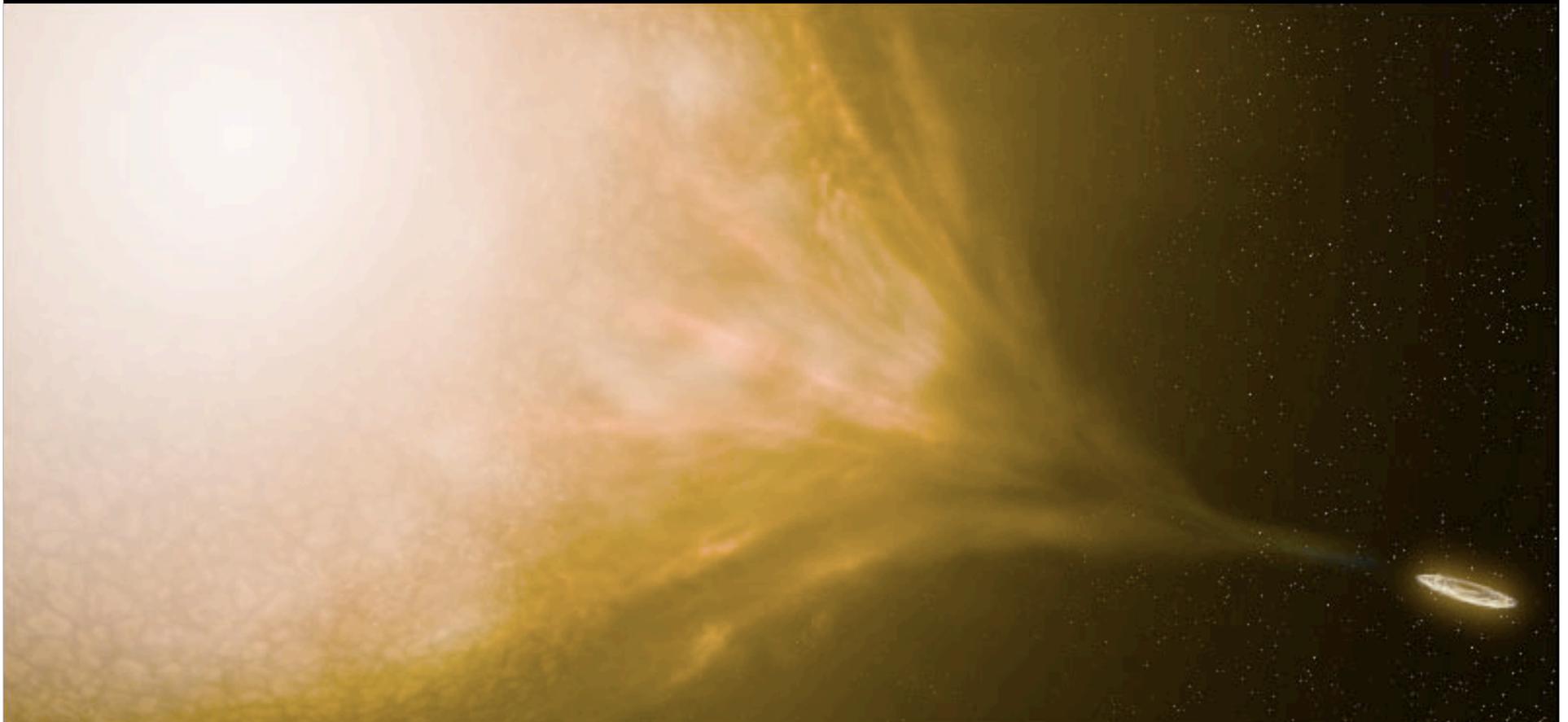


bottlenecks & waiting points in novae & x-ray burst nucleosynthesis

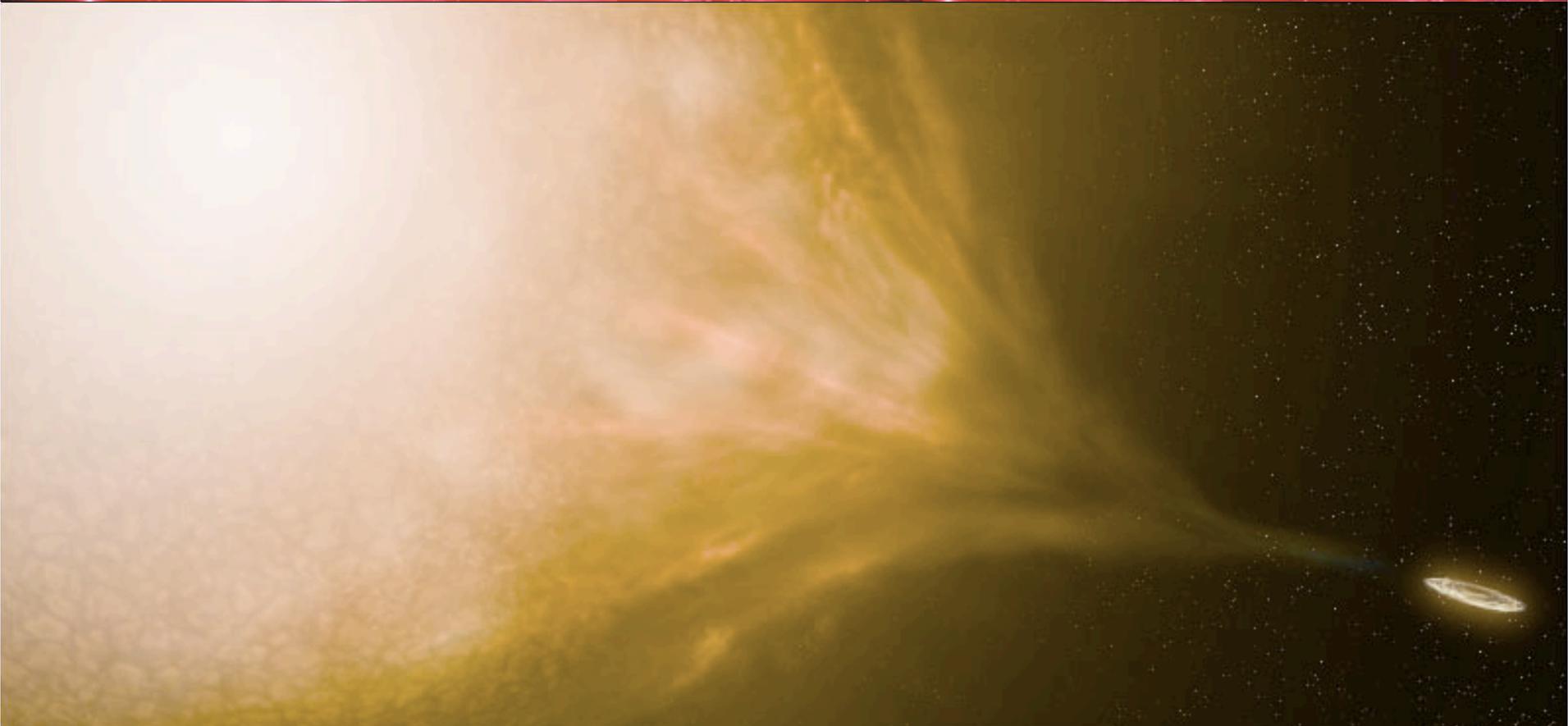


michael smith, tomomi sunayama*, w. raphael hix,
eric j. lingerfelt, kim buckner, caroline nesaraja

physics division, oak ridge national laboratory, oak ridge, tennessee, usa

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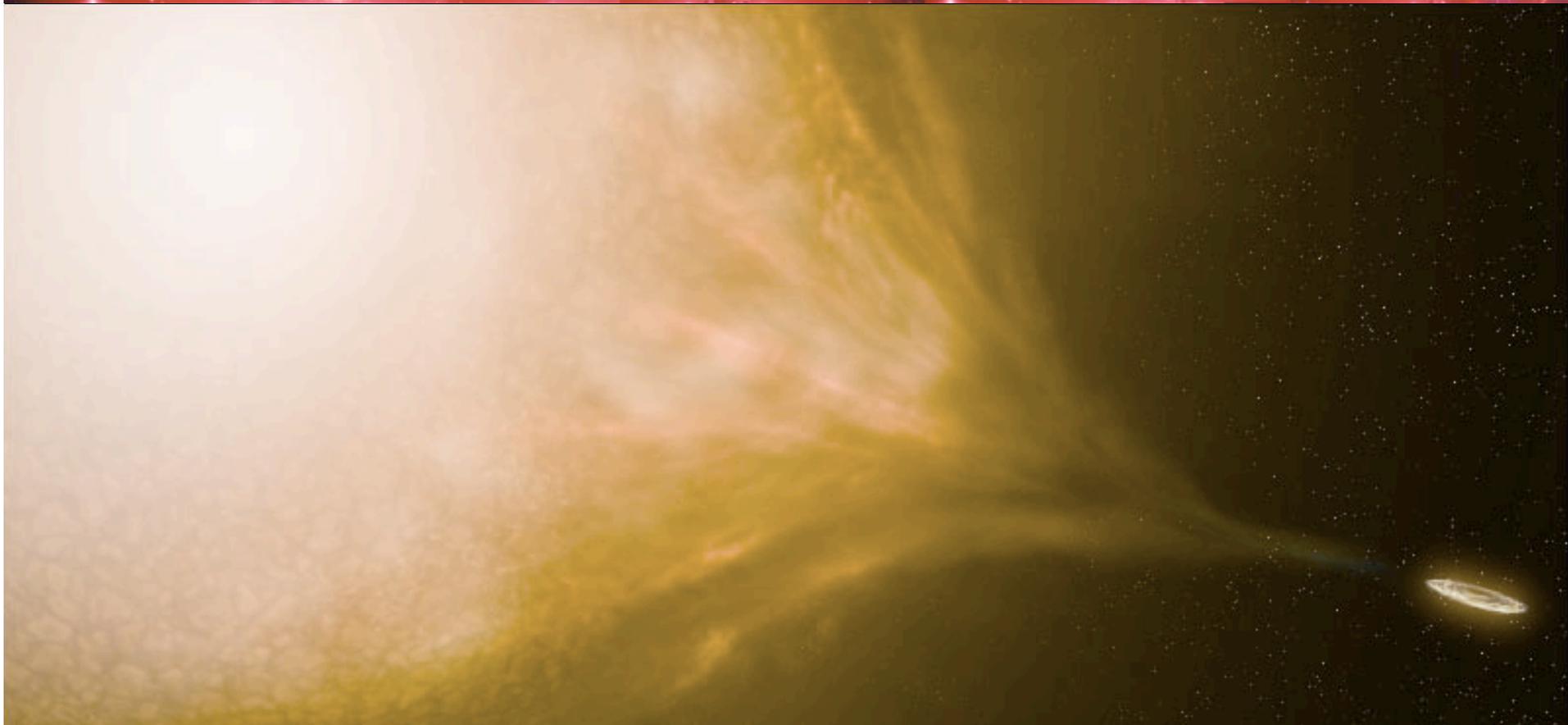
overview



nova and x-ray bursts are powered by hundreds to thousands of thermonuclear
reactions on proton-rich unstable nuclei

