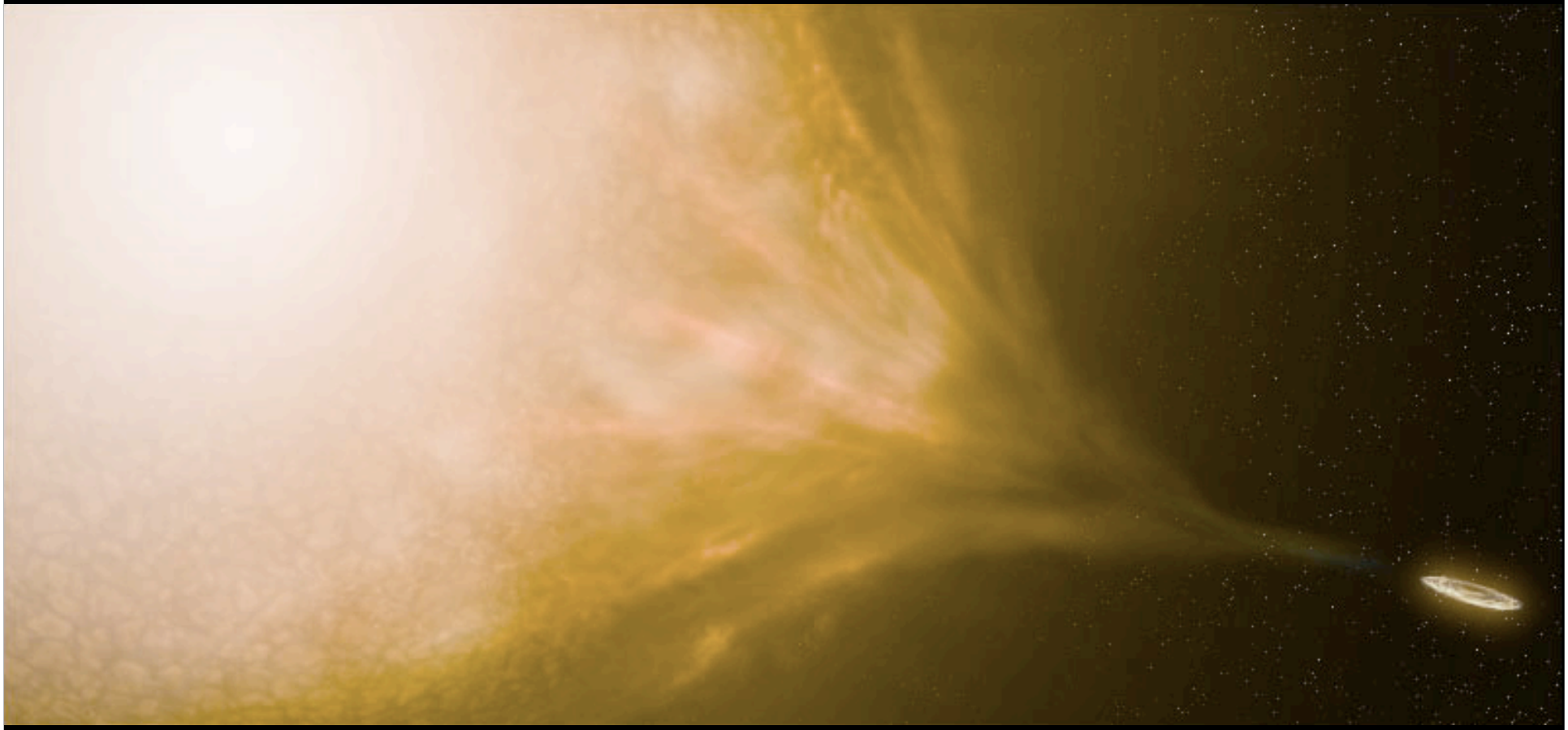
bottlenecks & waiting points in novae & x-ray burst nucleosynthesis



michael smith, tomomi sunayama*, w. raphael hix,
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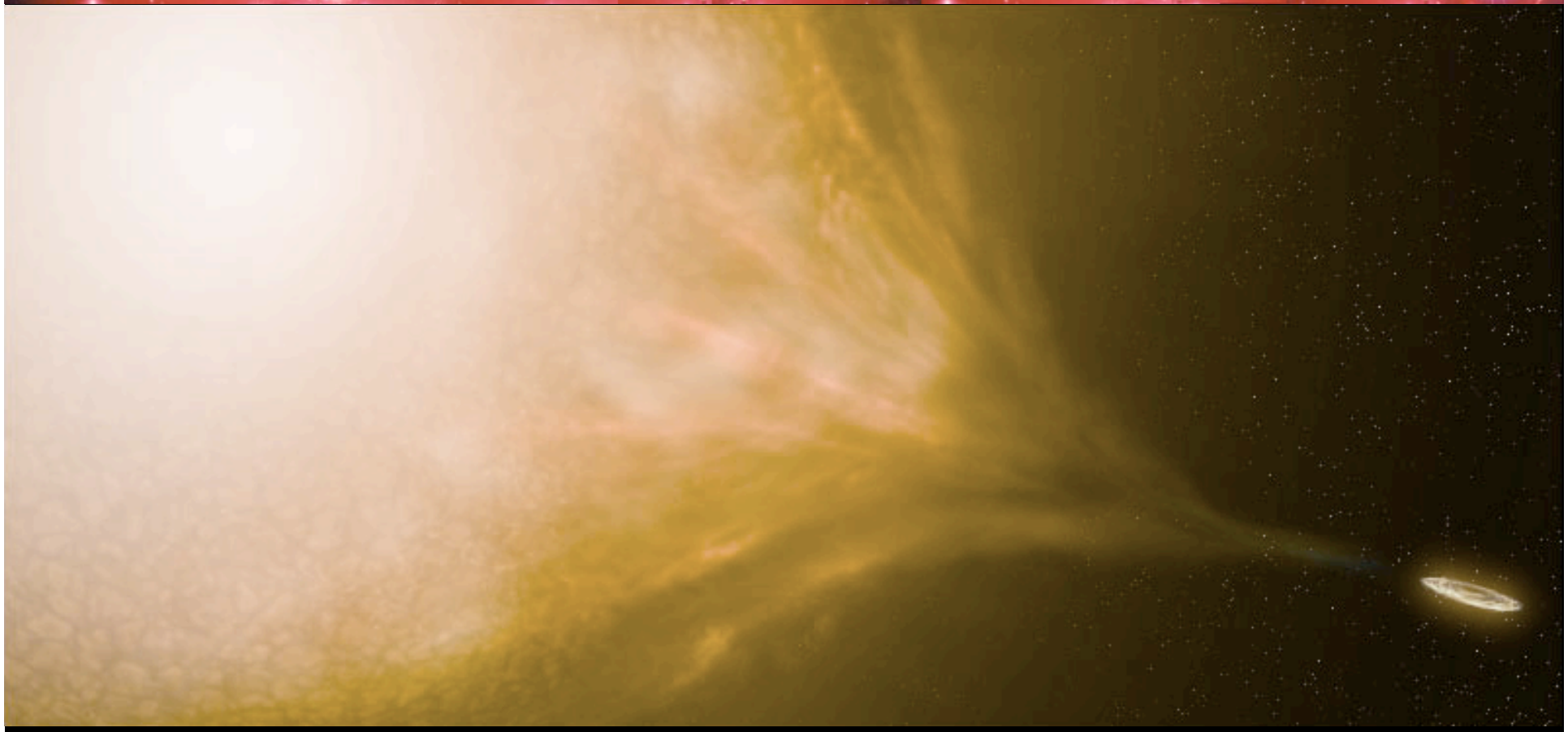
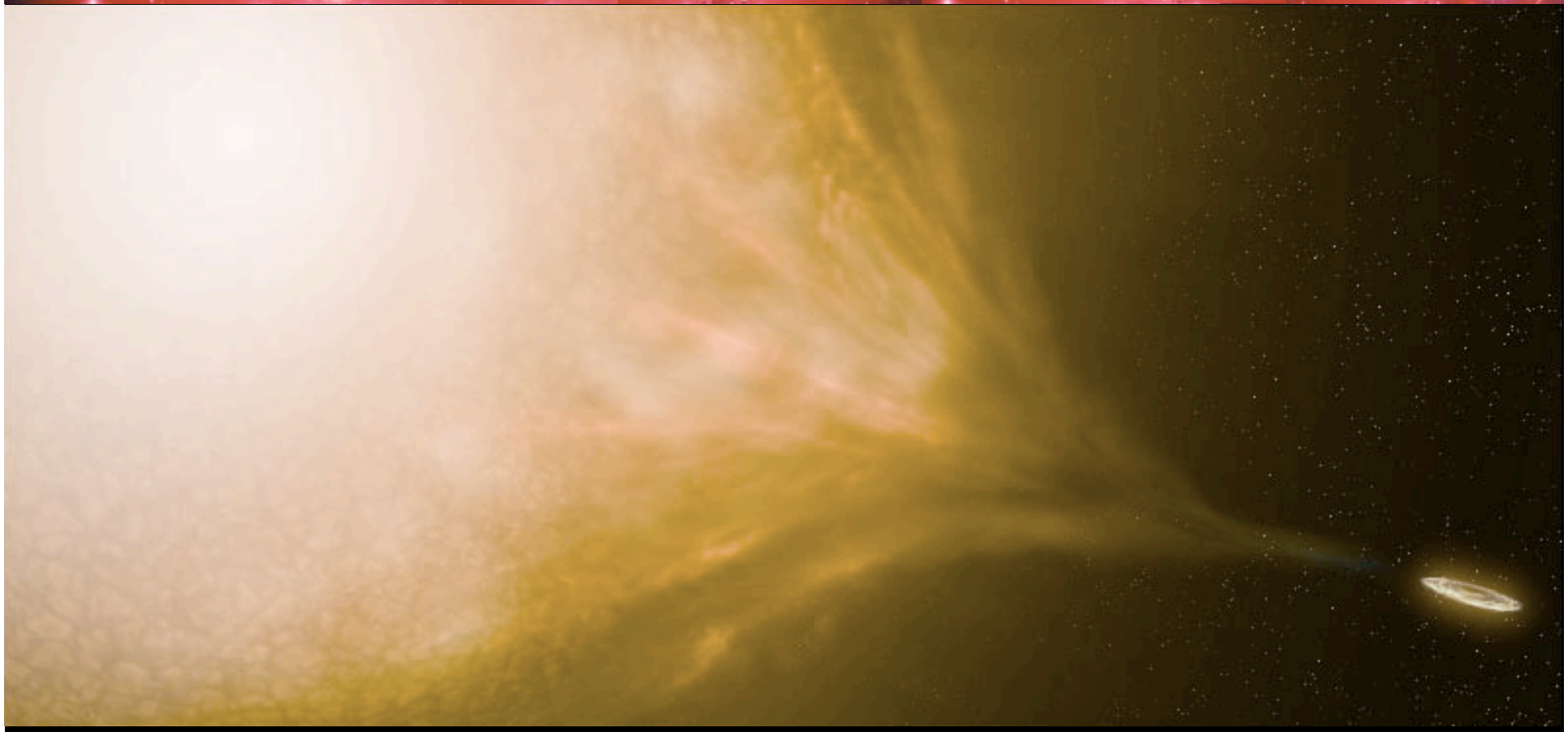
overview



