Coupled Sensitivities in rp-Process Nuclear Reaction Rates

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BERN18 - Prato

1. Why study sensitivities

They hide the physics from us in very interesting systems (neutron stars) that **provide observables** (bursts):

➔ **Nuclear matter**
Dense, neutron-rich phases, EOS

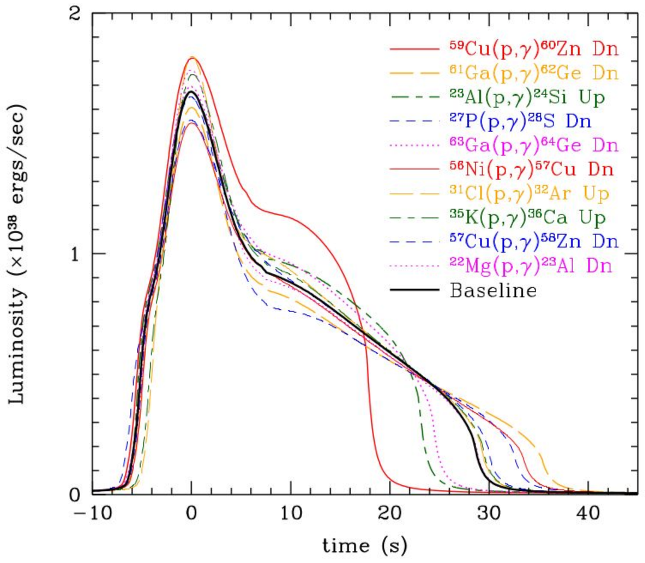
➔ **Crustal processes**
Neutronization, neutrino cooling, superbursts

➔ **Merger progenitors**
Ashes material and NS properties

Individual rate sensitivities

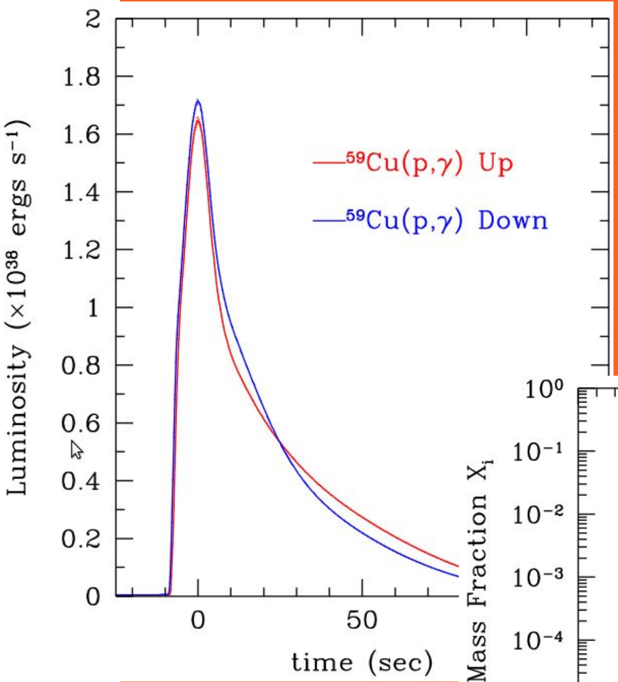
DEPENDENCE OF X-RAY BURST MODELS ON NUCLEAR REACTION RATES
Cyburt et al. ApJ (2016)

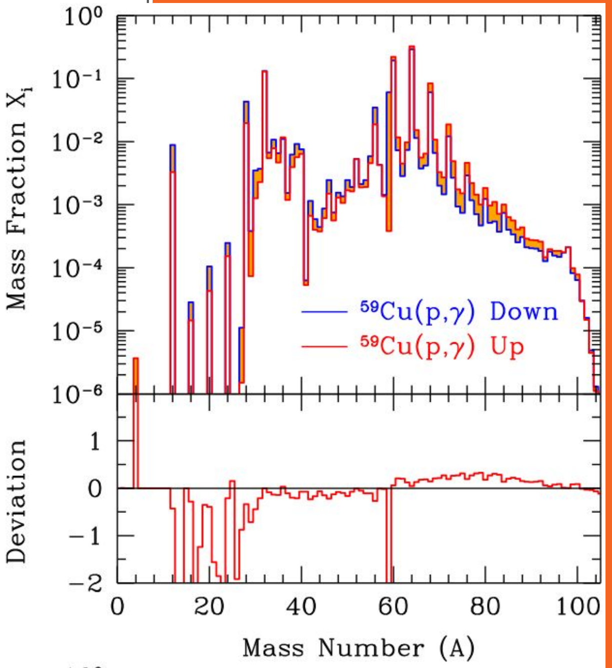
- ➔ All rp-process (p,γ) and (α,p) reaction rates
- ➔ Varied individually x100 and x0.01 in a single zone model w/ multi-zone calib. abundances.
- ➔ Multi-zone study in KEPLER of key reactions
- ➔ Roughly 80 burst chains in KEPLER runs
  - ◆ About 14 bursts per chain



Results

Examined light curves and ashes at upper and lower rate extremes





Results

Examined light curves and ashes at upper and lower rate extremes

Produced a ranked list of the most consequential reaction rate uncertainties

Table 2
Reactions that Impact the Burst Light Curve in the Multi-zone X-ray Burst Model

Rank	Reaction	Type[a]	Sensitivity[b]	Category
1	$^{15}O(\alpha,\gamma)^{19}Ne$	D	16	1
2	$^{56}Ni(\alpha,p)^{59}Cu$	U	6.4	1
3	$^{59}Cu(p,\gamma)^{60}Zn$	D	5.1	1
4	$^{61}Ga(p,\gamma)^{62}Ge$	D	3.7	1
5	$^{22}Mg(\alpha,p)^{25}Al$	D	2.3	1
6	$^{14}O(\alpha,p)^{17}F$	D	5.8	1
7	$^{23}Al(p,\gamma)^{24}Si$	D	4.6	1
8	$^{18}Ne(\alpha,p)^{21}Na$	U	1.8	1
9	$^{63}Ga(p,\gamma)^{64}Ge$	D	1.4	2
10	$^{19}F(p,\alpha)^{16}O$	U	1.3	2
11	$^{12}C(\alpha,\gamma)^{16}O$	U	2.1	2
12	$^{26}Si(\alpha,p)^{29}P$	U	1.8	2
13	$^{17}F(\alpha,p)^{20}Ne$	U	3.5	2
14	$^{24}Mg(\alpha,\gamma)^{28}Si$	U	1.2	2
15	$^{57}Cu(p,\gamma)^{58}Zn$	D	1.3	2
16	$^{60}Zn(\alpha,p)^{63}Ga$	U	1.1	2
17	$^{17}F(p,\gamma)^{18}Ne$	U	1.7	2
18	$^{40}Sc(p,\gamma)^{41}Ti$	D	1.1	2
19	$^{48}Cr(p,\gamma)^{49}Mn$	D	1.2	2

Notes.
[a] Up (U) or down (D) variation that has the largest impact.
[b] $M_{LC}^{(i)}$ in units of 10^{38} erg s^{-1}.