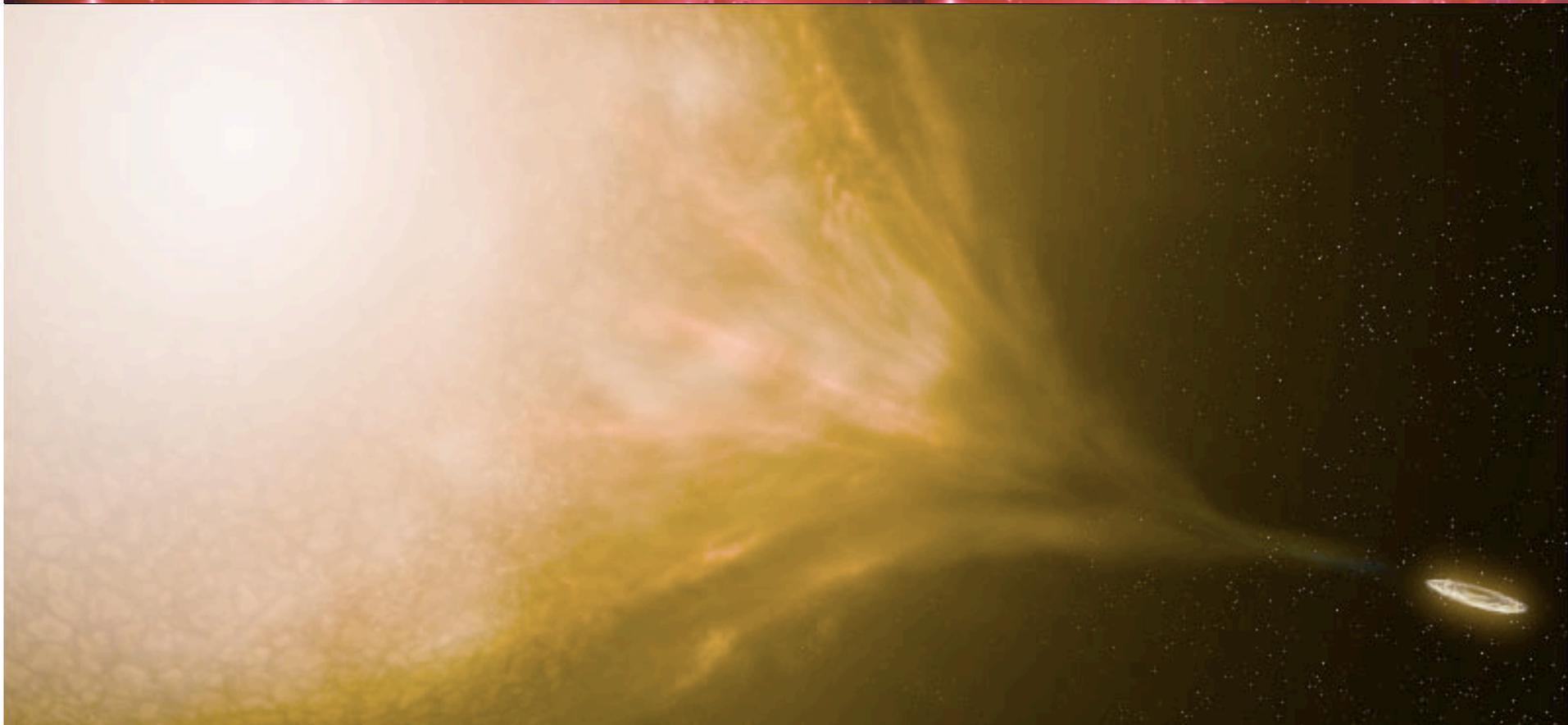
Waiting Point Nuclei and Bottleneck Reactions can impact the element creation and
energy generation in these explosions & should be identified for further study

overview



we have devised the **first quantitative definition** of Waiting Points and Bottlenecks in the rp-process and put this into an **online tool that anyone can use**

we have **verified** many Waiting Points and Bottlenecks in the literature and found **some new ones**; systematic calculations are underway



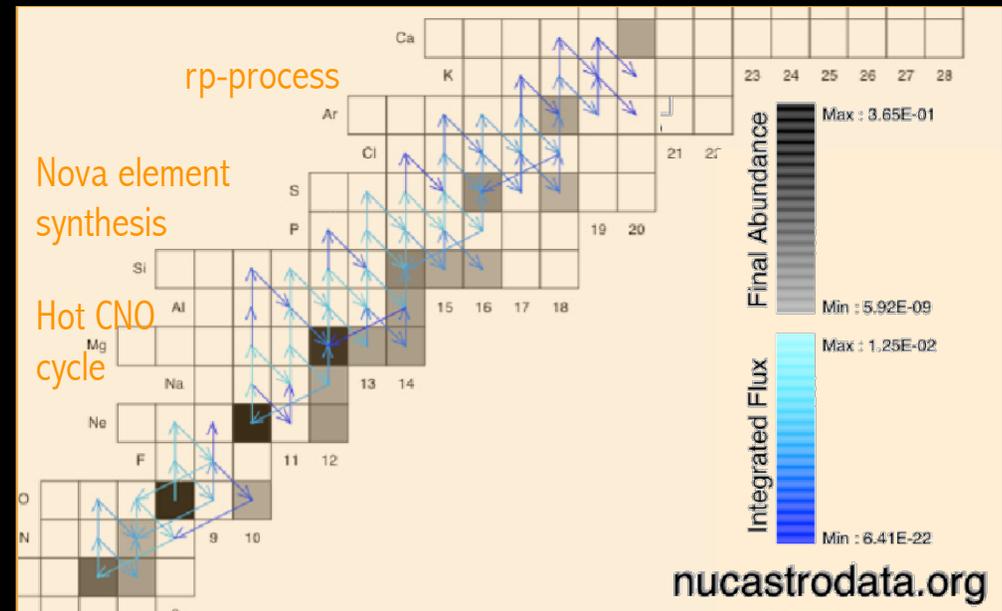
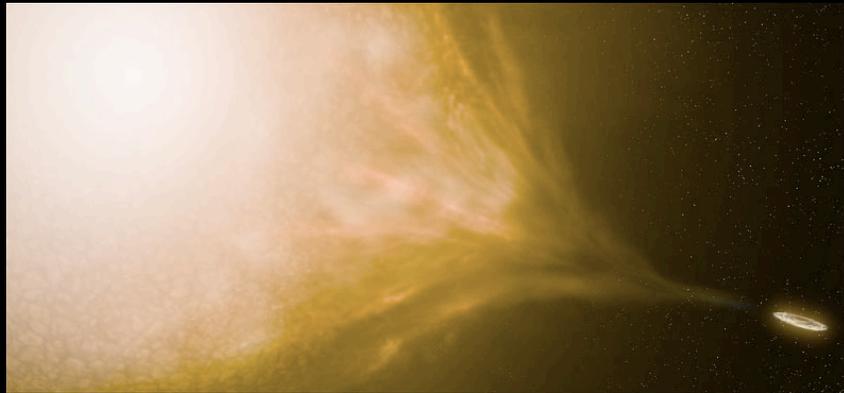
the online tool, part of the **Computational Infrastructure for Nuclear Astrophysics**, would be useful to **guide work on proton-rich nuclei** such as

measurements of masses, decay lifetimes, branching ratios

measurements of capture cross sections

theoretical calculation of structure & reactions of dripline nuclei

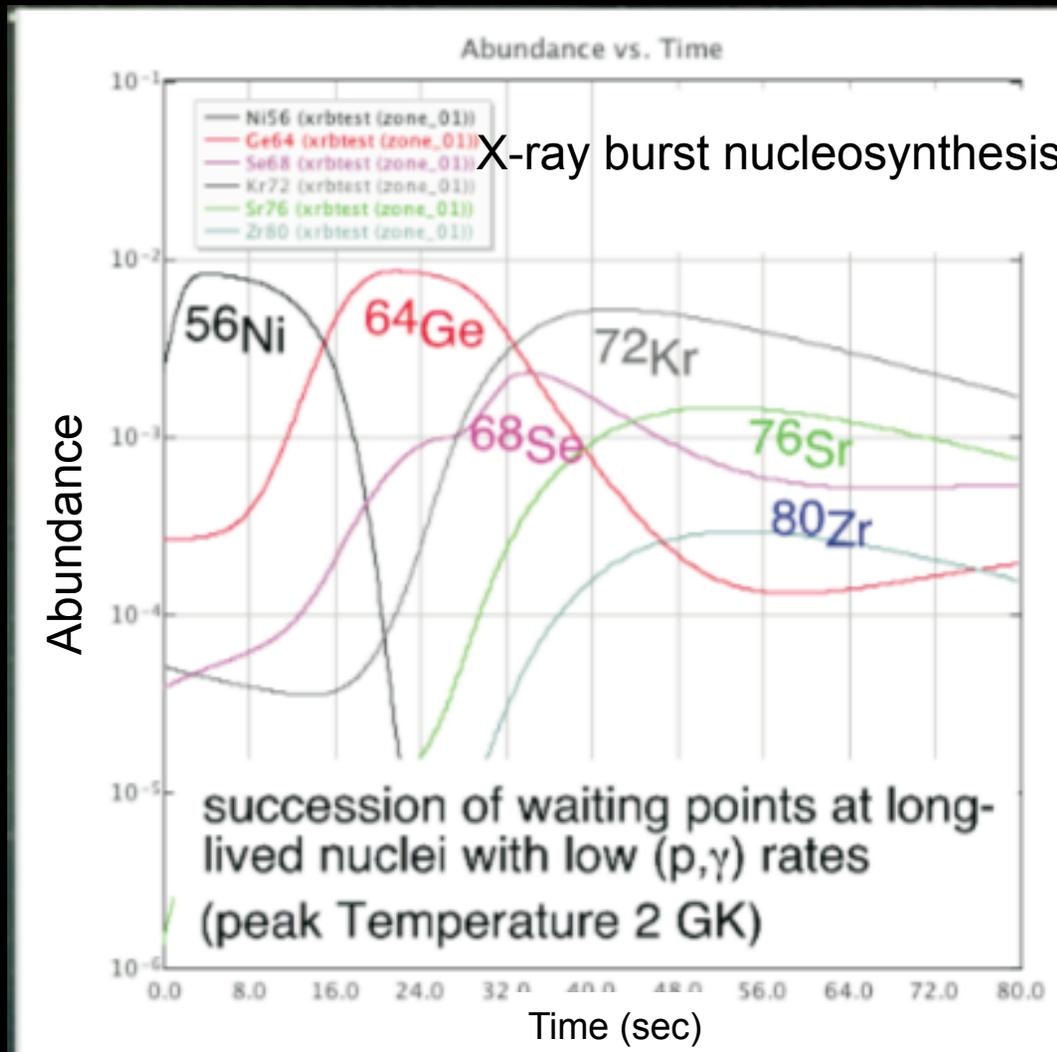
motivation – novae, x-ray bursts, & unstable nuclei



