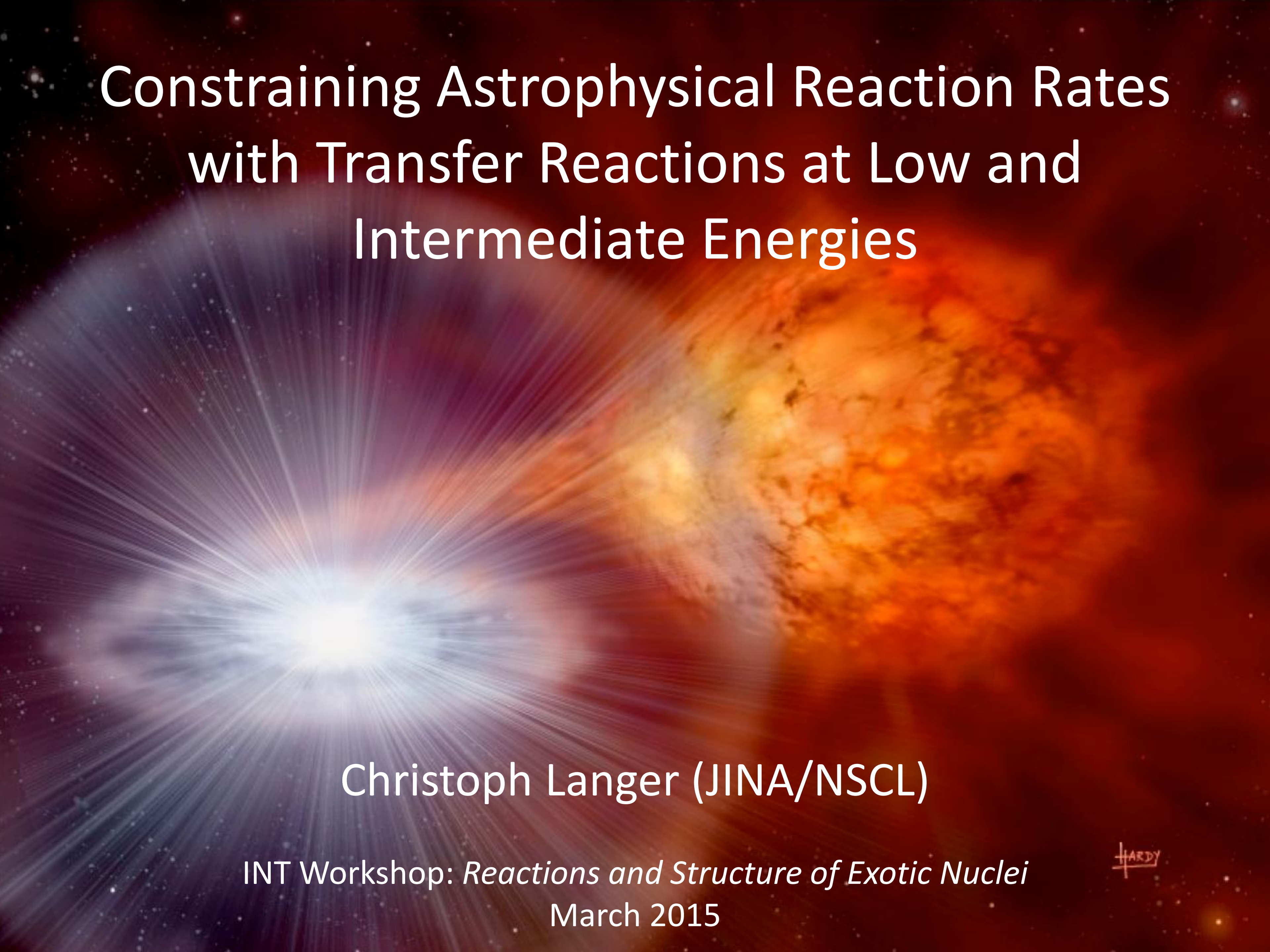
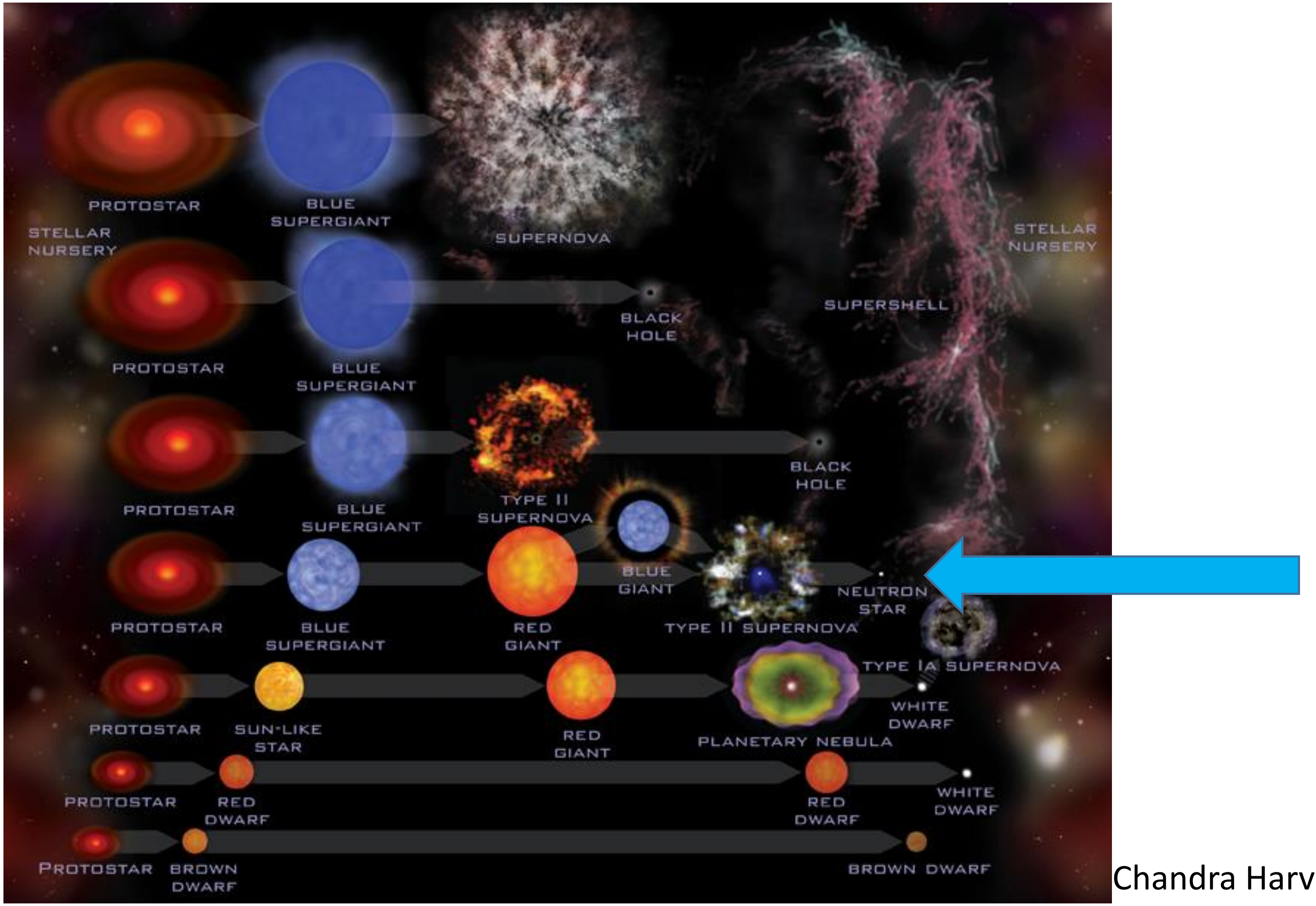


Constraining Astrophysical Reaction Rates with Transfer Reactions at Low and Intermediate Energies

Christoph Langer (JINA/NSCL)

