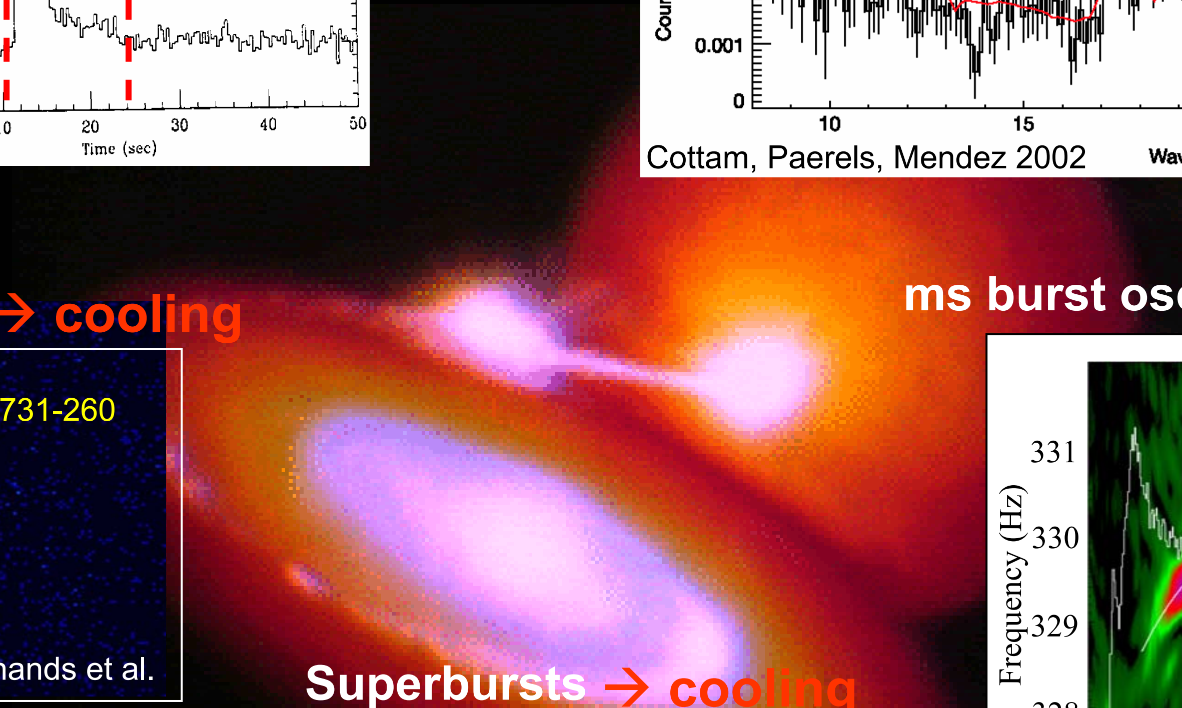
Novae

X-ray bursts → cooling



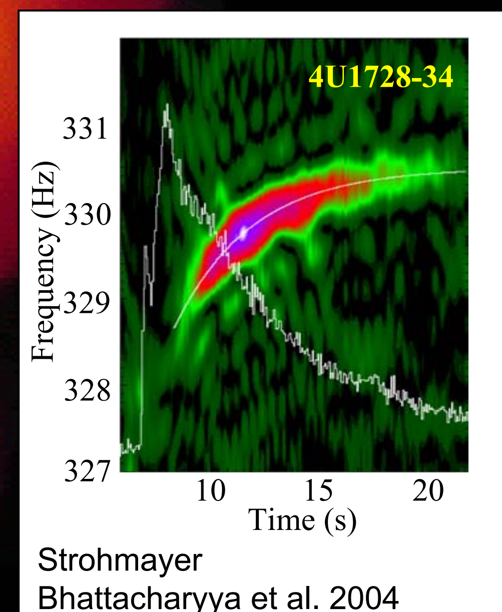
Lines during bursts → M,R



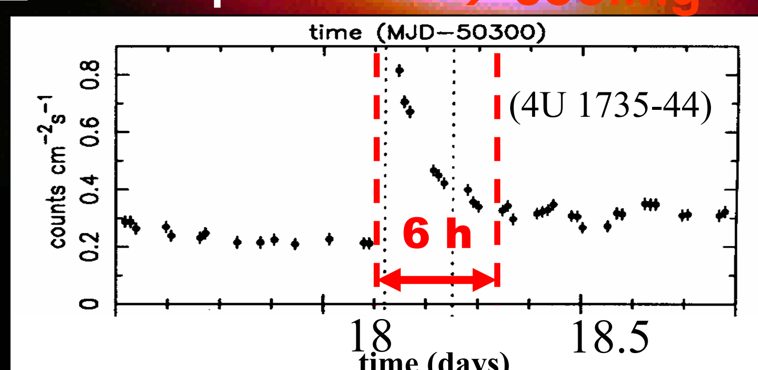


Off-state Lum. → cooling

ms burst oscillations → M,R

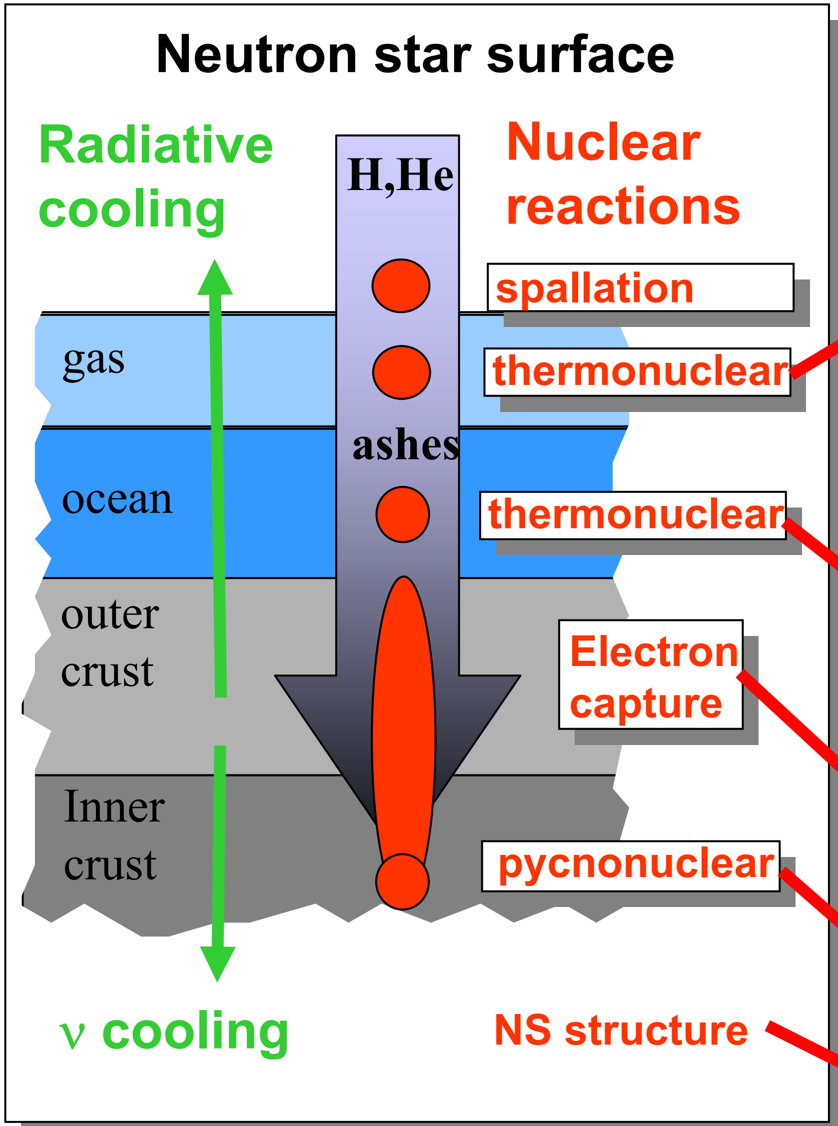


Superbursts → cooling



Major driver are new observations – "golden era of X-ray astronomy"

JINA X-ray binary program



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)

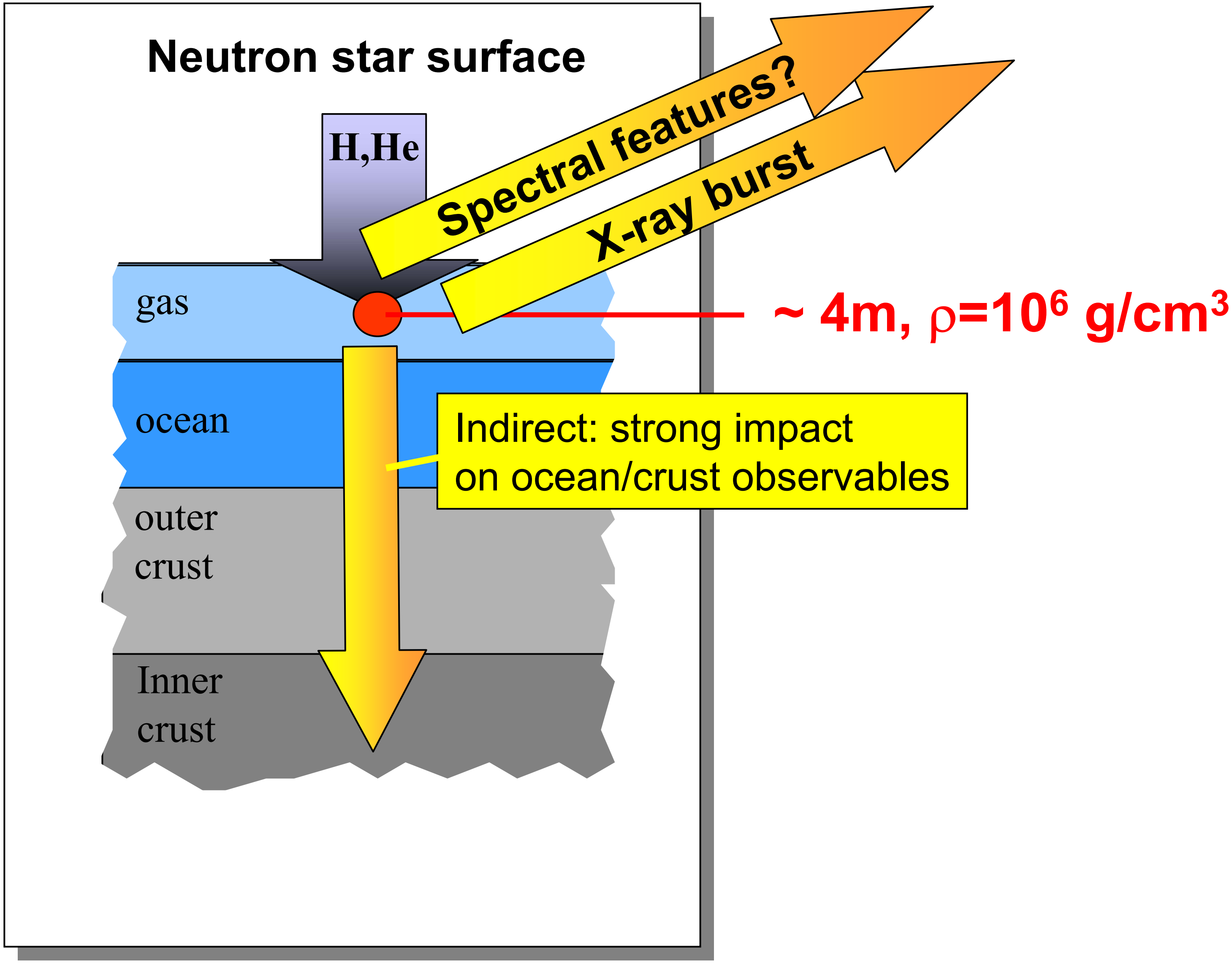
Superburst ignition as probe (NSCL)

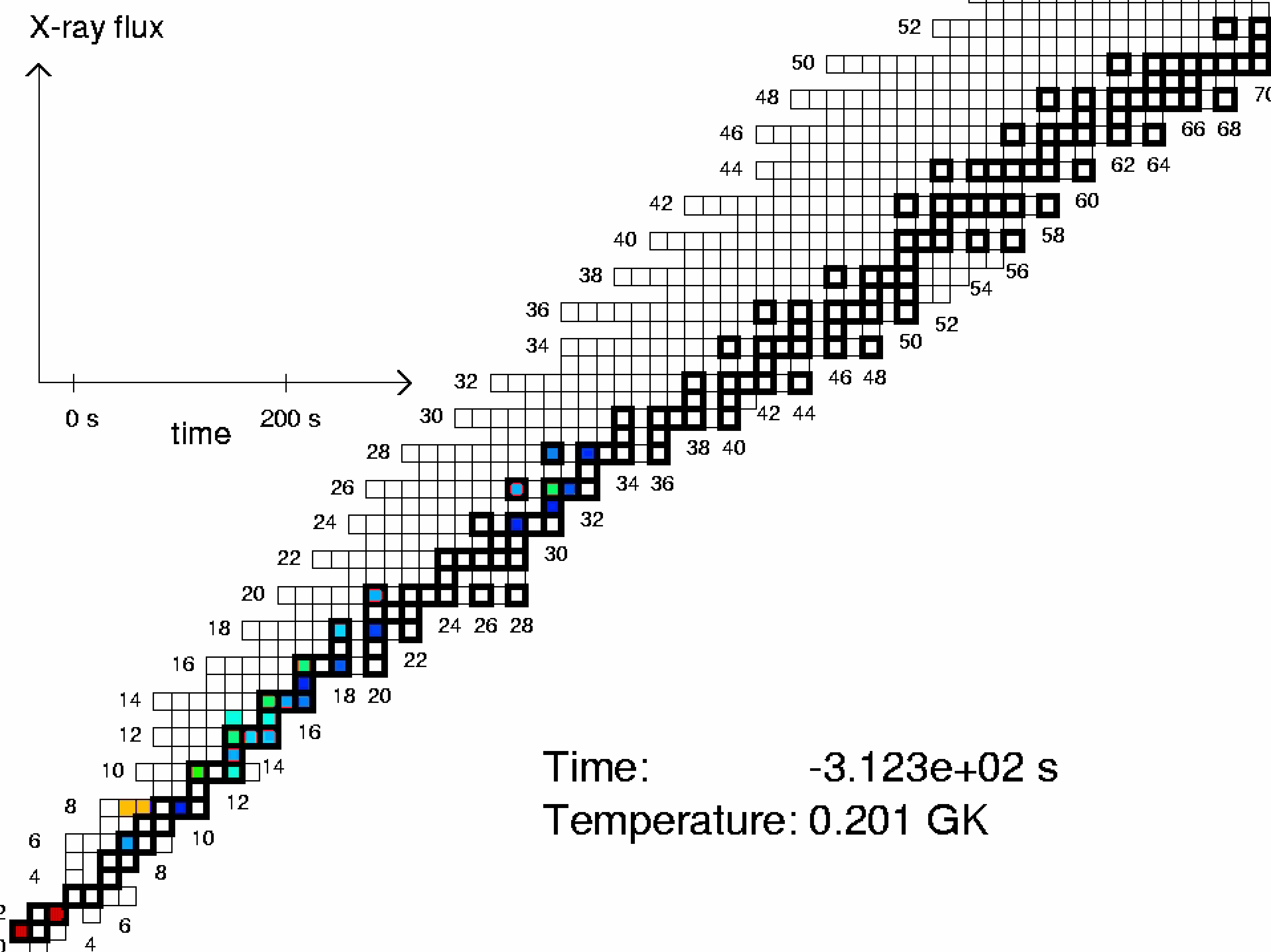
Crust experiments (= r-process) (NSCL)
Crust modeling
(LANL, Mainz, ND, NSCL, UCSB/KITP)
EC rates (GSI, LANL, NSCL)

Pycnonuclear fusion (GSI,ND,NSCL)

Nuclear matter EOS (NSCL, WMU)

Step 1: Thermonuclear burning in atmosphere



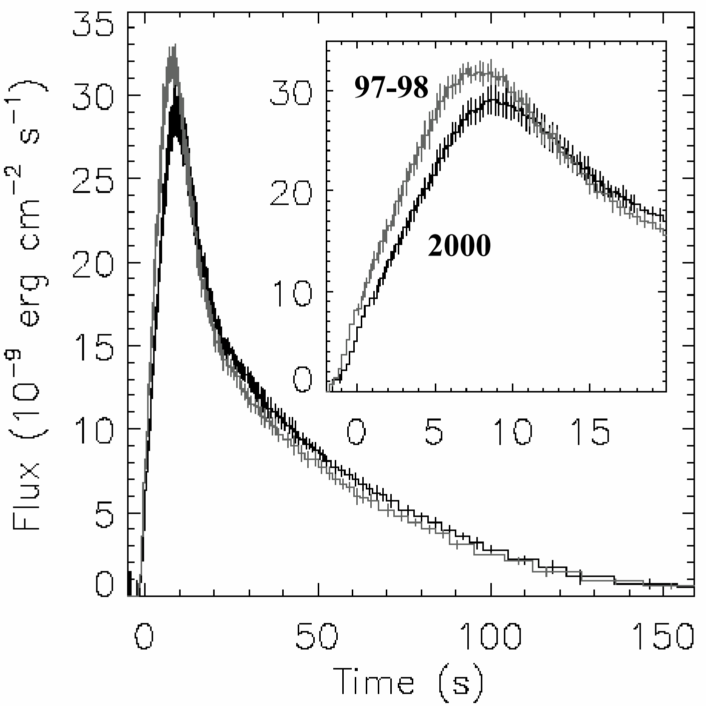


X-ray flux
0 s
time
200 s
Time: -3.123e+02 s
Temperature: 0.201 GK

Interpreting observations: light curve

Precision X-ray observations

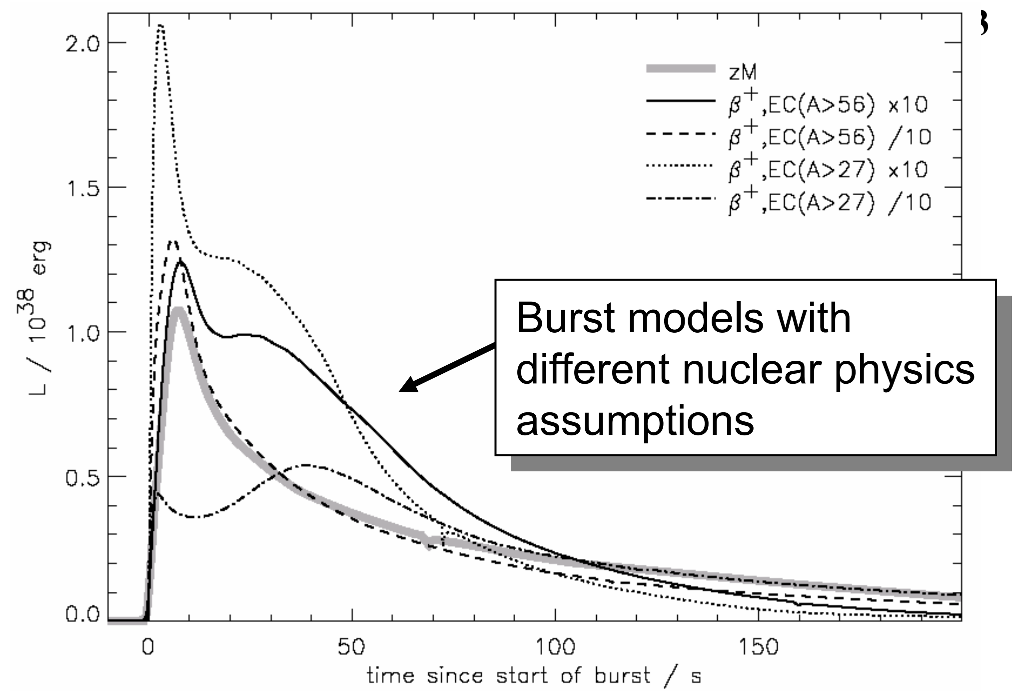
(NASA's RXTE)