Limitations?

➔ **Single zone first step**
Limits observed sensitivities

➔ **Extremes only & single rate var.**
No complex or higher order effects

➔ **Single accretion model**
Proximate to only some sources

What to do next?

➔ **A fully multi-zone study**
Full mixing and comp. inertia effects

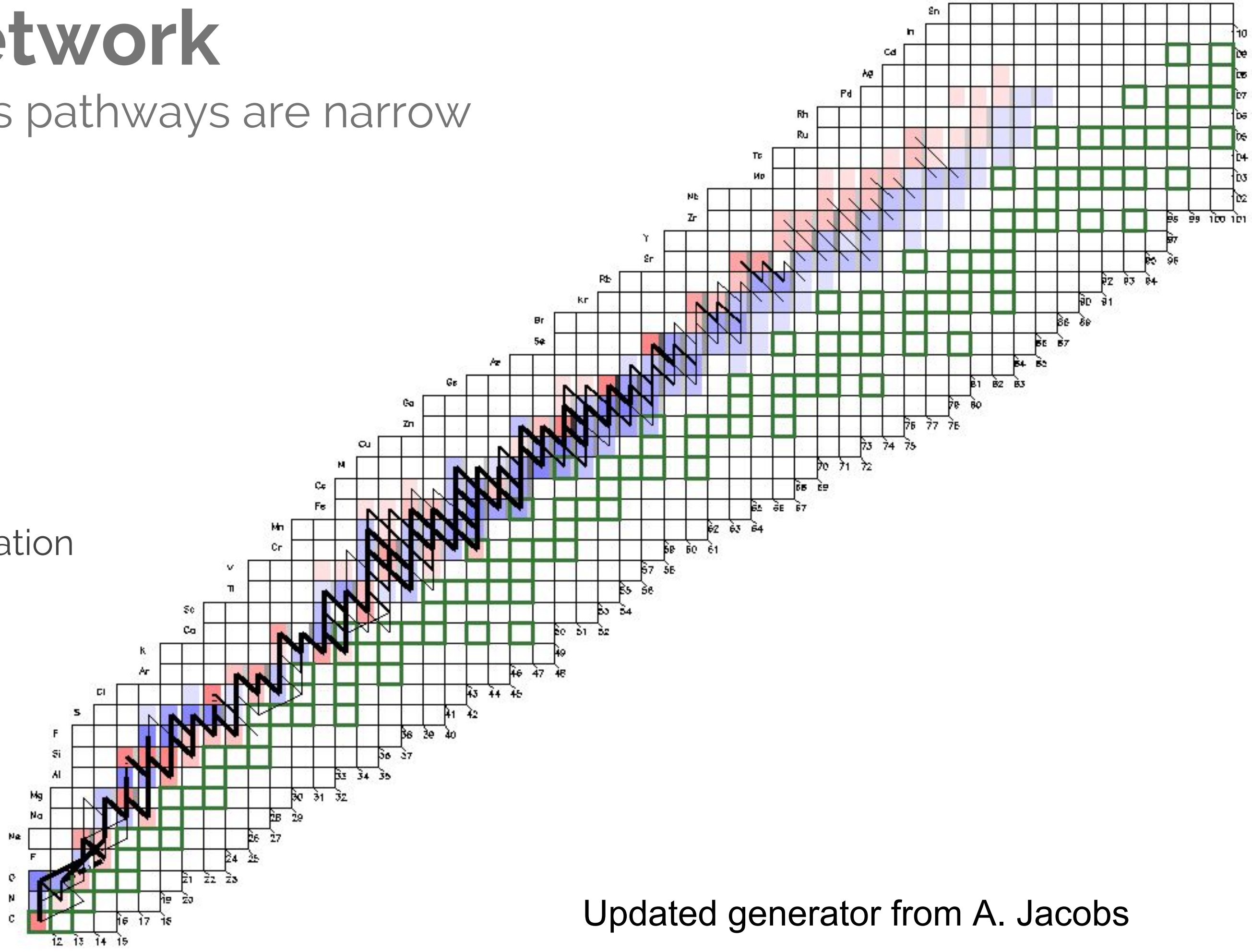
➔ **Continuous rate variations**
Monte Carlo sampling

➔ **Multiple or continuous models**
Monte Carlo sampling for Z and mdot

rp-Process network

Dominant instantaneous pathways are narrow

- **Closer to stability**
  - Get depopulated by capture
  - Longer decay times
- **Farther from stability**
  - Higher Coulomb barriers (compared along isobar)
  - Lower level densities
  - Enhanced photodisintigration (near drip lines)
- **Path and waiting points are relative**
  - Local thermodynamic conditions
  - Local composition