INT Workshop: *Reactions and Structure of Exotic Nuclei*
March 2015

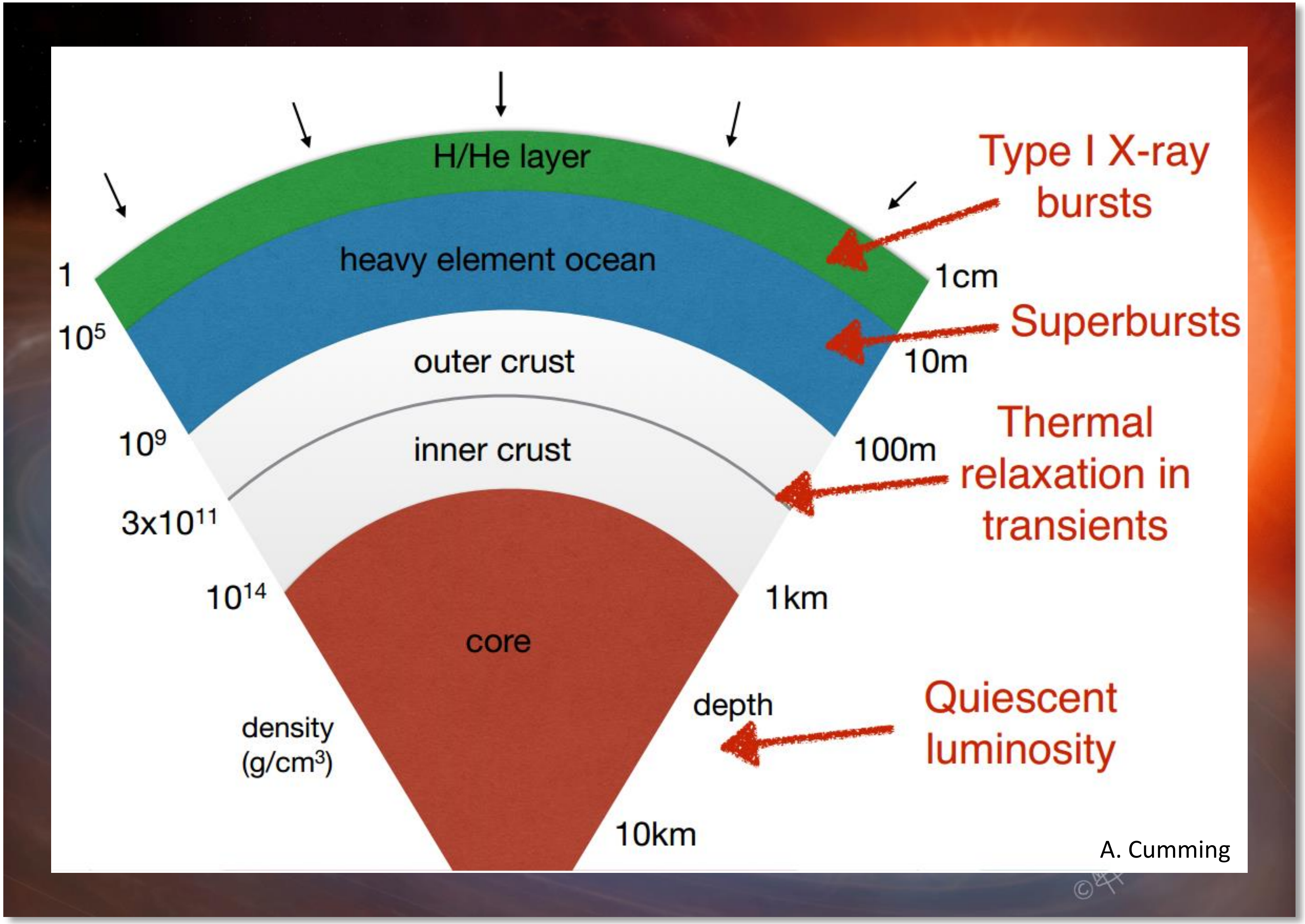
Understanding the origin of heavy elements – Understanding our own origin



Chandra Harvard

→ **Modeling stellar evolution requires reliable nuclear physics input**

A special class of X-ray sources



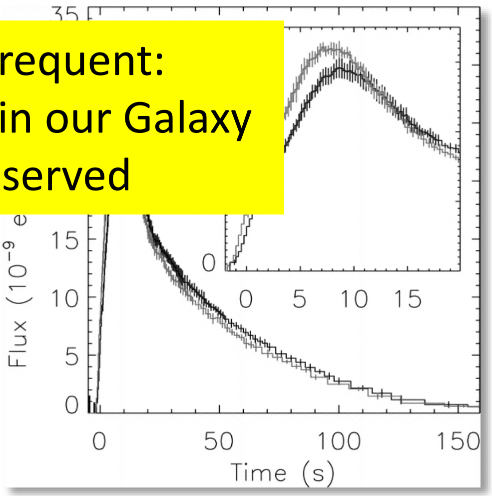
A. Cumming

What if the H/He-layer ignites?

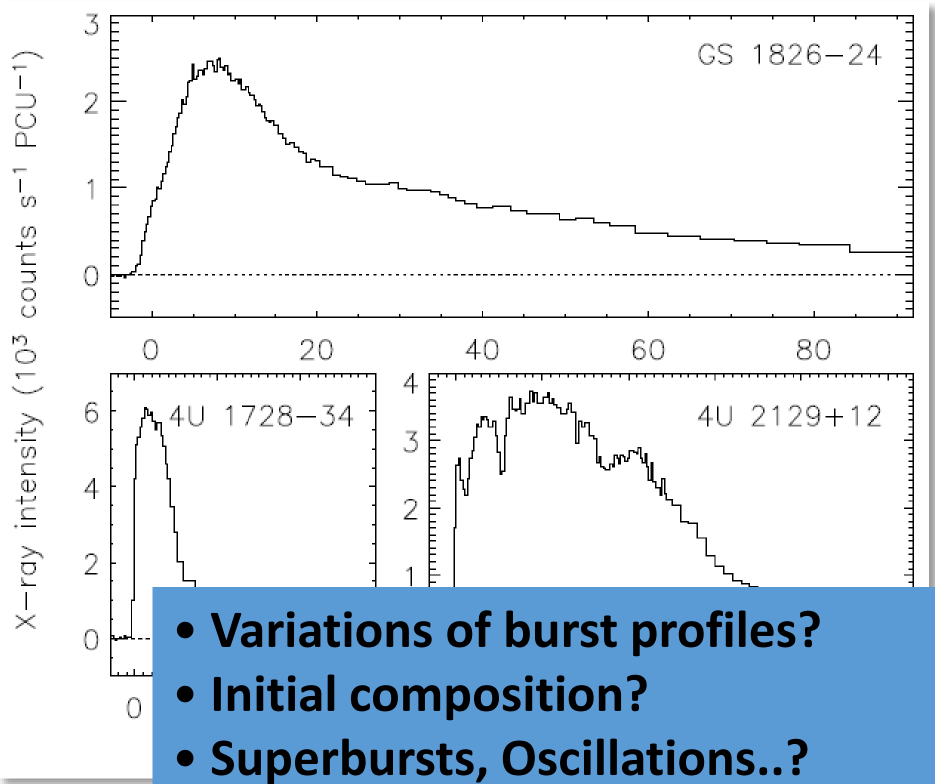
→ A type I X-ray burst takes place!

They are very bright!!