→ 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

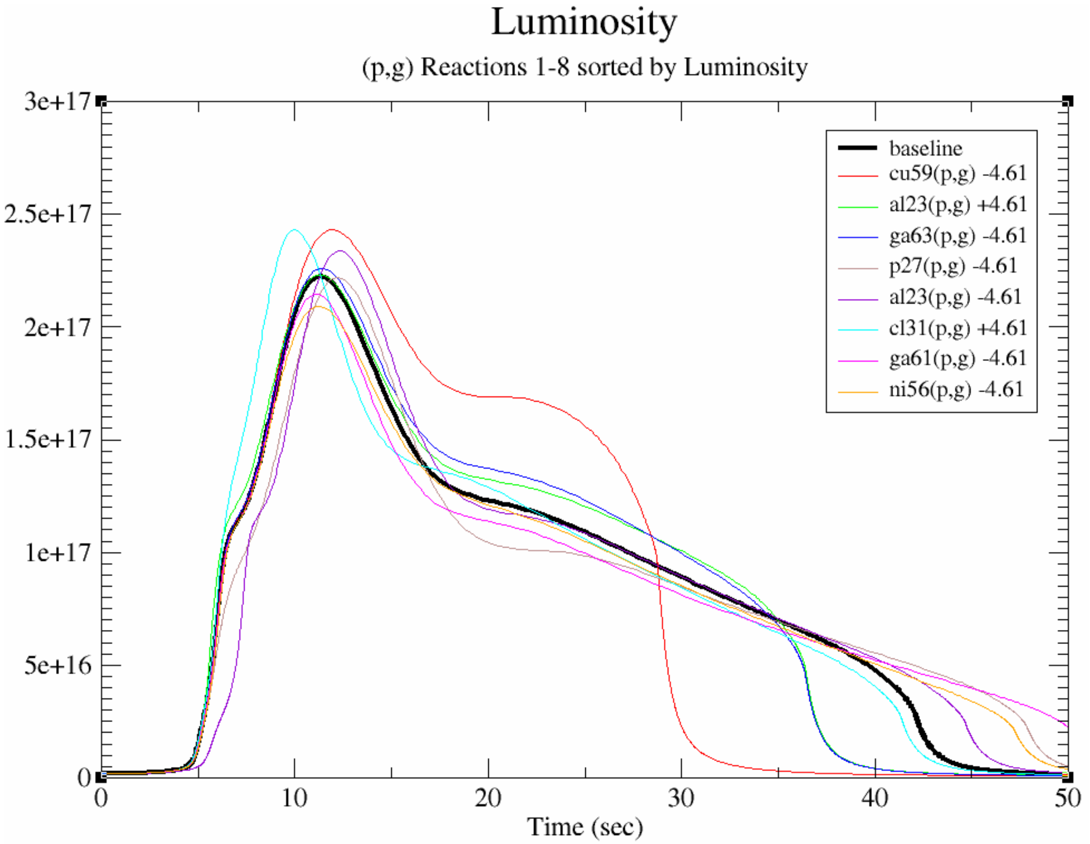
Sensitivity studies: JURA undergraduate/high school student project

- Emily Johnson (Undergraduate, REU)
- Jared Dunmon (High School:2007 Intel Talent Search Semi-finalist with JINA project
- Karl Smith (Undergraduate)

Method:

1. Calibrate fast 1-zone model with full 1D code
2. Vary all reaction rates by fixed amount
3. Identify candidates for key rates
4. Estimate realistic errors
5. Rerun with 1-zone and 1D codes

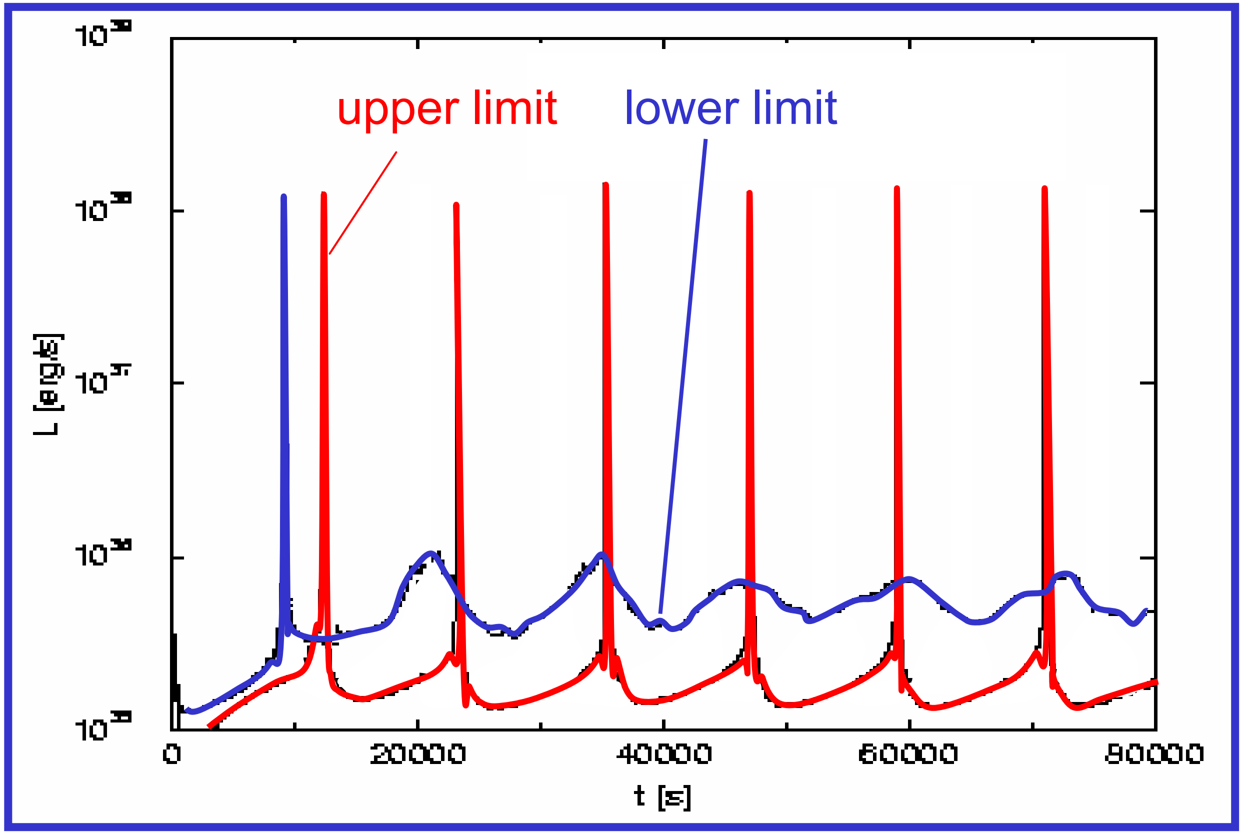
→ NSCL proposals in prep.



Collaboration with M. Amthor (MSU), A. Heger (LANL), H. Schatz (MSU)

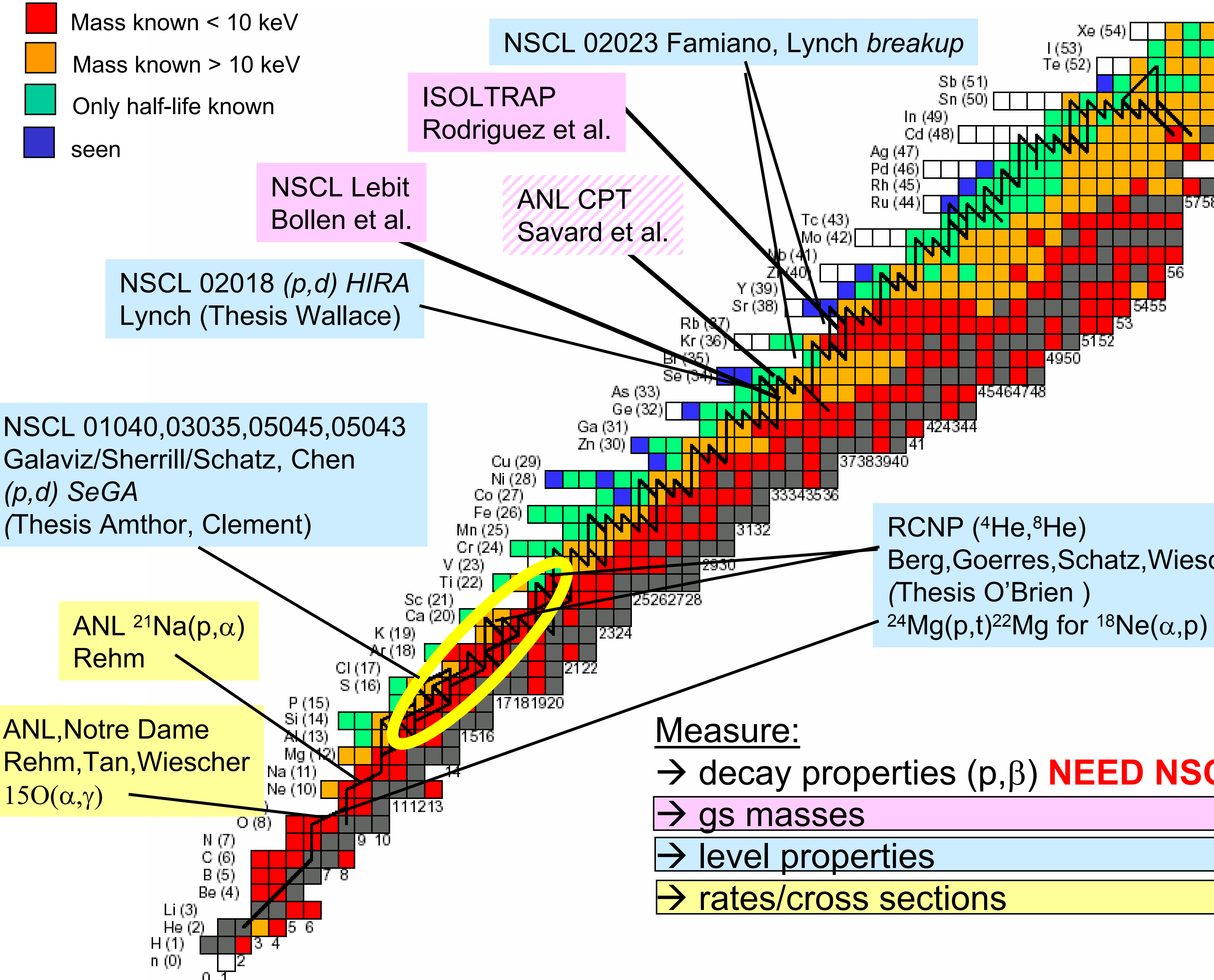
Interpreting observations: burst behavior and $^{15}O(\alpha,\gamma)$

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



Fisker et al. 2004

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



NSCL 02023 Famiano, Lynch *breakup*

ISOLTRAP
Rodriguez et al.

NSCL Lebit
Bollen et al.

ANL CPT
Savard et al.

NSCL 02018 *(p,d) HIRA*
Lynch (Thesis Wallace)

NSCL 01040,03035,05045,05043
Galaviz/Sherrill/Schatz, Chen
(p,d) SeGA
(Thesis Amthor, Clement)

RCNP (^{4}He,^{8}He)
Berg,Goerres,Schatz,Wiescher
(Thesis O'Brien)
^{24}Mg(p,t)^{22}Mg for ^{18}Ne(α,p)

ANL ^{21}Na(p,α)
Rehm

ANL,Notre Dame
Rehm,Tan,Wiescher
15O(α,γ)

Measure:

→ decay properties (p,β) **NEED NSCL RFFS !**

→ gs masses

→ level properties

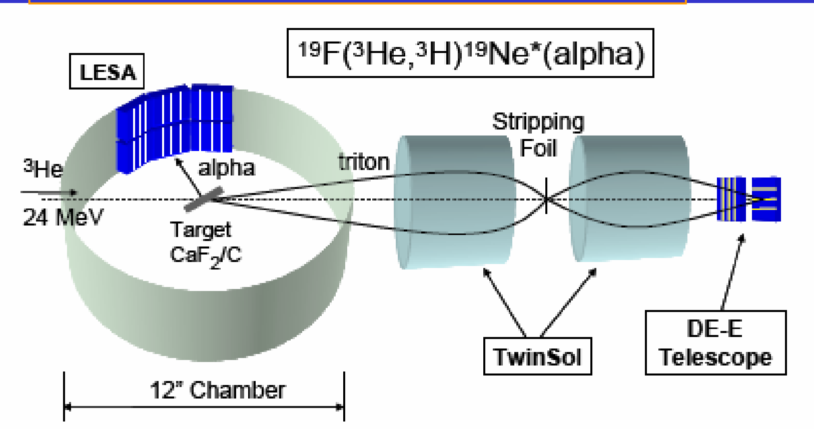
→ rates/cross sections

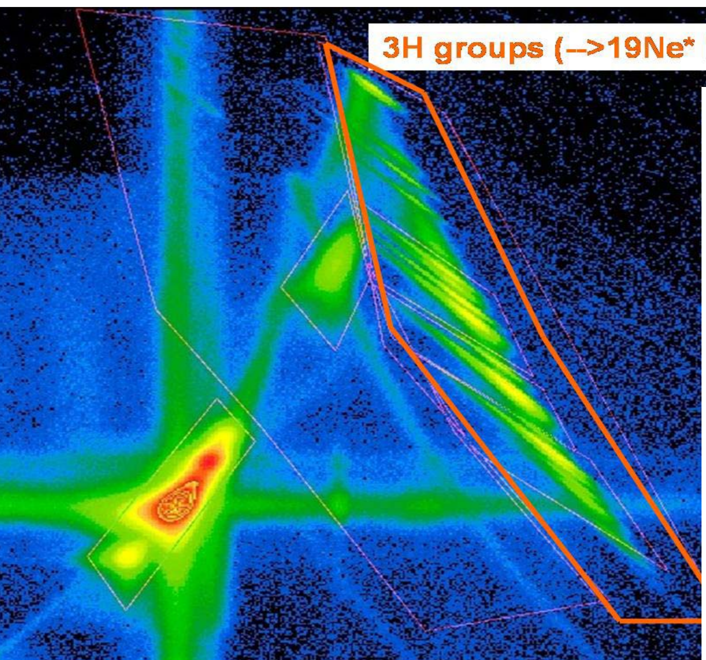
Figure: Schatz&Rehm, Nucl. Phys. A, to be published

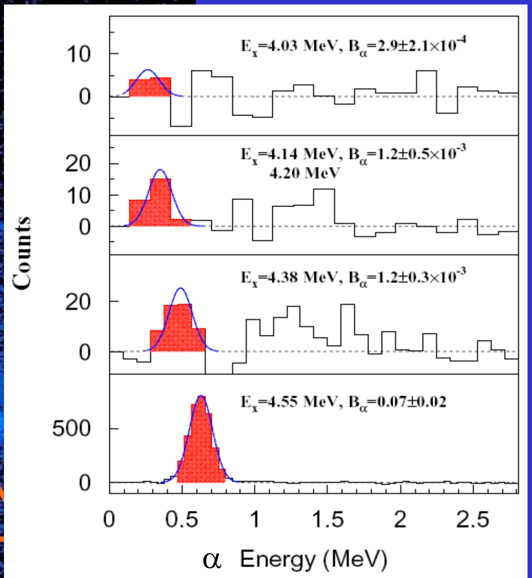
$^{15}O(\alpha,\gamma)$ Γ_α/Γ and Γ measurements @ ND

Tan et al., submitted to Phys. Rev. Lett.