- reactions on **proton-rich unstable nuclei** power novae & x-ray bursts
- rates of these reactions are **crucial inputs** into **simulations** of these explosions, **influencing element creation & energy generation ...** and almost all **unmeasured**
- which reactions – of the 100s or 1000s – should be measured with RIBs ?
 - use **sensitivity studies** (change individual rates, examine changes in model predications)
 - use **Monte Carlo studies** (change all rates simultaneously, run 1000s of trials, examine correlations)
- consider “special” nuclei and reactions – Waiting Points and Bottlenecks

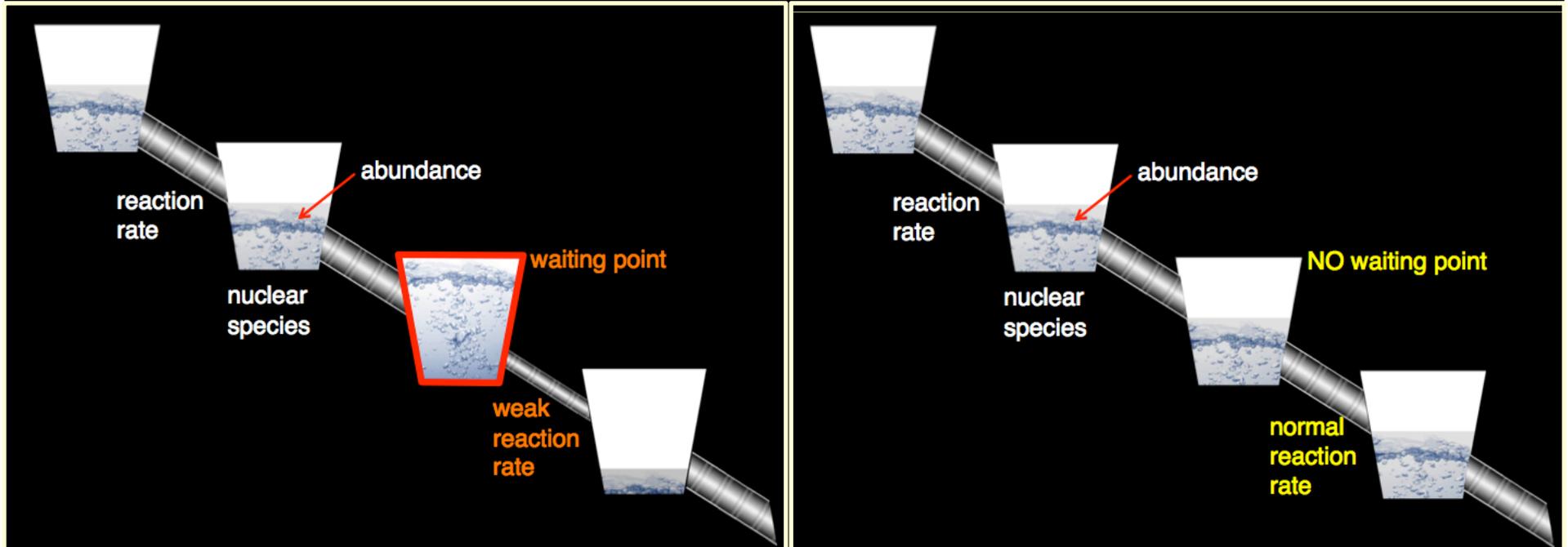
waiting points

waiting points: nuclear species that happen to “collect” material – FLOW goes in quickly but out slowly



waiting points

waiting points: nuclear species that happen to “collect” material – FLOW goes in quickly but out slowly



if flow goes out **faster**, no more collection of material, and many abundances **changed**

how do we **FIND** waiting points for further theoretical & experimental studies ?

waiting points

VOLUME 92, NUMBER 19

PHYSICAL REVIEW LETTERS

week ending
14 MAY 2004

Precise Mass Measurement of ^{68}Se , a Waiting-Point Nuclide along the rp Process

J. A. Clark,^{1,2} G. Savard,² K. S. Sharma,¹ J. Vaz,^{1,2} J. C. Wang,^{1,2} Z. Zhou,² A. Heinz,^{2,3} B. Blank,^{2,4} F. Buchinger,⁵
J. E. Crawford,⁵ S. Gulick,⁵ J. K. P. Lee,⁵ A. F. Levand,² D. Seweryniak,² G. D. Sprouse,⁶ and W. Trimble²

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(Received 26 November 2003; published 13 May 2004)

Eur. Phys. J. A **24**, 193–198 (2005)
DOI 10.1140/epja/i2004-10146-1

THE EUROPEAN
PHYSICAL JOURNAL A

Half-lives of rp -process waiting point nuclei

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THE ASTROPHYSICAL JOURNAL, 608:L61–L64, 2004 June 10

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PHYSICAL REVIEW C **79**, 015803 (2009)

β -decay half-life of the rp -process waiting-point nuclide ^{84}Mo

J. B. Stoker,^{1,2} P. F. Mantica,^{1,2} D. Bazin,² A. Becerril,^{2,3,4} J. S. Berryman,^{1,2} H. L. Crawford,^{1,2} A. Estrade,^{2,3,4}
C. J. Guess,^{2,3,4} G. W. Hitt,^{2,3,4} G. Lorusso,^{2,3,4} M. Matos,^{2,4} K. Minamisono,² F. Montes,^{2,4} J. Pereira,² G. Perdikkakis,²
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THE NUCLEAR REACTION WAITING POINTS: ^{22}Mg , ^{26}Si , ^{30}S , AND ^{34}Ar AND BOLOMETRICALLY DOUBLE-PEAKED TYPE I X-RAY BURSTS

JACOB LUND FISKER AND FRIEDRICH-KARL THIELEMANN

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Received 2004 January 29; accepted 2004 April 28; published 2004 May 7

New pathways to bypass the ^{15}O waiting point

I. Stefan, F. de Oliveira Santos, M.G. Pellegriti, M. Angélique, J.C. Dalouzy, F. de Grancey, M. Fadil, S. Grévy, M. Lenhardt, M. Lewitowicz, A. Navin, L. Perrot, M.G. Saint Laurent, I. Ray, O. Sorlin, C. Stodel, J.C. Thomas*, G. Dumitru, A. Buta, R. Borcea, F. Negoita, D. Pantelica[†], J.C. Angélique**, E. Berthoumieux[‡], A. Coc, J. Kiener, A. Lefebvre-Schuhl, V. Tatischeff[§], J.M. Daugas, O. Roig^{||}, T. Davinson^{||} and M. Stanoiu^{††}

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PHYSICAL REVIEW C

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JANUARY 1995

Bridging the waiting points: The role of two-proton capture reactions in the rp process

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Friedrich-Karl Thielemann

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(Received 15 August 1994)

many discussions of waiting points in the literature, but **NO quantitative definition**

bottlenecks and waiting points

michael smith ornl

waiting points - definition

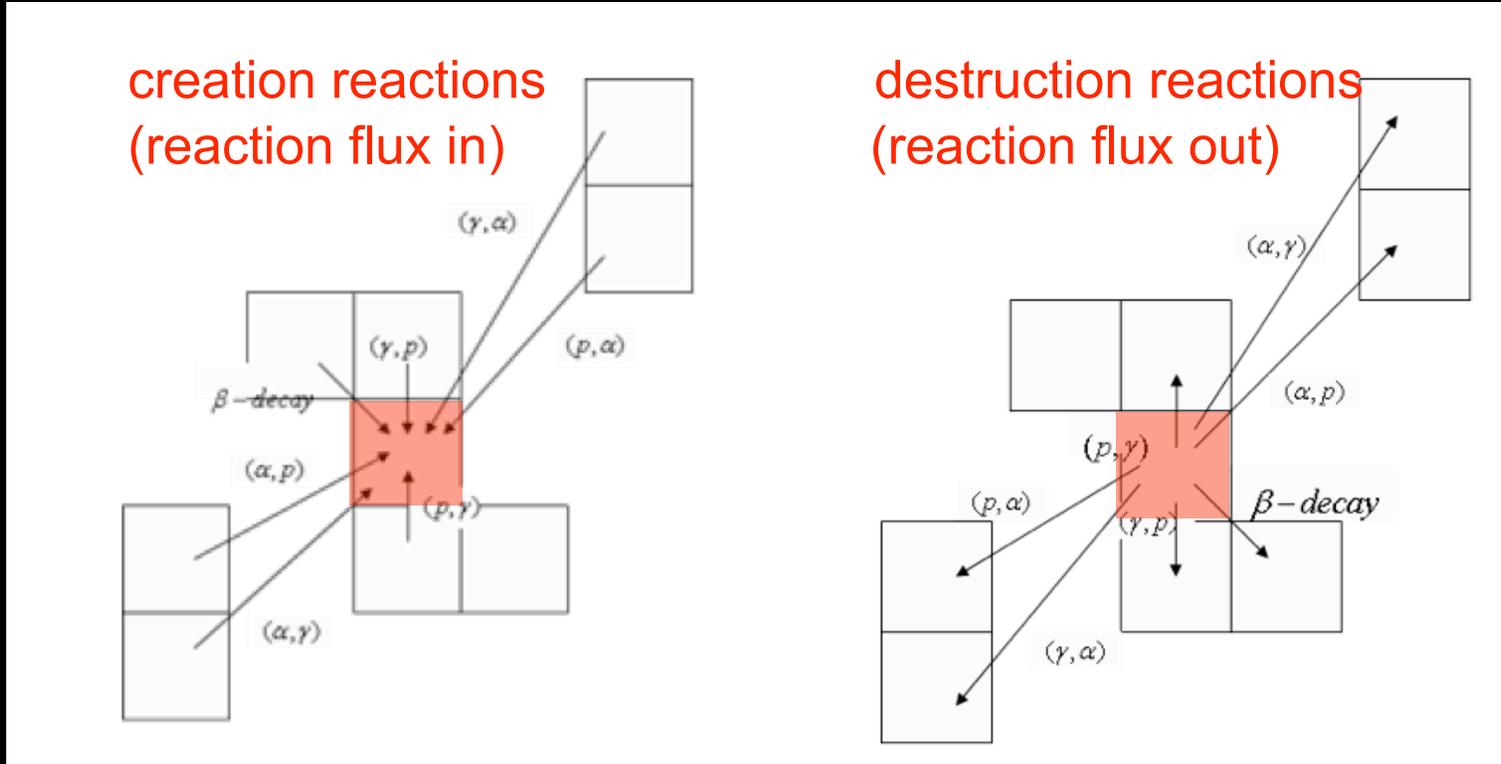
devise a **quantitative definition** of waiting point nuclei