They are very frequent:
~ 100 bursters in our Galaxy
~ 10^4 bursts observed



D. Galloway, astro-ph/0608259

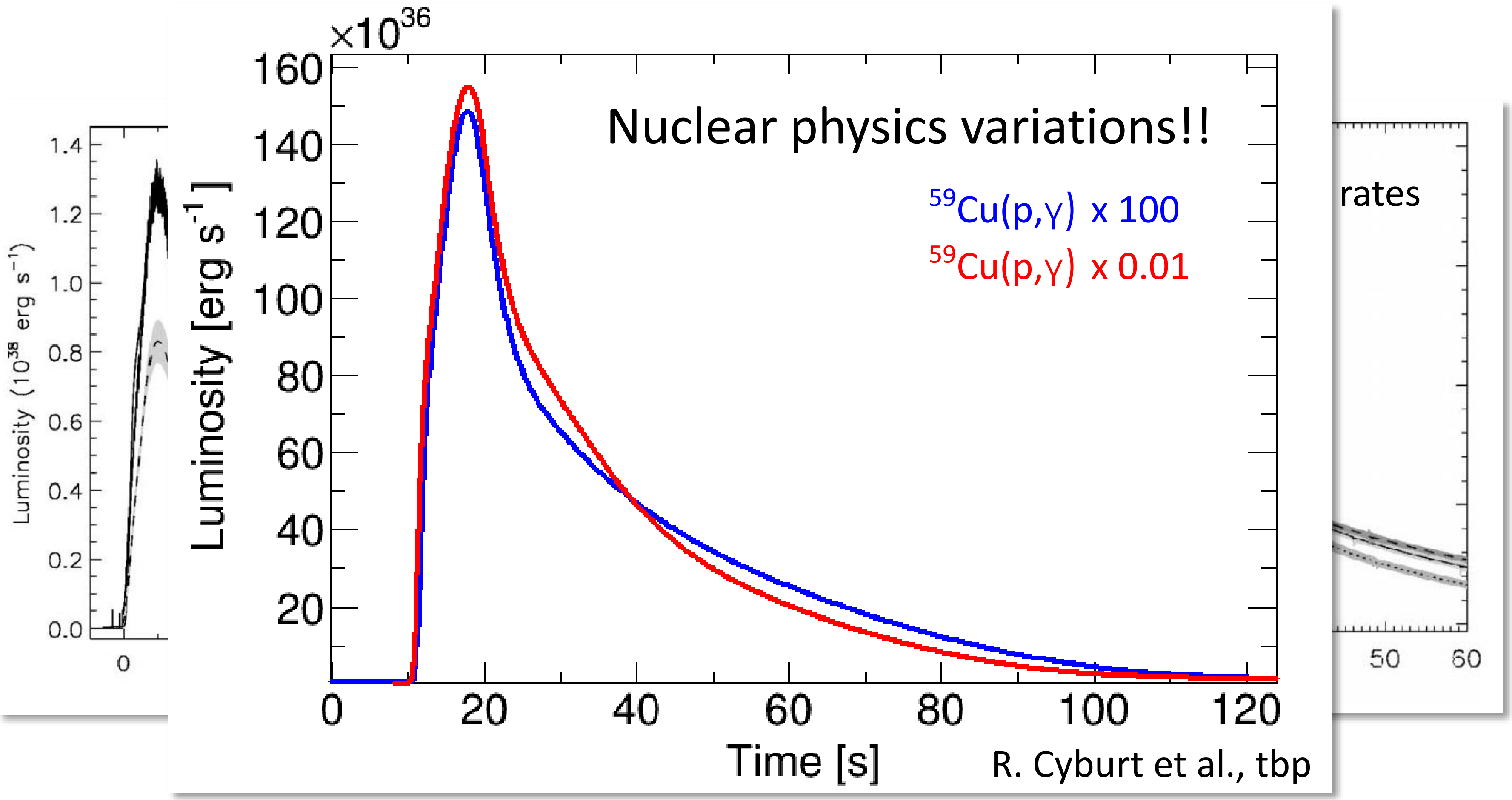


- **Variations of burst profiles?**
- **Initial composition?**
- **Superbursts, Oscillations..?**

ion?

Goal: extract astrophysical information from x-ray burst light curve
→ need nuclear physics input

Astrophysical simulations with realistic nuclear physics



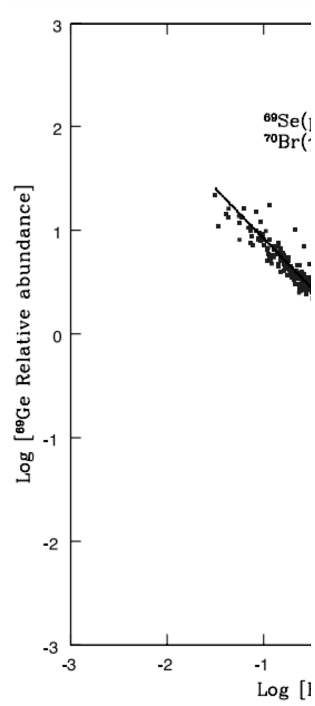
Nuclear physics variations!!

R. Cyburt et al., tbp

Goal: remove (reduce) uncertainties induced by nuclear physics
→ stellar parameters can be addressed