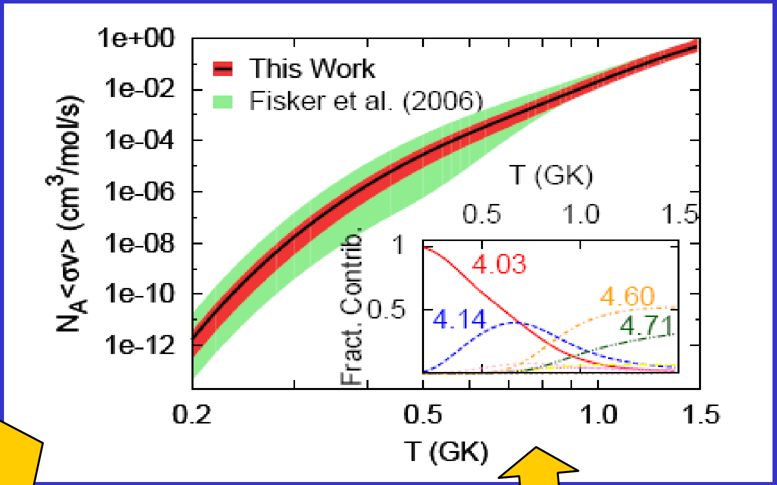
α−decay branching ratios' measurement



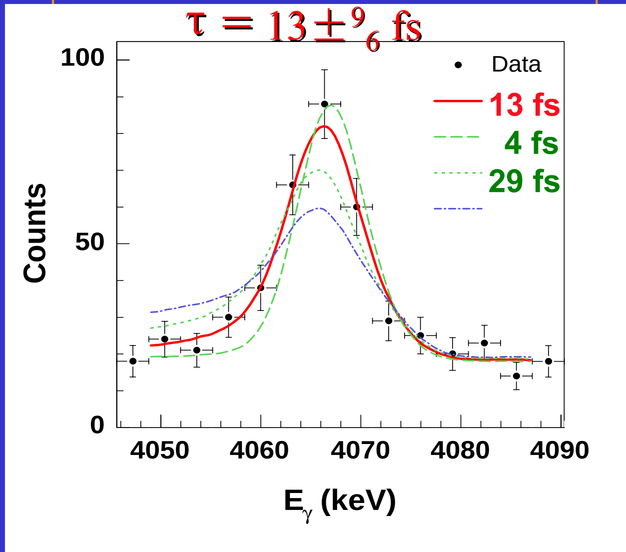




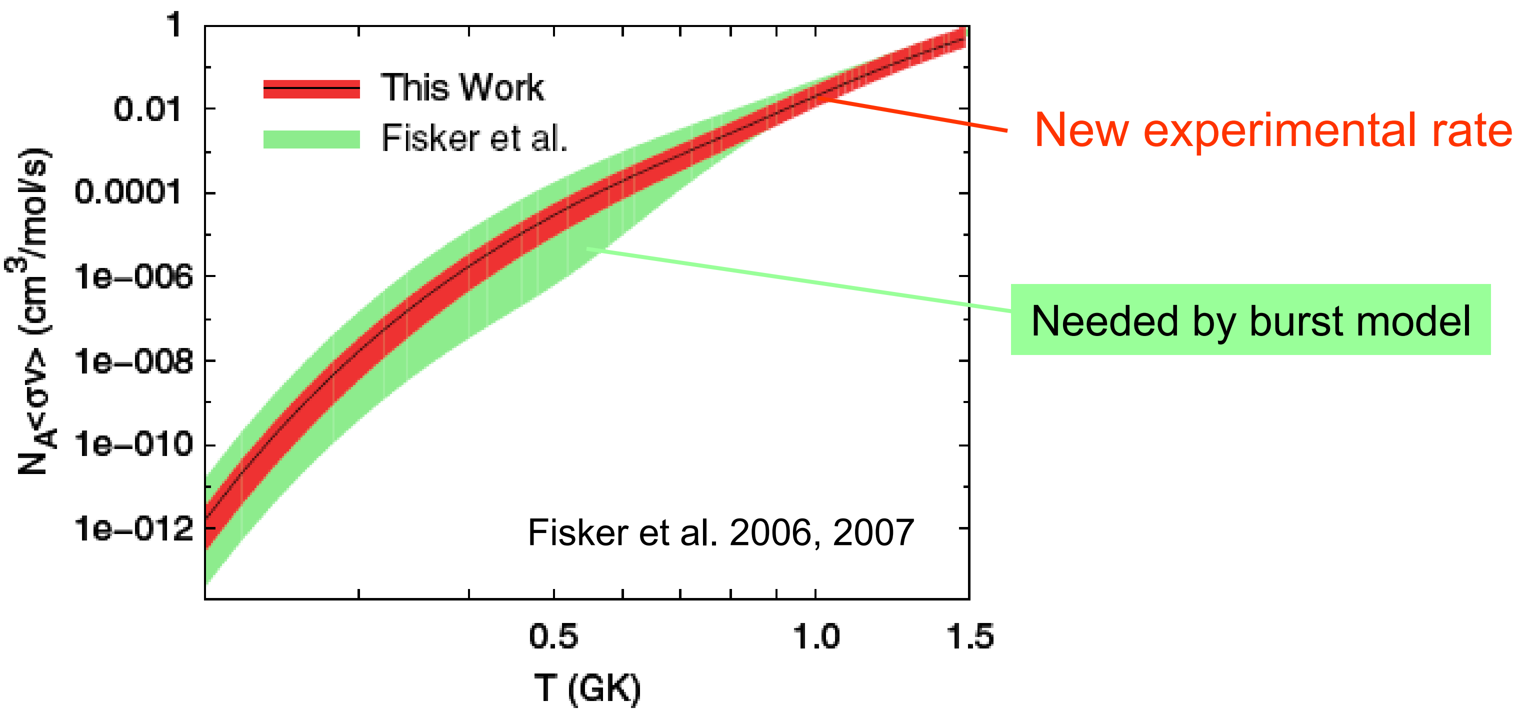
New Rate



Lifetimes' measurement by Tan et al., Phys.Rev. C 2005



Interpreting observations: burst behavior and $^{15}O(\alpha,\gamma)$



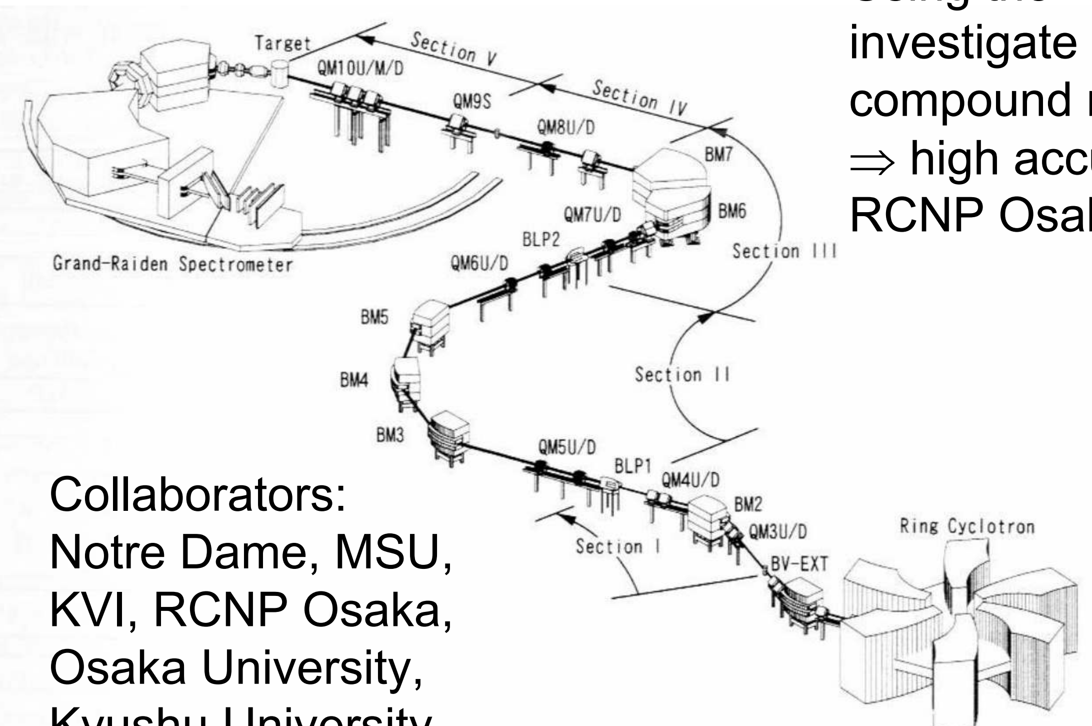
- first experimental determination of $^{15}O(\alpha,\gamma)$ reaction rate
- experimental rate within the range required to produce bursts in model
- much more precise determination of transition to stable burning – at 1.7 M_{Edd}

BUT

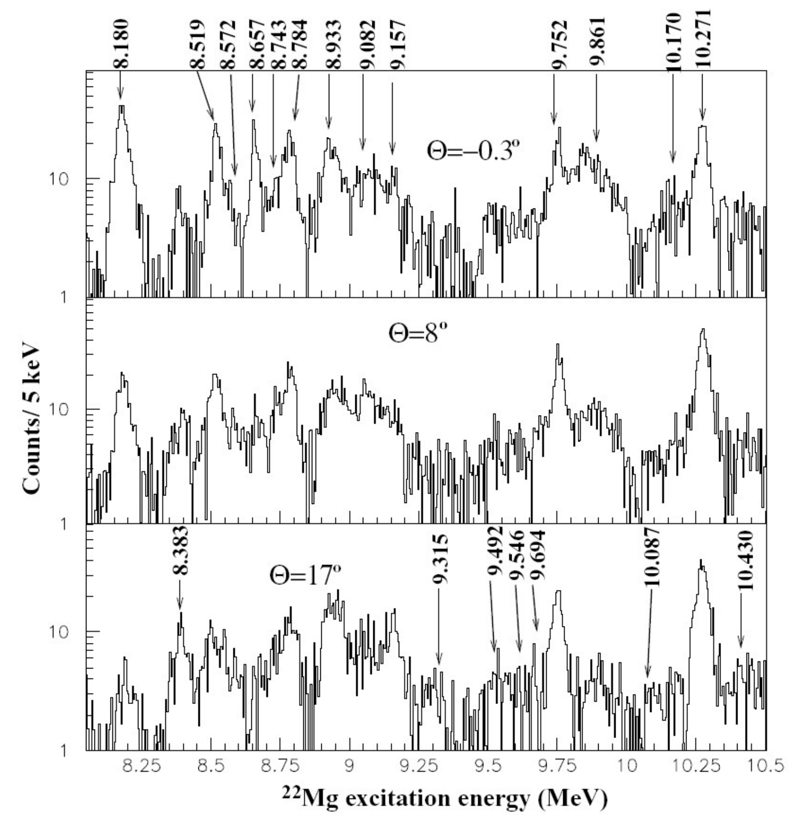
- observed transition to stable burning is much lower – models do not yet match reality – but one major uncertainty has now been removed …

CNO Break-out reaction $^{18}Ne(\alpha,p)^{21}Na$

Using the $^{24}Mg(p,t)^{22}Mg$ reaction at 100 MeV to investigate unbound states (resonances) in the compound nucleus ^{22}Mg
$\Rightarrow$ high accuracy energy determination at the RCNP Osaka GRAND RAIDEN spectrometer

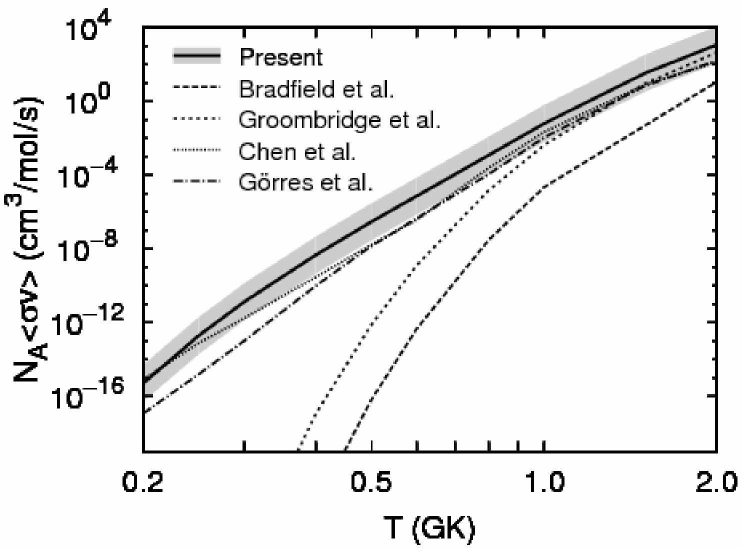


Collaborators:
Notre Dame, MSU, KVI, RCNP Osaka, Osaka University, Kyushu University



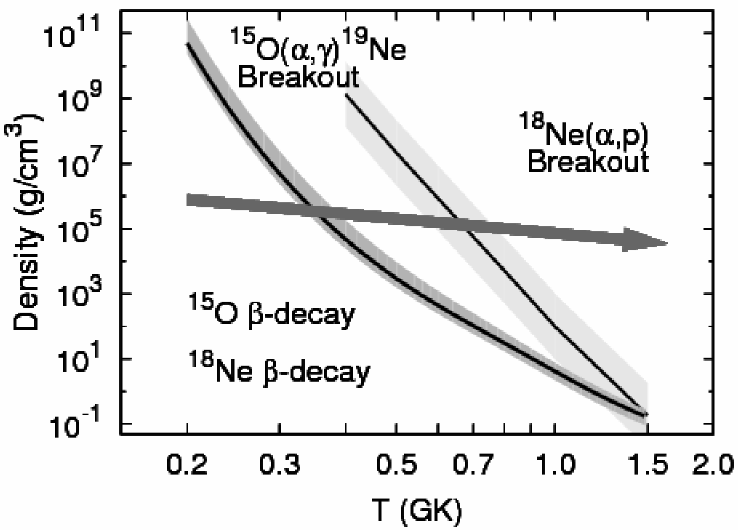
Many new resonances measured above the $^{18}Ne+\alpha$ threshold in ^{22}Mg at 8.15 MeV, energies determined with ±3keV accuracy. Level spins and partial widths adopted from mirror nucleus ^{22}Ne to determine resonance strengths.

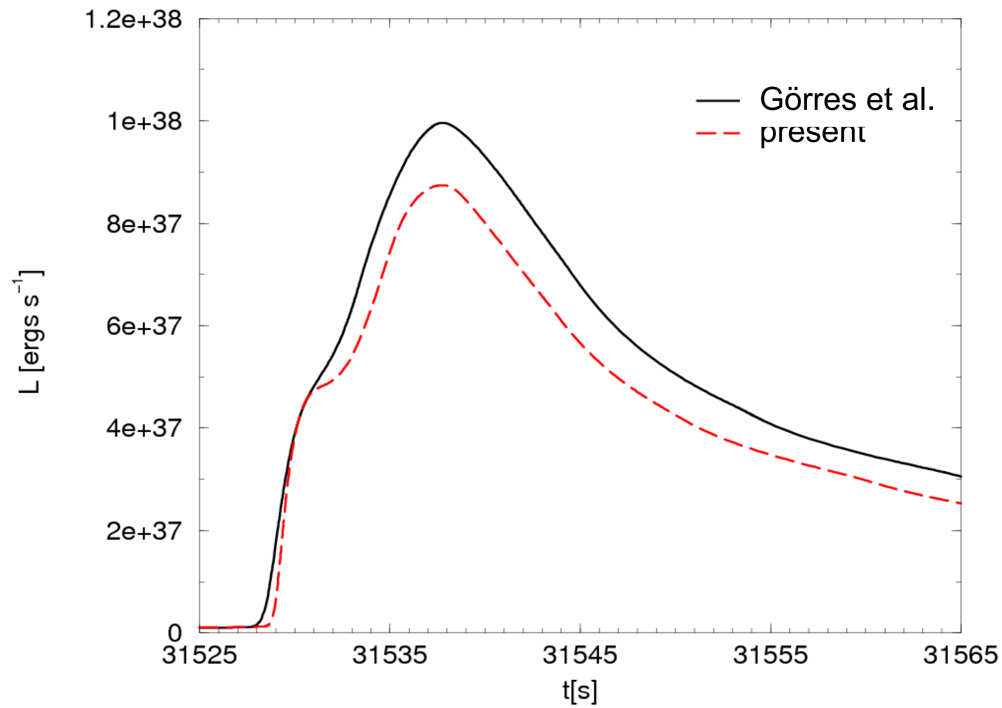
Consequences for X-ray burst light curves



$$N_A \langle \sigma v \rangle_{\text{res}} = \left(\frac{2\pi}{(\mu \cdot kT)} \right)^{+3/2} \cdot \hbar^2 \cdot \sum_i \omega\gamma_i \cdot \exp\left(-\frac{E_i}{kT} \right)$$

Simulations of burst with XRB model indicates change in light curve depending on the choice of reaction rate.

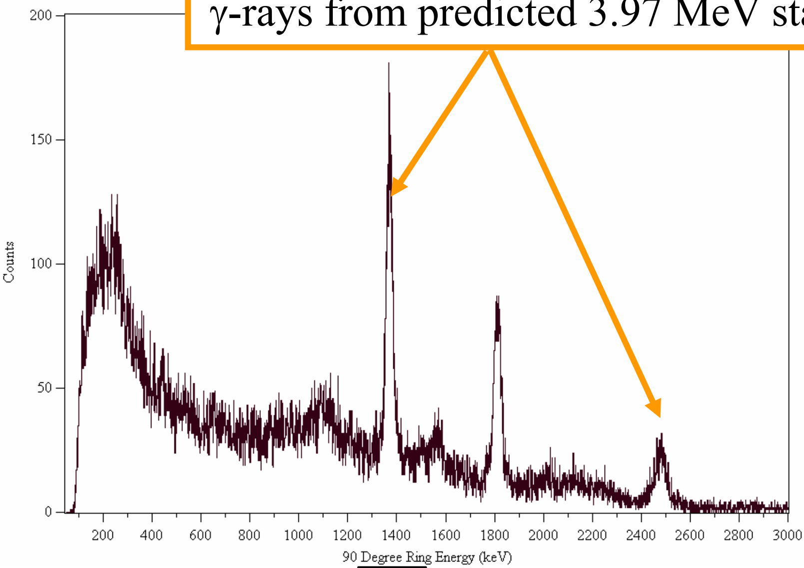




NSCL Experiments: New ^{32}Cl(p,g)^{33}Ar rate

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

γ-rays from predicted 3.97 MeV state



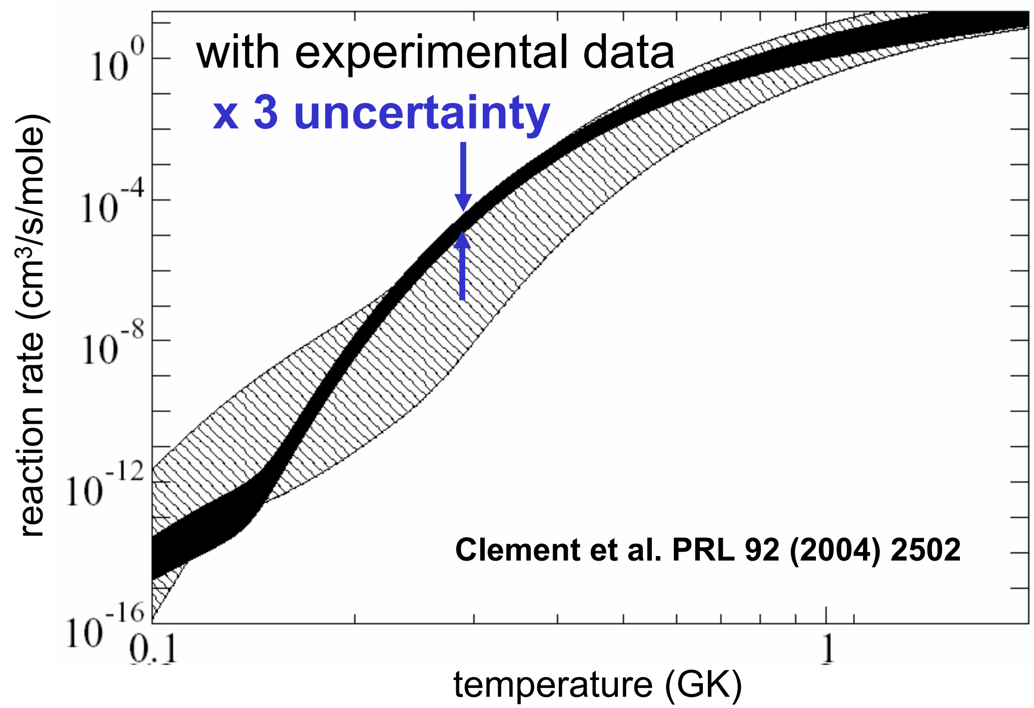
^{33}Ar level energies measured:
^{33}Ar level energies measured:

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

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

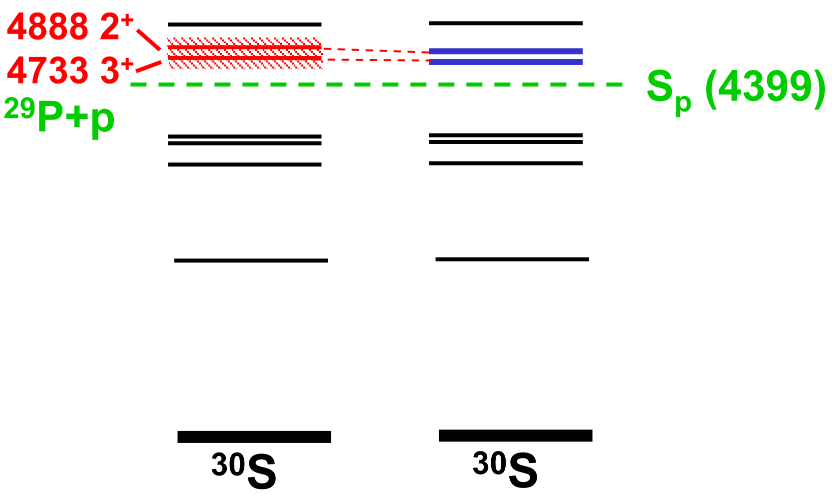
Use ^{34}Ar(p,d)^{33}Ar* → ^{33}Ar + γ

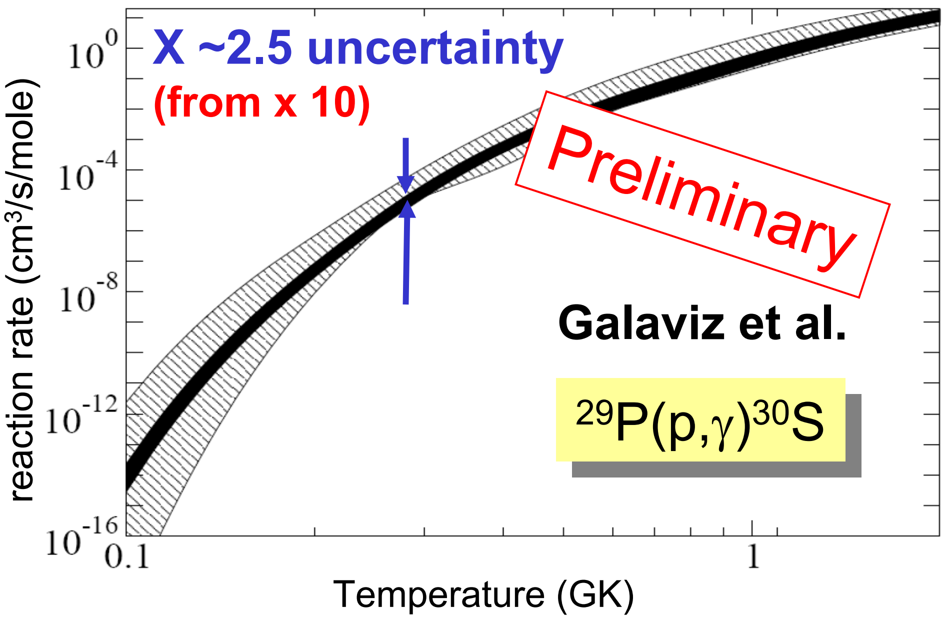
stellar reaction rate



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

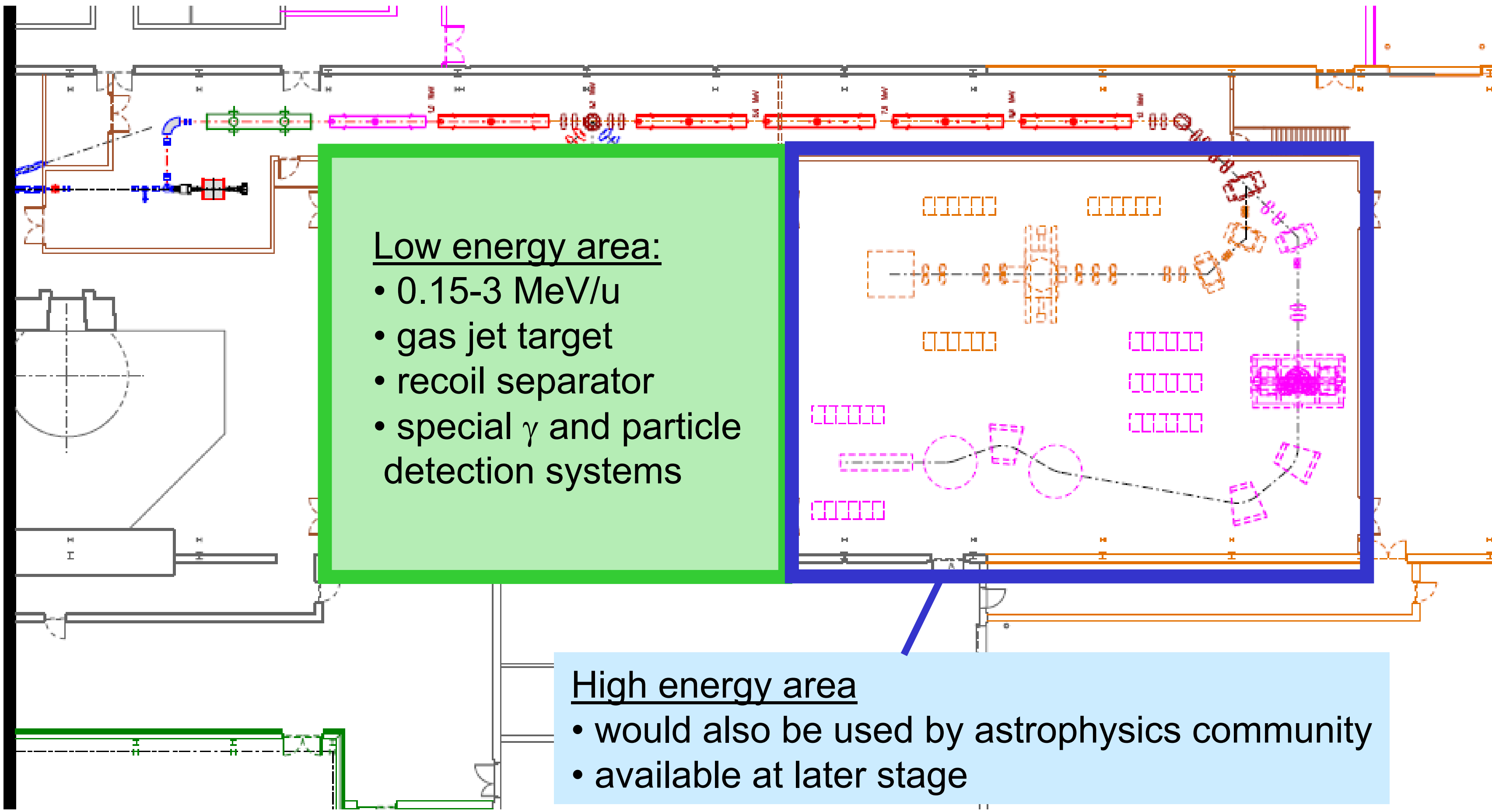
Program continued with 2 experiments for 4 additional rates





→ Large portion of rp-process within reach at the NSCL

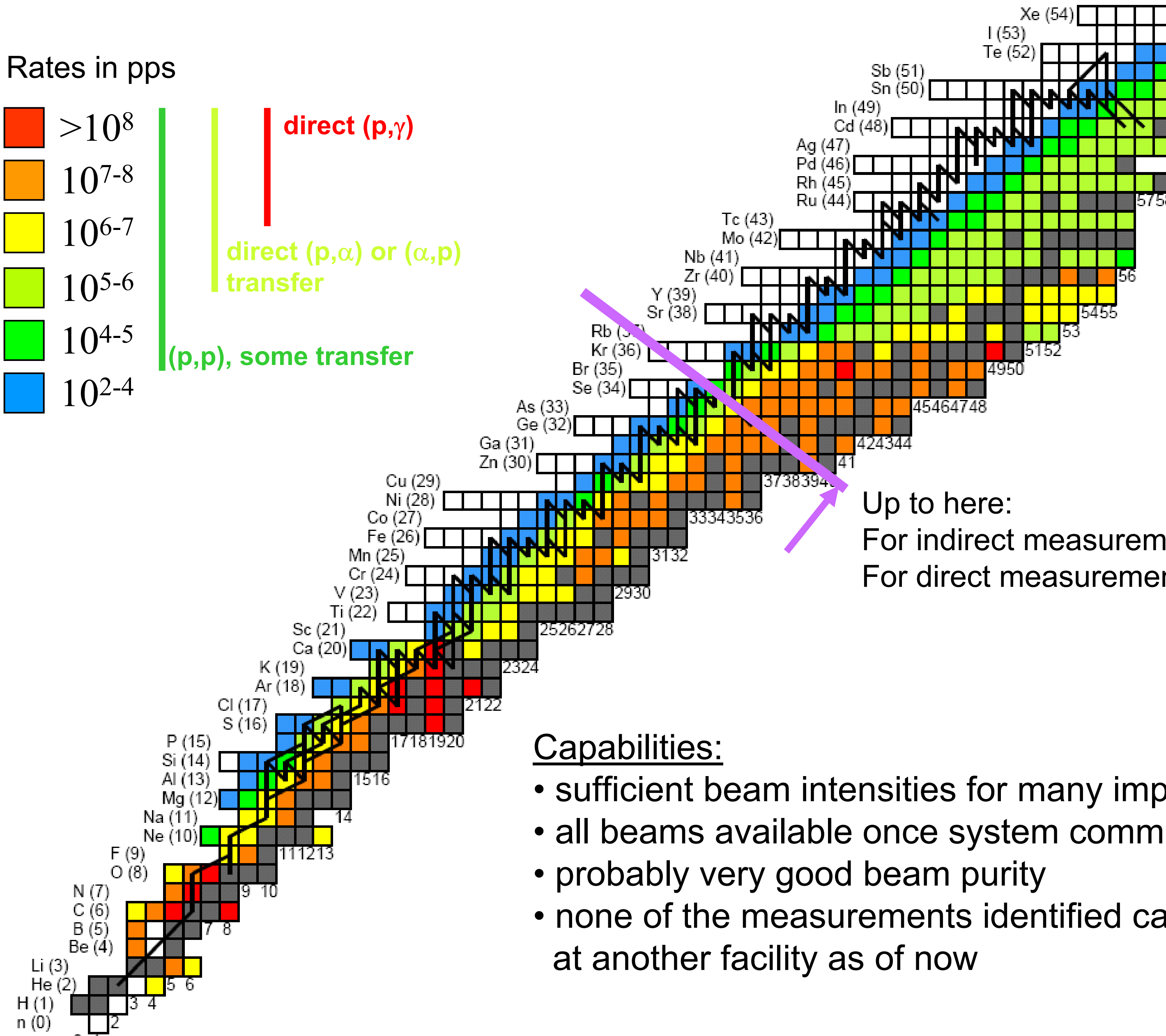
NSCL Plans: facility for reaccelerated low energy beams



→ Synergies with ND program: gas target/recoil separator development

→ Opportunity for a new experimental direction for new JINA

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

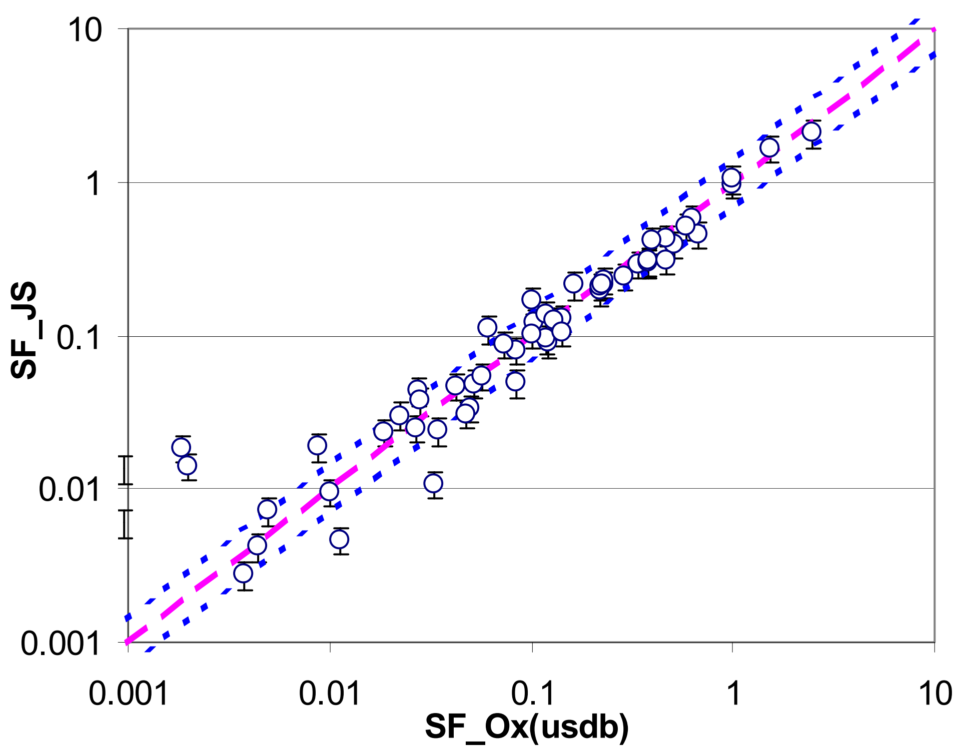
Nuclear Theory: test sd-shell model spectroscopic factors against experiment

- developed consistent analysis procedure and reanalyzed all experimental data from transfer reactions
- found agreement within 20% for ground state n-spectroscopic factors
- JINA project: look at spectroscopic factors of excited states

Analysis of SF from excited states of $^{17-18}O$, ^{21}Ne, ^{24}Na, $^{25-27}Mg$, $^{29,31}Si$, $^{33,35}S$ show that agreement with shell model is better than 30% for SF_exp>0.05. The mirror nuclei of above isotopes are of astrophysical interest.

→Reliable error bars for shell model Based reaction rates

→Guidance for sensitivity studies and experimental programs



B. Tsang, S. Warren (undergrad)
S.C. Sue (visiting undergrad Hongkong)
W.D. Pang (visiting from Peking University)

Database for spectroscopic data

(p,d) and (d,p) Reaction Database

References

- Survey of ground State neutron Spectroscopic Factors from Li to Cr isotopes, M.B. Tsang, Jenny Lee, W. G. Lynch, Phys. Rev. Lett., 95, 222501 (2005)
- Neutron Spectroscopic Factors from Transfer Reactions, Jenny Lee, M.B. Tsang, W. G. Lynch, submitted to Phys. Rev. C, nucl-ex/0511024

This database of (p,d) and (d,p) reactions is compiled by the HiRA Group at the National Superconducting Cyclotron Laboratory at Michigan State University. It is an ongoing project.

Most data files are digitized from published figures. Only the CH89 calculations are posted here. No spectroscopic factors have been applied to the calculations. Each file contains the reaction element and type, reaction energy, theta and dsigma/domega values, and references. Files are grouped by reaction and target isotope and are listed in ascending order by reaction energy.

http://groups.nscl.msu.edu/nscl_library/pddp/database.html

Theoretical burst projects– connecting nuclear physics and astrophysics

Detailed analysis of reaction flows in X-ray bursts as a function of depth

- (Fisker et al.)

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

- Ejection of burst ashes into space (Weinberg, Bildsten, Schatz)

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

- Spectral line formation and lineshape fit for EXO 0748-676 (Chang, Bildsten) prediction of observables in other systems

Origin of burst oscillations

- Burst oscillations due to surface modes (Piro, Bildsten)

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

- Sedimentation (Peng, Brown)
- 1D Burst modeling: Sensitivity and systematic behavior (Fisker and Heger)

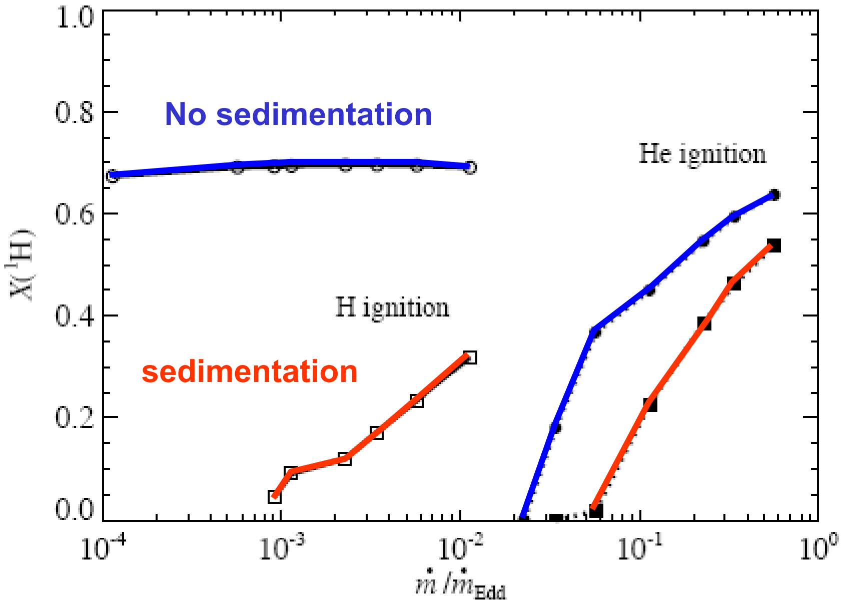
Nature of NS atmospheres

- Diffusive nuclear burning and NS/magnetar atmospheres (Chang, Bildsten)

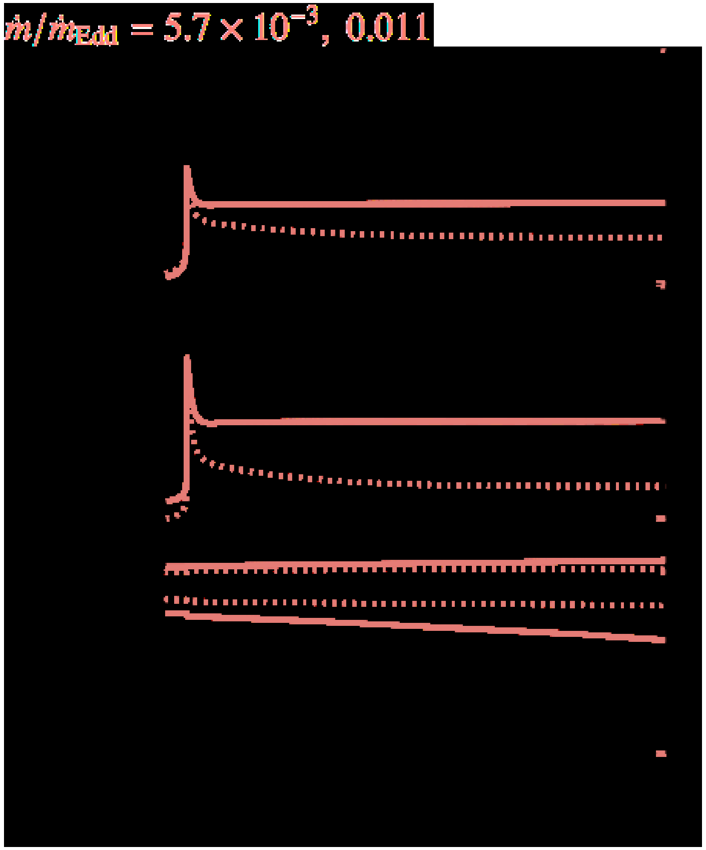
Weak hydrogen flashes on accreting neutron stars

MSU-Chicago JINA collaboration: Peng, Brown, & Truran (2007), ApJ, 654, 1022

Effect of element sedimentation:



1-zone burst calculation at low accretion rate:

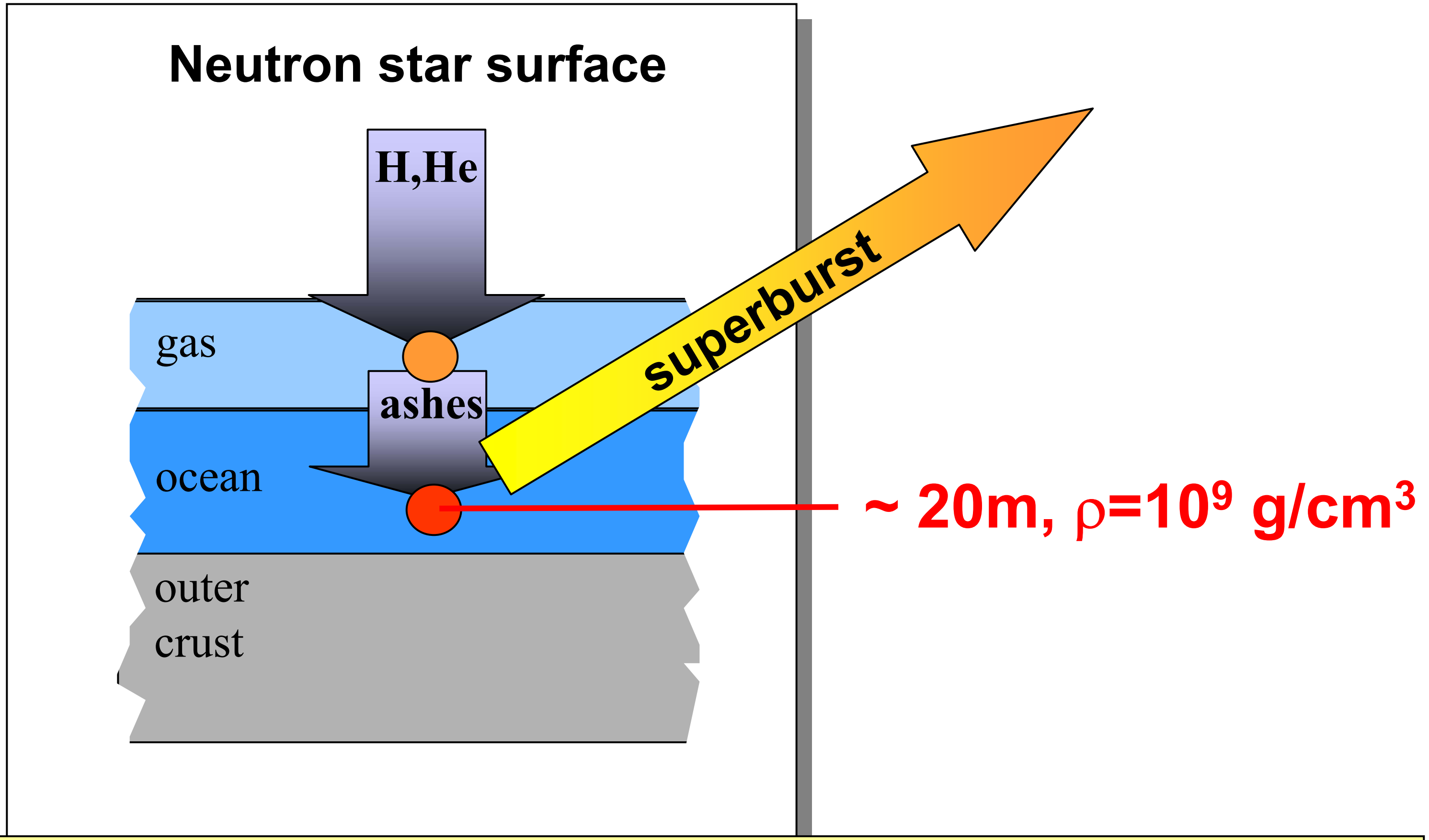


Role of heavy element sedimentation:
→ Huge effect at low accretion rate
→ not negligible at large accretion rates should be put into 1D codes

New burning regime between ~ 0.005-0.01
→Weak H-flashes accumulate He layer (probably not observable)
→ Occasionally strong He flash – matches observations

H. Schatz

Step 2: Deep ocean burning: Superbursts

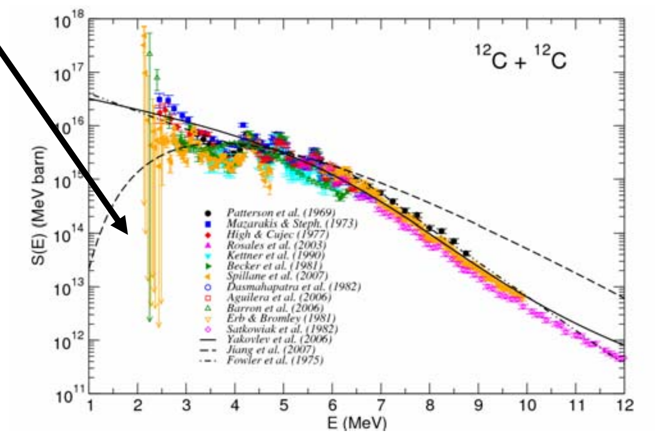


Superbursts

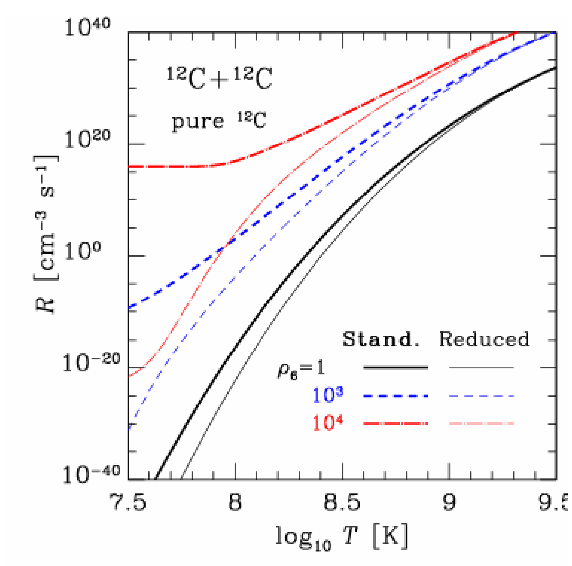
- Superbursts are probes for NS cooling (Peng, Brown)
- Problem: superbursts recur too frequent compared to current models

Impact of subbarrier fusion hindrance on C-ignition

Motivated from experiments for heavier (endothermic) systems Jiang et al. propose subbarrier fusion hindrance

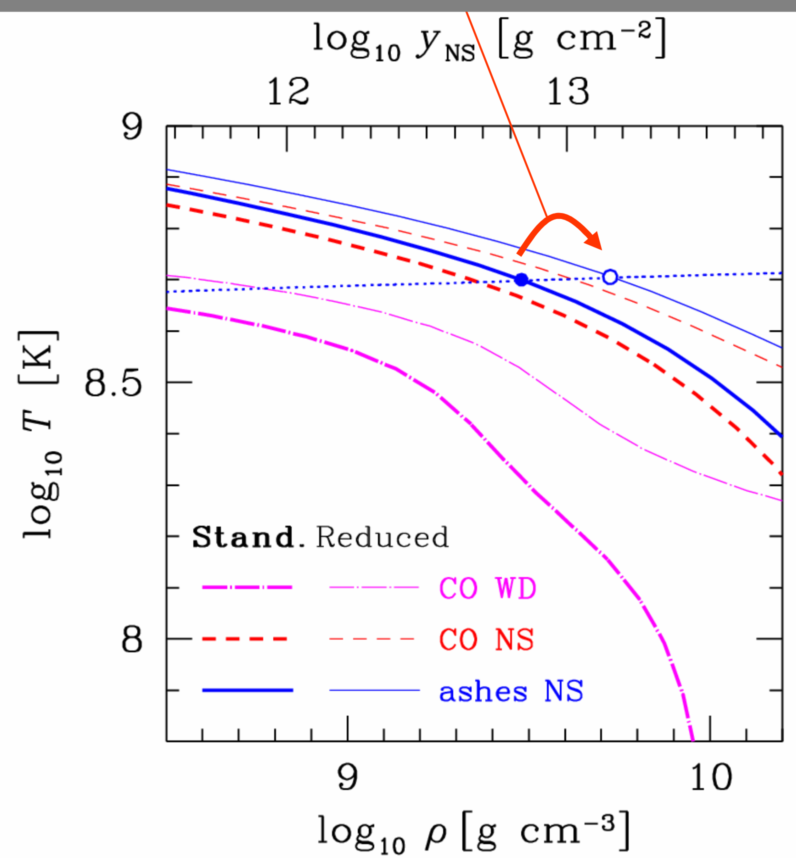


Greatly reduced fusion rate

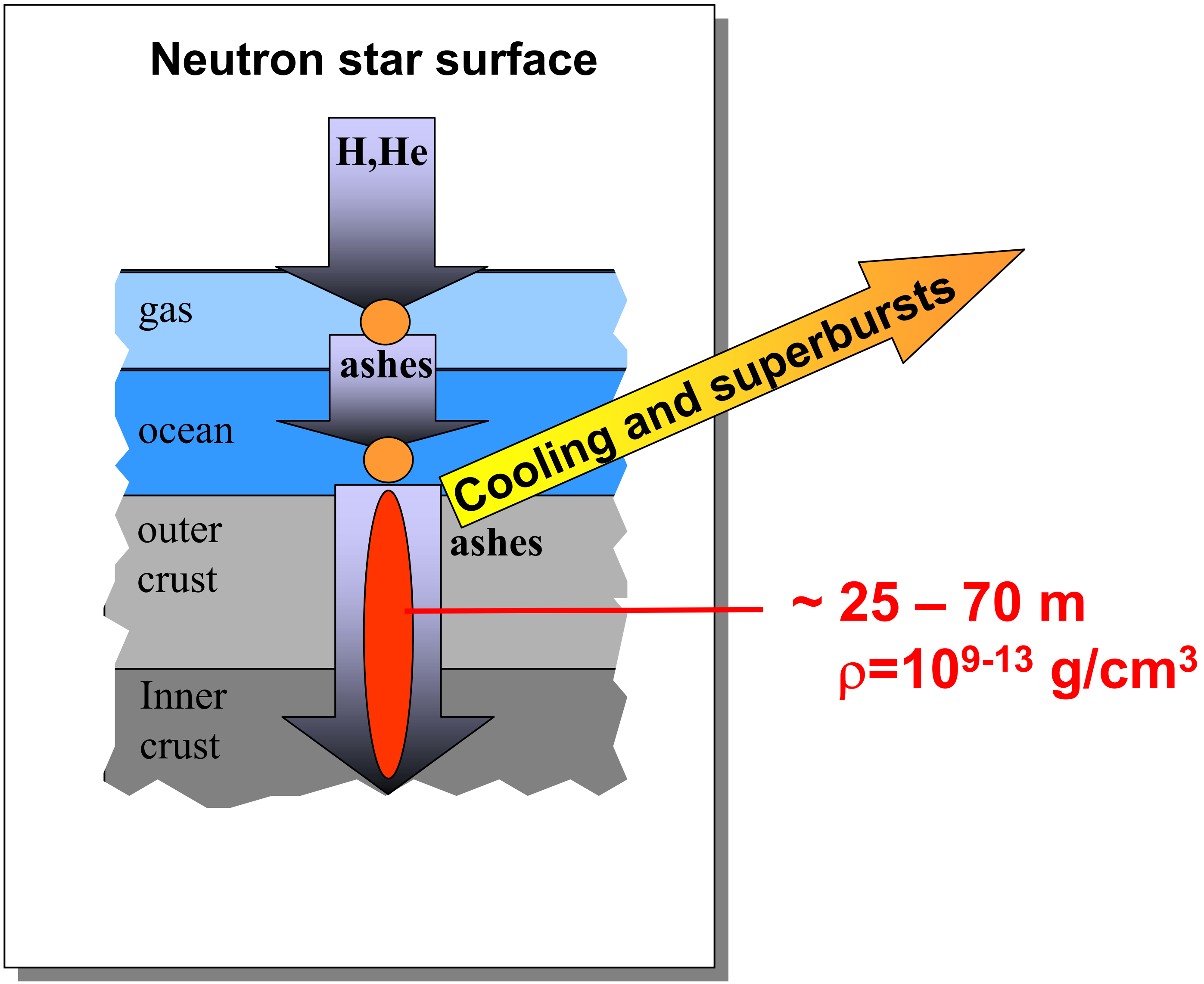


JINA collaboration explored impact on C-ignition for superbursts:

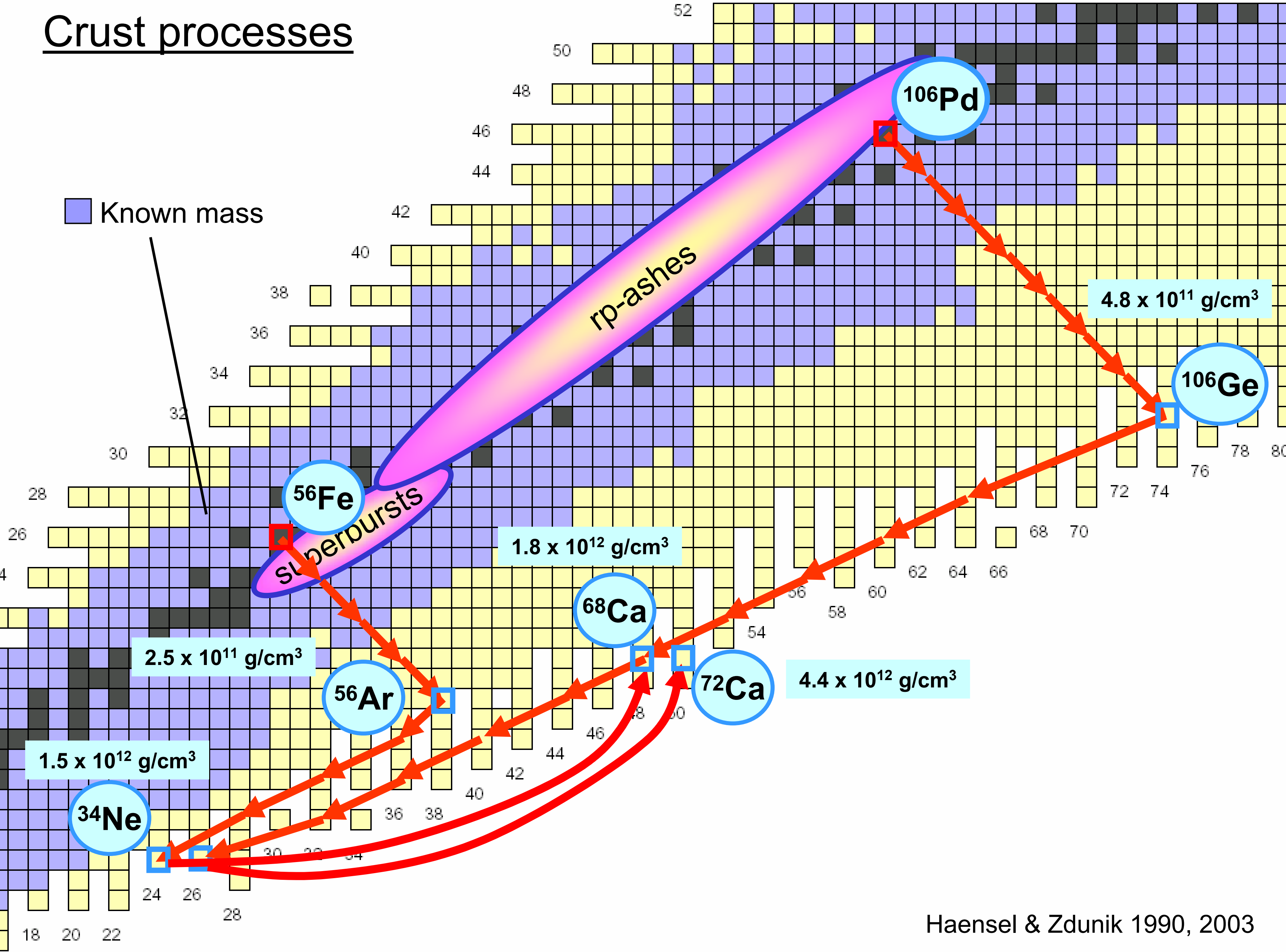
→ Ignition moves deeper
Superbursts predicted to occur even less frequent