each property we considered has some drawbacks

Quantity	Motivation	Exceptions and Issues
Q-value for (p, γ)	Low Q-value usually means suppressed (p, γ) capture rate	Q-value does not always track with rate, especially as temperatures vary widely during explosion
Reaction rate	Suppressed destruction reactions suggest a possible waiting point	Does not account for total rate of destruction which depends on reaction rate and abundance
β^+ decay lifetime	Long decay lifetime suggests a possible waiting point	Other reactions such as (p, γ) and (α, p) may destroy this nucleus
Destruction lifetime	Long lifetime suggests a possible waiting point	This tracks better than decay lifetime and also works for stable nuclei
abundance	Having a large abundance that increases suggests a waiting point	More flow may pass through neighboring nuclei and give them higher abundances
Reaction flux	Flux into nuclei should be larger than flux out	Better measure than reaction rate; can depend sensitively on time interval

we **COMBINE** these properties to come up with a good way to find waiting points

waiting points – search procedure

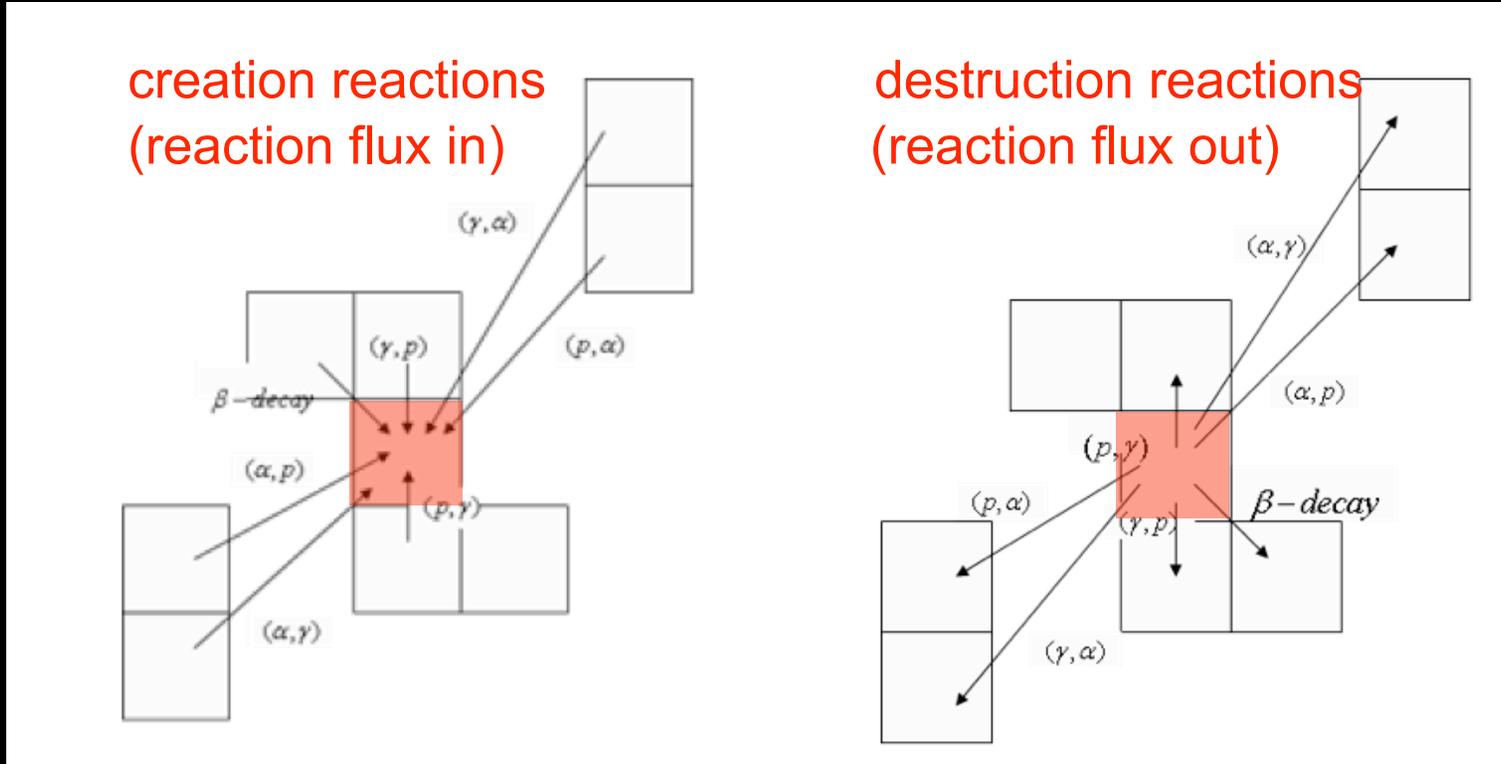


run an element synthesis calculation, store the abundance vs. time and reaction flux vs. time information

choose a **TIME INTERVAL**

examine each nucleus & compare to its neighbors in the N-Z plane

waiting points – search procedure



REJECT nuclei with

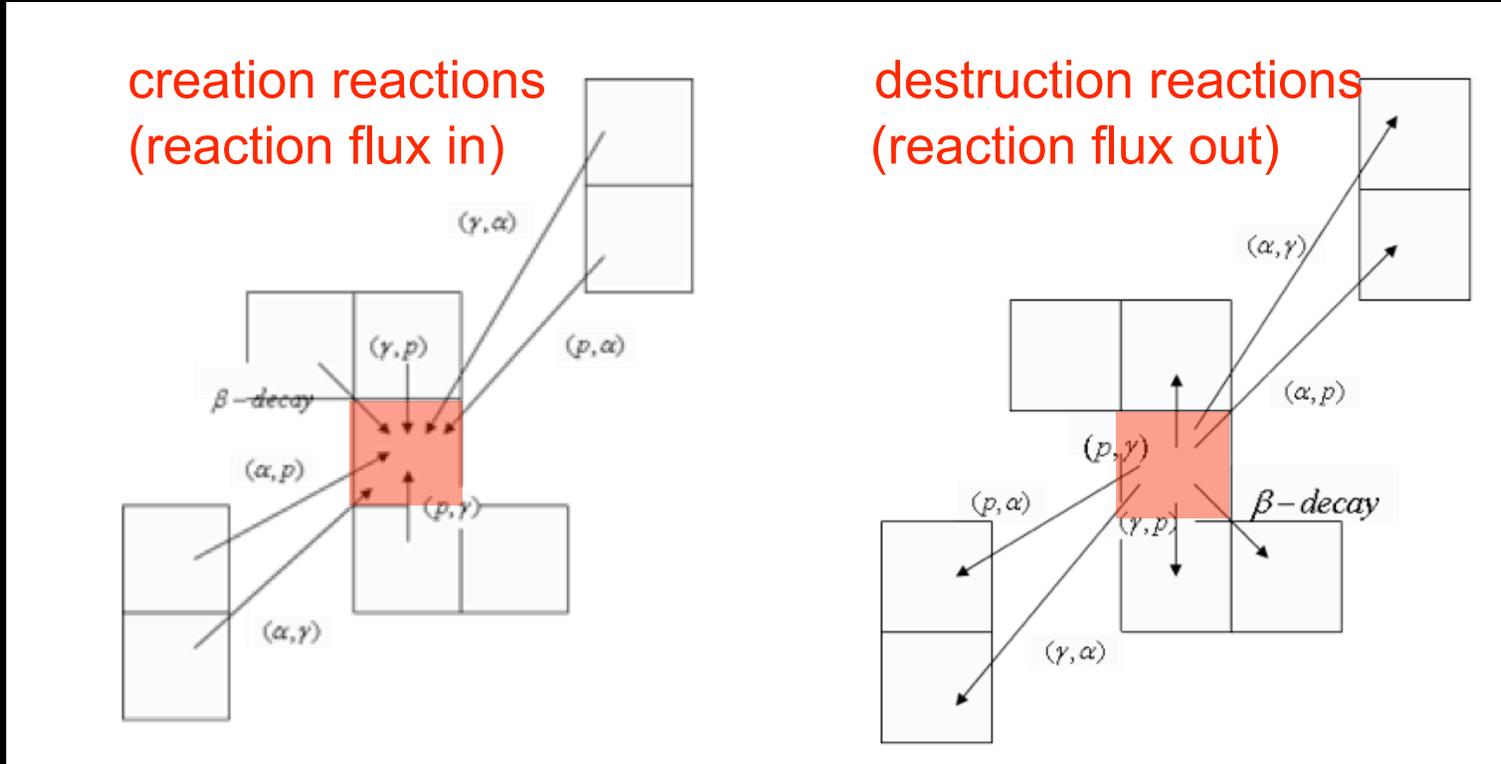
short destruction lifetime [< 0.2 sec]

low abundance [$< 10^{-6}$]

peak Flux out $>$ peak Flux in

negative total integrated flux [net flux is negative, abundance is decreasing]