Extracting the important nuclear physics

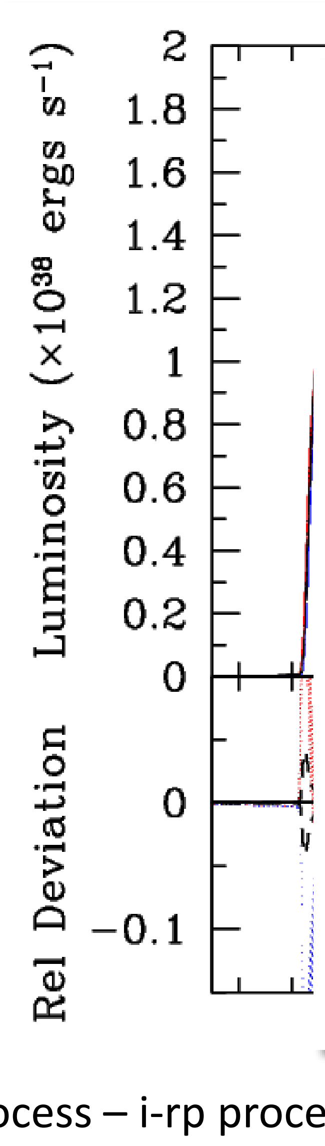
Corre

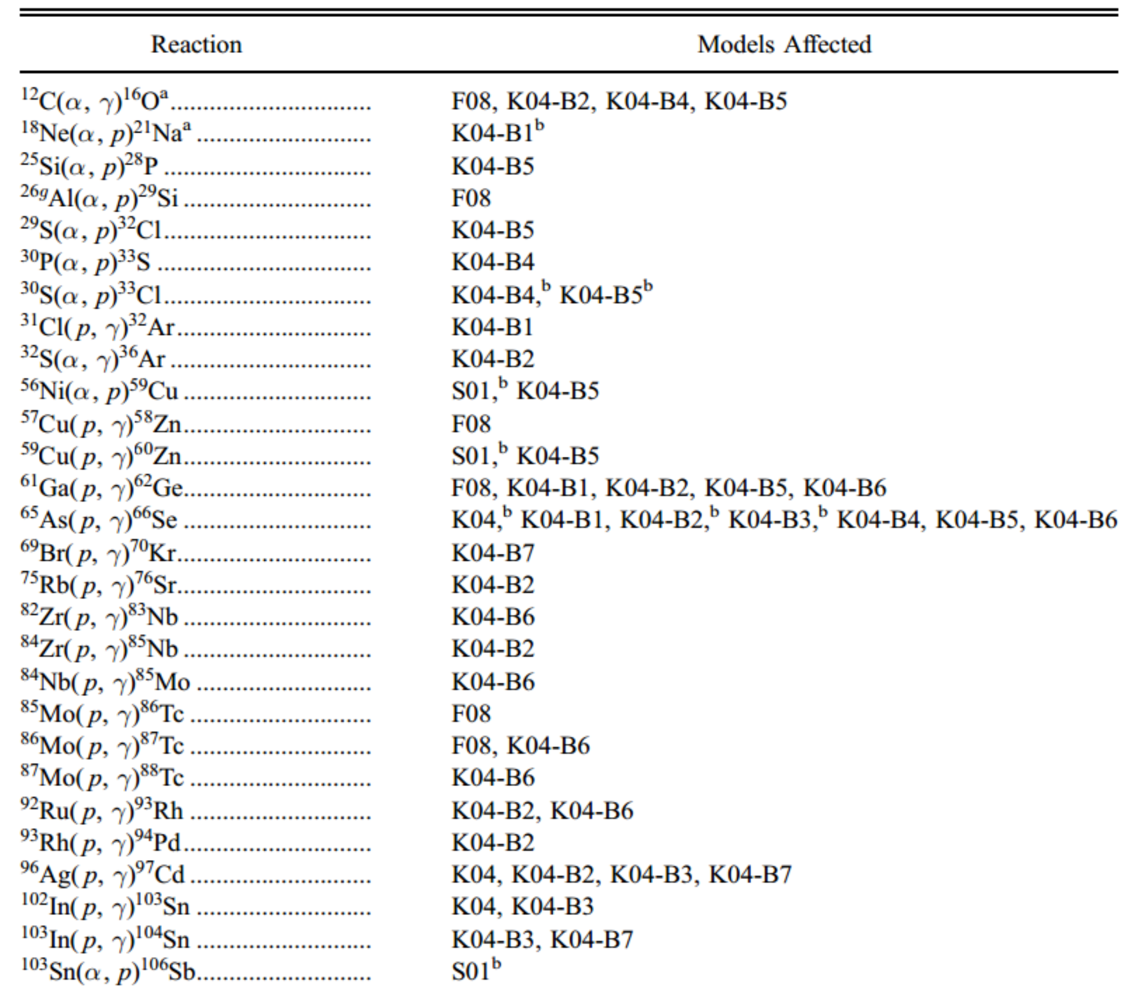


A. Parik

A. Parik

Reaction rates





Reaction	Models Affected
$^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$[a]	F08, K04-B2, K04-B4, K04-B5
$^{18}\mathrm{Ne}(\alpha,p)^{21}\mathrm{Na}$[a]	K04-B1[b]
$^{25}\mathrm{Si}(\alpha,p)^{28}\mathrm{P}$	K04-B5
$^{26g}\mathrm{Al}(\alpha,p)^{29}\mathrm{Si}$	F08
$^{29}\mathrm{S}(\alpha,p)^{32}\mathrm{Cl}$	K04-B5
$^{30}\mathrm{P}(\alpha,p)^{33}\mathrm{S}$	K04-B4
$^{30}\mathrm{S}(\alpha,p)^{33}\mathrm{Cl}$	K04-B4,[b] K04-B5[b]
$^{31}\mathrm{Cl}(p,\gamma)^{32}\mathrm{Ar}$	K04-B1
$^{32}\mathrm{S}(\alpha,\gamma)^{36}\mathrm{Ar}$	K04-B2
$^{56}\mathrm{Ni}(\alpha,p)^{59}\mathrm{Cu}$	S01,[b] K04-B5
$^{57}\mathrm{Cu}(p,\gamma)^{58}\mathrm{Zn}$	F08
$^{59}\mathrm{Cu}(p,\gamma)^{60}\mathrm{Zn}$	S01,[b] K04-B5
$^{61}\mathrm{Ga}(p,\gamma)^{62}\mathrm{Ge}$	F08, K04-B1, K04-B2, K04-B5, K04-B6
$^{65}\mathrm{As}(p,\gamma)^{66}\mathrm{Se}$	K04,[b] K04-B1, K04-B2,[b] K04-B3,[b] K04-B4, K04-B5, K04-B6
$^{69}\mathrm{Br}(p,\gamma)^{70}\mathrm{Kr}$	K04-B7
$^{75}\mathrm{Rb}(p,\gamma)^{76}\mathrm{Sr}$	K04-B2
$^{82}\mathrm{Zr}(p,\gamma)^{83}\mathrm{Nb}$	K04-B6
$^{84}\mathrm{Zr}(p,\gamma)^{85}\mathrm{Nb}$	K04-B2
$^{84}\mathrm{Nb}(p,\gamma)^{85}\mathrm{Mo}$	K04-B6
$^{85}\mathrm{Mo}(p,\gamma)^{86}\mathrm{Tc}$	F08
$^{86}\mathrm{Mo}(p,\gamma)^{87}\mathrm{Tc}$	F08, K04-B6
$^{87}\mathrm{Mo}(p,\gamma)^{88}\mathrm{Tc}$	K04-B6
$^{92}\mathrm{Ru}(p,\gamma)^{93}\mathrm{Rh}$	K04-B2, K04-B6
$^{93}\mathrm{Rh}(p,\gamma)^{94}\mathrm{Pd}$	K04-B2
$^{96}\mathrm{Ag}(p,\gamma)^{97}\mathrm{Cd}$	K04, K04-B2, K04-B3, K04-B7
$^{102}\mathrm{In}(p,\gamma)^{103}\mathrm{Sn}$	K04, K04-B3
$^{103}\mathrm{In}(p,\gamma)^{104}\mathrm{Sn}$	K04-B3, K04-B7
$^{103}\mathrm{Sn}(\alpha,p)^{106}\mathrm{Sb}$	S01[b]

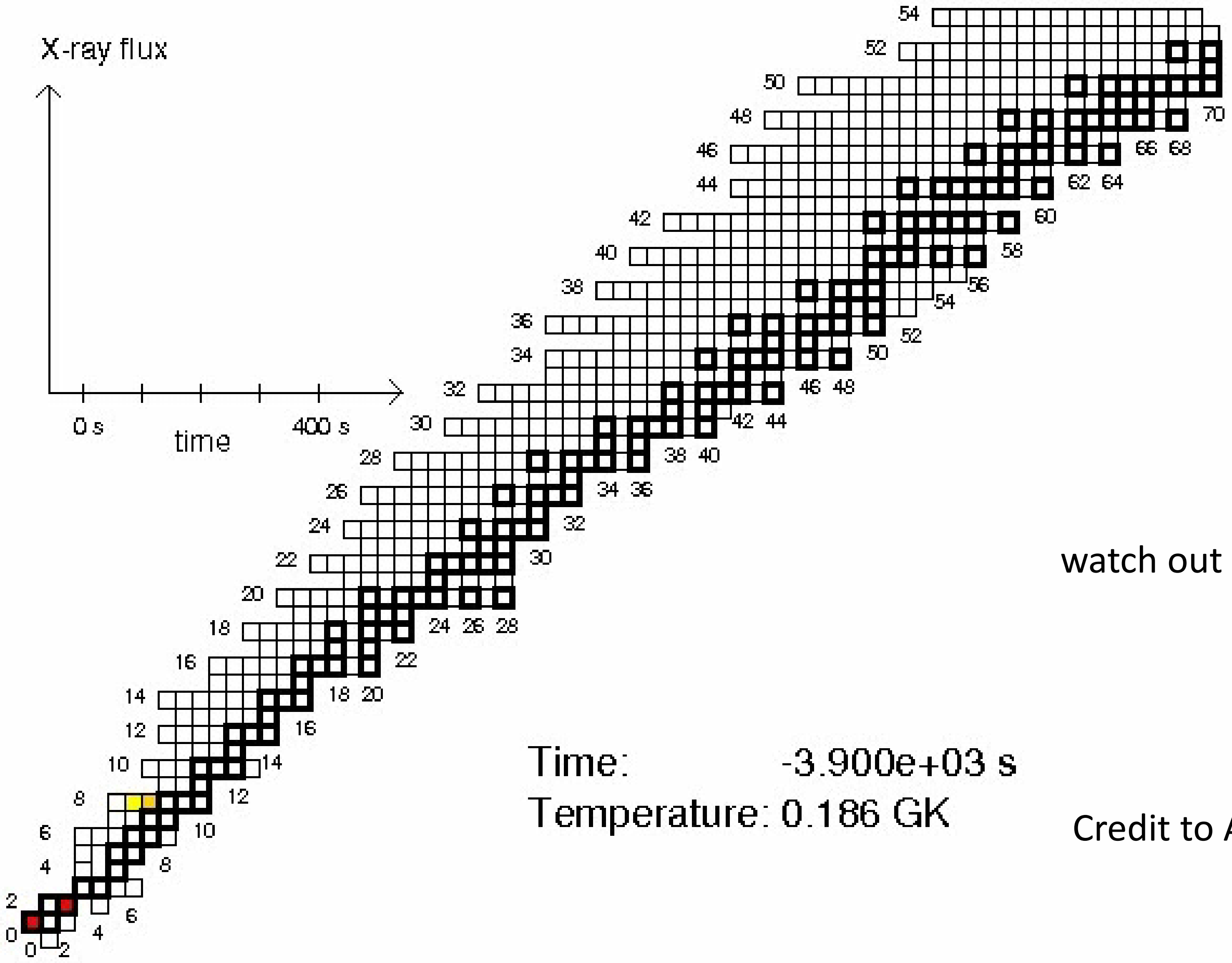
rt

Z,[a]

For “classic” rp process – i-rp process?