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

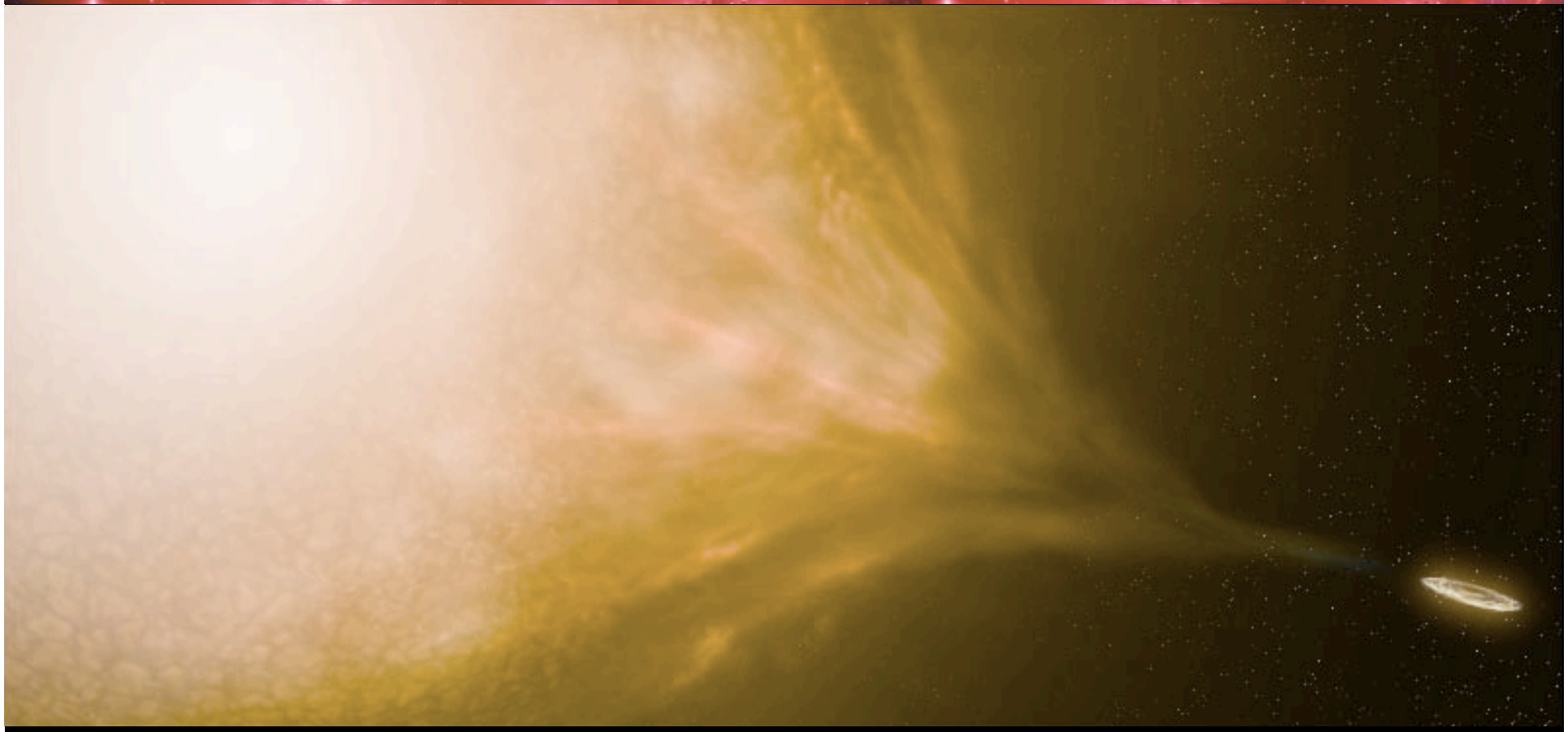
overview



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

overview



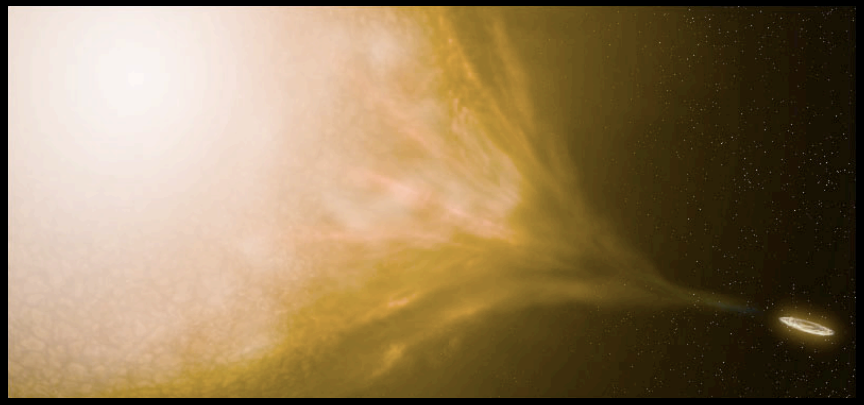
the online tool, part of the Computational Infrastructure for Nuclear Astrophysics, would be useful to guide work on proton-rich nuclei such as

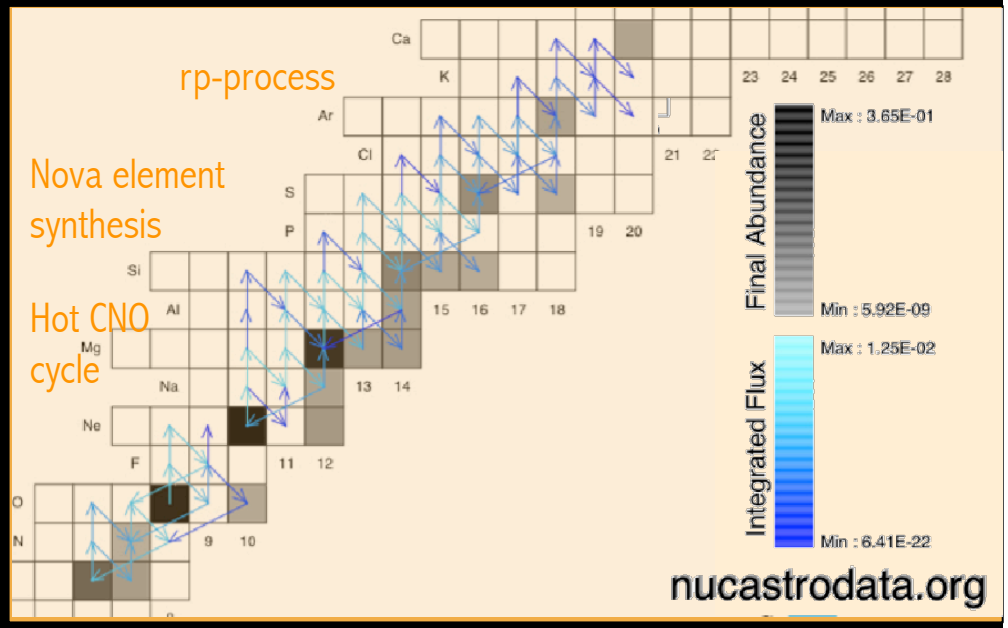
measurements of masses, decay lifetimes, branching ratios

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

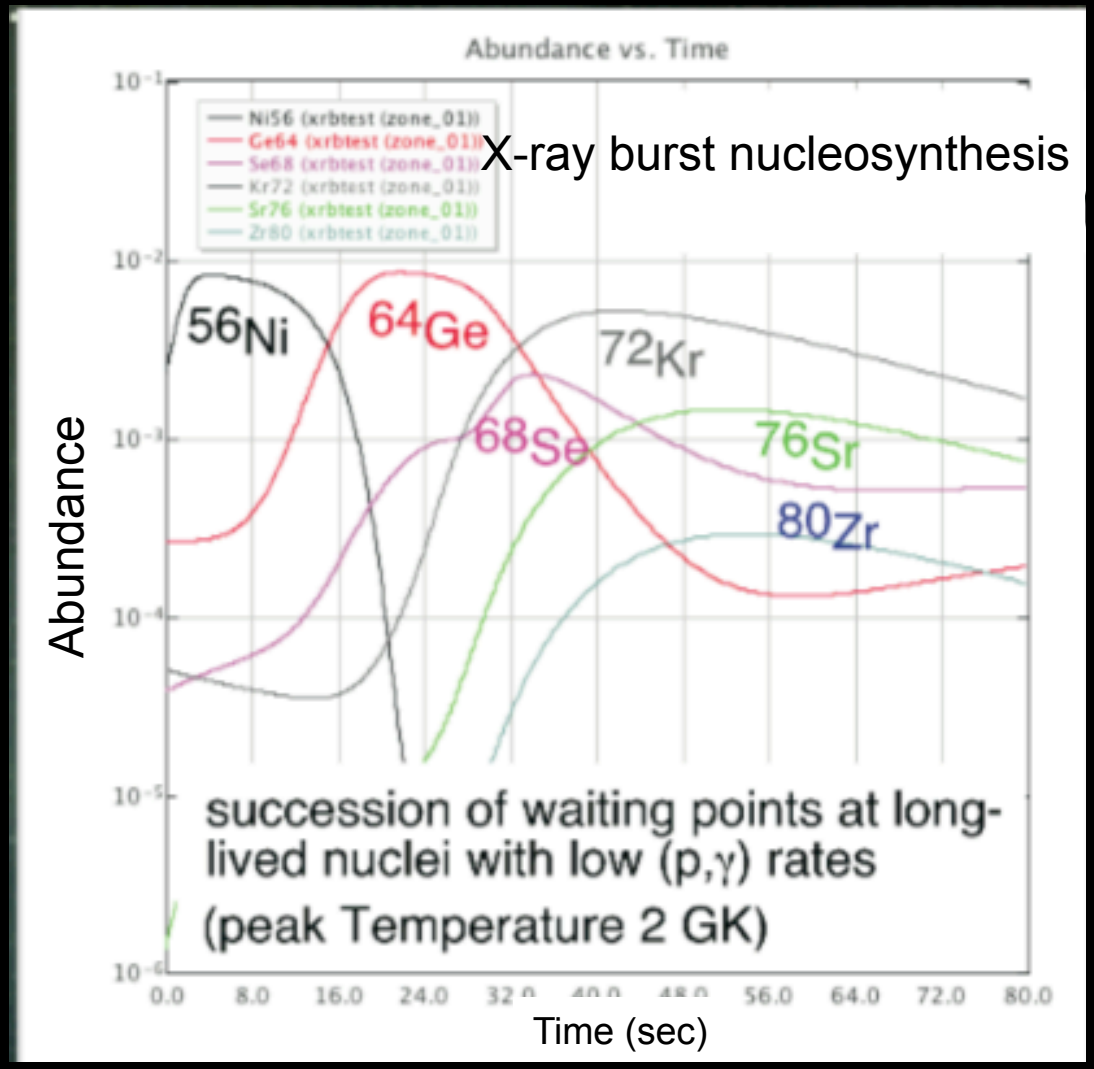
- rates of these reactions are crucial inputs into simulations of these explosions, influencing element creation & energy generation … and almost all unmeasured

- 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

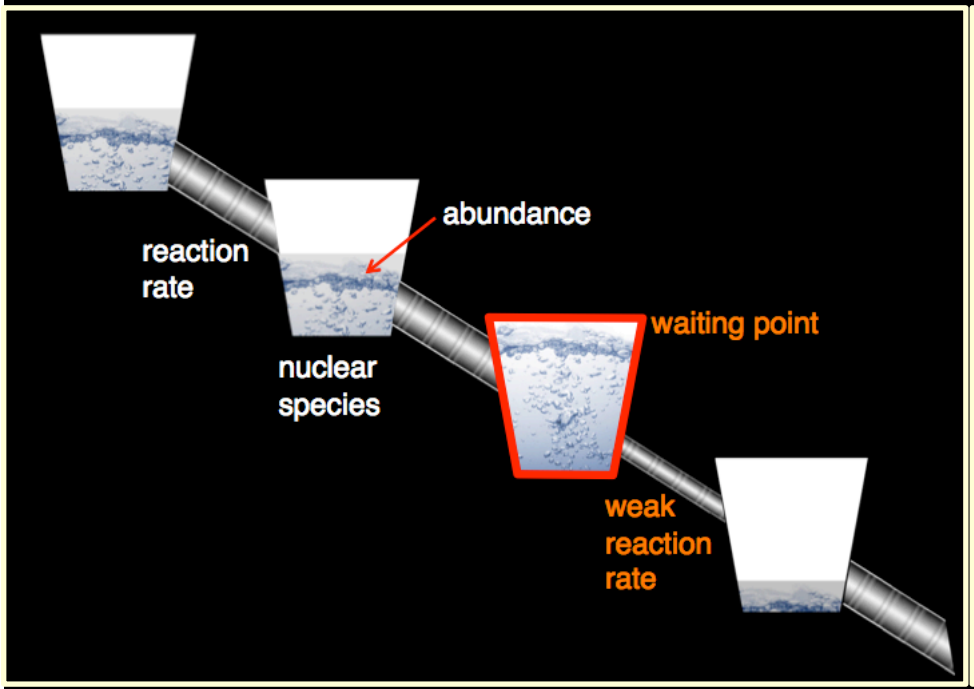
waiting points

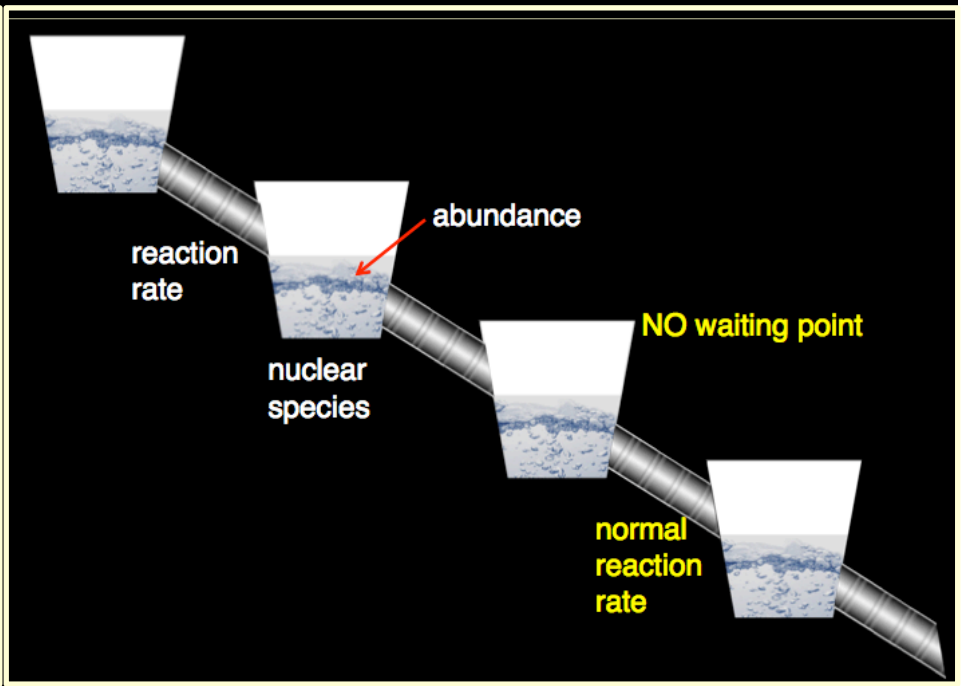
waiting points: nuclear species that happen to “collect” material – FLOW goes in quickly but out slowly



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

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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

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

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

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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

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

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PHYSICAL REVIEW C VOLUME 51, NUMBER 1 JANUARY 1995

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

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(Received 15 August 1994)