Updated generator from A. Jacobs

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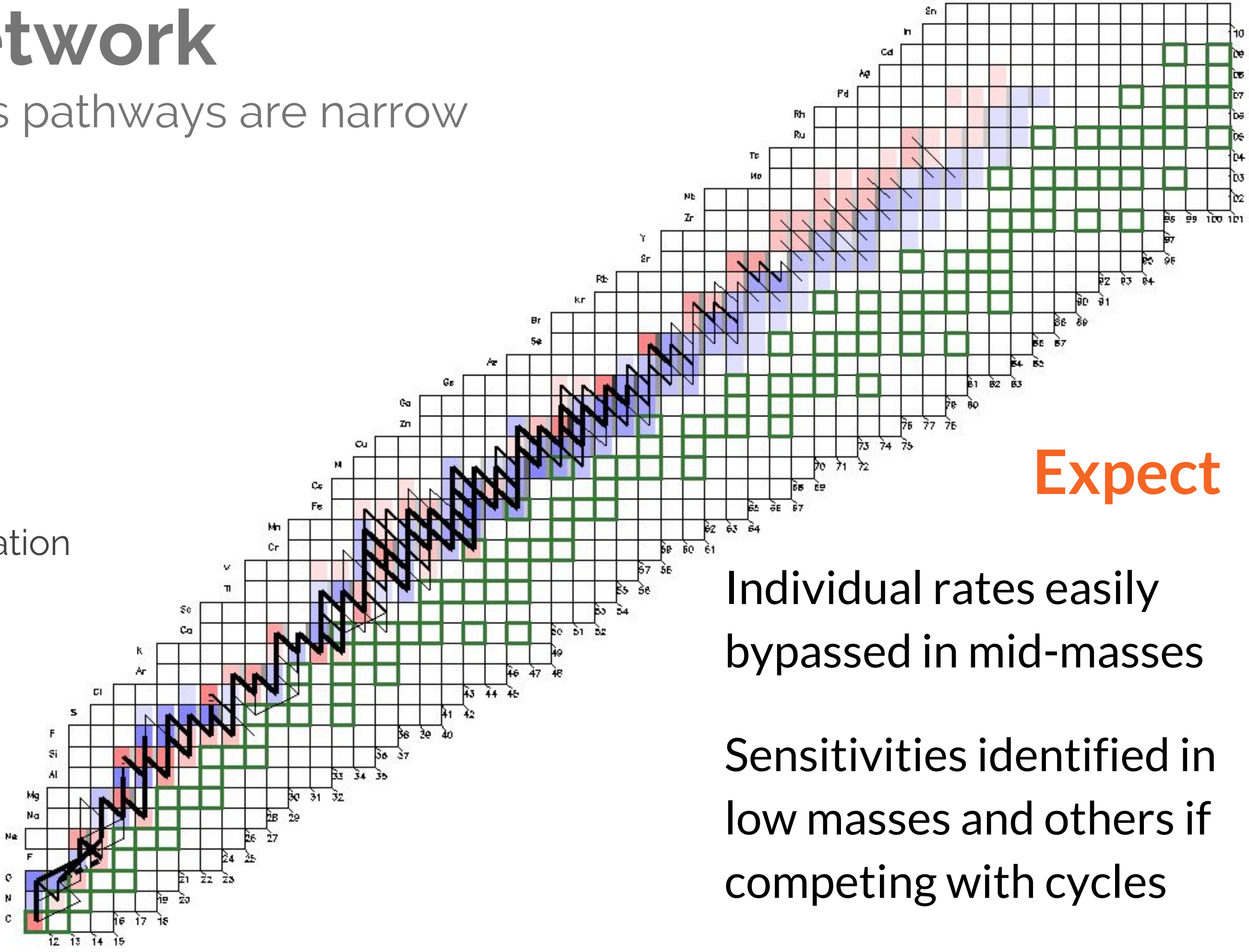

Expect

Individual rates easily bypassed in mid-masses

Sensitivities identified in low masses and others if competing with cycles

Results of single vars.

Indeed they are ***all*** either: low masses or related to cycles (closed by (p,alpha) reactions)

Wait! What about 40Sc(p,g)?

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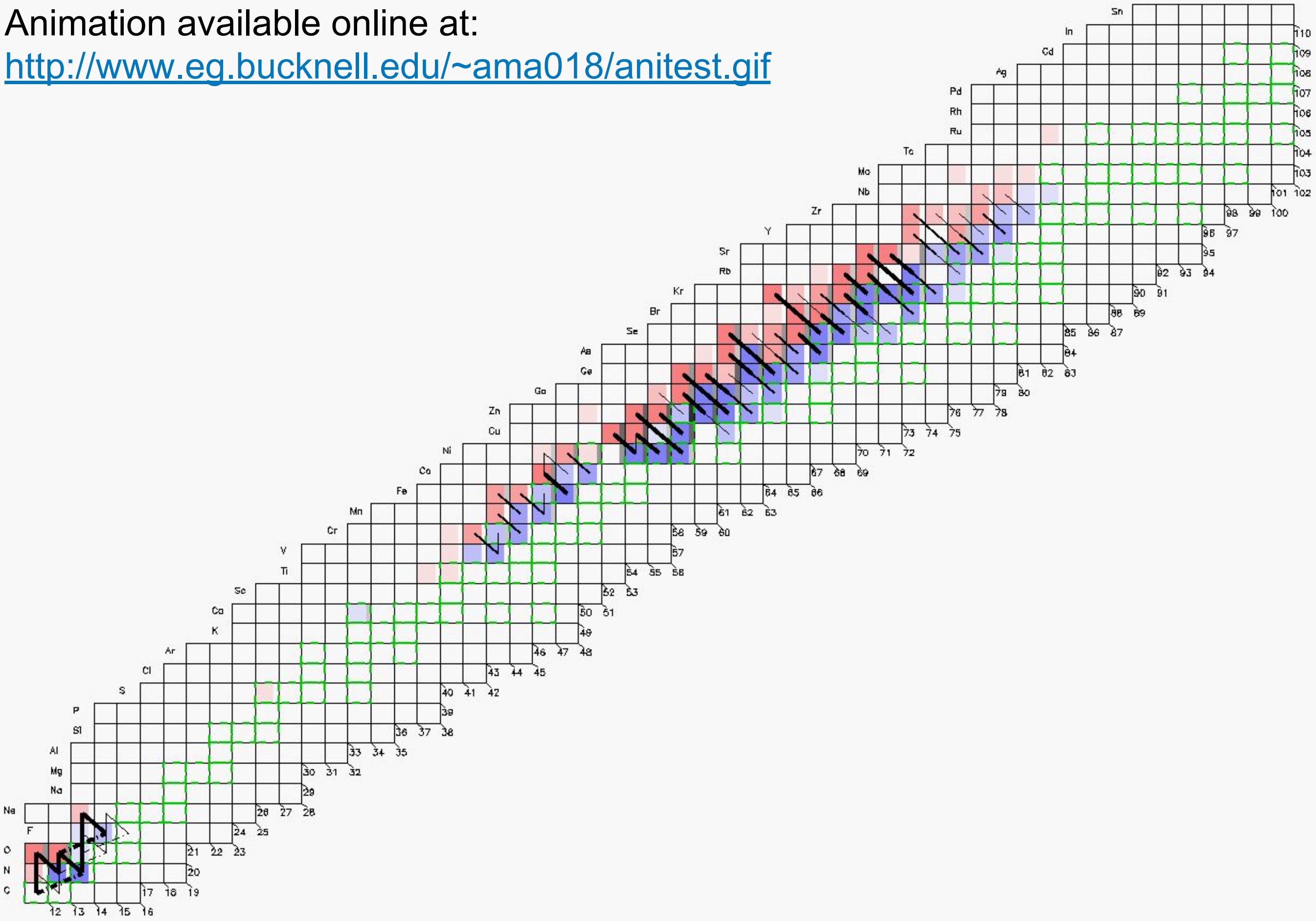
Animation available online at:
http://www.eg.bucknell.edu/~ama018/anitest.gif



2. Why no non-cycle sensitivities for Z>14

➔ **There are none**
Move on...