R. Cyburt et al., tbp

A thermonuclear explosion on your PC



Time: -3.900e+03 s
Temperature: 0.186 GK

watch out for RED!

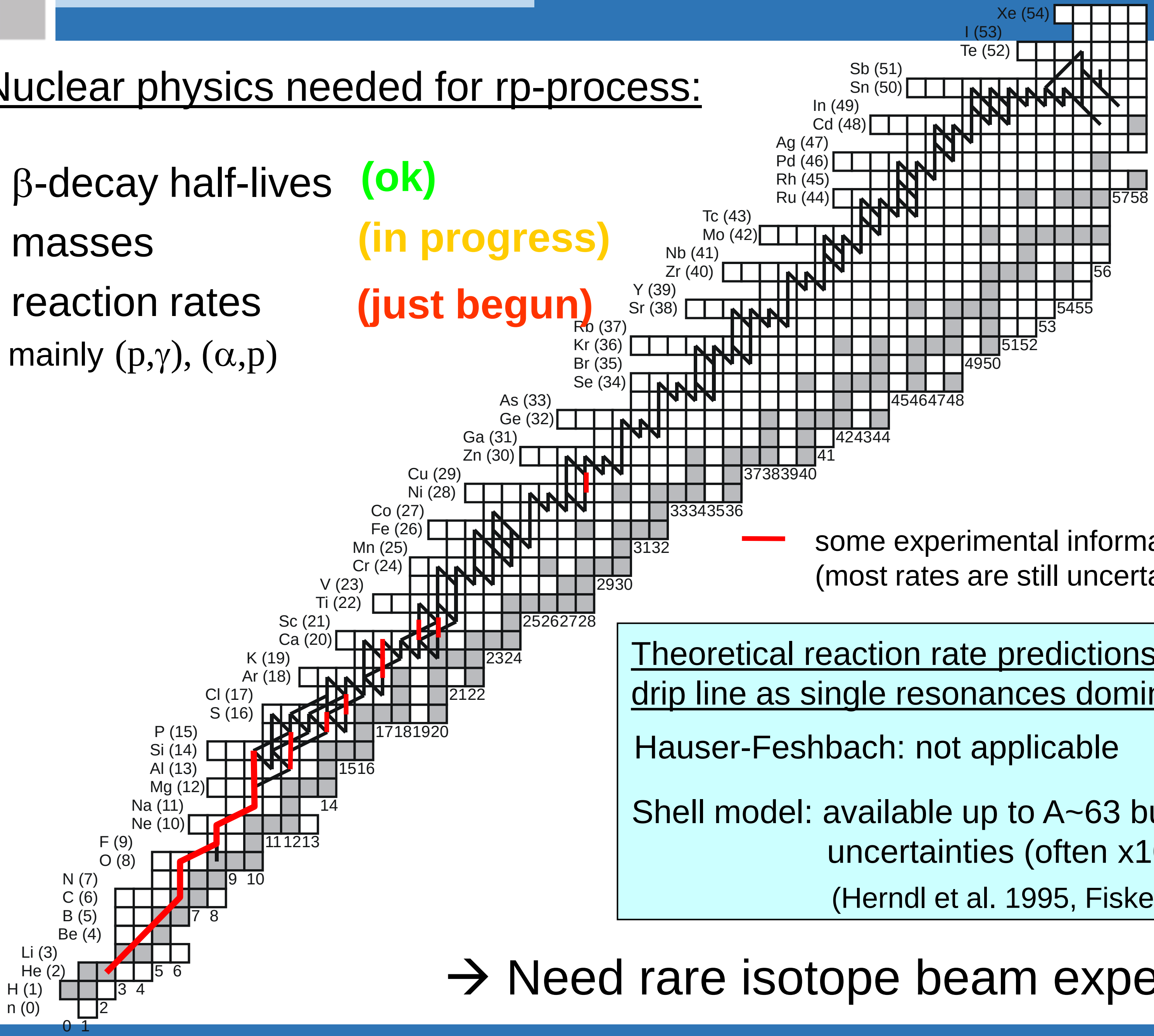
Credit to A. Heger

Slide from H. Schatz

Nuclear physics needed for rp-process:

- β-decay half-lives **(ok)**
- masses **(in progress)**
- reaction rates **(just begun)**

mainly (p,γ), (α,p)



— some experimental information available (most rates are still uncertain)

<u>Theoretical reaction rate predictions difficult near drip line as single resonances dominate rate:</u>

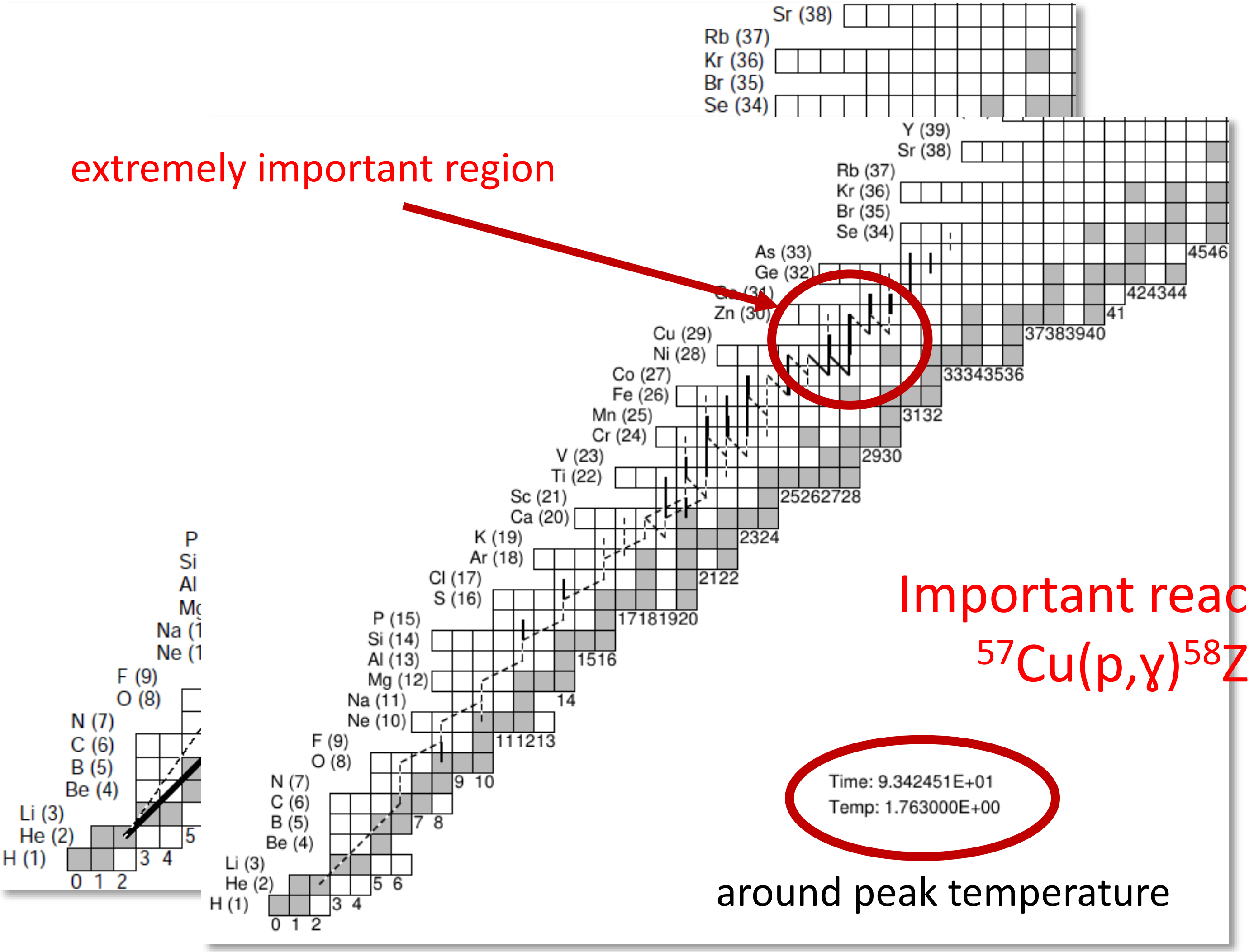
Hauser-Feshbach: not applicable

Shell model: available up to A~63 but large uncertainties (often x1000 - x10000)