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

waiting points - definition

devise a quantitative definition of waiting point nuclei

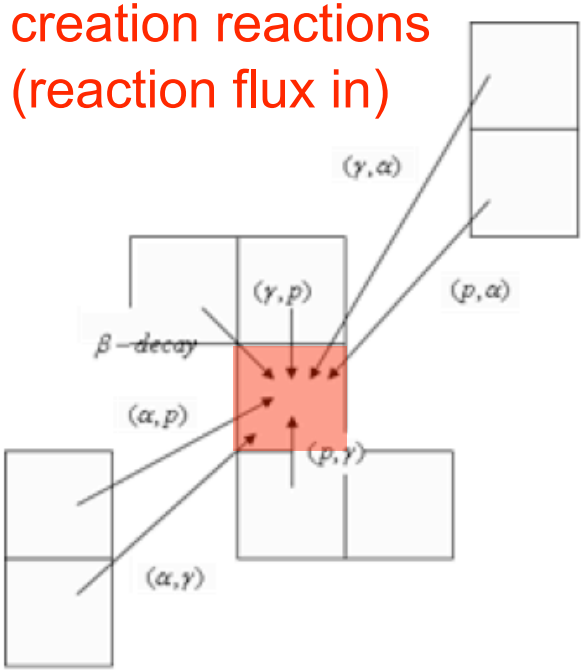
each property we considered has some drawbacks

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

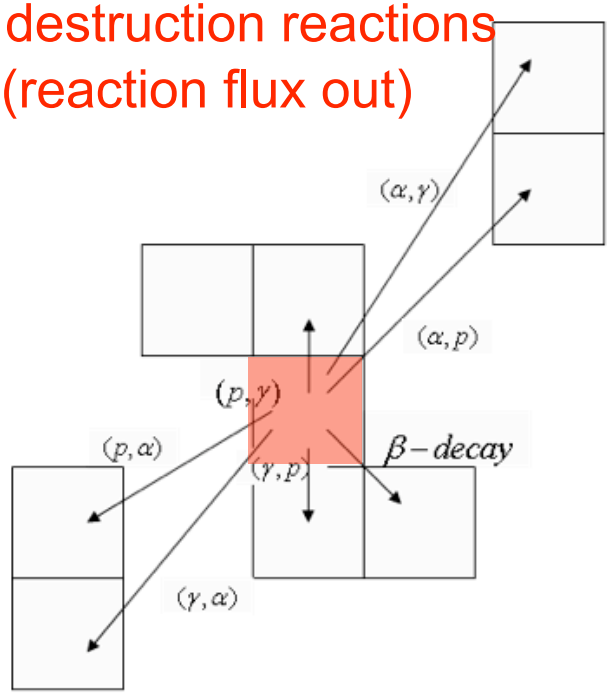
we COMBINE these properties to come up with a good way to find waiting points

waiting points – search procedure

creation reactions
(reaction flux in)



destruction reactions
(reaction flux out)



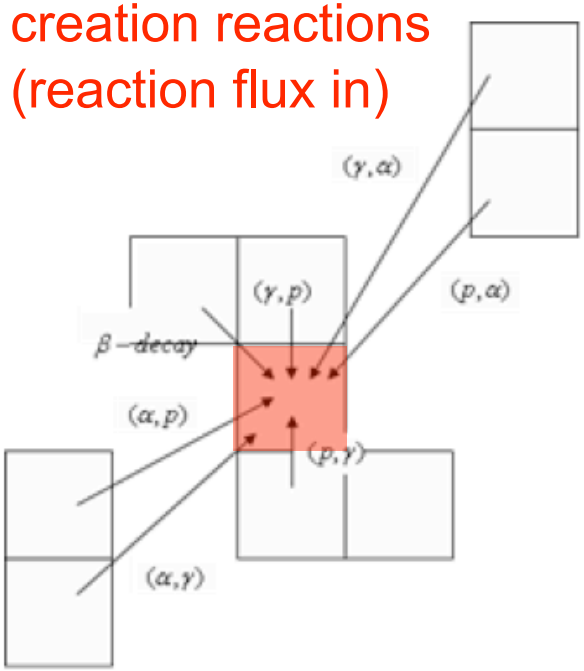
run an element synthesis calculation, store the abundance vs. time and reaction flux vs. time information

choose a TIME INTERVAL

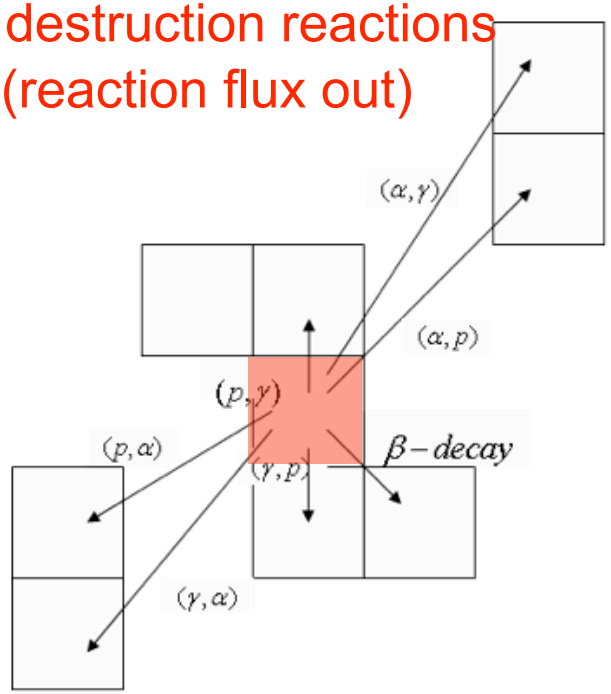
examine each nucleus & compare to its neighbors in the N-Z plane

waiting points – search procedure

creation reactions
(reaction flux in)



destruction reactions
(reaction flux out)



REJECT nuclei with

short destruction lifetime [<0.2 sec]

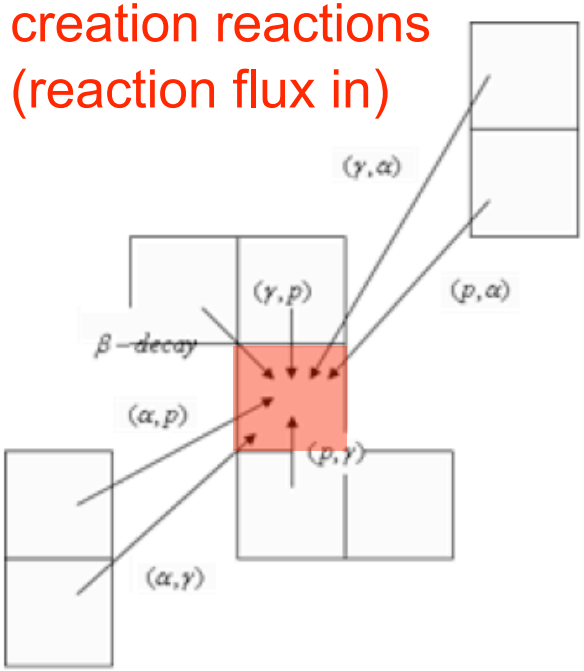
low abundance [< 10^{-6}]

peak Flux out > peak Flux in

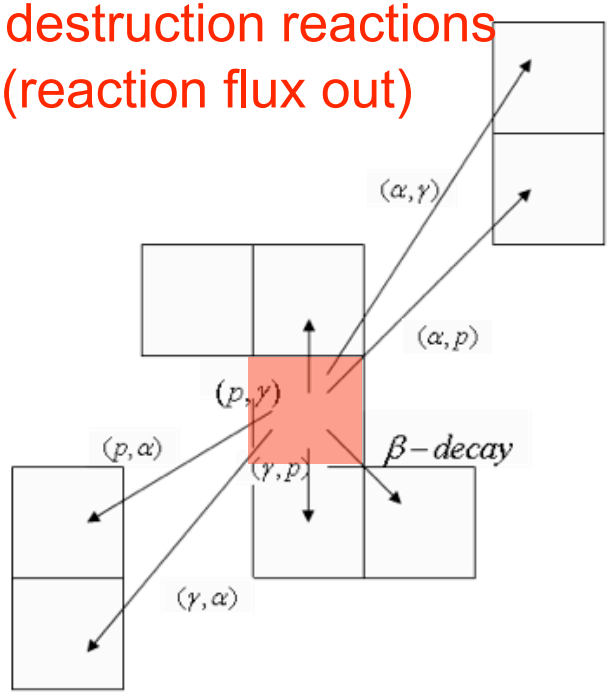
negative total integrated flux [net flux is negative, abundance is decreasing]

waiting points – search procedure

creation reactions
(reaction flux in)



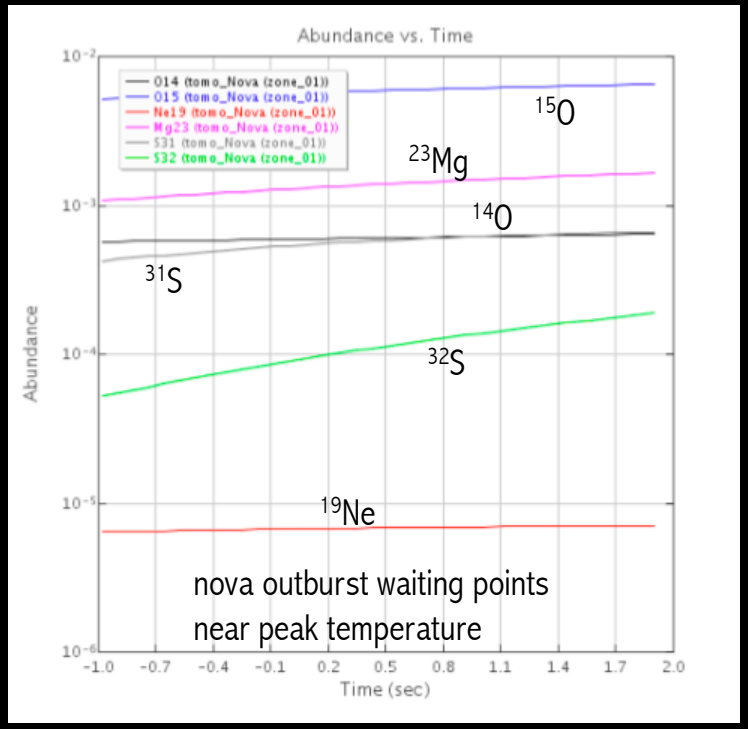
destruction reactions
(reaction flux out)

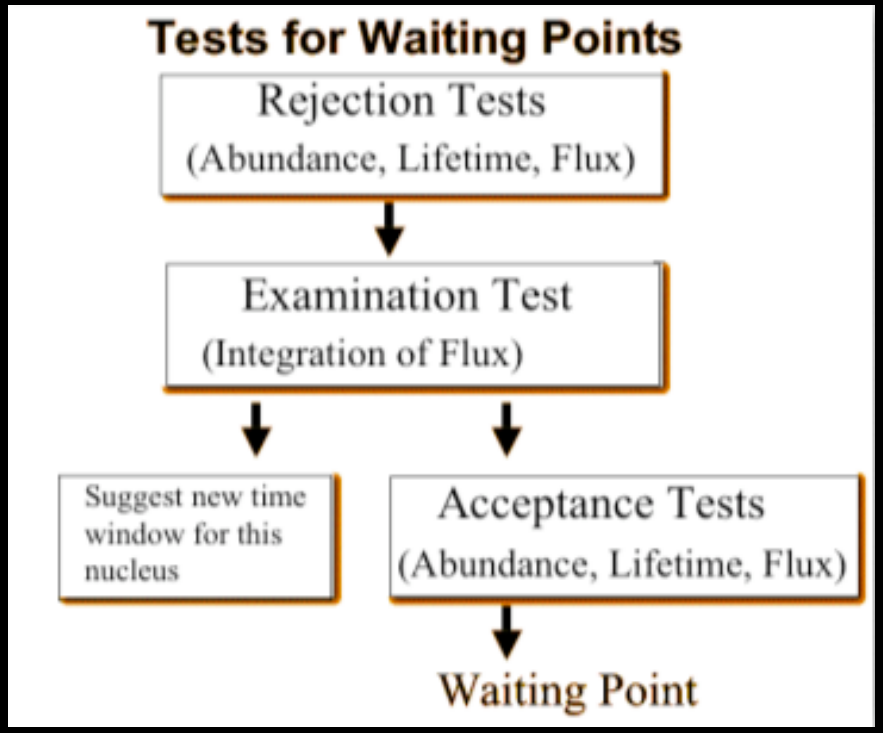


ACCEPT nuclei with
reasonably large total integrated Flux [> 10^{-4}]
AND reasonably long lifetime [> 1 sec]