➔ **Nuclear Reaction rate Sensitivities for Z>14 [for this accretion model] are > 1st order**
Will not be observed without including more than one rate uncertainty simultaneously,

Previous Monte Carlo Rate Studies

Parikh, 2008

Postprocessing

X-ray burst

Multiple accretion models

1000[-20000] bursts

Mass fractions only

Roberts, 2006

Postprocessing

X-ray burst

50000 bursts

Hix, 2003

Postprocessing

Nova

169 isotope network

10000 bursts

Smith, 2002

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? proceedings

10000 bursts

None seemed to look at coupled rate sensitivity

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We want: Fully coupled x-ray burst Monte Carlo sensitivity study with a full network looking at observable effects of first order and correlated rate variations.

3. What does this study look like?

- **> 10000 KEPLER burst chains**
  About 1.5 CPU days each
- **Simultaneous variation of astrophysical parameters**
  Sensitivity study for a variety of metallicities, accretion rates, etc.
- **"Circular blobs with lines through them"**
  Analysis focused on extracting very weak correlations

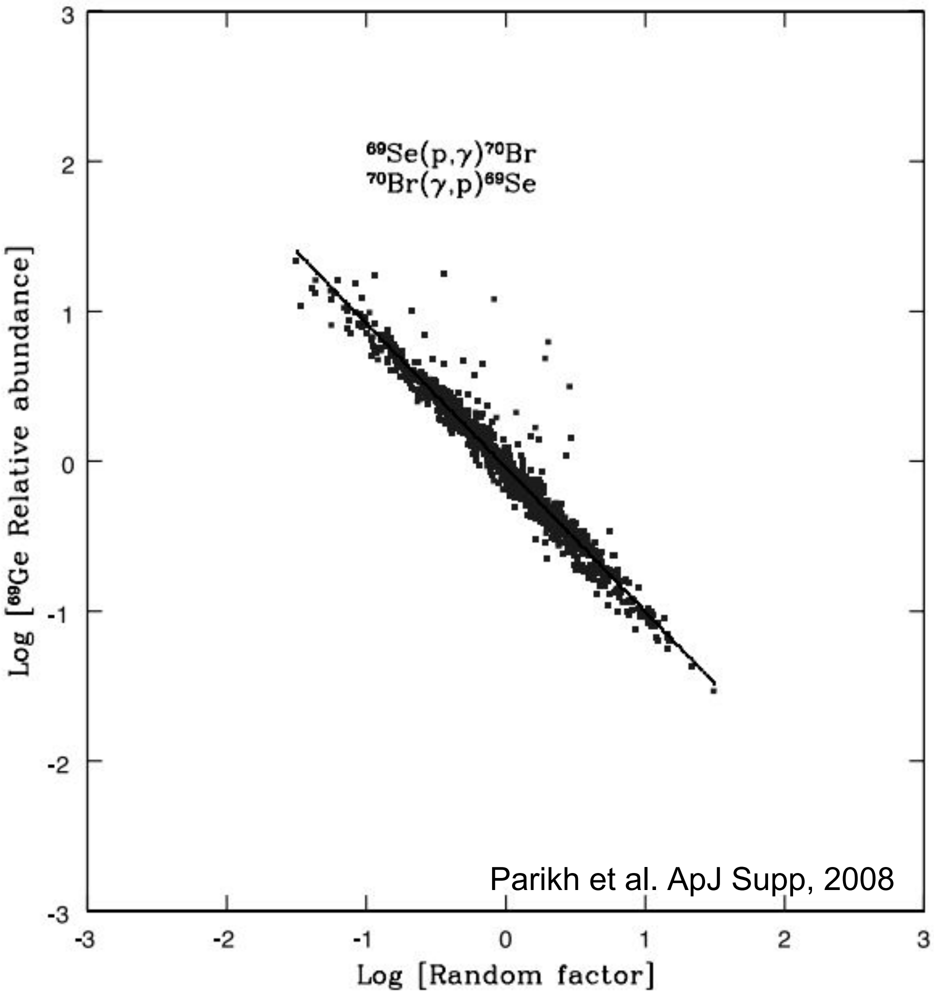
Circular blobs with lines through them

Correlations with **observables** for individual rates will mostly be small

Vary accretion model parameters simultaneously - a first order study for a variety of burst systems

(how to pick the ranges? help!)

Extract higher order **sensitivities of comparable importance** to the individual rate sensitivities