(Herndl et al. 1995, Fisker et al. 2001)

→ Need rare isotope beam experiments

Investigating the flow: the NiCuZn region

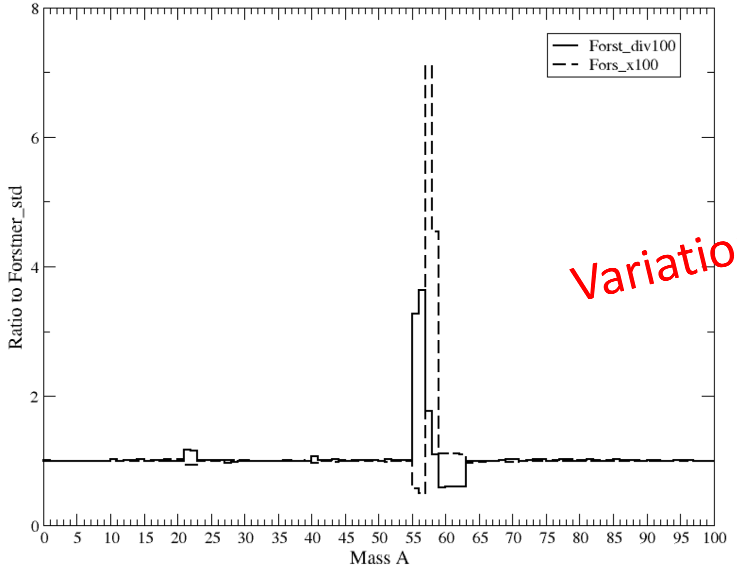


extremely important region

Important reaction:
$^{57}Cu(p,\gamma)^{58}Zn$

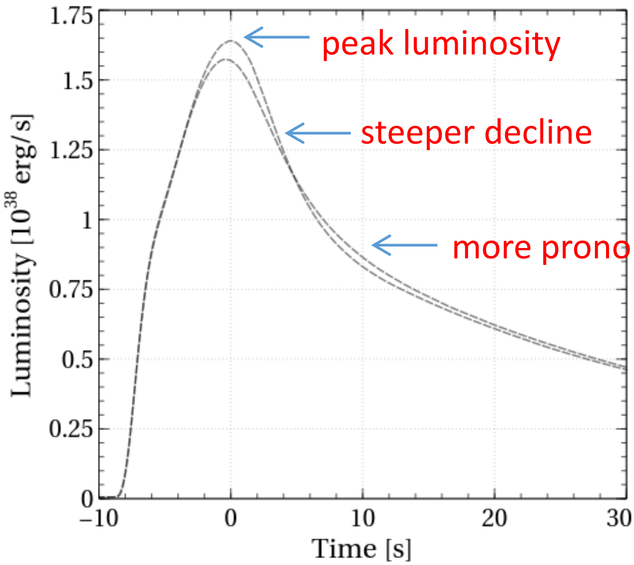
around peak temperature

Abundance changes -> compositional inertia



Variation of rate

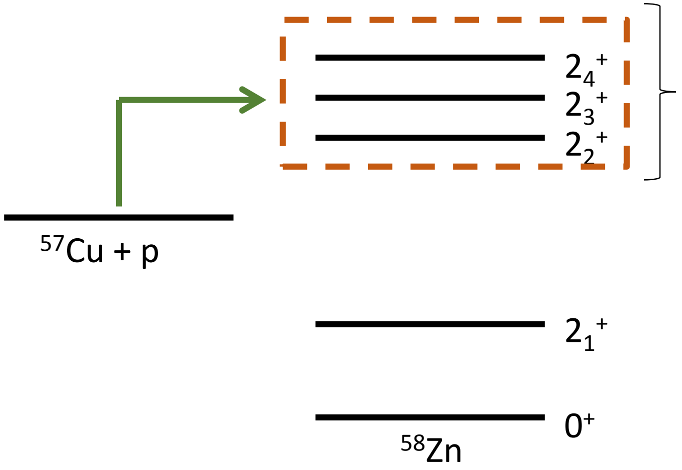
light curve uncertainties



peak luminosity

steeper decline

more pronounced kink



Gamow window
(E_0 ~ 1.15 ± 0.73 MeV)

So far: no states measured
-> only from theory with
big uncertainties!

C. Langer et al., EPJ Web of Conferences 66 (2014)

Reaction rate dominated by 2^+ resonances

Using an indirect method
(direct reaction not possible at the moment)

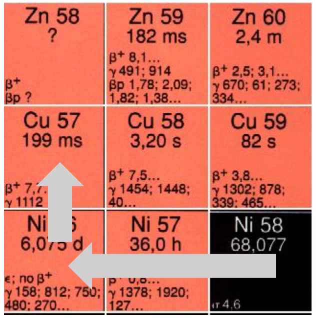
Rate: $\langle \sigma v \rangle = \left(\frac{2\pi}{\mu k T} \right)^{3/2} \sum_i (\omega\gamma)_i e^{-{E_r}_i / kT}$

Resonance Energy: $E_r = E_x - Q$

Reaction Q-value: $Q = \Delta M_H - \Delta M(^{55}\mathrm{Ni}) - \Delta M(^{56}\mathrm{Cu})$

Resonance Strength: $\omega\gamma = \frac{2J_R+1}{(2J_S+1)(2J_p+1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma}$

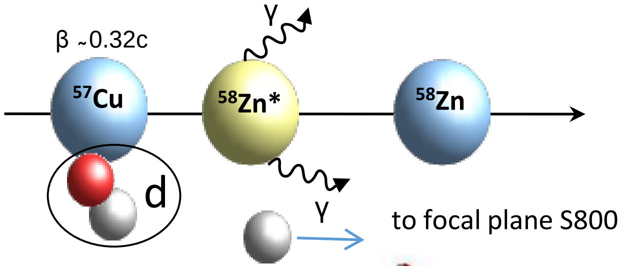
Experimental method: enlarge cross section via (d,n) as surrogate BUT: use high beam energy at ~ 80 MeV/nucleon