REPEAT the test for all nuclei in the simulation

waiting points – testing procedure





- 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

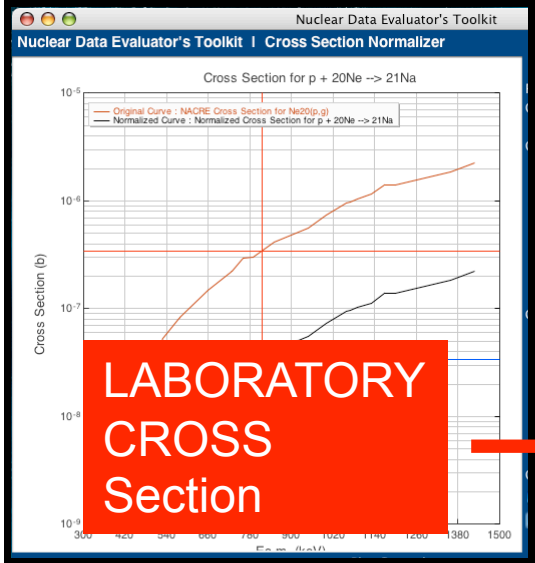
- change input rates in simulation to “create” a new waiting point or “destroy” an existing one – verify that our procedure works

online software for simulations & data processing

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

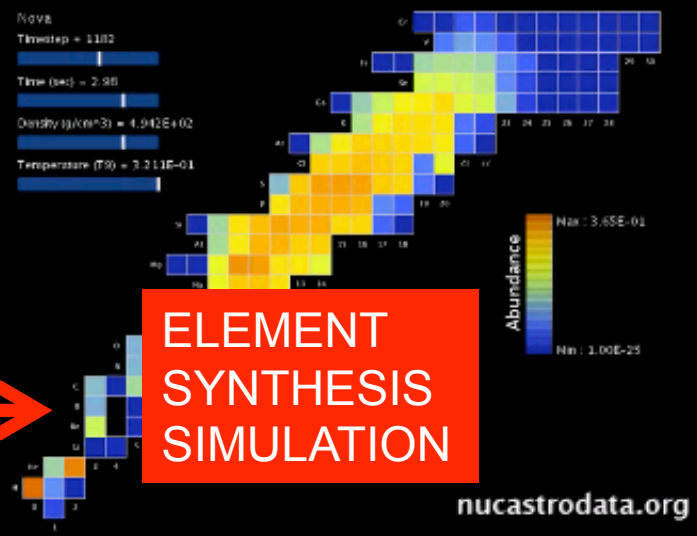
computational infrastructure for nuclear astrophysics

available at nucastrodata.org



LABORATORY CROSS Section

REACTION RATE



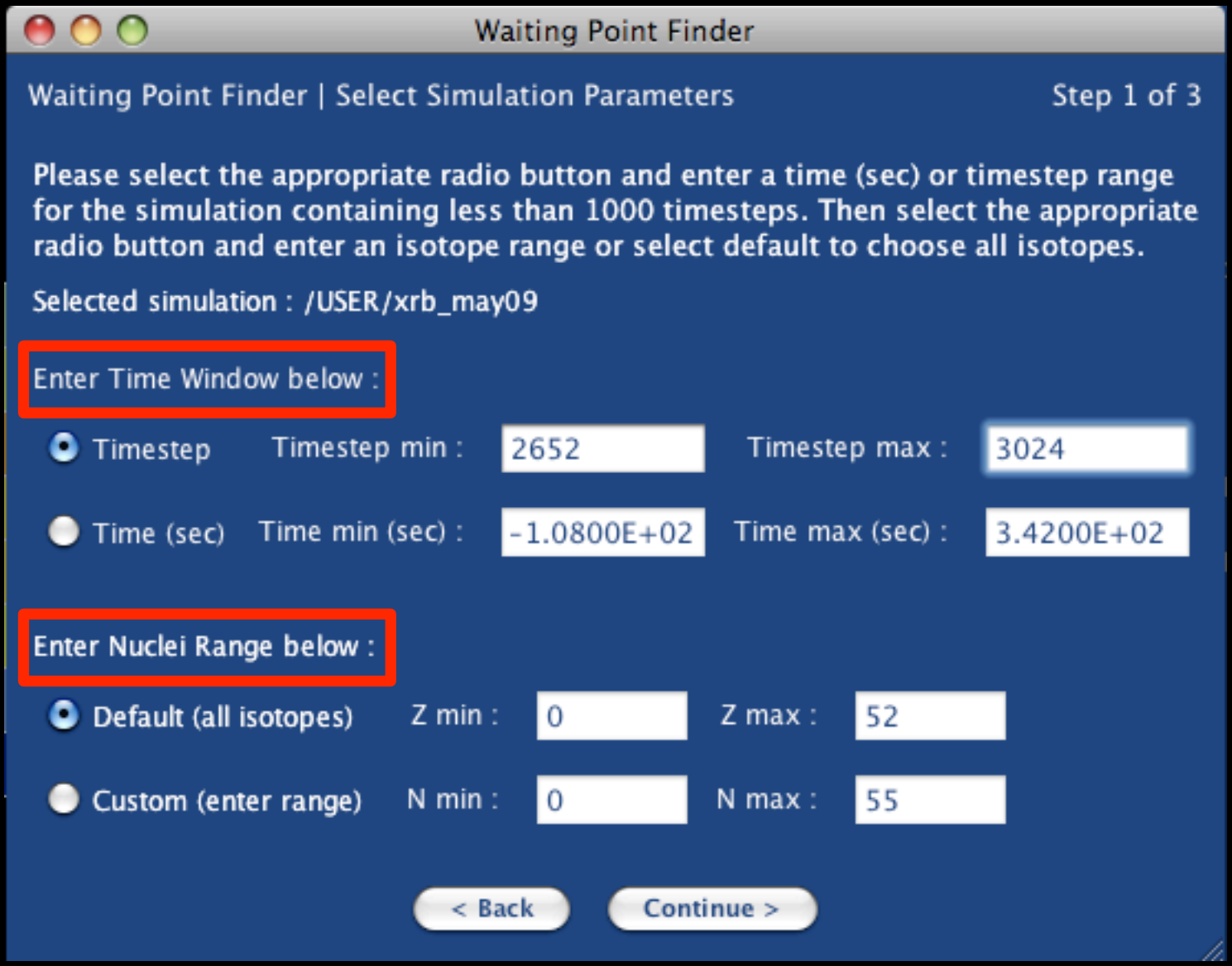
ELEMENT SYNTHESIS SIMULATION

users in 70 institutions in 20 countries

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

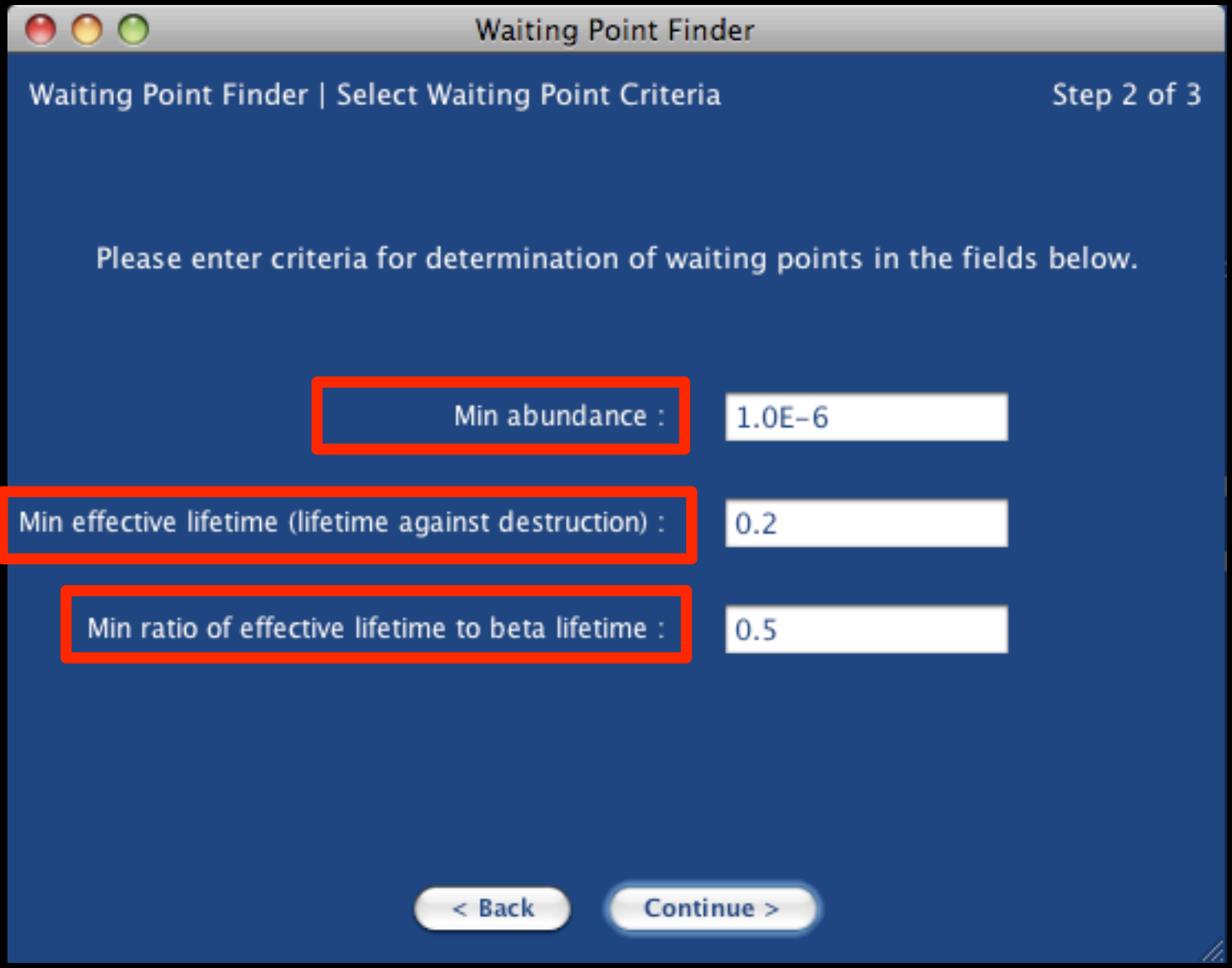
- what we already measured
- what we propose to **measure next**

online software tool – waiting point finder



quickly perform searches for waiting points with custom parameters

online software tool – waiting point finder



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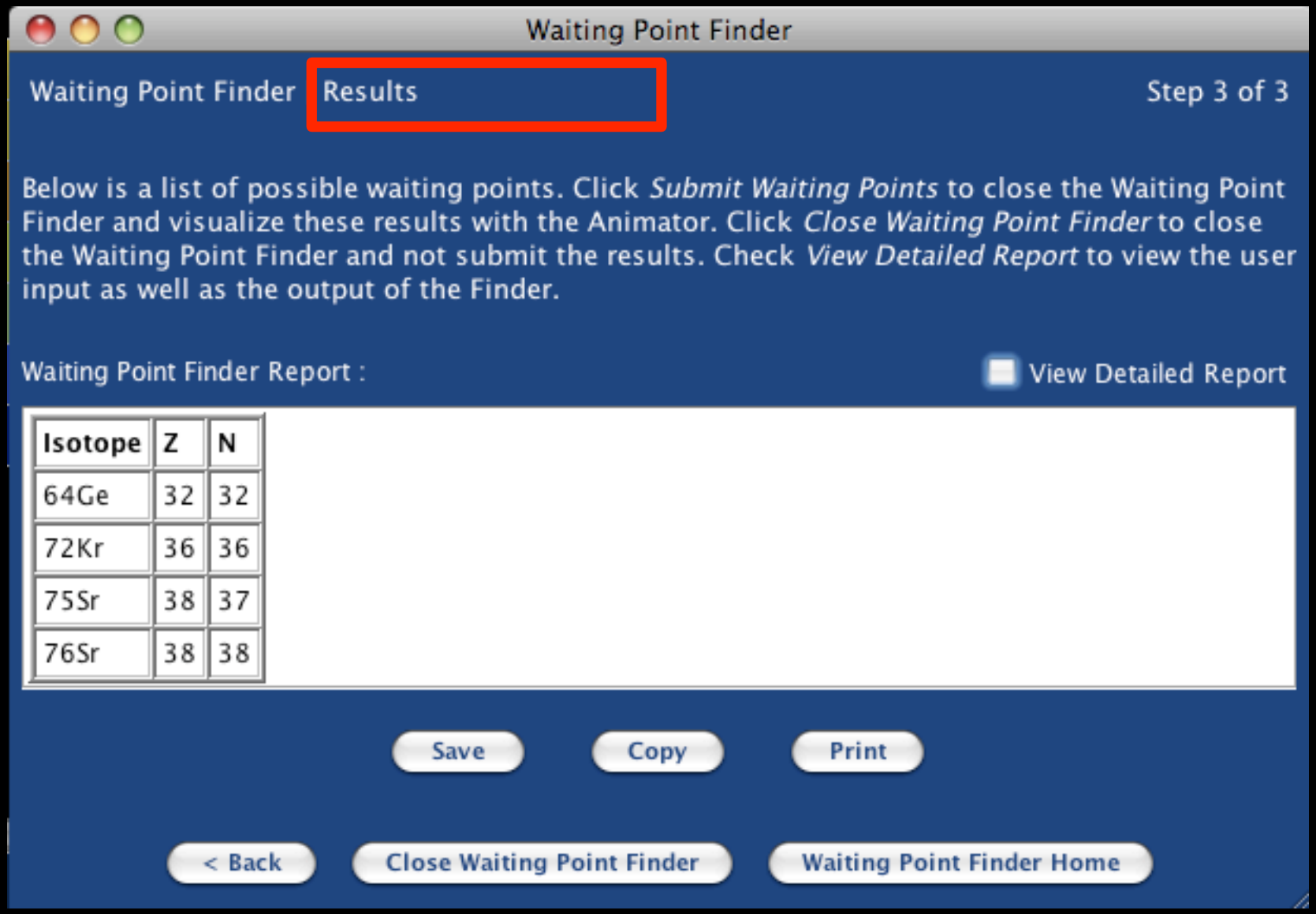
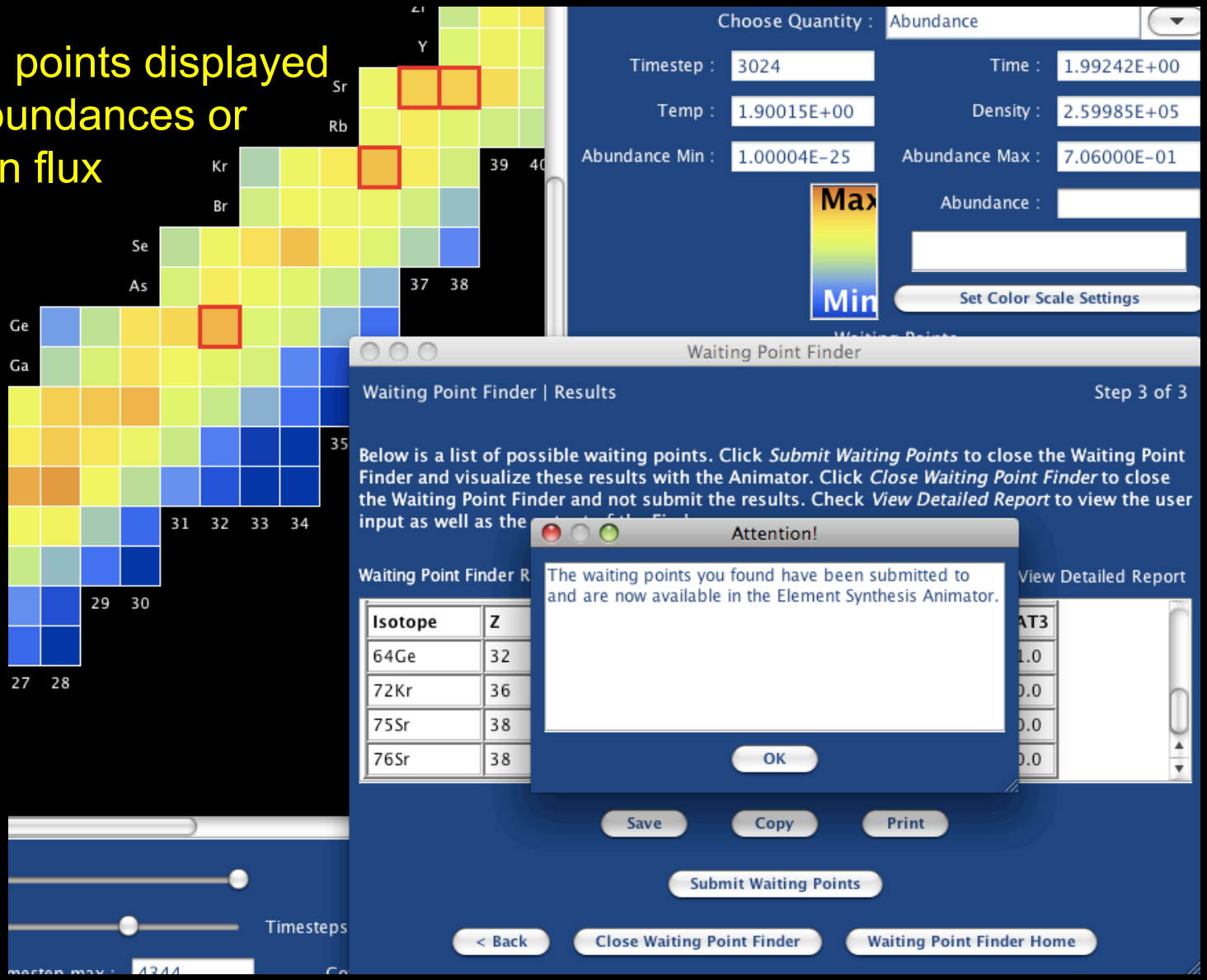