Parikh et al. ApJ Supp, 2008

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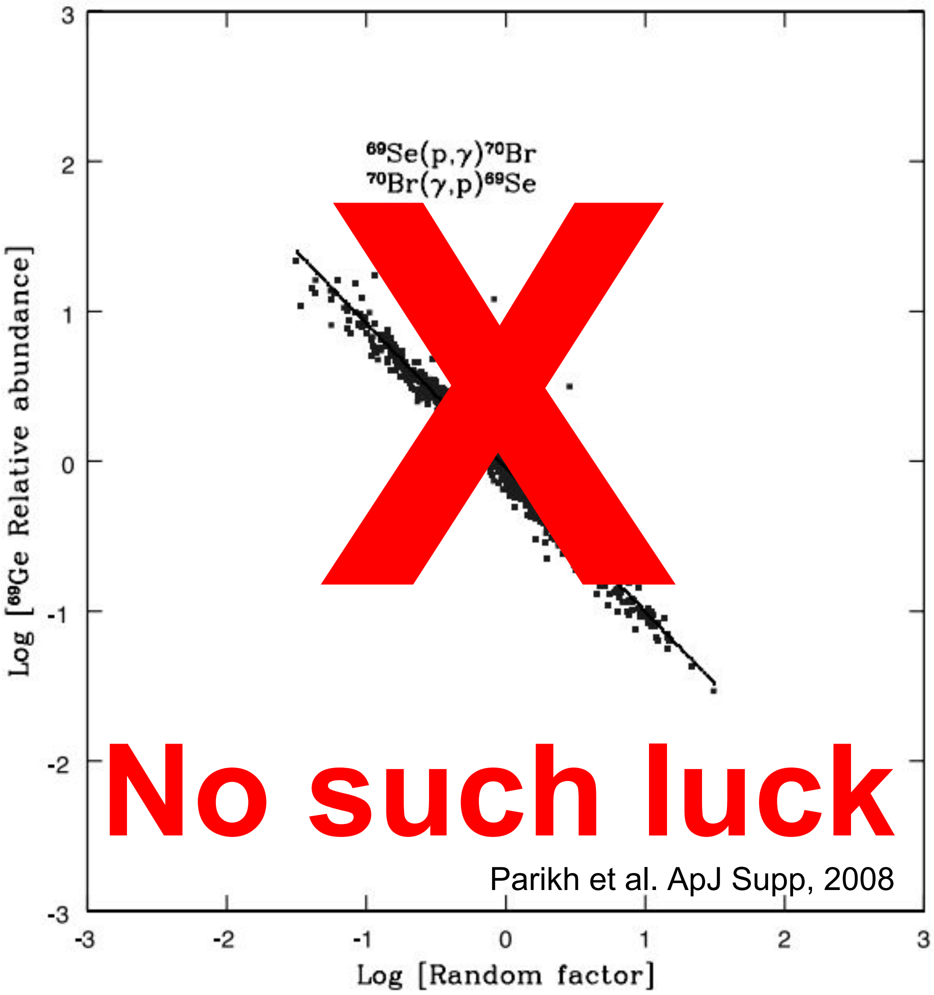

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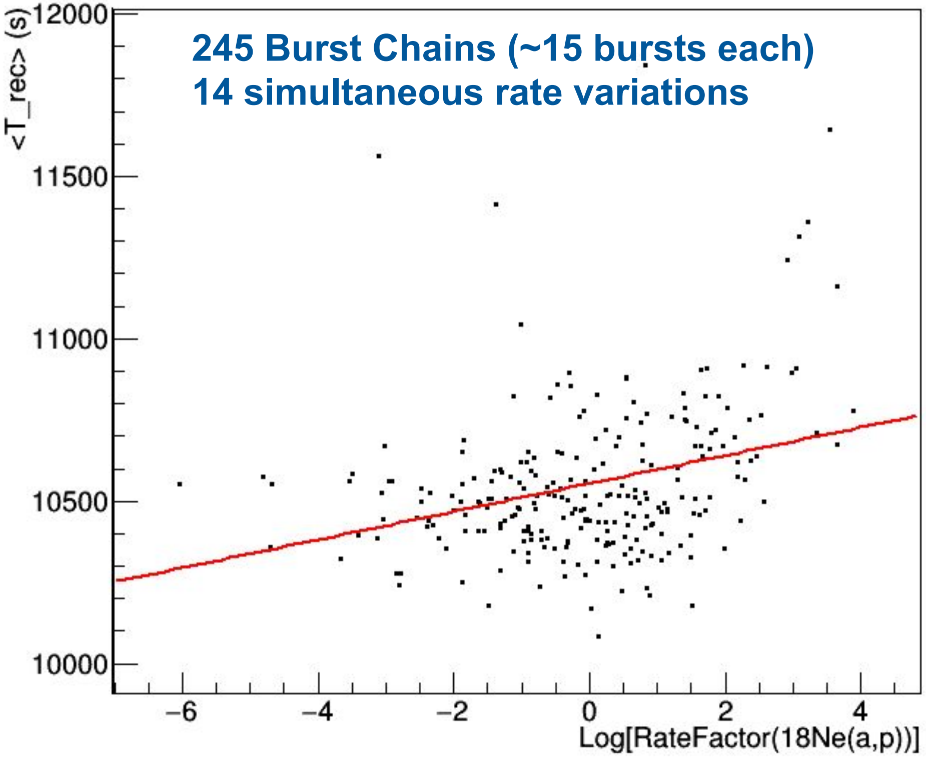