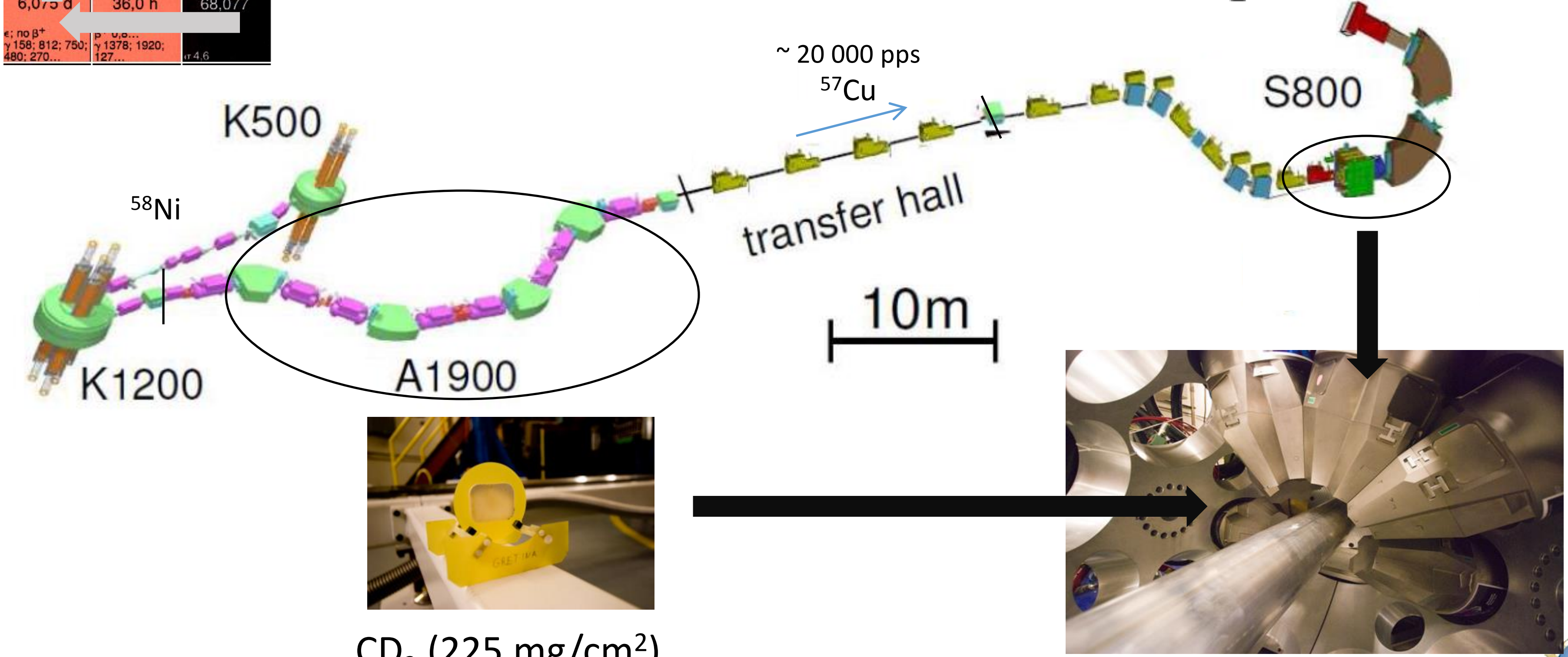


Zn 58 ? β^+ βp ?	Zn 59 182 ms β^+ 8,1... γ 491; 914 βp 1,78; 2,09; 1,82; 1,38...	Zn 60 2,4 m β^+ 2,5; 3,1... γ 670; 61; 273; 334...
Cu 57 199 ms β^+ 7,7. γ 1112	Cu 58 3,20 s β^+ 7,5... γ 1454; 1448; 40...	Cu 59 82 s β^+ 3,8... γ 1302; 878; 339; 465...
Ni [illegible]6 6,07[illegible] d ε; no β^+ γ 158; 812; 750; 480; 270...	Ni 57 36,0 h β^+ 0,8... γ 1378; 1920; 127...	Ni 58 68,077 σ 4,6

production of ^{57}Cu : **many-nucleon transfer reactions** in a Be target

[A. Gade et al., Phys. Rev. Lett. 102 (2009) 182502]

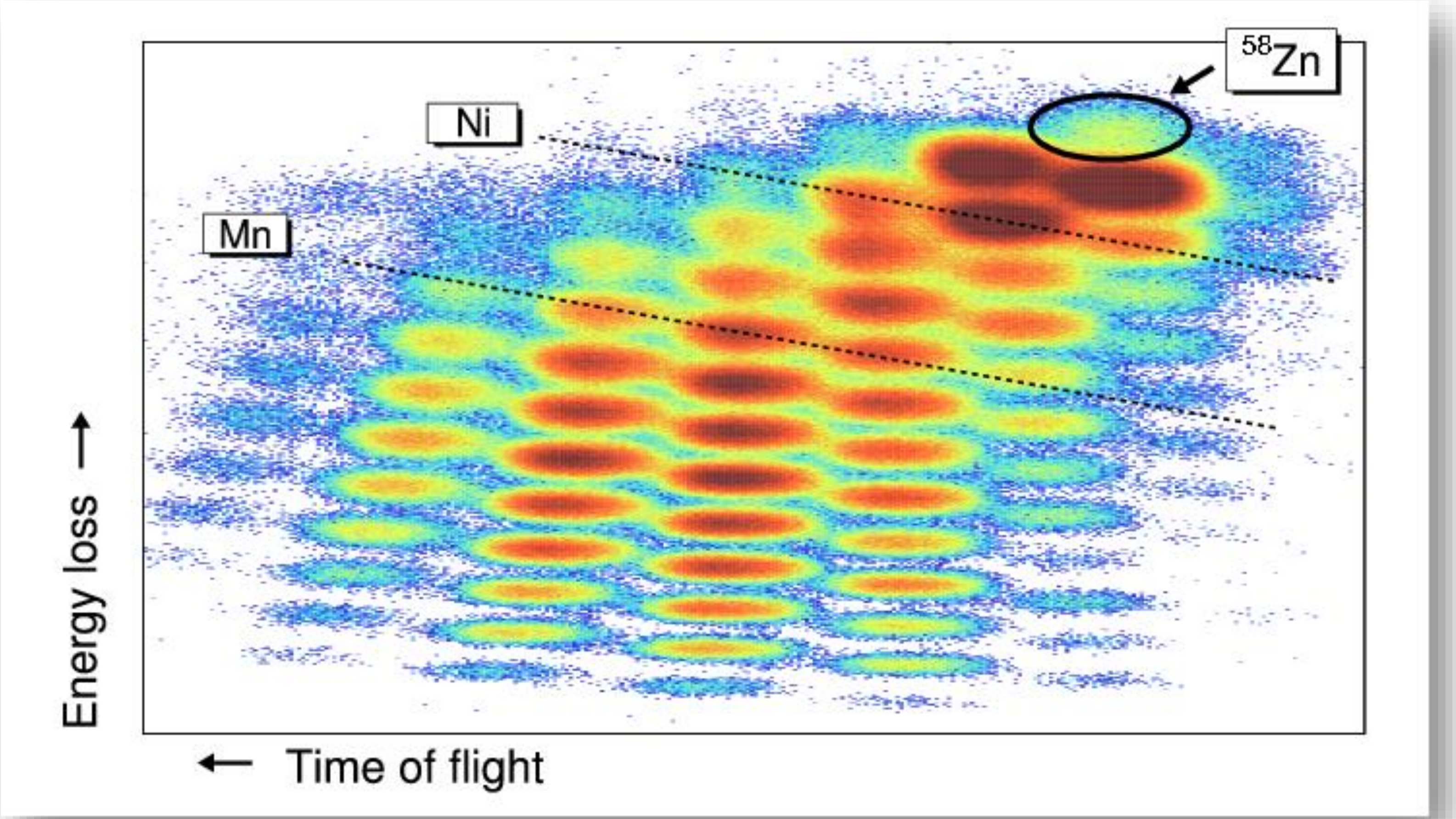




CD_2 (225 mg/cm^2)

Successfully produced ^{58}Zn

@ 80 Mev/u



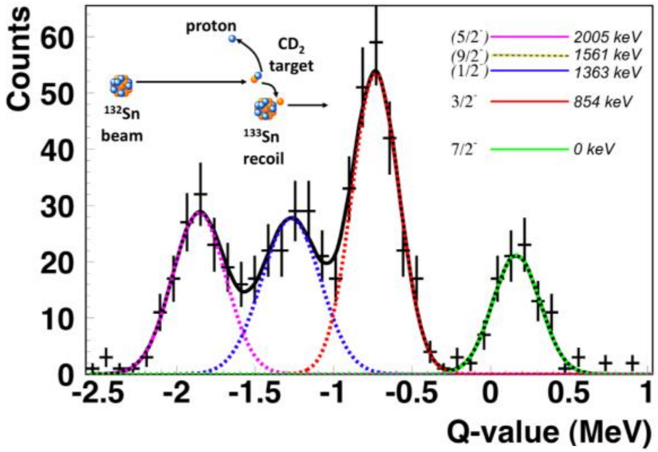
Question: is it a pure (d,n) reaction? Multistep reaction?

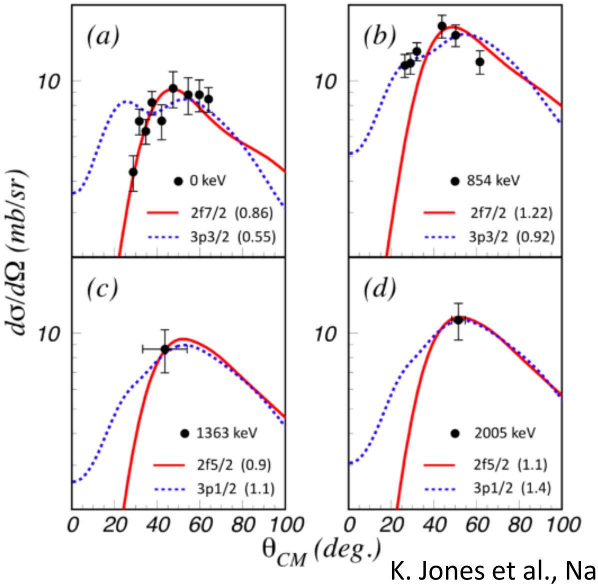
No way to experimentally verify it!