quickly perform searches for waiting points with custom parameters

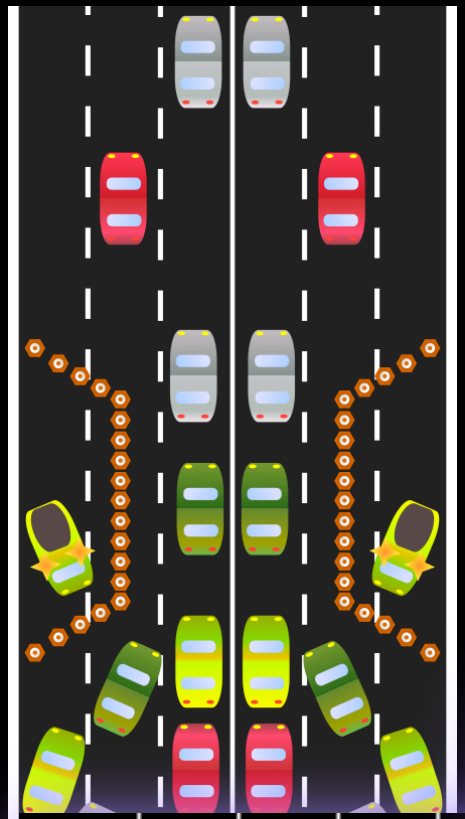
online software tool – waiting point finder

waiting points displayed with abundances or reaction flux



quickly perform searches for waiting points with custom parameters

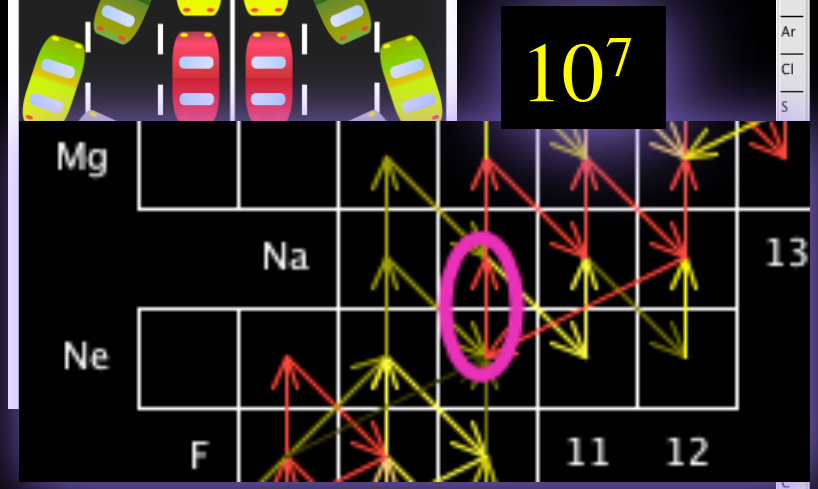
bottlenecks

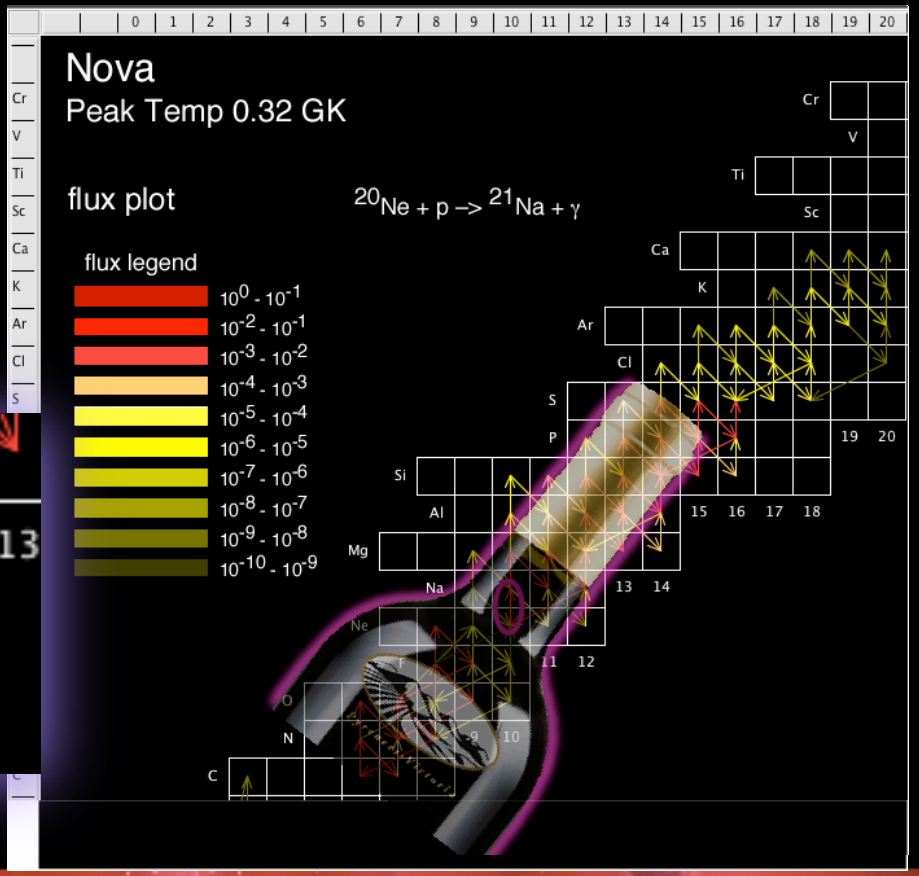


all reaction FLOW passes through these reactions

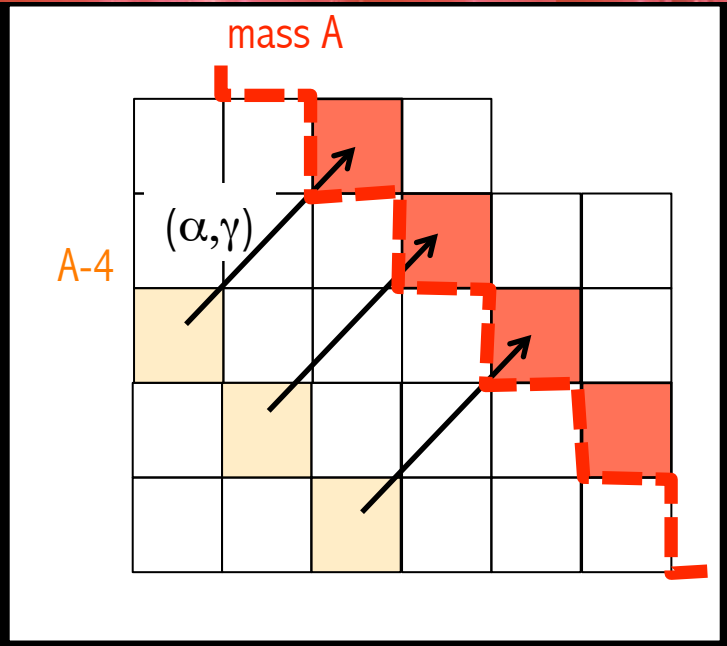
if a bottleneck reaction is turned off, result is a "Thermonuclear Traffic Jam"

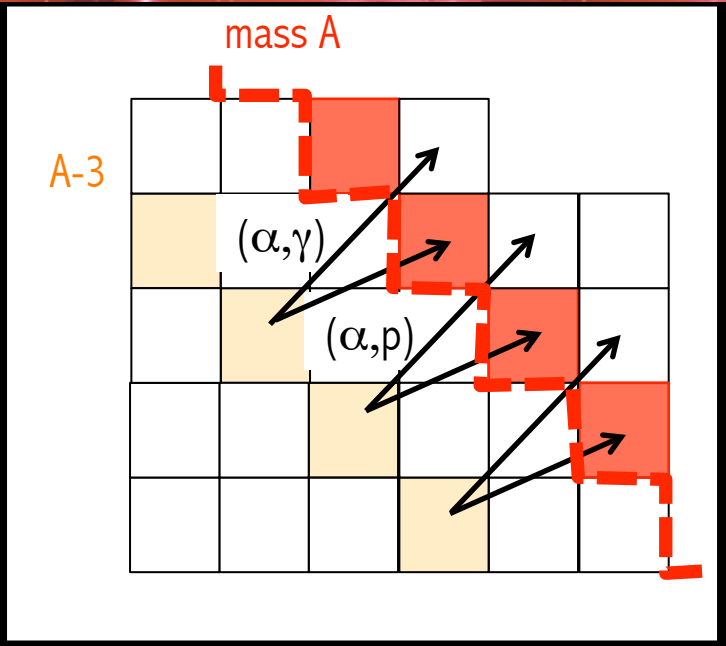
how do we define & find bottlenecks ?