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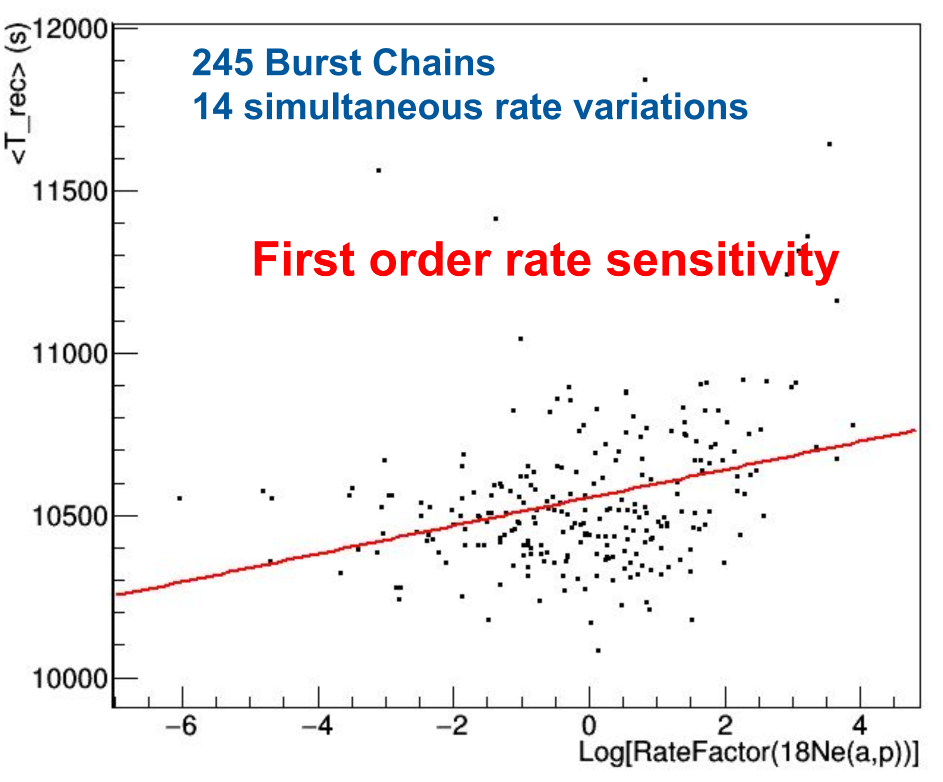
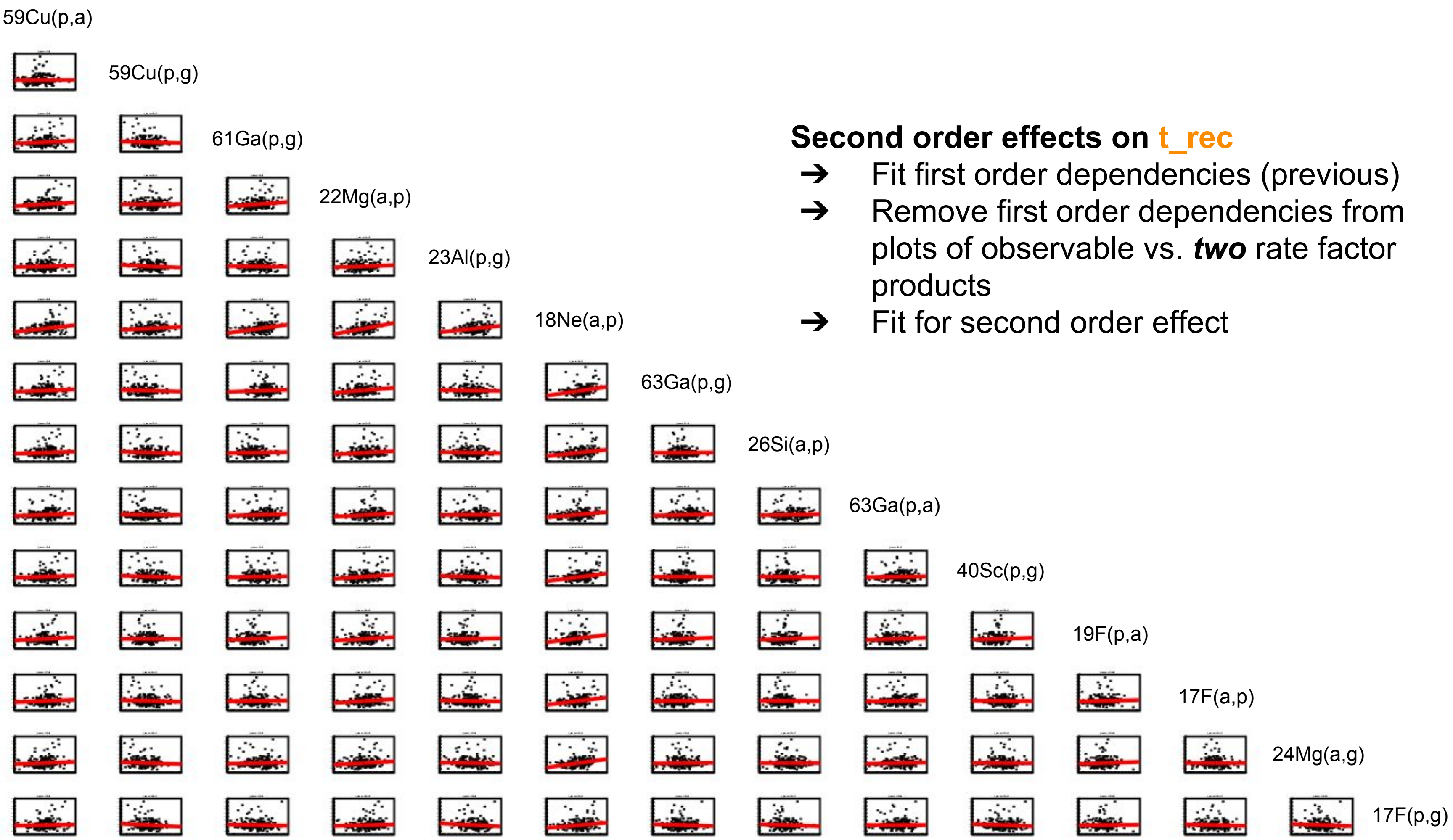
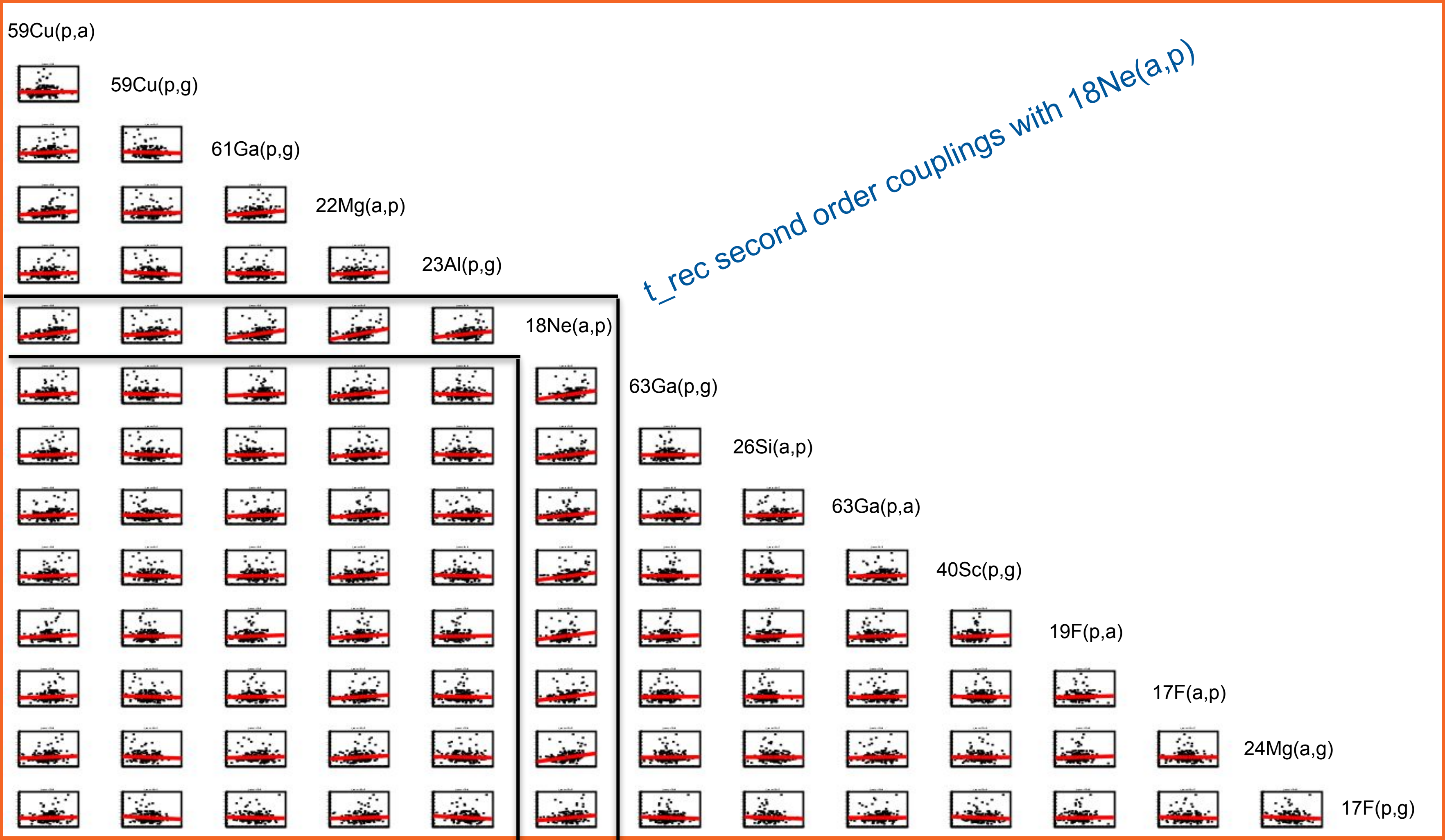