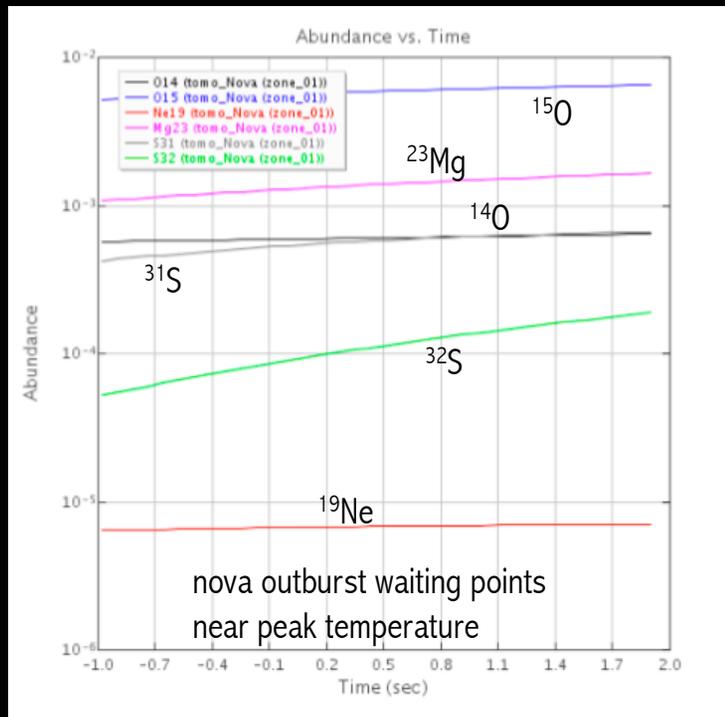
waiting points – search procedure



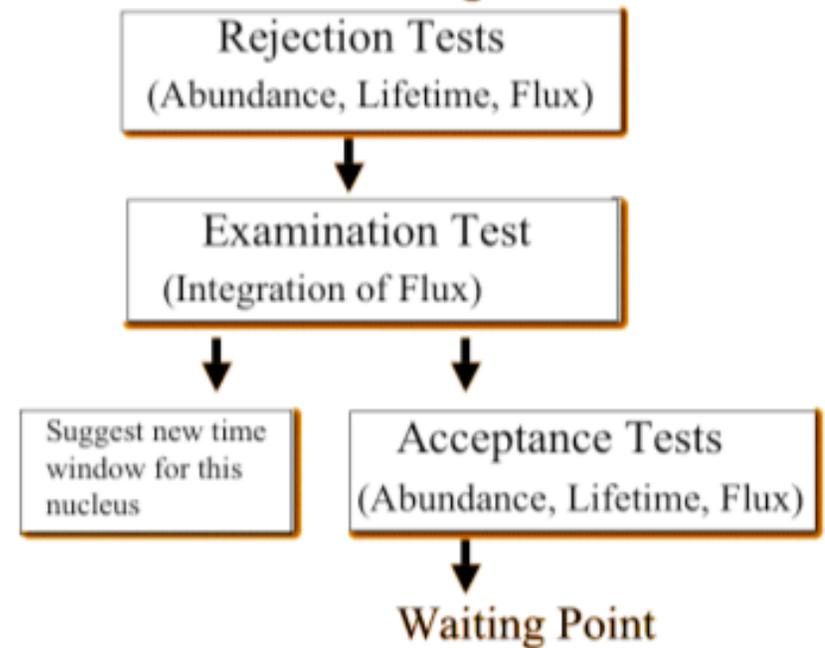
ACCEPT nuclei with
reasonably large total integrated Flux [$> 10^{-4}$]
AND reasonably long lifetime [> 1 sec]

REPEAT the test for all nuclei in the simulation

waiting points – testing procedure



Tests for Waiting Points



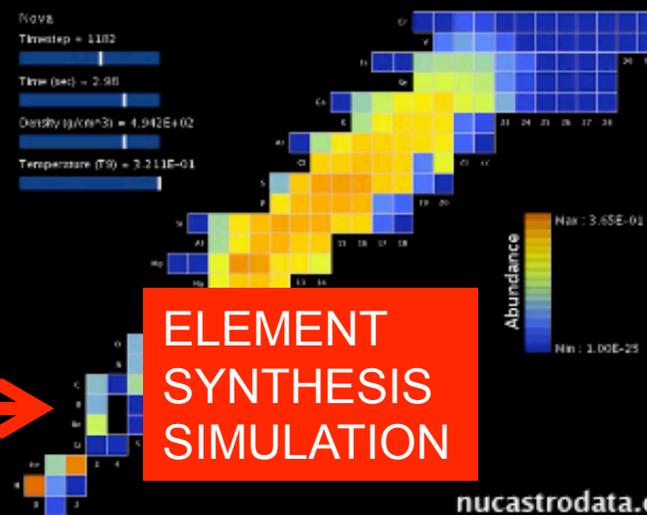
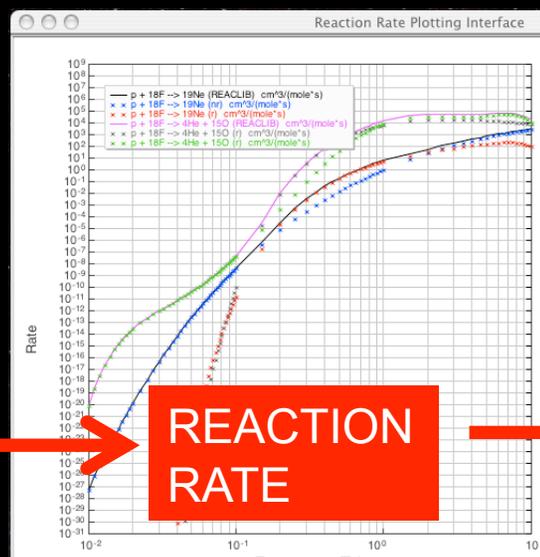
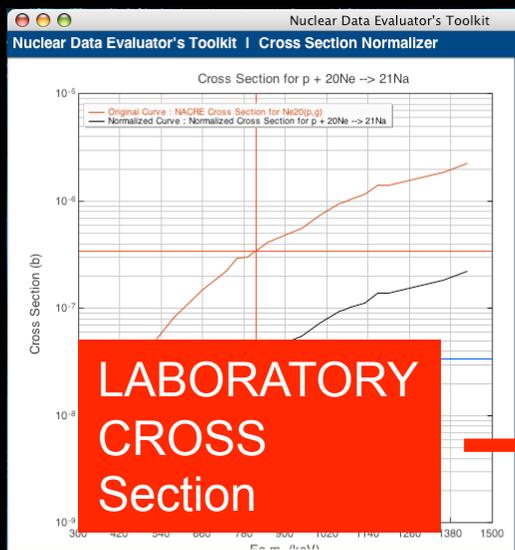
- **test algorithm** on a series of simulations
 - **verify** that **every waiting point** found by procedure meets our criteria
 - **verify** that there are **no other waiting points** missed by procedure
- try to **reproduce some known waiting points** from the literature
- change input rates in simulation to “create” a new waiting point or “destroy” an existing one – verify that our procedure works

online software for simulations & data processing

we put our waiting point finder tool online so anyone can use it ...

computational infrastructure for nuclear astrophysics

available at nucastrodata.org



users in 70 institutions in 20 countries

online system can determine the **astrophysical impact** of

- what we already measured
- what we propose to **measure next**

bottlenecks and waiting points

michael smith ornl

online software tool – waiting point finder

Waiting Point Finder | Select Simulation Parameters Step 1 of 3

Please select the appropriate radio button and enter a time (sec) or timestep range for the simulation containing less than 1000 timesteps. Then select the appropriate radio button and enter an isotope range or select default to choose all isotopes.

Selected simulation : /USER/xrb_may09

Enter Time Window below :

Timestep Timestep min : Timestep max :

Time (sec) Time min (sec) : Time max (sec) :

Enter Nuclei Range below :

Default (all isotopes) Z min : Z max :

Custom (enter range) N min : N max :

quickly perform searches for waiting points with custom parameters

online software tool – waiting point finder

Waiting Point Finder | Select Waiting Point Criteria Step 2 of 3

Please enter criteria for determination of waiting points in the fields below.

Min abundance :	1.0E-6
Min effective lifetime (lifetime against destruction) :	0.2
Min ratio of effective lifetime to beta lifetime :	0.5

[< Back](#) [Continue >](#)

quickly perform searches for waiting points with custom parameters

online software tool – waiting point finder

Waiting Point Finder **Results** Step 3 of 3

Below is a list of possible waiting points. Click *Submit Waiting Points* to close the Waiting Point Finder and visualize these results with the Animator. Click *Close Waiting Point Finder* to close the Waiting Point Finder and not submit the results. Check *View Detailed Report* to view the user input as well as the output of the Finder.

Waiting Point Finder Report : [View Detailed Report](#)

Isotope	Z	N
64Ge	32	32
72Kr	36	36
75Sr	38	37
76Sr	38	38

[Save](#) [Copy](#) [Print](#)

[< Back](#) [Close Waiting Point Finder](#) [Waiting Point Finder Home](#)

quickly perform searches for waiting points with custom parameters

online software tool – waiting point finder

waiting points displayed
with abundances or
reaction flux

The screenshot displays the 'waiting point finder' interface. On the left is a heatmap of isotopes, with elements labeled Ge, Ga, As, Se, Br, Kr, Rb, Sr, Y, Zr. The heatmap shows abundance or reaction flux values for various isotopes, with some cells highlighted in red. On the right is a control panel with the following settings:

- Choose Quantity: Abundance
- Timestep: 3024
- Time: 1.99242E+00
- Temp: 1.90015E+00
- Density: 2.59985E+05
- Abundance Min: 1.00004E-25
- Abundance Max: 7.06000E-01
- Abundance: [input field]
- Set Color Scale Settings

In the center, a 'Waiting Point Finder | Results' window shows 'Step 3 of 3'. It contains the following text:

Below is a list of possible waiting points. Click *Submit Waiting Points* to close the Waiting Point Finder and visualize these results with the Animator. Click *Close Waiting Point Finder* to close the Waiting Point Finder and not submit the results. Check *View Detailed Report* to view the user input as well as the output of the Finder.