Crust burning

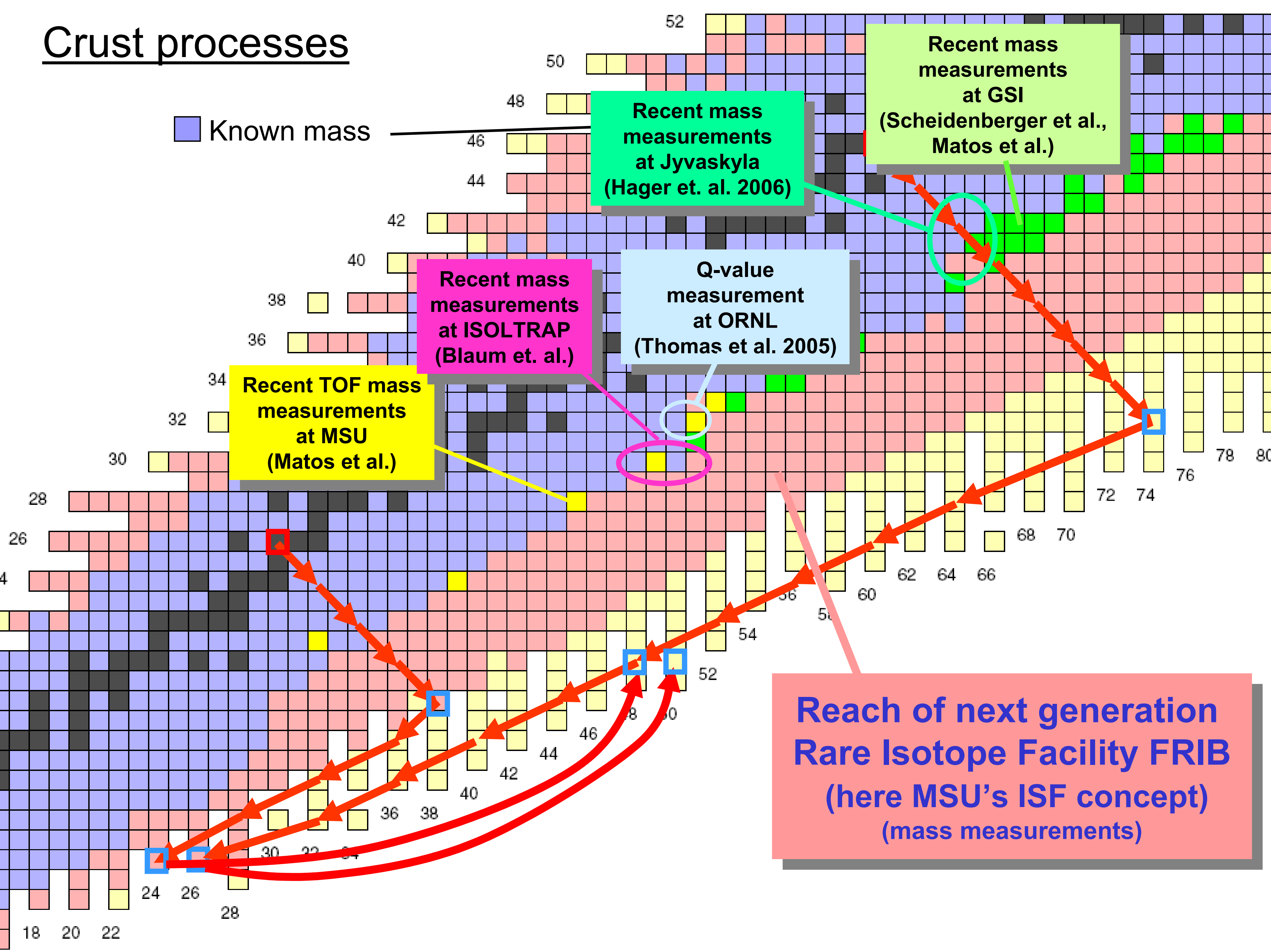


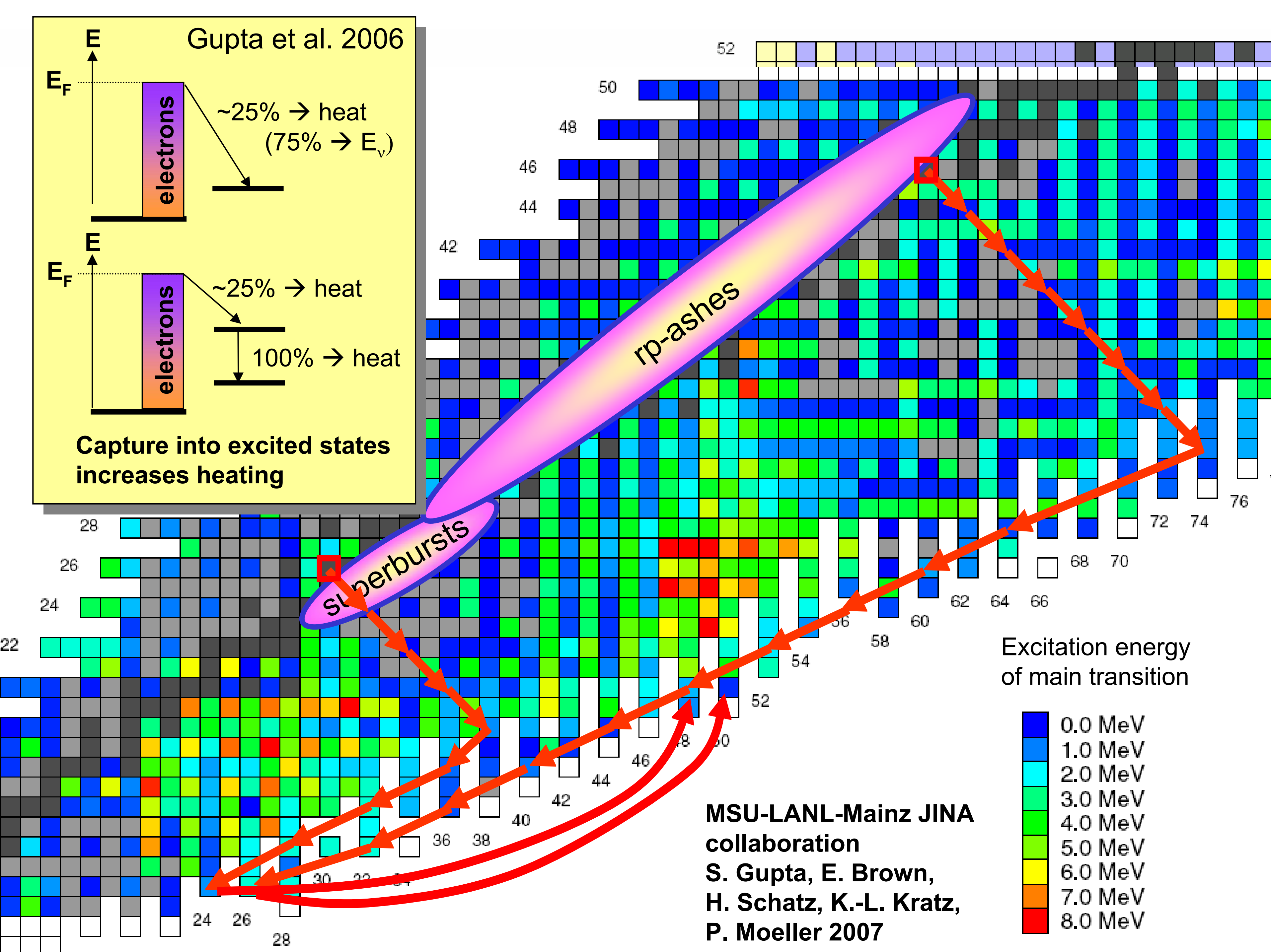
Crust processes



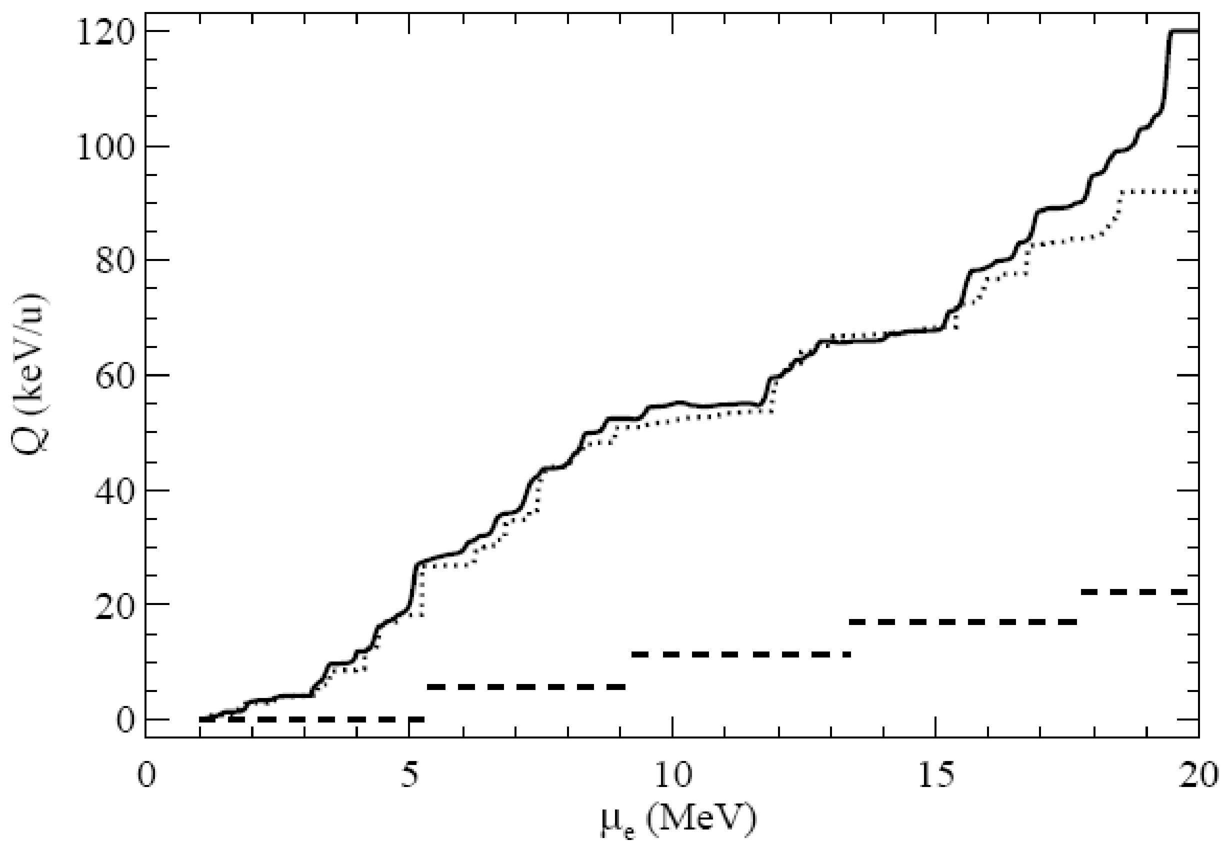
Haensel & Zdunik 1990, 2003

Crust processes




Gupta et al. 2006
E
E_F
electrons
~25% → heat
(75% → E_ν)
E
E_F
electrons
~25% → heat
100% → heat
Capture into excited states increases heating
rp-ashes
superbursts
Excitation energy of main transition
0.0 MeV
1.0 MeV
2.0 MeV
3.0 MeV
4.0 MeV
5.0 MeV
6.0 MeV
7.0 MeV
8.0 MeV
MSU-LANL-Mainz JINA collaboration
S. Gupta, E. Brown,
H. Schatz, K.-L. Kratz,
P. Moeller 2007

Enhanced crust heating



New heating enhanced by x 5-6

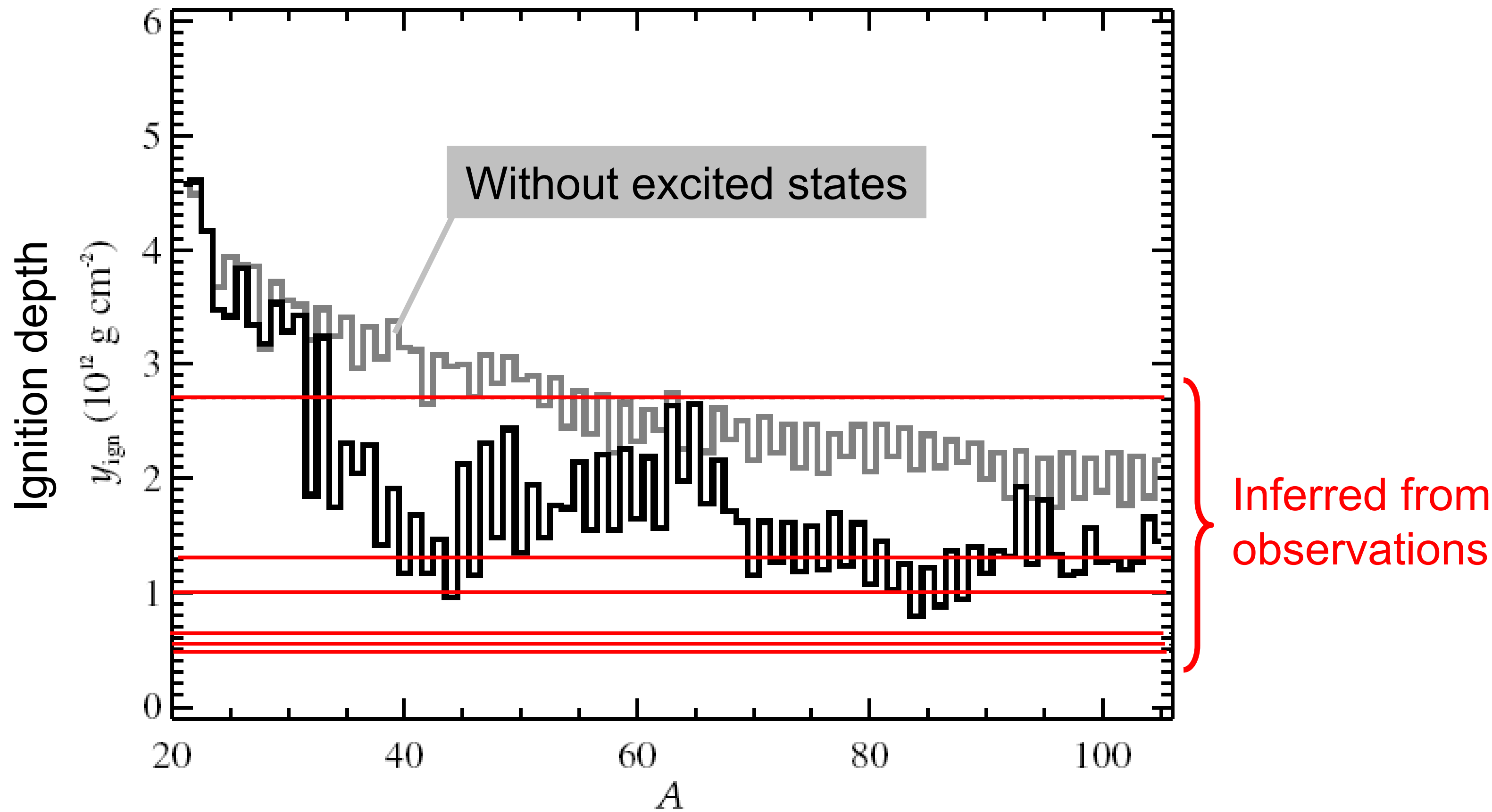
Former estimate

→ Heats entire crust and increases ocean temperature from 480 Mio K to 500 Mio K

Impact of new crust modeling on superbursts

Can the additional heating from EC into excited states make the crust hot enough to get the superburst ignition depth in line with observations ?

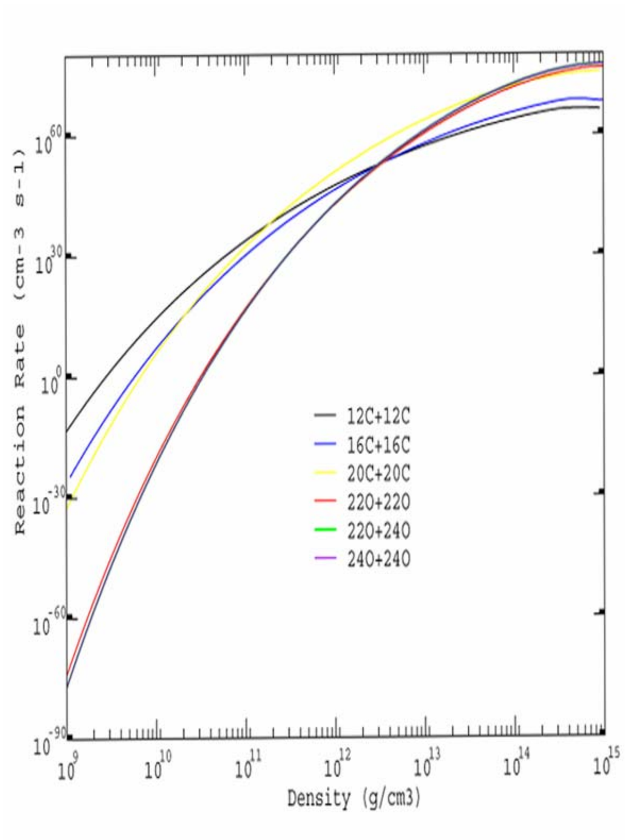
Almost:

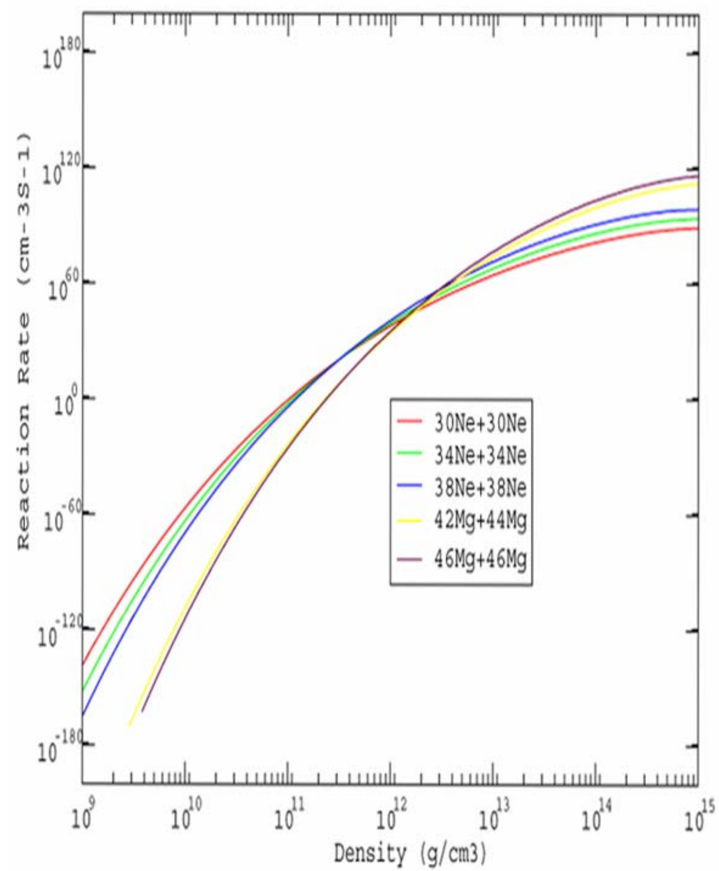


Mass number of crust composition (pure single species crust)

Pycnonuclear fusion reaction rates

M. Beard, L. Gasques, M. Wiescher, D. Yakovlev





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

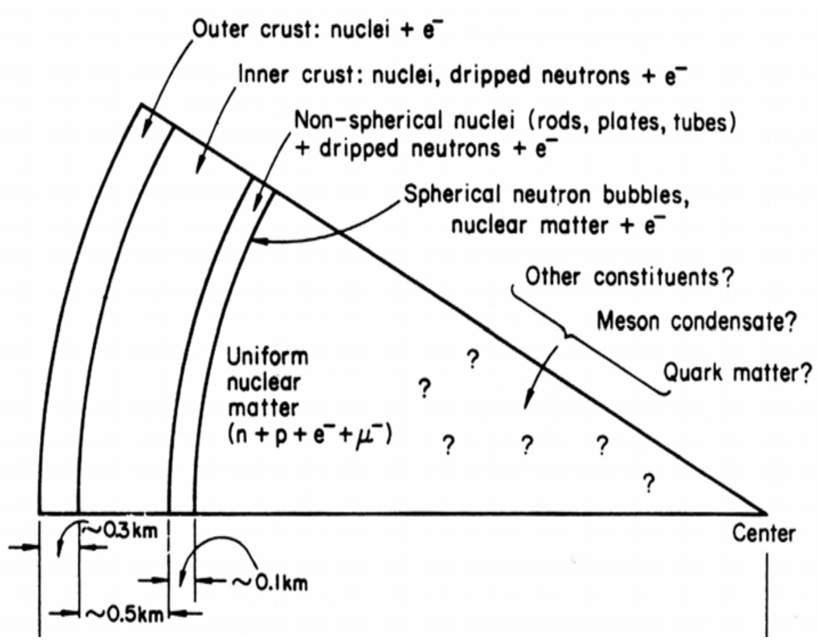
For higher Z-values the rates decrease steeply at density values less than 10^{12} g/cm^3 because of the strong Z-dependence in the pycno equation.

EOS, Symmetry energy, Neutron stars

- Neutron Star stability against gravitational collapse
- Stellar density profile
- Internal structure: occurrence of various phases.
- Observational consequences:
  - Stellar masses, radii and moments of inertia.
  - Cooling rates of proto-neutron stars
  - Cooling rates for X-ray bursters.