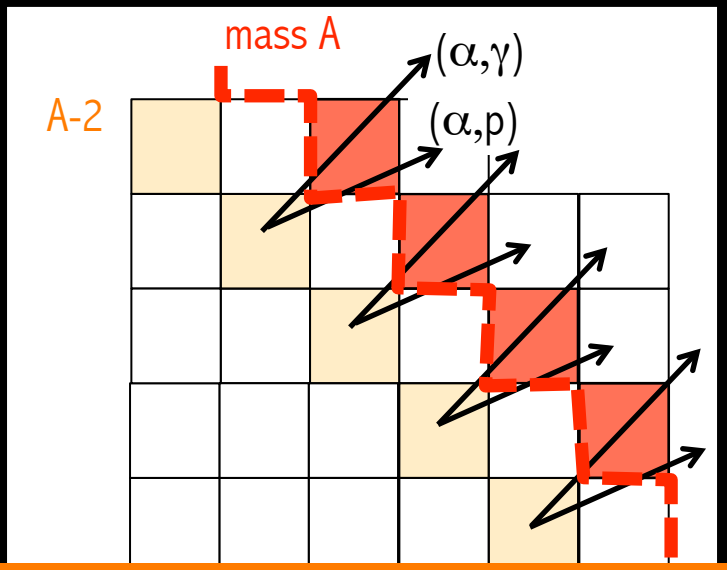


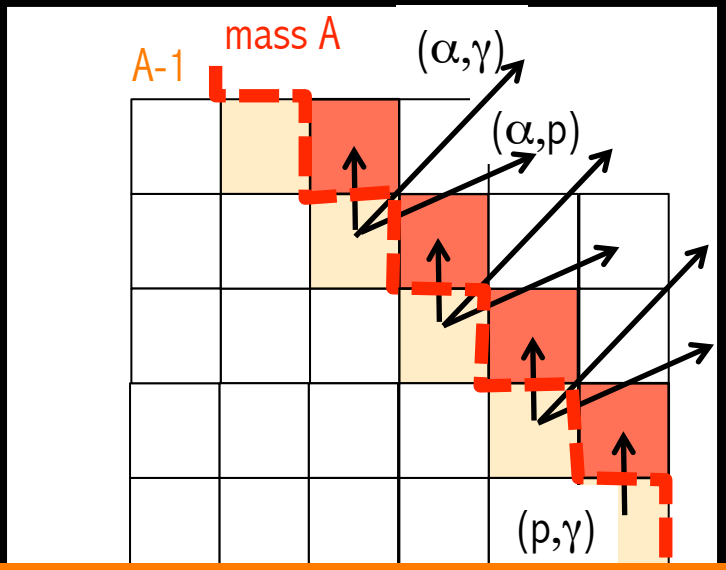


bottlenecks – definition



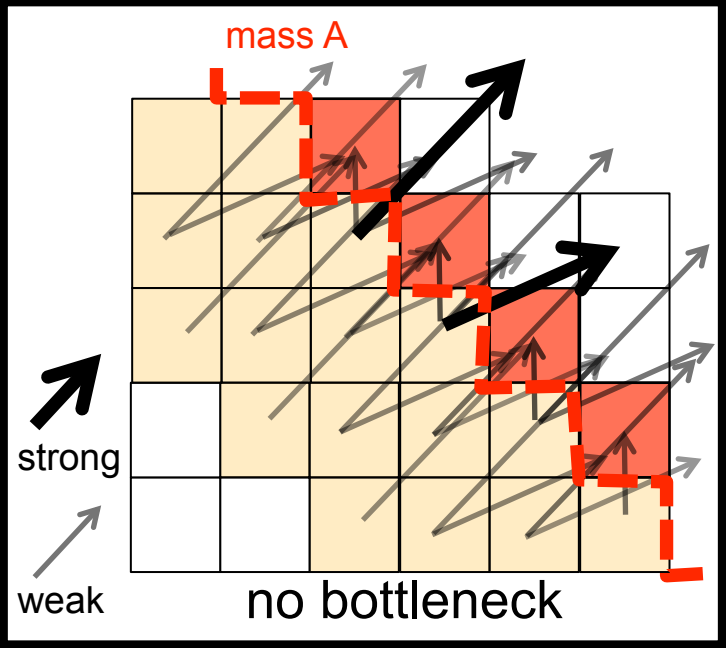


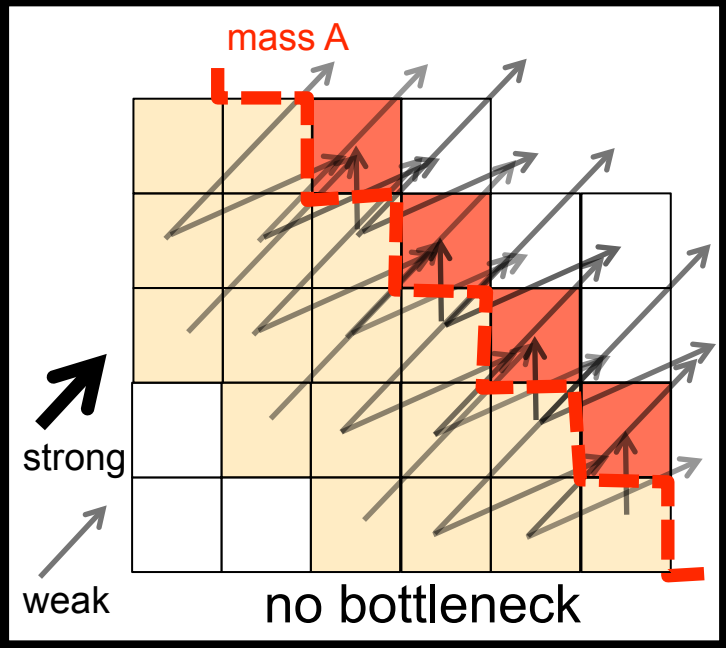




consider all reactions that produce nuclei with mass greater than or equal to A

bottlenecks – search procedure



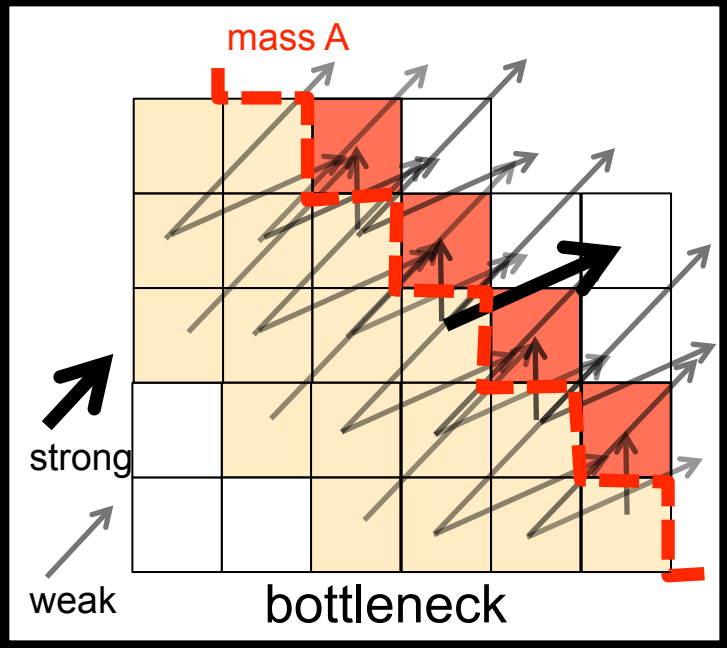


REJECT presence of bottleneck if

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

bottlenecks – search procedure



REJECT presence of bottleneck if

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

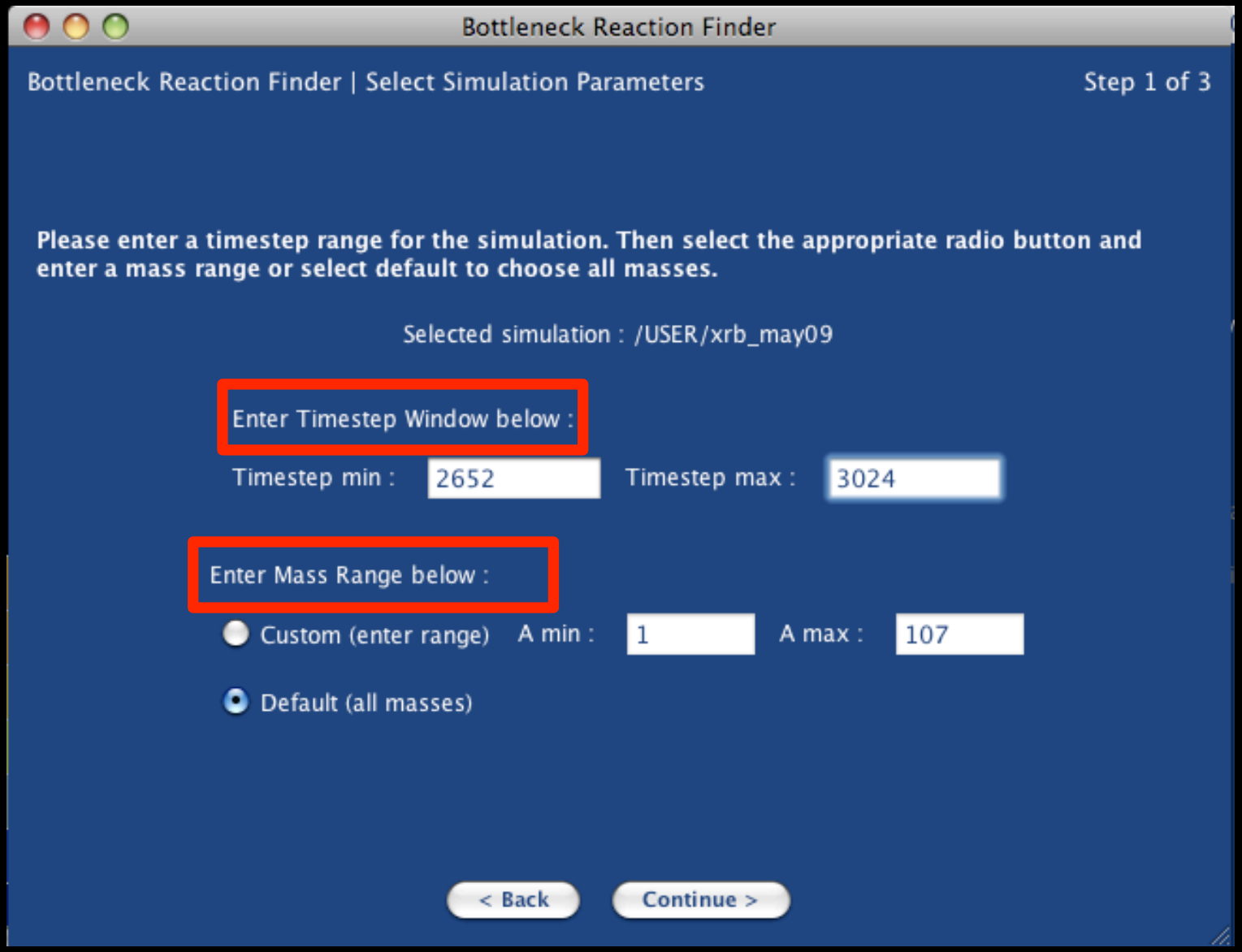
OR two or more fluxes are too high [$> 10^{-6}$] relative to largest flux

ACCEPT presence of bottleneck if

only ONE FLUX is high [$> 10^{-6}$] AND all other fluxes much lower [factor 10^{-4} down]

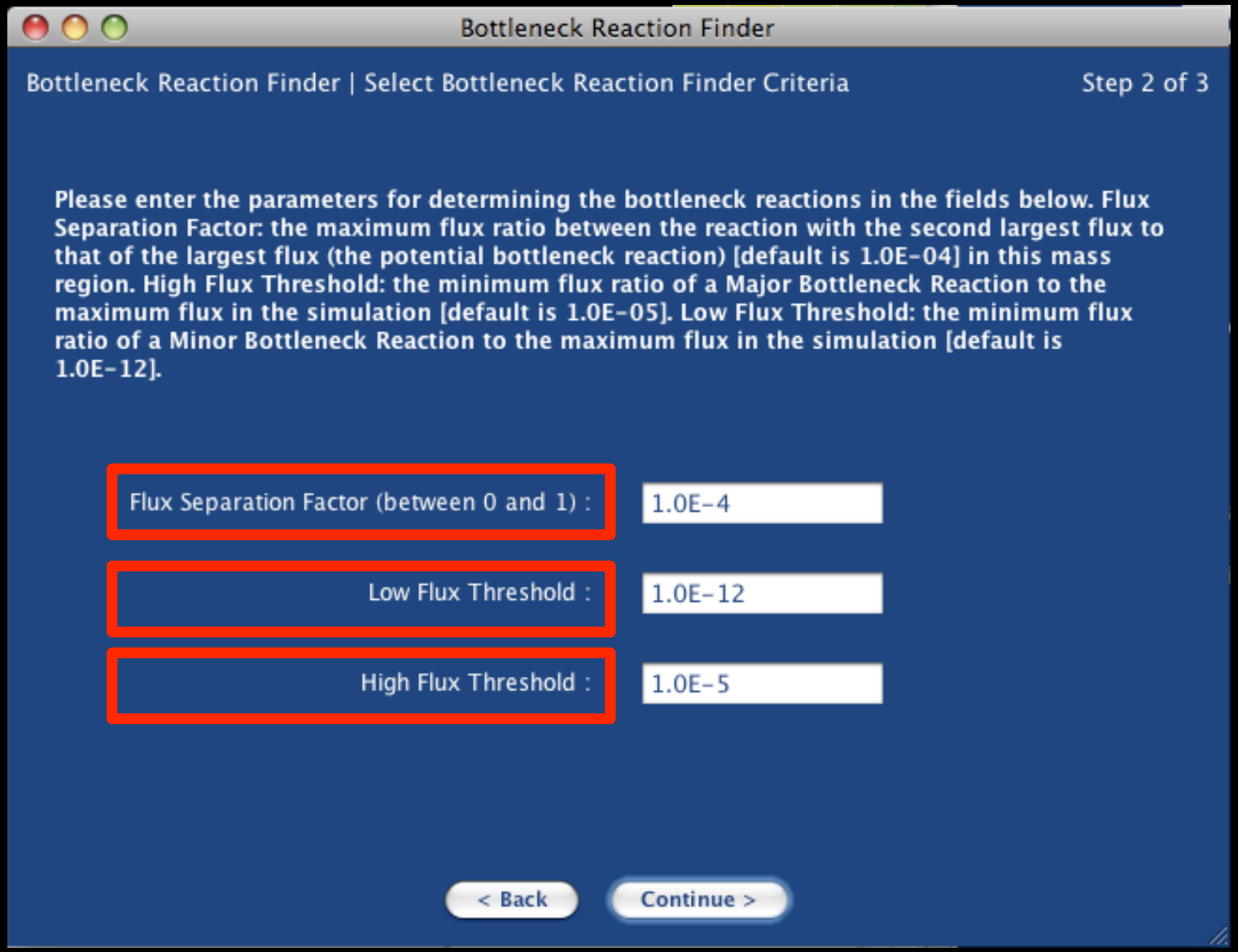
REPEAT for all mass values in the simulation