Below this text is a table of waiting points:

Isotope	Z
64Ge	32
72Kr	36
75Sr	38
76Sr	38

An 'Attention!' dialog box is overlaid on the results window, stating: 'The waiting points you found have been submitted to and are now available in the Element Synthesis Animator.' Below the dialog are buttons for 'OK', 'Save', 'Copy', 'Print', 'Submit Waiting Points', '< Back', 'Close Waiting Point Finder', and 'Waiting Point Finder Home'.

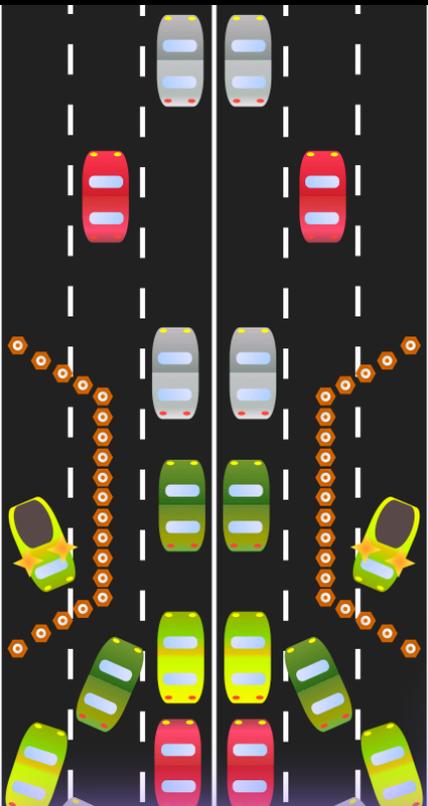
quickly perform searches for waiting points with custom parameters

bottlenecks

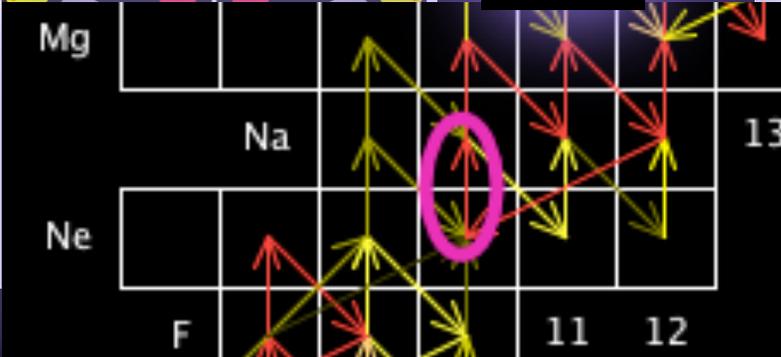
all reaction FLOW passes through these reactions

if a bottleneck reaction is turned off, result is a
“Thermonuclear Traffic Jam”

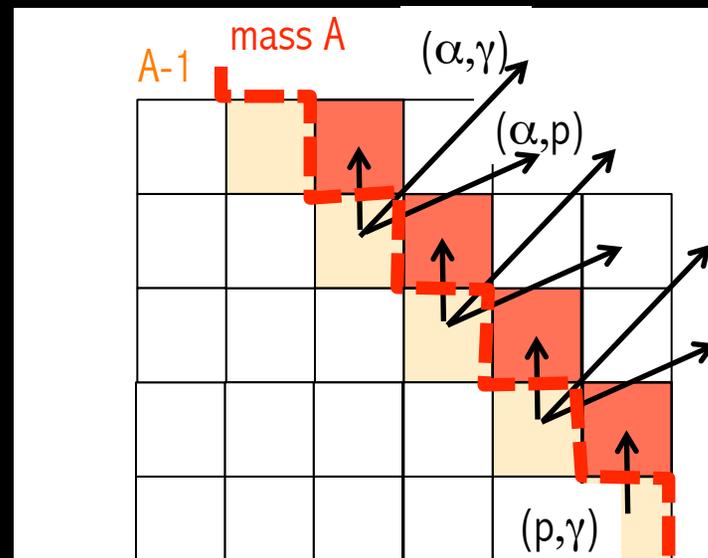
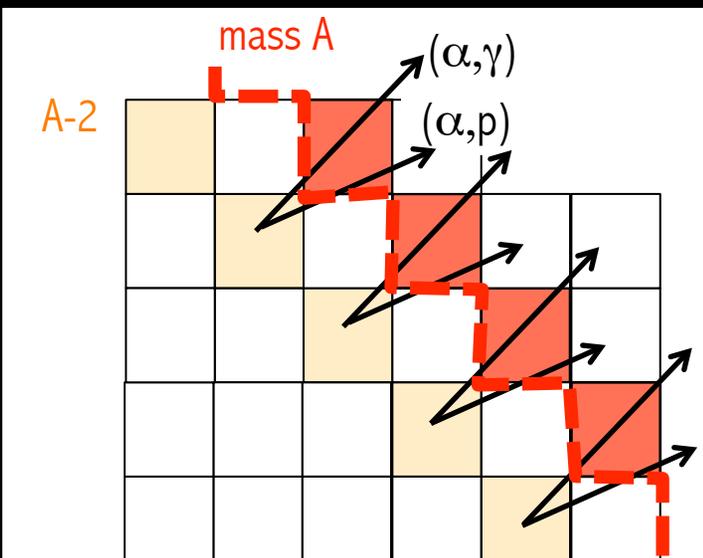
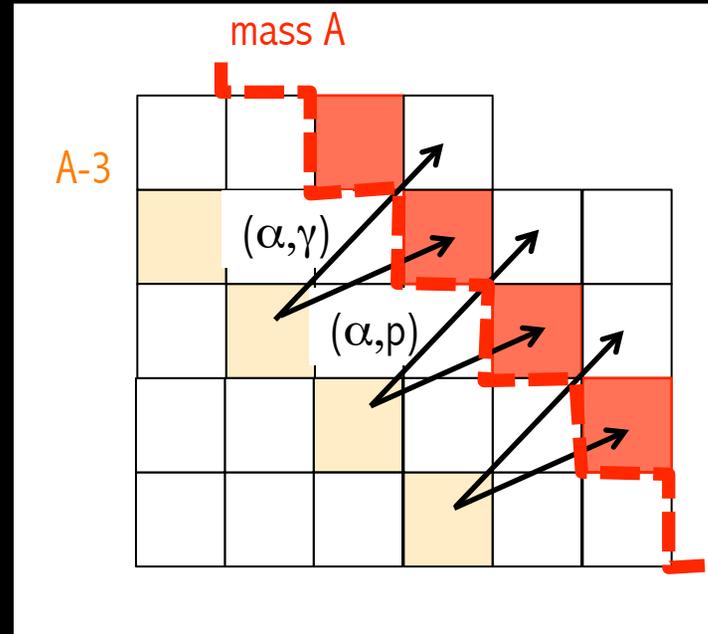
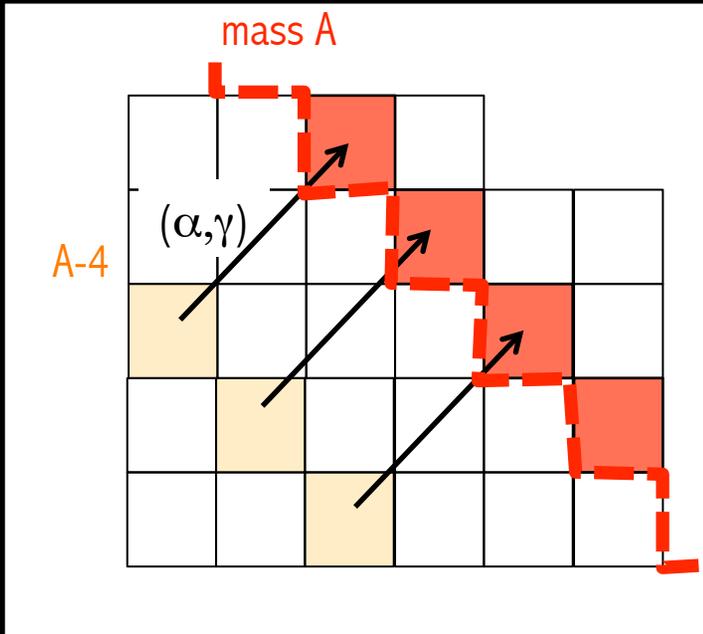
how do we define & find bottlenecks ?



10^7



bottlenecks – definition

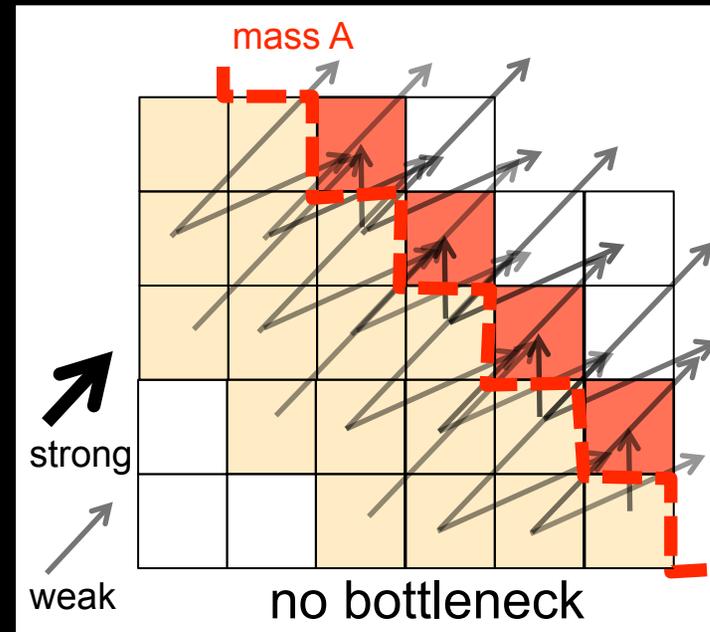
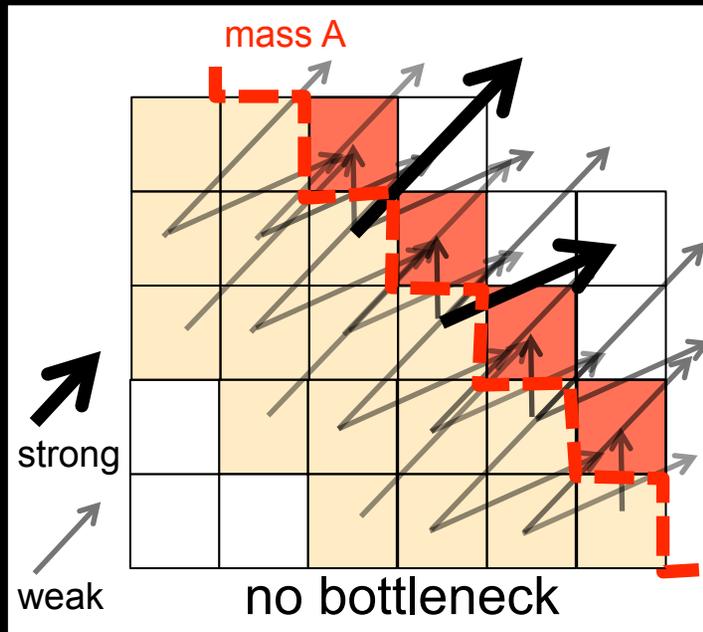


consider all reactions that produce nuclei with mass greater than or equal to A

bottlenecks and waiting points

michael smith ornl

bottlenecks – search procedure



REJECT presence of bottleneck if

all reaction fluxes too low [$< 10^{-12}$] relative to largest flux in simulation

OR two or more fluxes are too high [$> 10^{-6}$] relative to largest flux

online software tool – bottleneck finder

Bottleneck Reaction Finder | Select Simulation Parameters Step 1 of 3

Please enter a timestep range for the simulation. Then select the appropriate radio button and enter a mass range or select default to choose all masses.