Neutron Star Structure:

Pethick and Ravenhall, Ann. Rev. Nucl. Part. Sci. 45, 429 (1995)

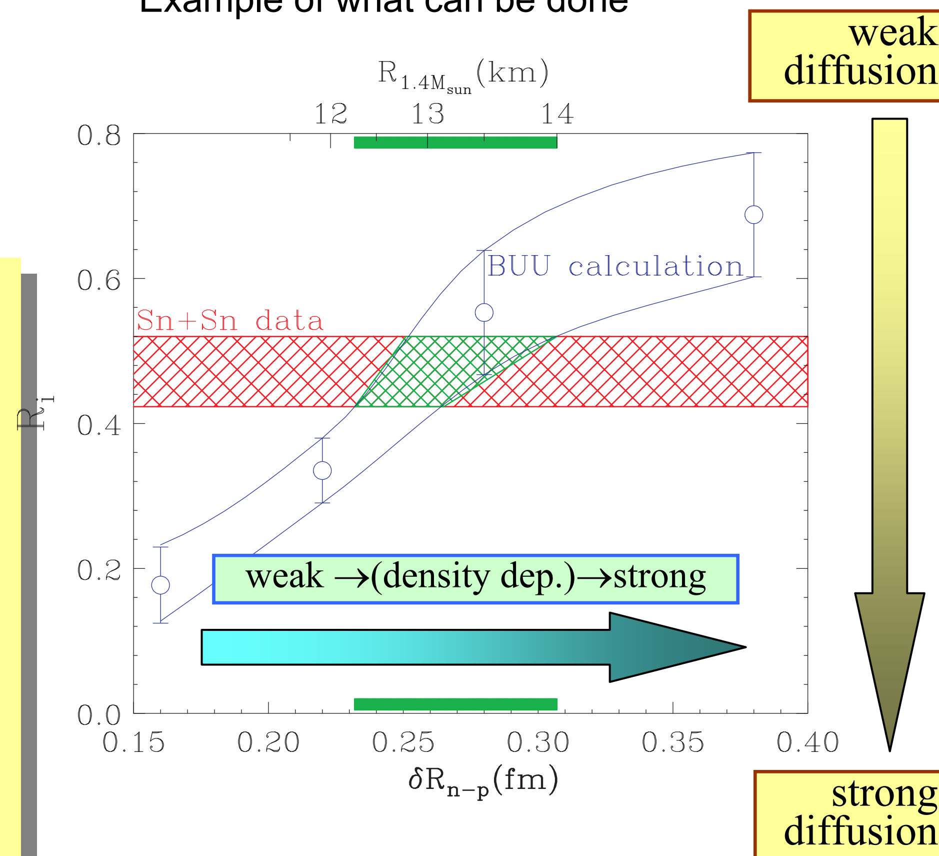


JINA project: understanding experimental signatures that constrain symmetry energy

JINA visitor: Yingxun Zhang

- Symmetry energy observables:
  - Isospin diffusion.
  - Pion production
  - Neutron vs. proton flow.
  - Neutron vs. proton matter radii.
- JINA project emphasis:
  - What properties of the symmetry energy does each probe?
  - What are the model uncertainties?
  - What experiments should be performed to constrain them and the symmetry energy?
  - What are the impacts of such constraints on neutron star observables?

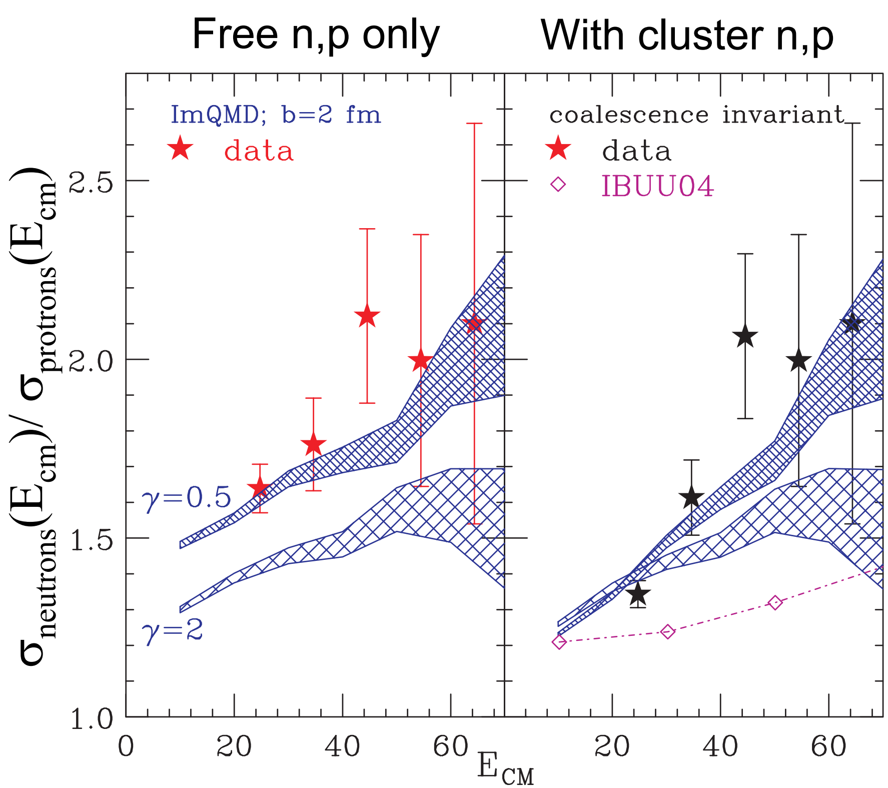
Example of what can be done



Tsang et. al., PRL 92, 062701 (2004)
Chen et al., PRL 94, 032701 (2005)
Horowitz and Piekarewicz, PRL 86, 5647 (2001)
Li and Steiner,nucl-th/0511064

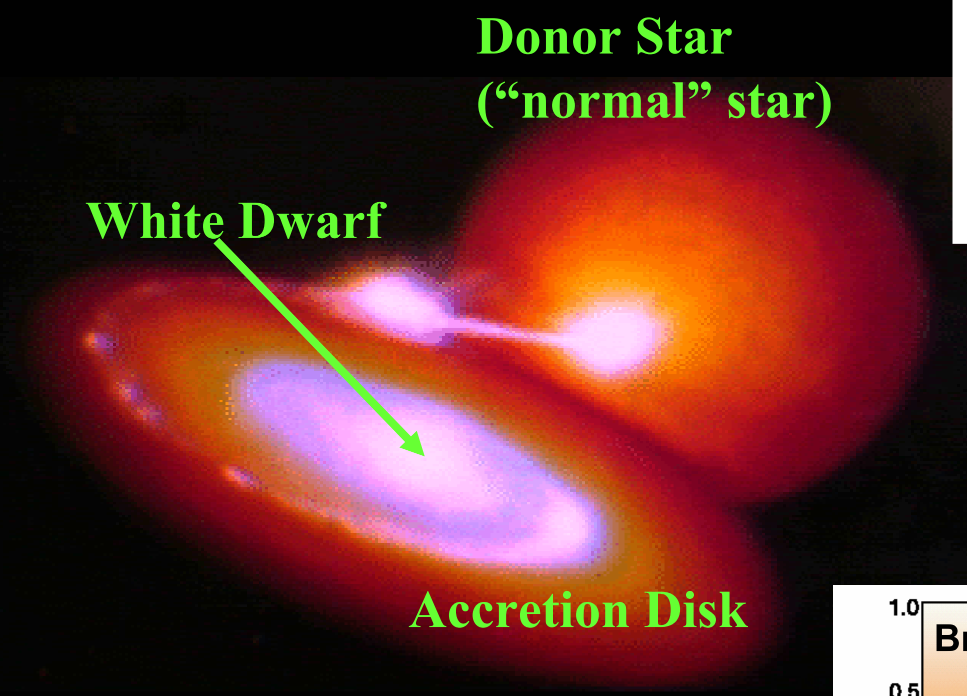
First results: explore role of cluster production

- Mean field theories like BUU treat the production of clusters (d,t,^{3}He,α, etc.) perturbatively.
- Do the clusters influence the mean field dynamics and the predictions for observables? Can we understand differences in theoretical models?



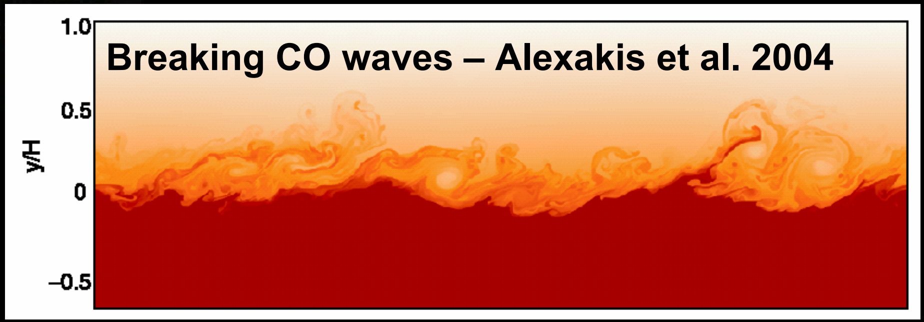
- Comparisons of QMD and BUU:
  - Effect of cluster production clear and theoretically reproduced by QMD.
- Difference between ImQMD and IBUU04 in right panel is one focus of current investigations.
  - BUU and QMD should agree.
  - Does it result from differences in the assumptions about m_n^* and m_p^* in the two calculations?

Novae



<u>JINA work:</u>

- mixing processes
- CV/Nova population (Townsley&Bildsten)
- 2D models of accretion flow (Fisker & Balsara)

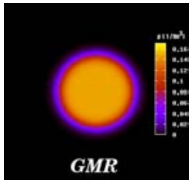


MRC3 focused workshops

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

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 – resubmit 2008?
Continue Heaven on Earth: next meeting at ???

Summary

X-ray binaries …

- Identify X-ray burst observables and their nuclear physics sensitivities
- Address nuclear physics uncertainties (reaclib database project!)
- Comprehensive self consistent model of nuclear processes on accreting neutron stars
  - Bursts (done)
  - Ocean, superbursts (done)
  - Outer crust (done)
  - Inner crust (next year – incorporate pycnonuclear fusion, beta decay, …)

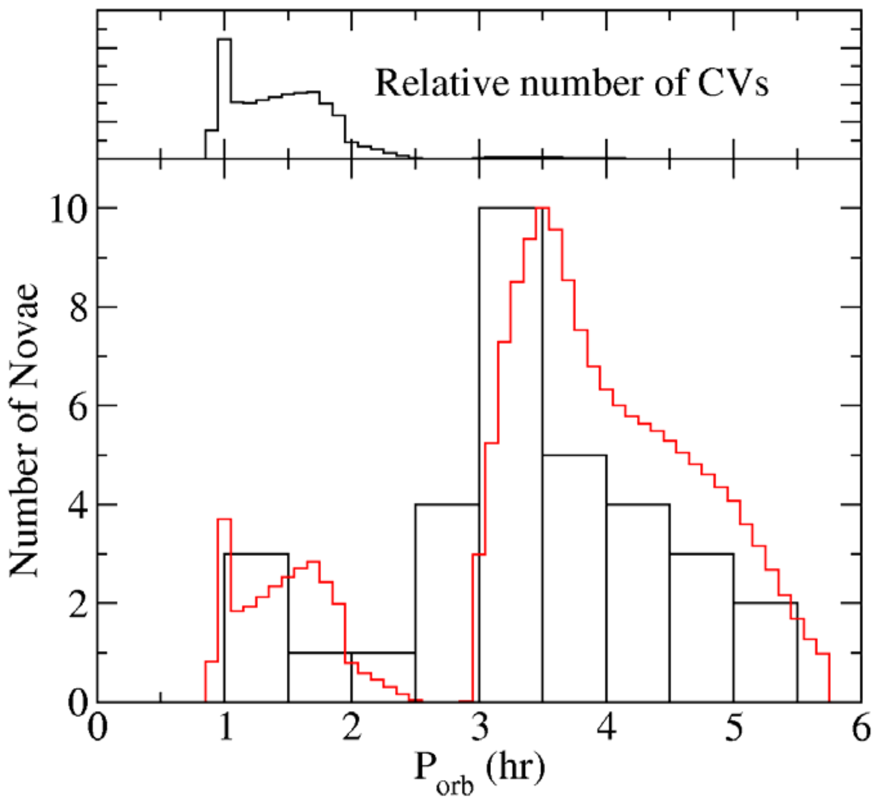
EOS

- new direction – lively connection between astrophysics and nucelar physics has emerged over last year, at least in part stimulated by JINA
- direction: density dependence of asymmetry, experimental signatures
- Develop further through workshops/collaborations/visitors

Novae

- growing interest due to type Ia connection
- theoretical progress with analytical models and multi D accretion models
- next step: translate into 1D models with nucleosynthesis

Model orbital period distribution of classical Novae



Townsley & Bildsten 2005, ApJ, 628, 395

Theory uses interrupted magnetic braking to calculate accretion rate from orbital period (Howell, Nelson & Rappaport 2001, ApJ, 550, 897)

Nova rate found from accretion rate with consistent WD thermal state (Townsley & Bildsten 2004, ApJ, 600, 390)

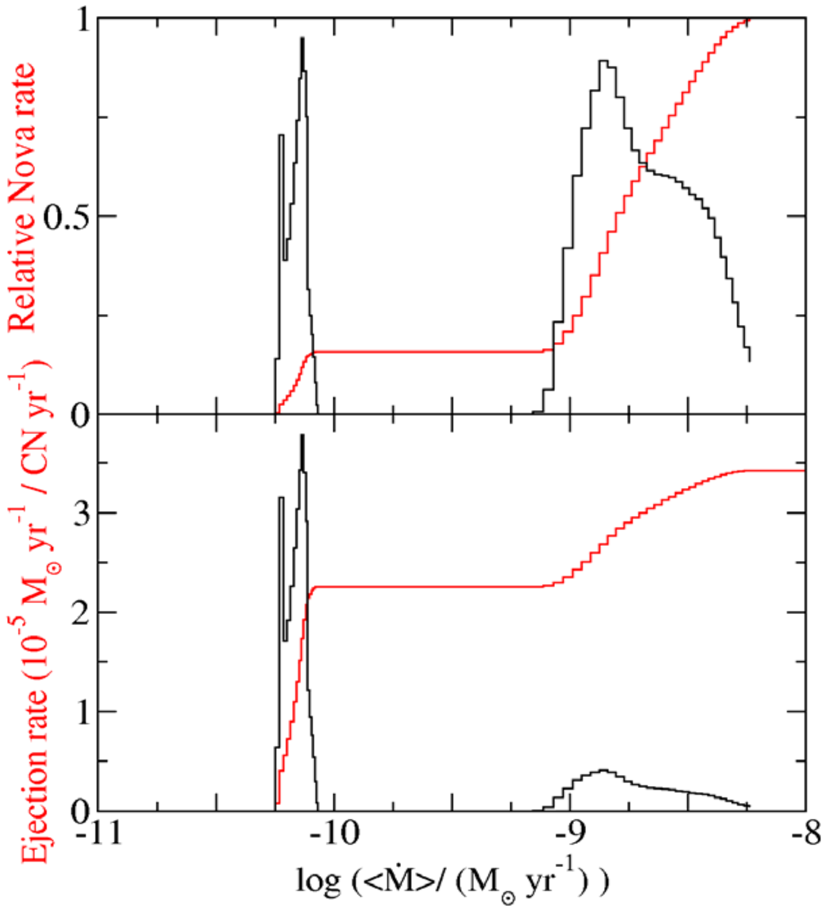
Data from Kolb & Ritter CV catalog

For the first time, can infer overall CV population from CN rate

(CN rate from Willia $10^6 L_{\odot,K}$ fter 2004, ApJ, 612, 867)

- 60-180 CVs $2\text{-}4 \times 10^{-4}$ yr^{-1} per $10^{10} L_{\odot,K}$,
- CV burthrate similar to Type Ia supernova rate in ellipticals

Accretion rate distribution of classical novae



High accretion rate CVs give

- 2% of CV population
- 90% of Nova events
- 30% of ejected material

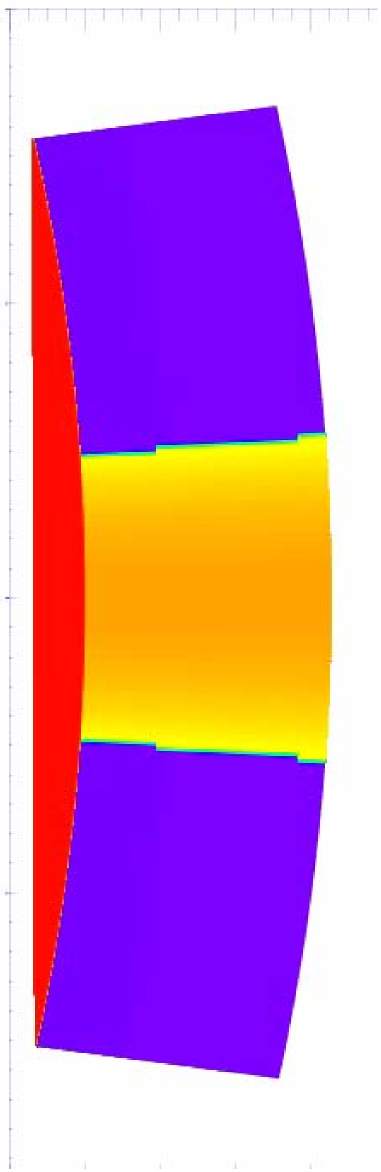
Low accretion rate Novae are expected to process ejected material more due to higher degeneracy at ignition

So far only 5 Novae confirmed to be of short orbital period and therefore low accretion rate. Orbital Period measurement is difficult.

→ Ejected mass matches accreted mass and observation and we know the population

→ Next step: nucleosynthesis modeling

Accretion onto white dwarf



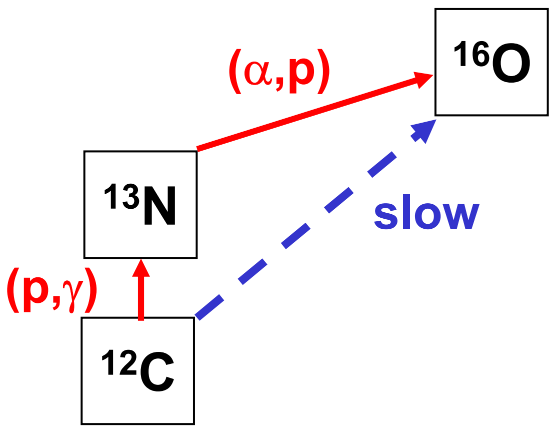
Address questions:

- Spectra of accreting white dwarfs ?
- Mixing of accreted matter with surface matter ? (directly impacts Novae)

2D simulation by Fisker & Balsara
astro-ph/0510780, astro-ph/0508691
→ understand structure of boundary conditions can explain associated spectral features

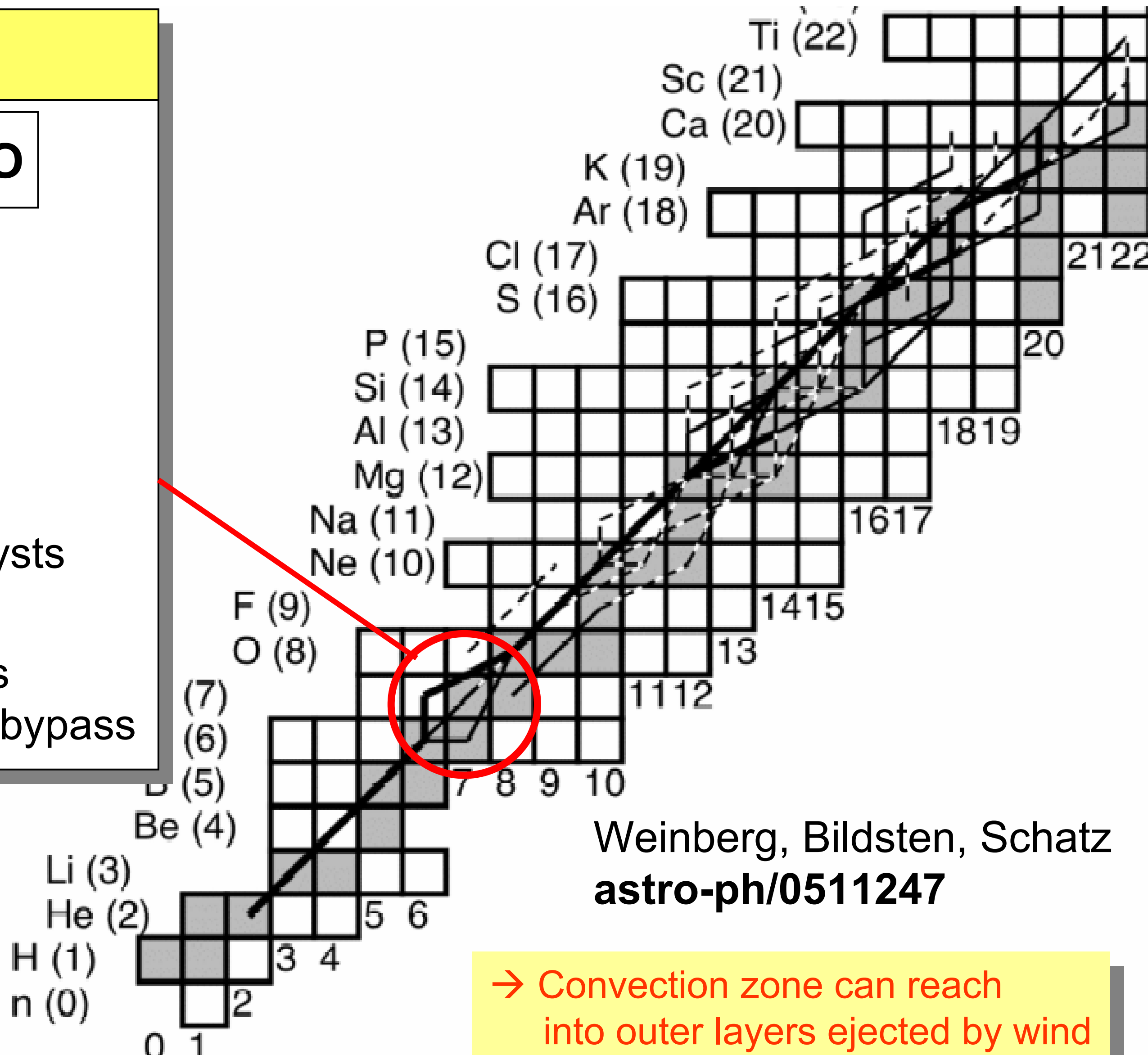
Reaction flow during burst rise in pure He flash PRE Bursts

$^{12}C(\alpha,\gamma)$ bypass



Need protons as catalysts ($\sim10^{-9}$ are enough !)