online software tool – bottleneck finder



quickly perform searches for bottlenecks with custom parameters

online software tool – bottleneck finder



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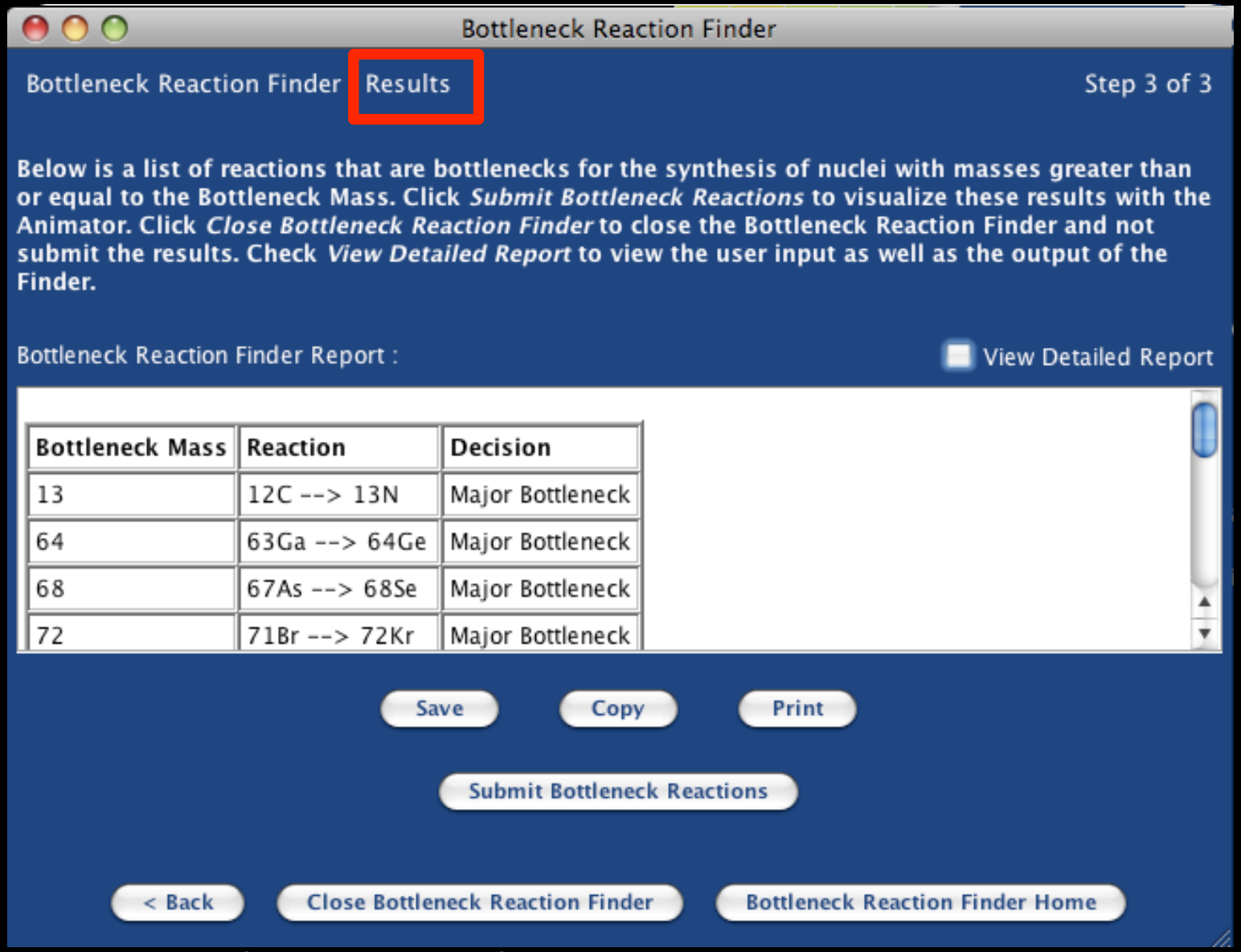
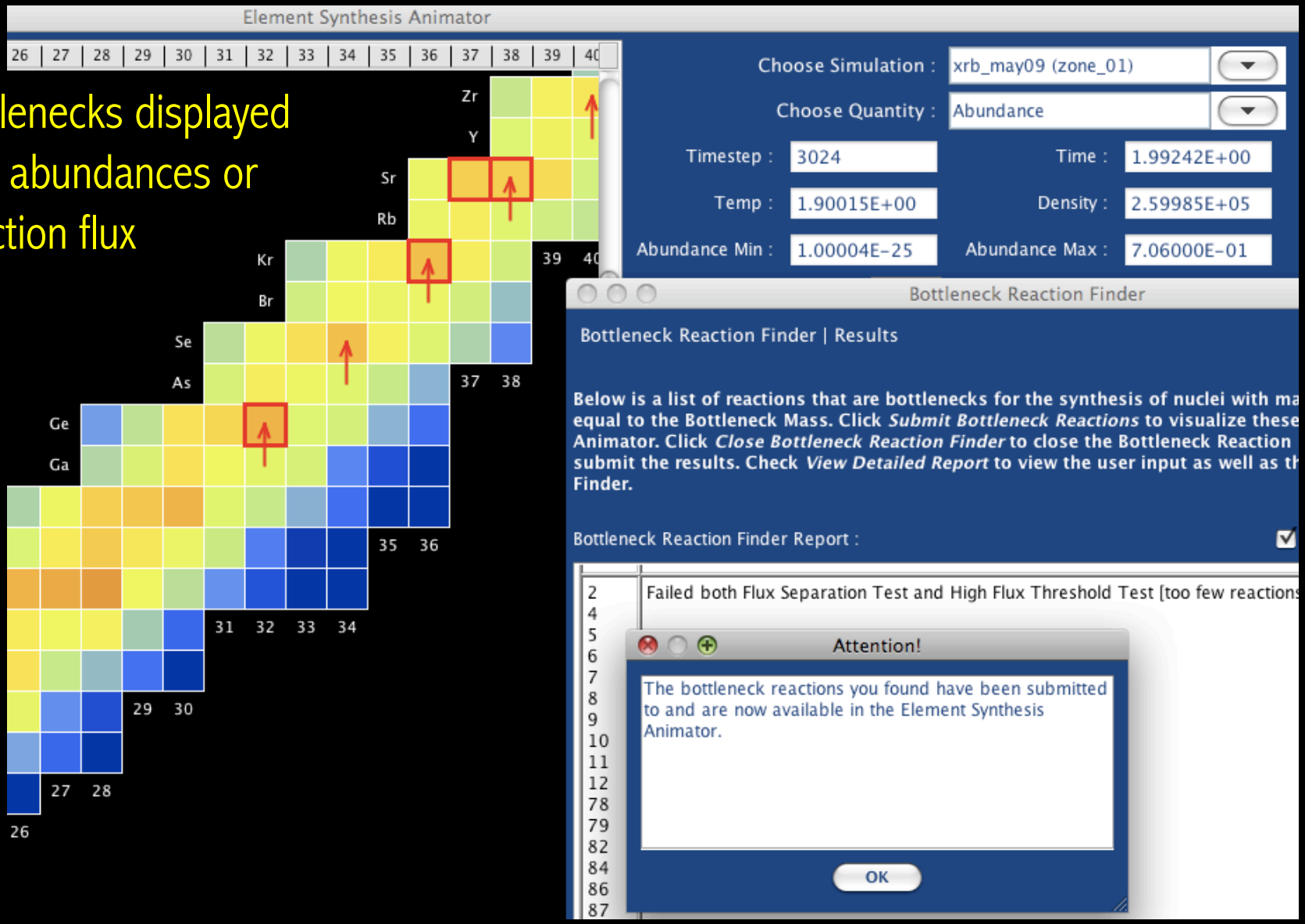
online software tool – bottleneck finder



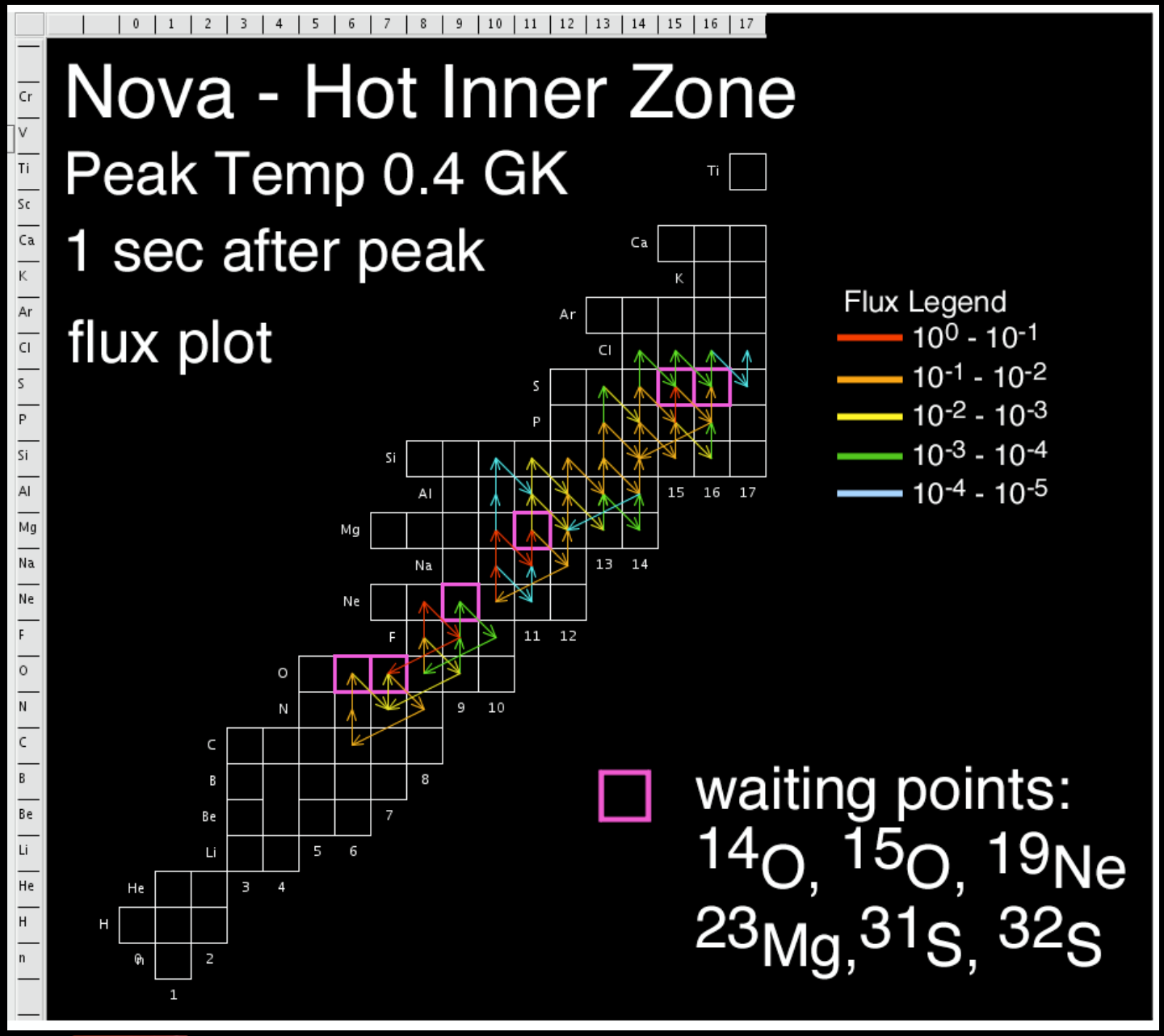
quickly perform searches for bottlenecks with custom parameters

online software tool – bottleneck finder

bottlenecks displayed with abundances or reaction flux

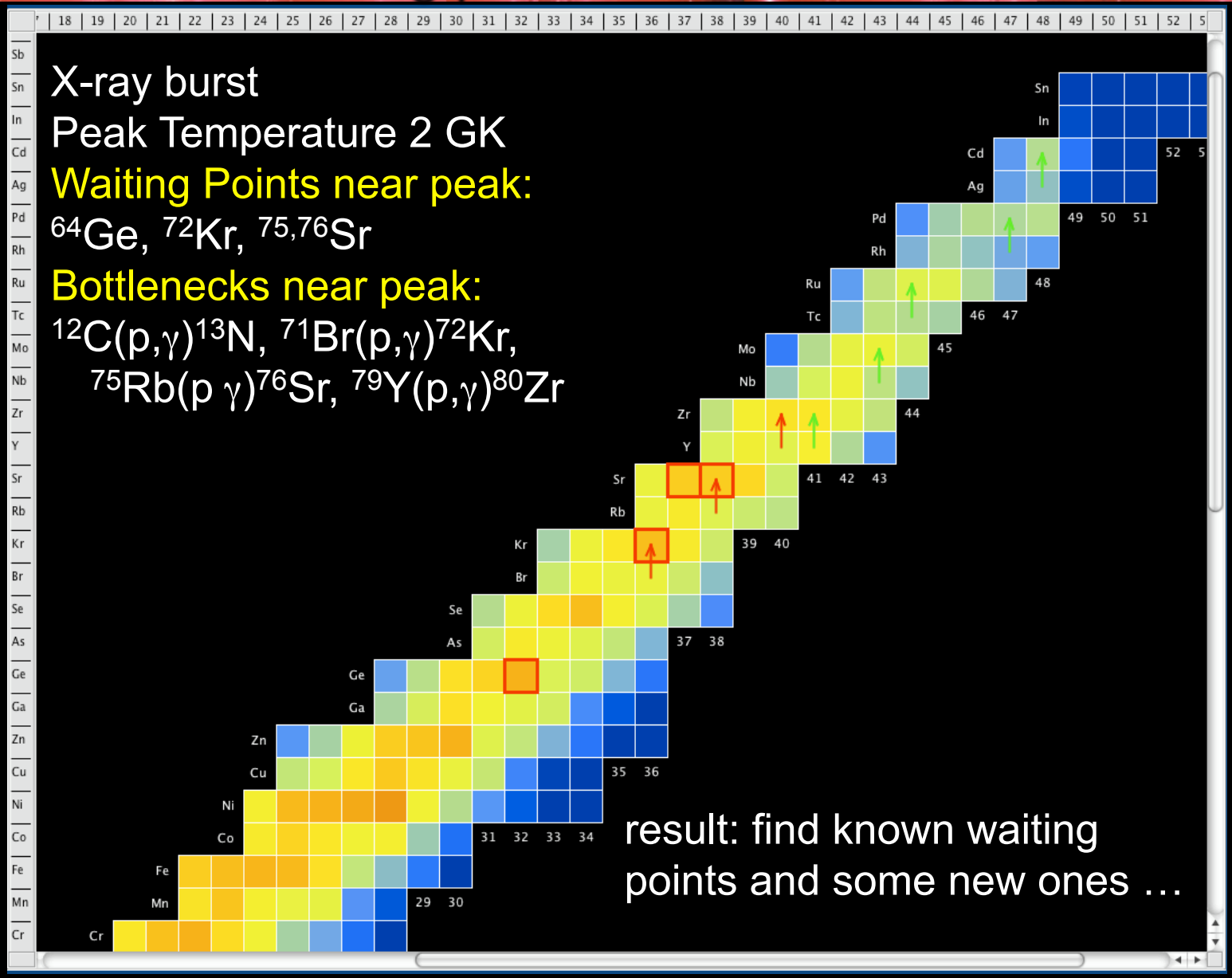


quickly perform searches for bottlenecks with custom parameters


Nova - Hot Inner Zone
Peak Temp 0.4 GK
1 sec after peak
flux plot
Ti
Flux Legend
10^{0} - 10^{-1}
10^{-1} - 10^{-2}
10^{-2} - 10^{-3}
10^{-3} - 10^{-4}
10^{-4} - 10^{-5}
waiting points:
^{14}O, ^{15}O, ^{19}Ne
^{23}Mg, ^{31}S, ^{32}S