Selected simulation : /USER/xrb_may09

Enter Timestep Window below :

Timestep min : Timestep max :

Enter Mass Range below :

Custom (enter range) A min : A max :

Default (all masses)

quickly perform searches for bottlenecks with custom parameters

online software tool – bottleneck finder

Bottleneck Reaction Finder

Bottleneck Reaction Finder | Select Bottleneck Reaction Finder Criteria Step 2 of 3

Please enter the parameters for determining the bottleneck reactions in the fields below. Flux Separation Factor: the maximum flux ratio between the reaction with the second largest flux to that of the largest flux (the potential bottleneck reaction) [default is 1.0E-04] in this mass region. High Flux Threshold: the minimum flux ratio of a Major Bottleneck Reaction to the maximum flux in the simulation [default is 1.0E-05]. Low Flux Threshold: the minimum flux ratio of a Minor Bottleneck Reaction to the maximum flux in the simulation [default is 1.0E-12].

Flux Separation Factor (between 0 and 1) :	<input type="text" value="1.0E-4"/>
Low Flux Threshold :	<input type="text" value="1.0E-12"/>
High Flux Threshold :	<input type="text" value="1.0E-5"/>

quickly perform searches for bottlenecks with custom parameters

online software tool – bottleneck finder

Bottleneck Reaction Finder **Results** Step 3 of 3

Below is a list of reactions that are bottlenecks for the synthesis of nuclei with masses greater than or equal to the Bottleneck Mass. Click *Submit Bottleneck Reactions* to visualize these results with the Animator. Click *Close Bottleneck Reaction Finder* to close the Bottleneck Reaction Finder and not submit the results. Check *View Detailed Report* to view the user input as well as the output of the Finder.

Bottleneck Reaction Finder Report : View Detailed Report

Bottleneck Mass	Reaction	Decision
13	$^{12}\text{C} \rightarrow ^{13}\text{N}$	Major Bottleneck
64	$^{63}\text{Ga} \rightarrow ^{64}\text{Ge}$	Major Bottleneck
68	$^{67}\text{As} \rightarrow ^{68}\text{Se}$	Major Bottleneck
72	$^{71}\text{Br} \rightarrow ^{72}\text{Kr}$	Major Bottleneck

Save Copy Print

Submit Bottleneck Reactions

< Back Close Bottleneck Reaction Finder Bottleneck Reaction Finder Home

quickly perform searches for bottlenecks with custom parameters

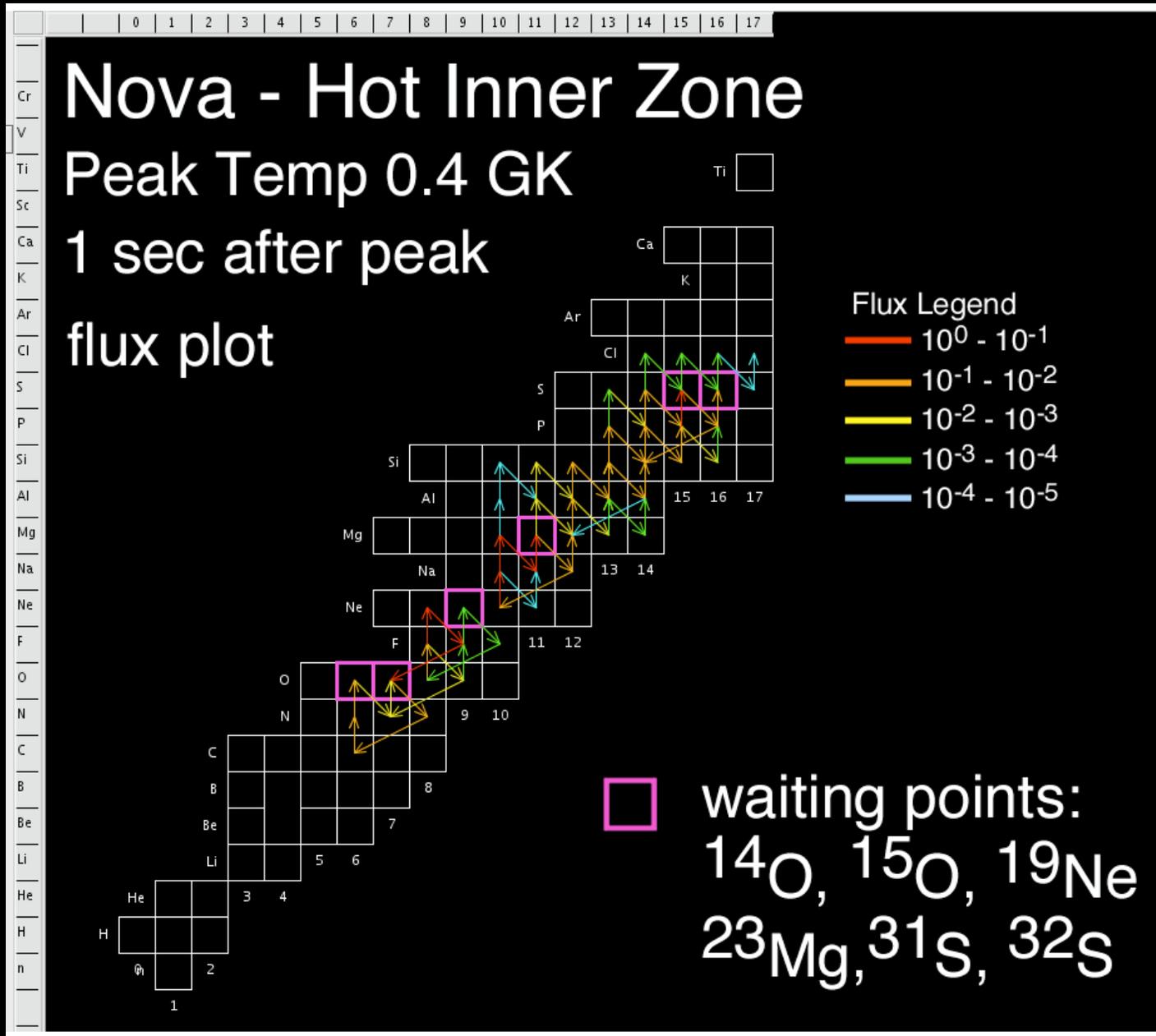
online software tool – bottleneck finder

bottlenecks displayed
with abundances or
reaction flux

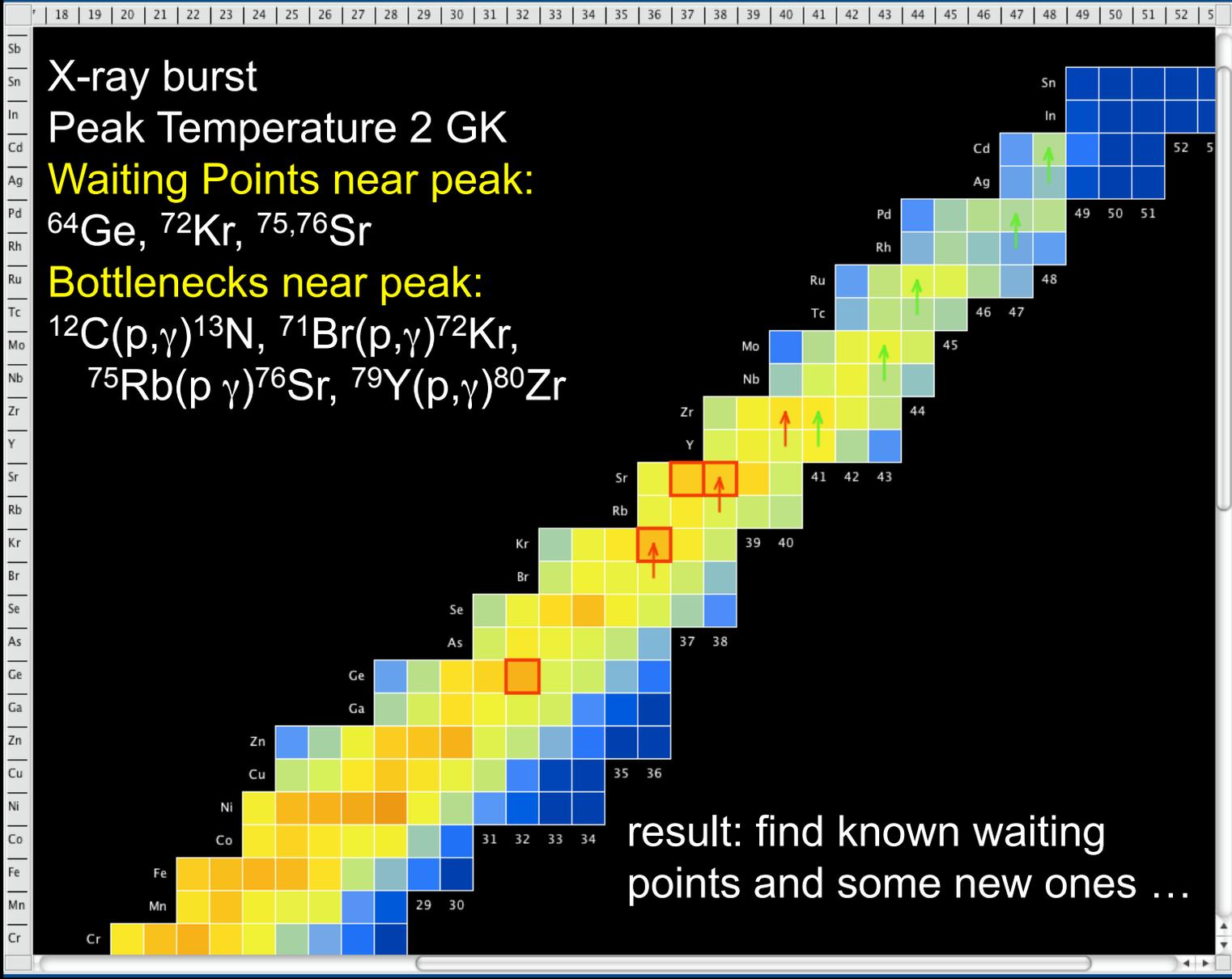
The screenshot shows the 'Element Synthesis Animator' interface on the left, displaying a grid of elements from atomic number 26 to 40. The grid is color-coded by abundance, with red boxes highlighting specific elements (Ga, Ge, As, Se, Br, Kr, Rb, Sr, Y, Zr) and red arrows pointing to them. On the right, the 'Bottleneck Reaction Finder' window is open, showing simulation parameters: 'Choose Simulation: xrb_may09 (zone_01)', 'Choose Quantity: Abundance', 'Timestep: 3024', 'Time: 1.99242E+00', 'Temp: 1.90015E+00', 'Density: 2.59985E+05', 'Abundance Min: 1.00004E-25', and 'Abundance Max: 7.06000E-01'. Below these parameters, the 'Bottleneck Reaction Finder | Results' section contains instructions and a 'Bottleneck Reaction Finder Report' section with a checked checkbox. A small 'Attention!' dialog box is overlaid on the report, stating: 'The bottleneck reactions you found have been submitted to and are now available in the Element Synthesis Animator.' with an 'OK' button.