Source: (α,p) reactions and feedback through bypass

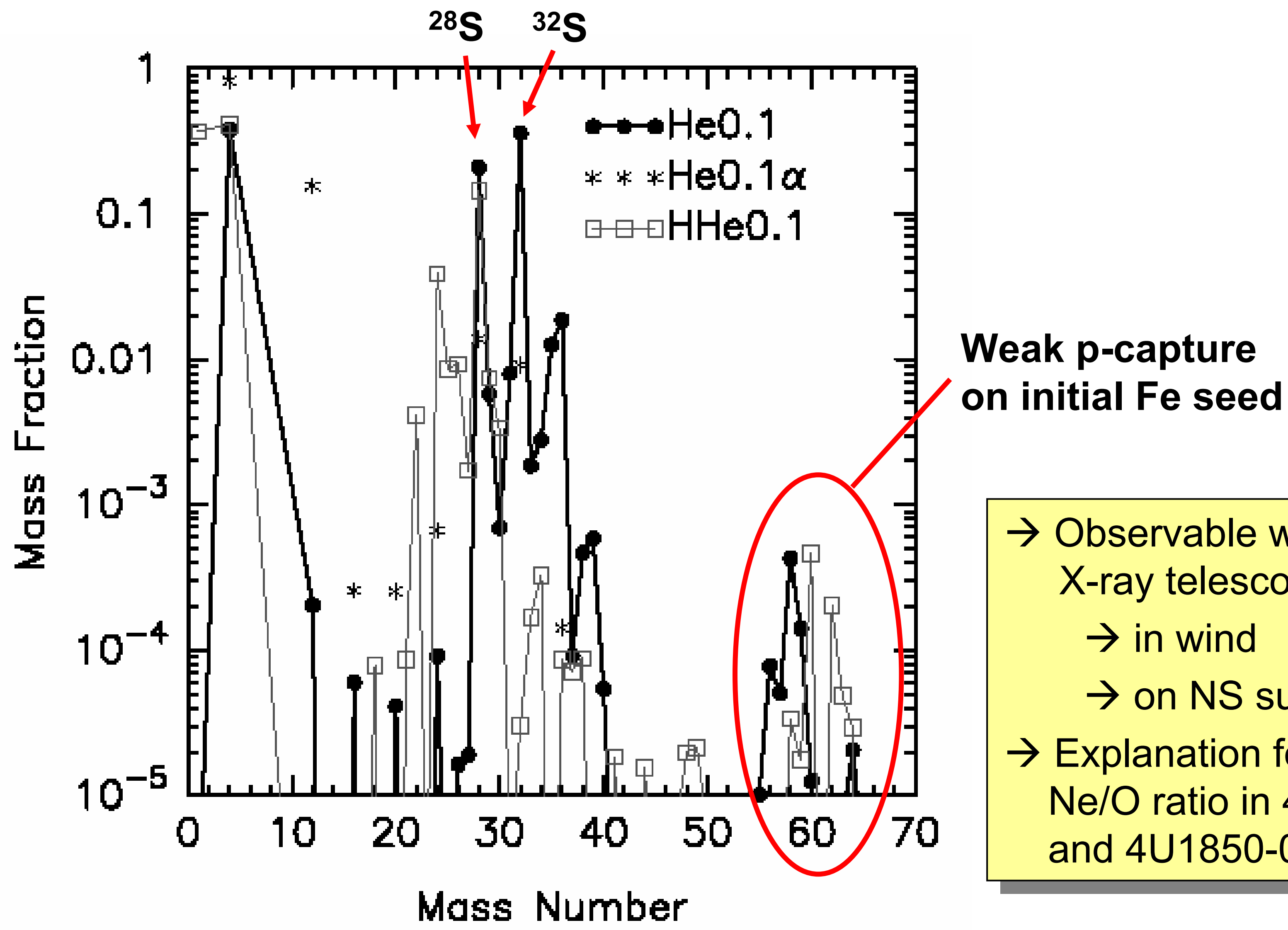


Outcome of JINA workshop

Weinberg, Bildsten, Schatz
astro-ph/0511247

→ Convection zone can reach into outer layers ejected by wind

Composition of ejected material



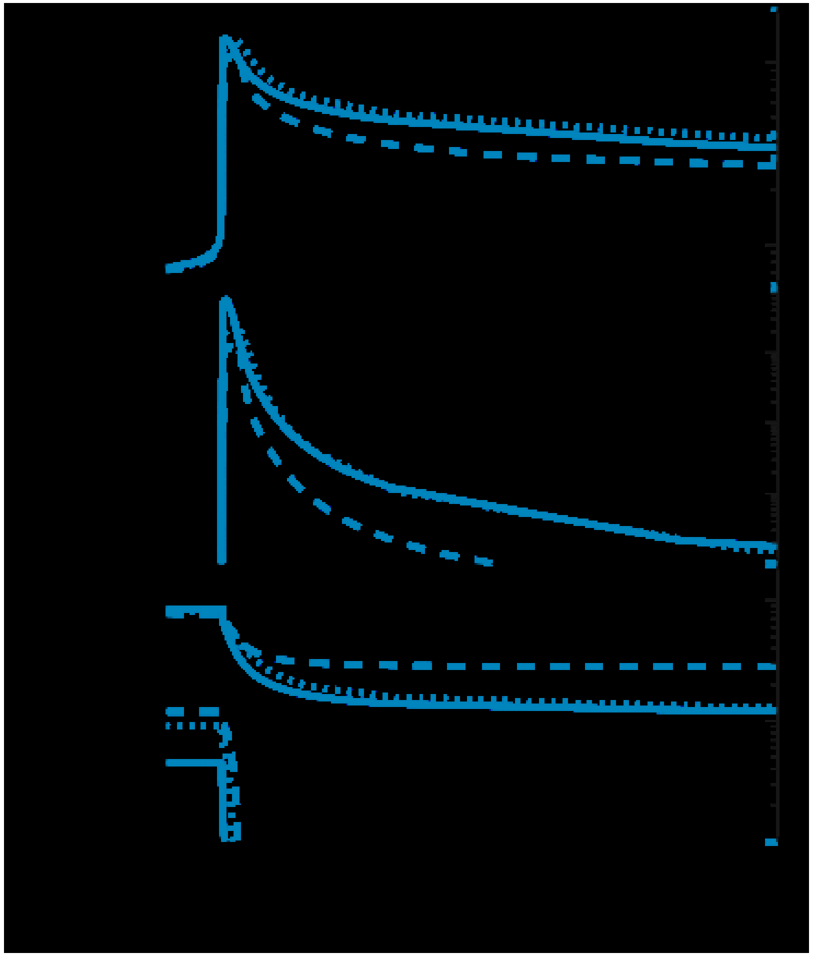
→ Observable with current X-ray telescopes

→ in wind

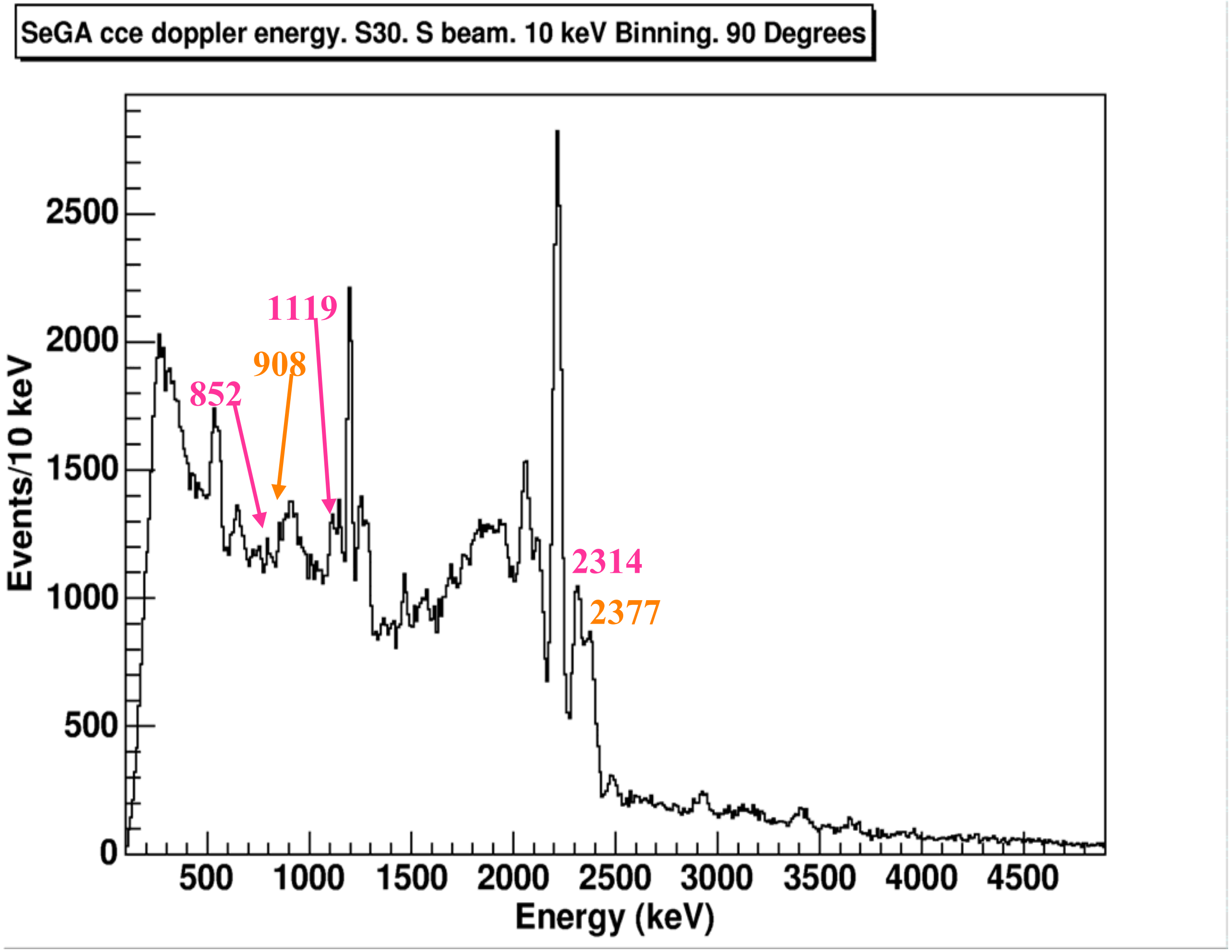
→ on NS surface

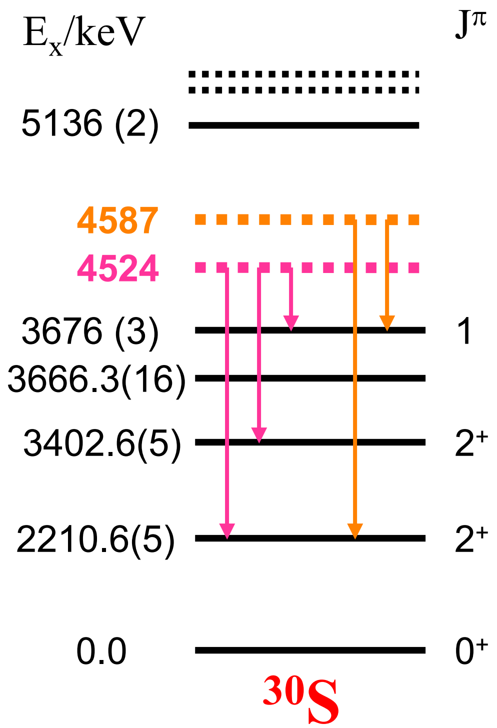
→ Explanation for enhanced Ne/O ratio in 4U1543-624 and 4U1850-087 ?

$\dot{m} = 9.1 \times 10^{-4}$–$2.3 \times 10^{-3}\ \dot{m}_{\rm Edd}$



New NSCL measurements: $^{29}P(p,\gamma)^{30}S$





D. Galaviz, B. Lynch, H. Schatz, B. Sherrill

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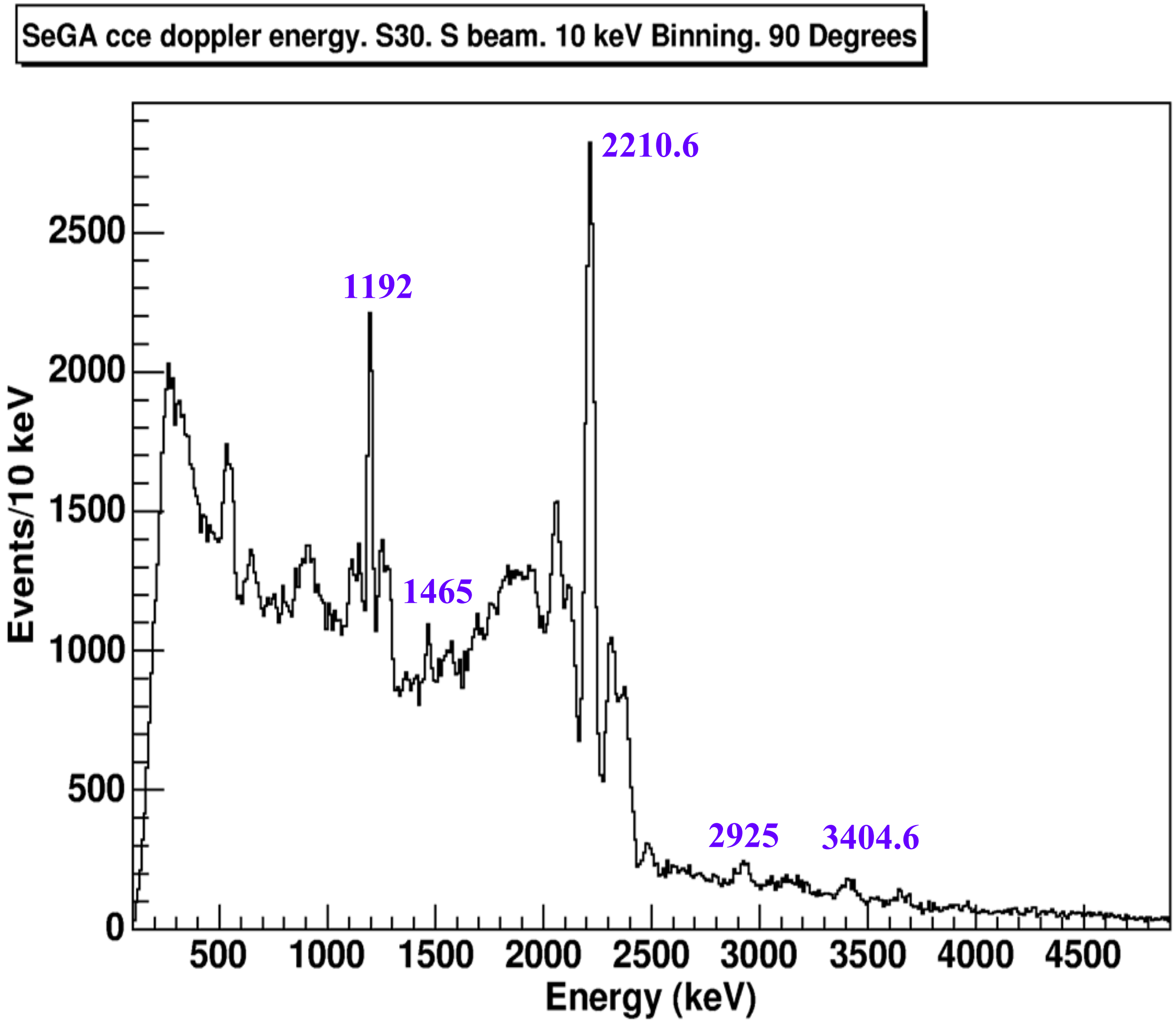

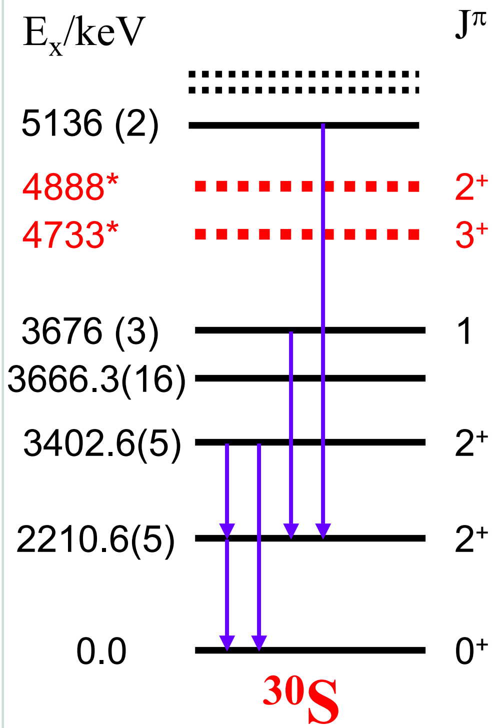

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