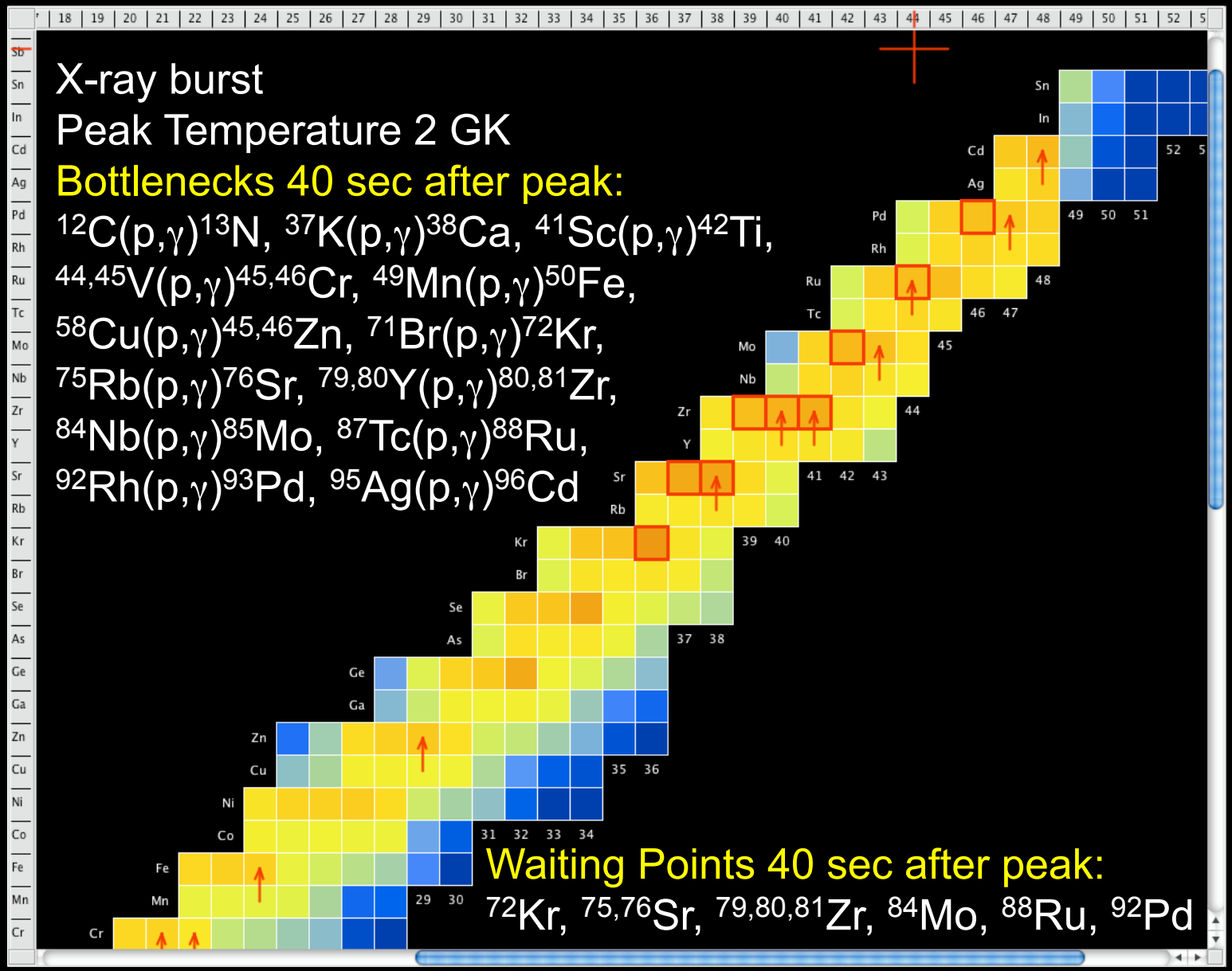
bottlenecks & waiting points - results

X-ray burst
Peak Temperature 2 GK
Waiting Points near peak:
^{64}Ge, ^{72}Kr, ^{75,76}Sr
Bottlenecks near peak:
^{12}C(p,γ)^{13}N, ^{71}Br(p,γ)^{72}Kr,
^{75}Rb(p γ)^{76}Sr, ^{79}Y(p,γ)^{80}Zr

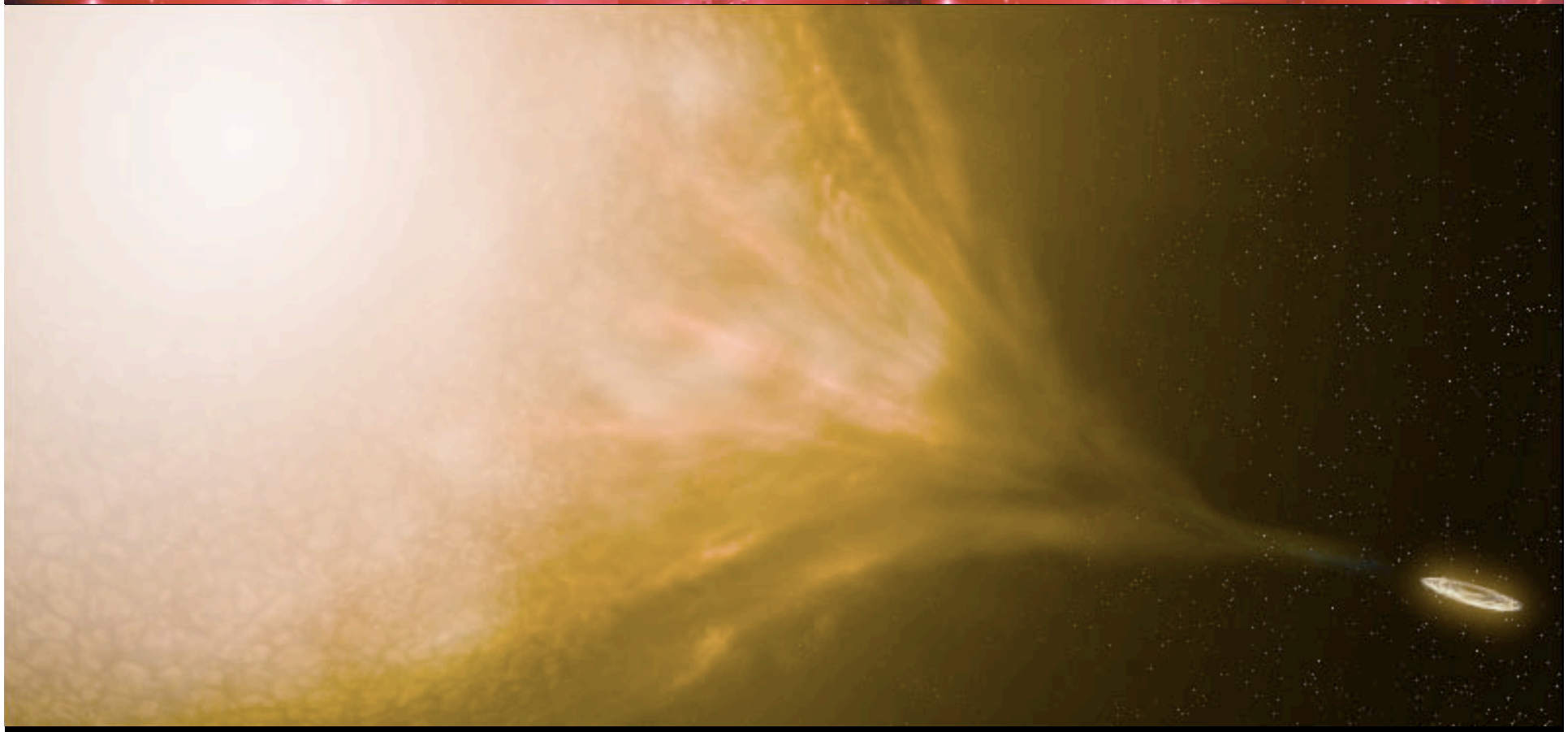


result: find known waiting points and some new ones …

bottlenecks & waiting points - results



future

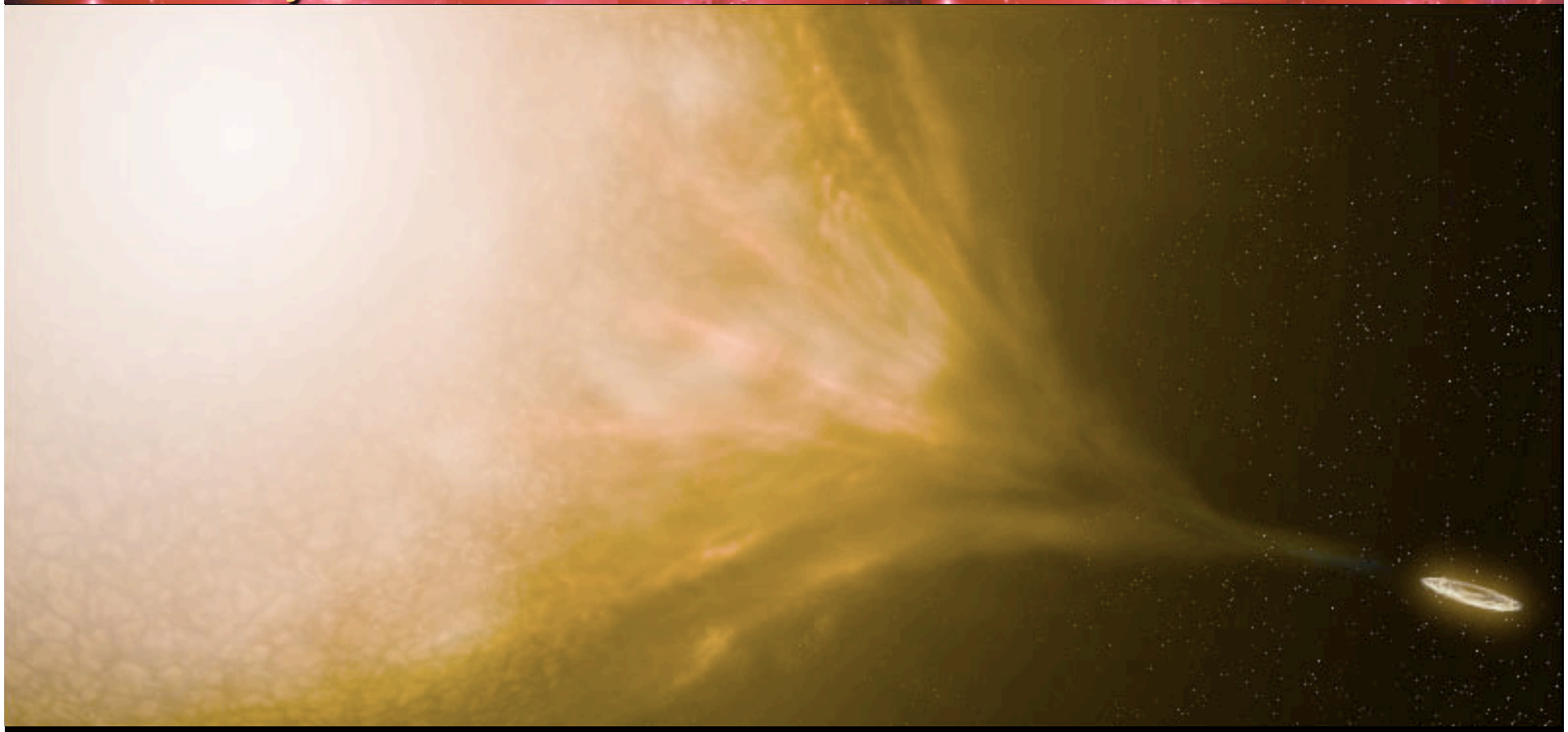


systematic searches of nova & x-ray burst simulations for Bottlenecks & Waiting Points – determine dependence on astrophysical model, search parameters, time window

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