quickly perform searches for bottlenecks with custom parameters

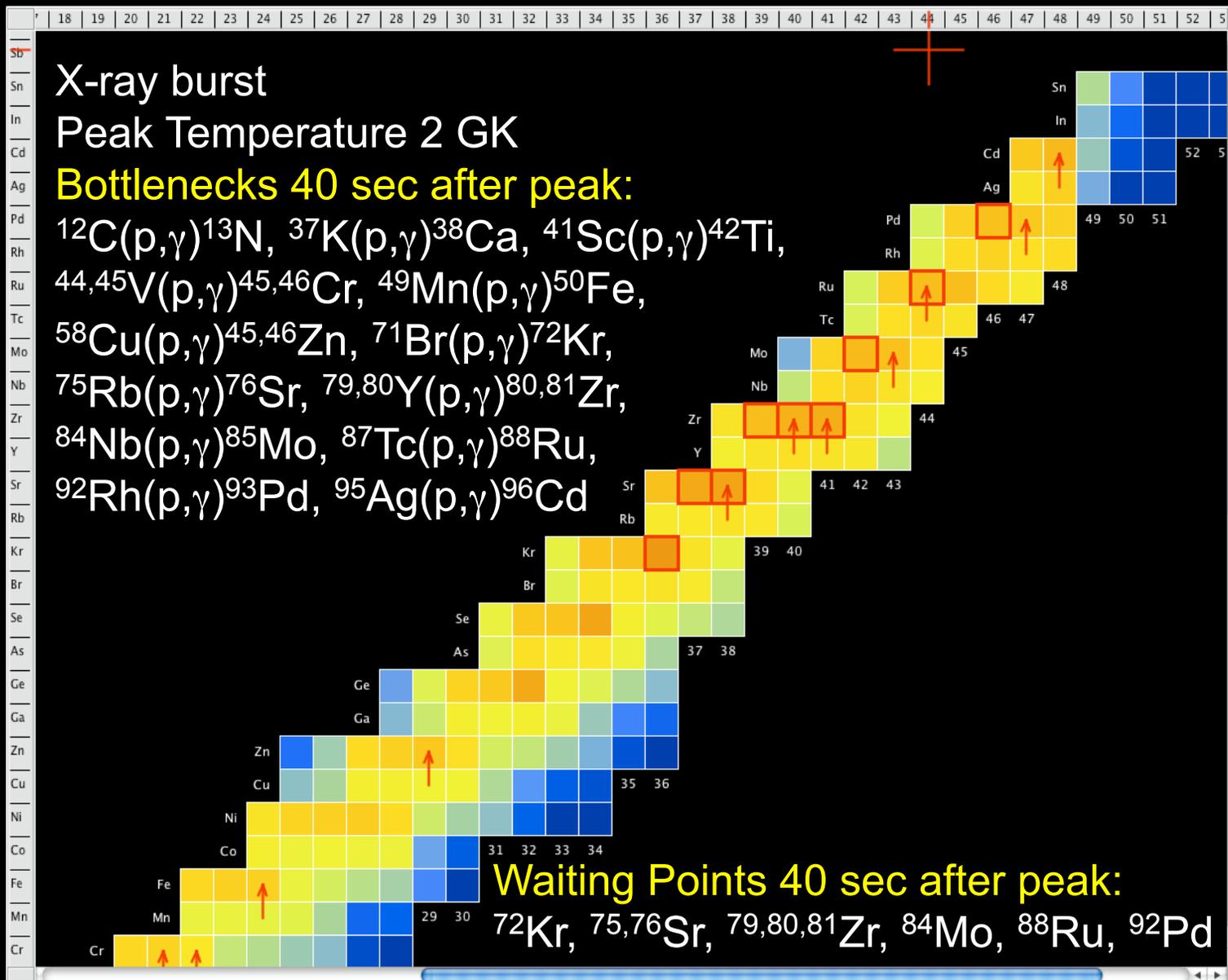
waiting points - results



bottlenecks & waiting points - results



bottlenecks & waiting points - results



future

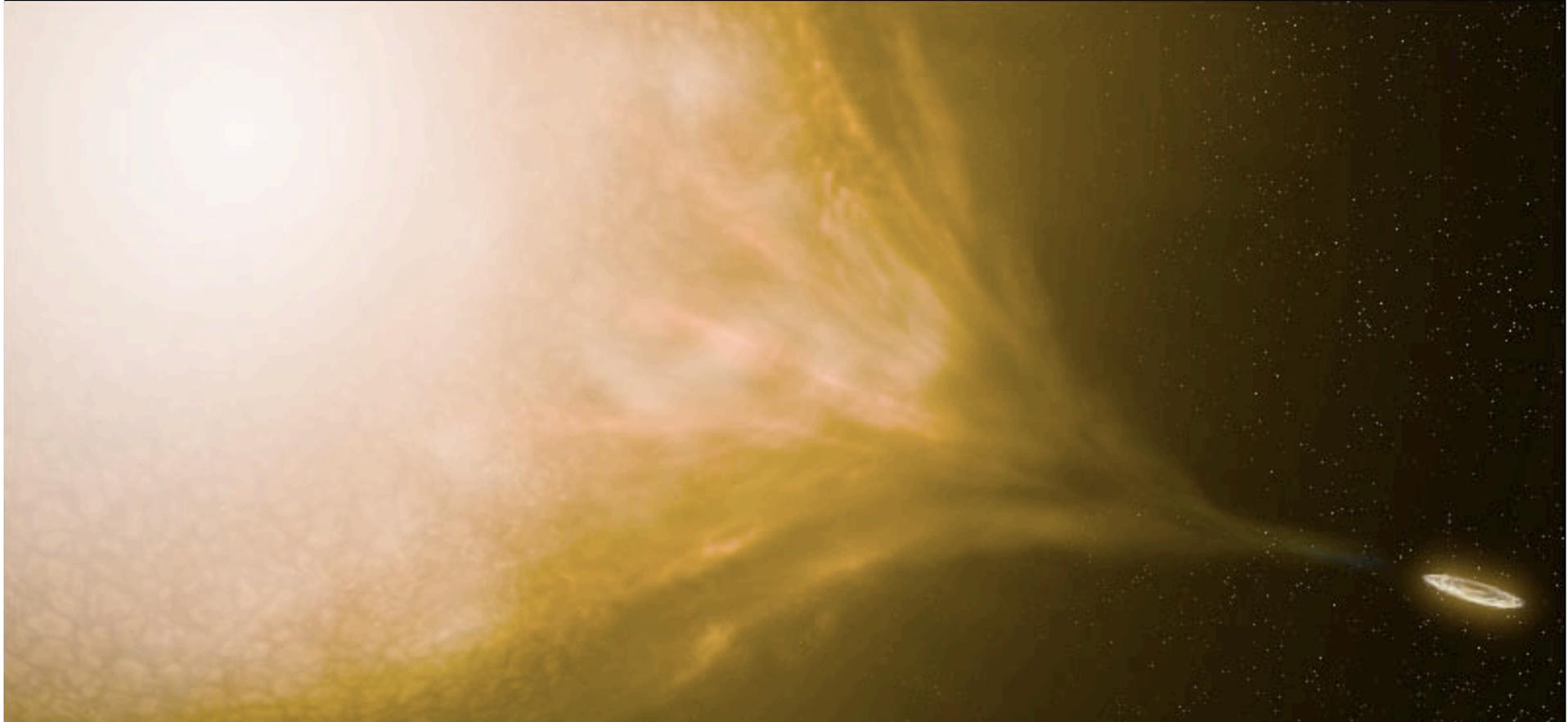


systematic searches of nova & x-ray burst simulations for Bottlenecks & Waiting Points –
determine dependence on astrophysical model, search parameters, time window

devise more elaborate criteria to **RANK** waiting points and bottlenecks

devise tools to **search for other “special” nuclei** and reactions in rp-process burning

summary



Waiting Point Nuclei and Bottleneck Reactions can impact the element creation and light curve of novae & x-ray bursts

we have quantitatively defined these concepts & built an **online tool** to find them

we used our tool to verify numerous waiting points / bottlenecks & find some new ones