Second order effects on t_rec

- ➔ Fit first order dependencies (previous)
- ➔ Remove first order dependencies from plots of observable vs. ***two*** rate factor products
- ➔ Fit for second order effect




t_rec second order couplings with 18Ne(a,p)
59Cu(p,a)
59Cu(p,g)
61Ga(p,g)
22Mg(a,p)
23Al(p,g)
18Ne(a,p)
63Ga(p,g)
26Si(a,p)
63Ga(p,a)
40Sc(p,g)
19F(p,a)
17F(a,p)
24Mg(a,g)
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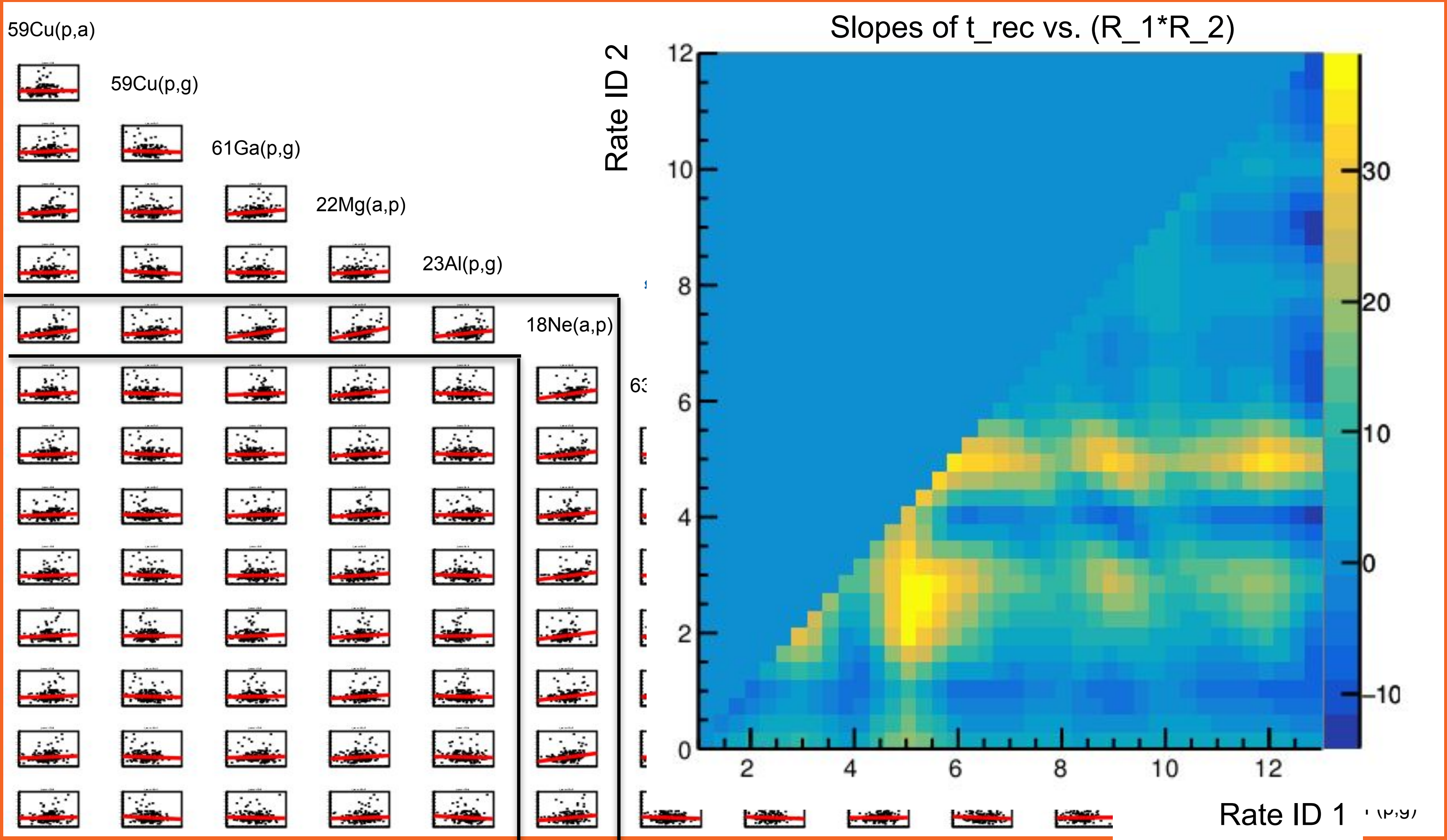
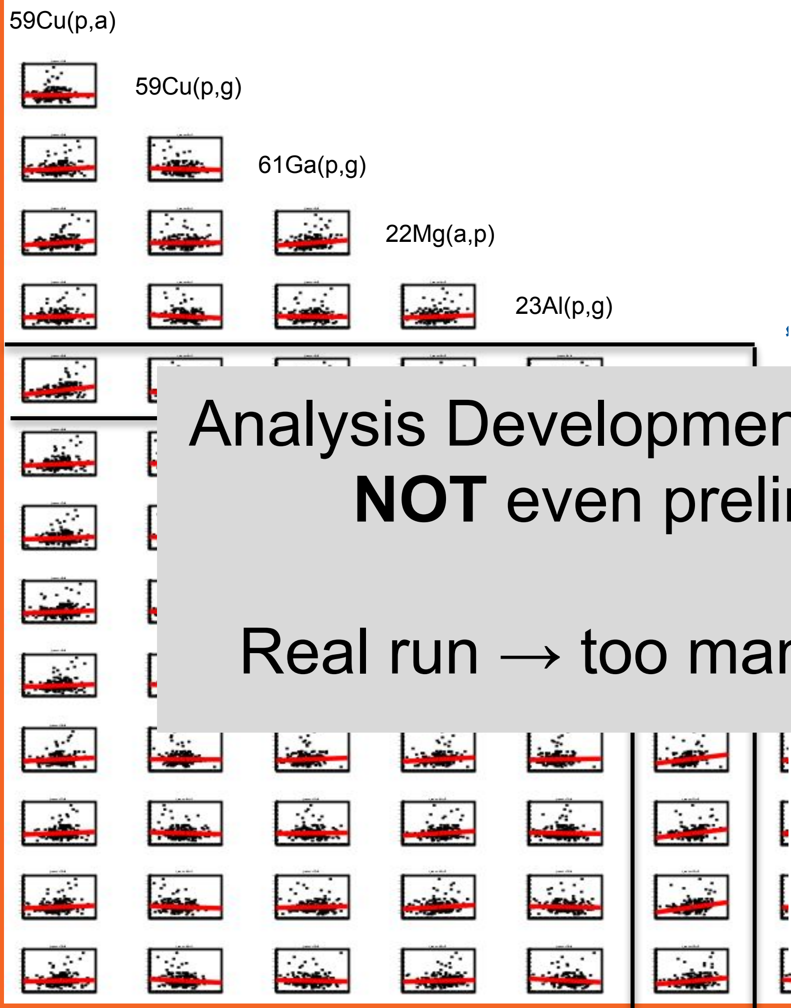
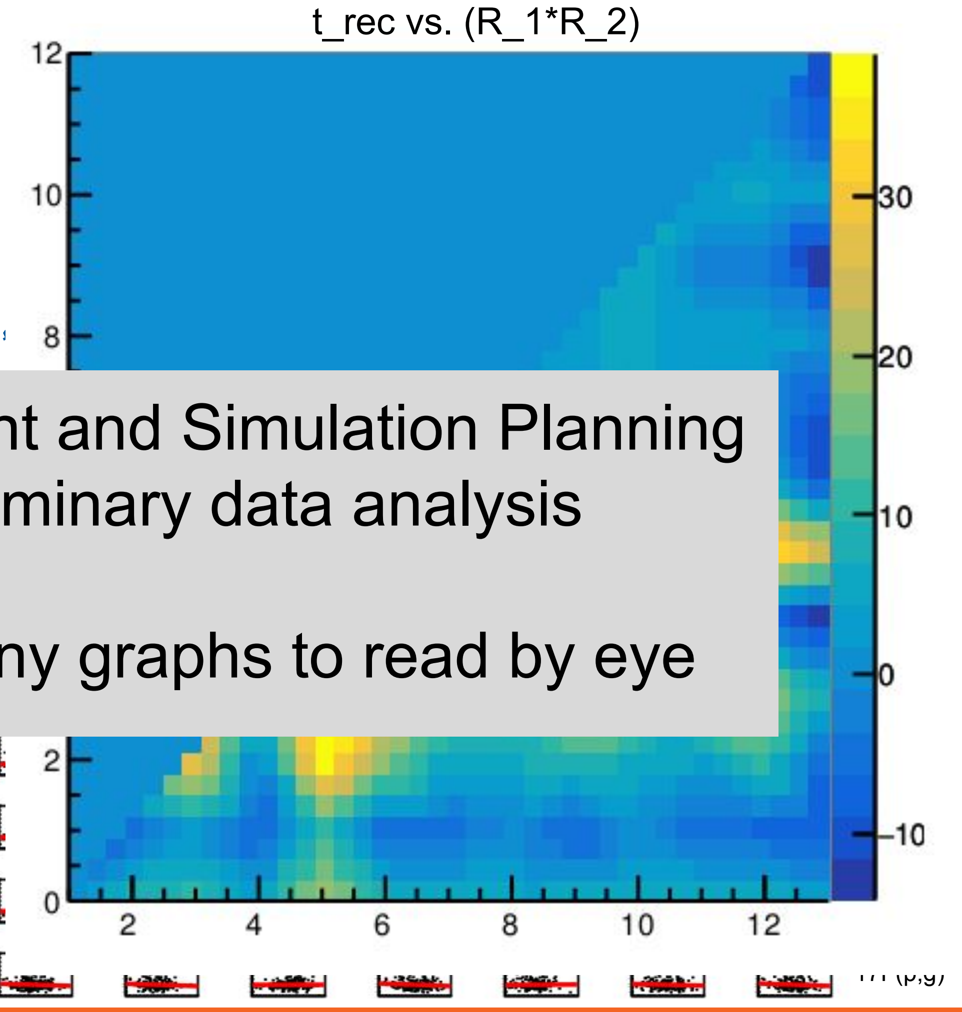

59Cu(p,a)
59Cu(p,g)
61Ga(p,g)
22Mg(a,p)
23Al(p,g)
18Ne(a,p)
Slopes of t_rec vs. (R_1*R_2)
Rate ID 2
Rate ID 1
0
2
4
6
8
10
12
30
20
10
0
-10





Analysis Development and Simulation Planning
NOT even preliminary data analysis

Real run → too many graphs to read by eye

Take home message:

We are still beginning to understand the effects of nuclear physics uncertainties in Type I x-ray bursts.

Questions to answer, wishlist:

- What are interesting ranges over which to vary the astrophysical parameters? Uniform distribution?
- Let's fit burst models to observations using a "particle swarm optimizer"
  - Global, validated with many degrees of freedom ~75
  - Parallelizable to complete within human and PhD run times
  - PSO does not provide confidence intervals itself
- What are the reasons for the differing observables between burst models using ReacLib 1.0, ReacLib 2.2? Are all the updates reliable?
- ISLA - a mass spectrometer for experiments with reaccelerated rare-isotope beams at FRIB