Not a “standard” transfer reaction

@ 80 Mev/u

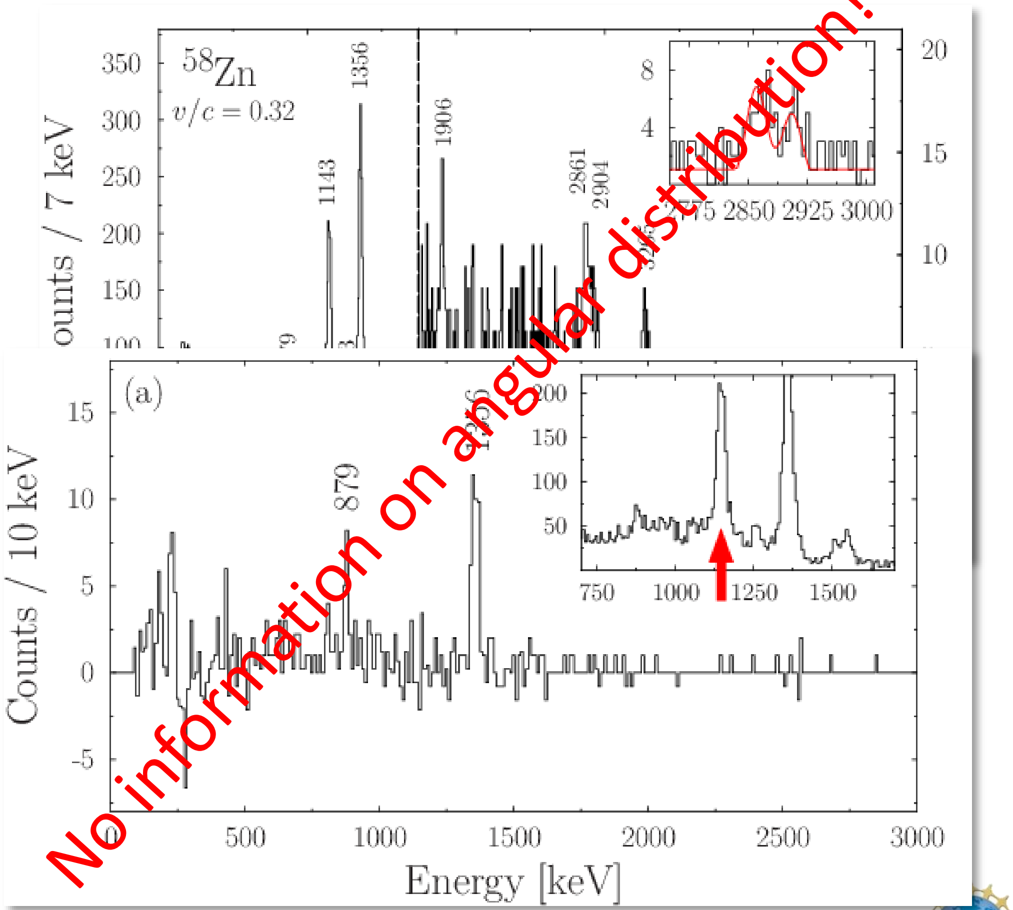
Goal: populate excited states in ^{58}Zn (l=1 and l=3 transfer)





K. Jones et al., Nature 465 (2010)

γ-decaying states

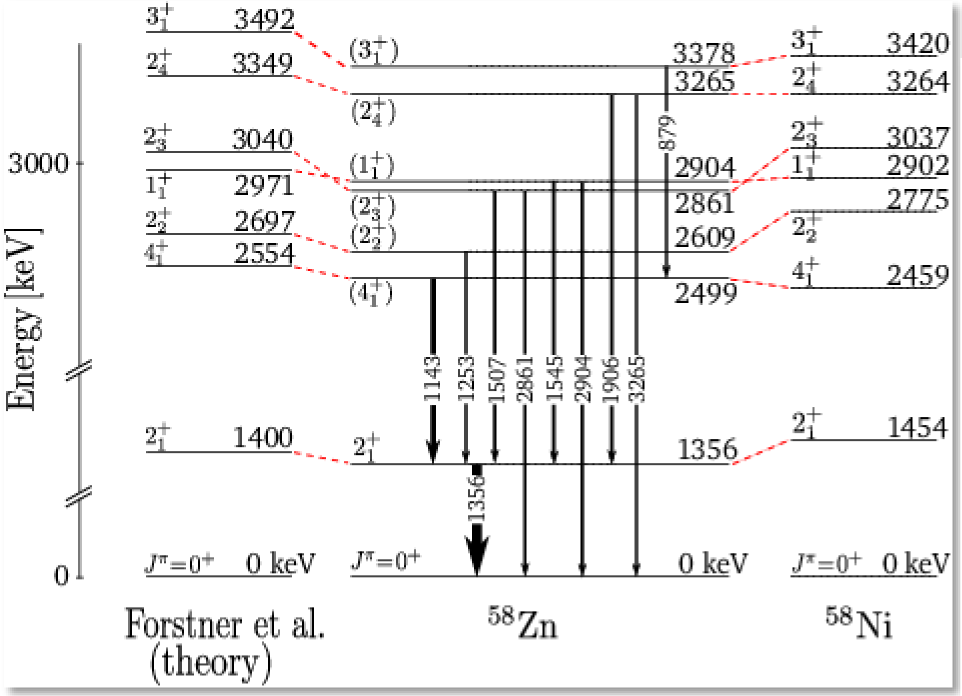


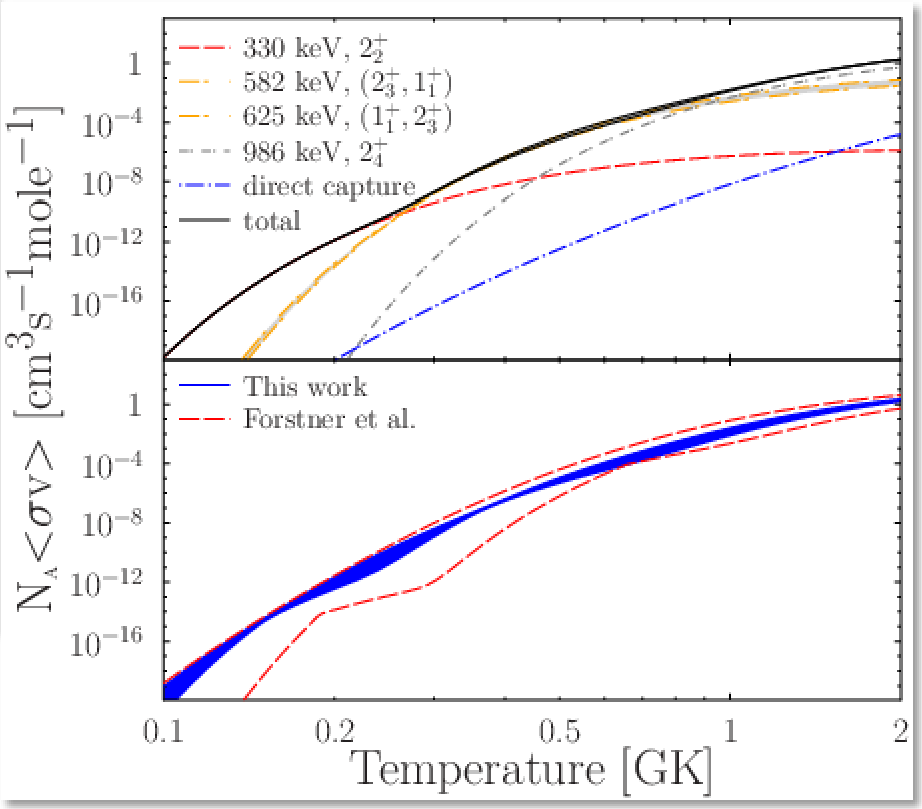
No information on angular distribution!

C. Langer et al., Phys. Rev. Letter 113 (2014)

Extracting the thermonuclear rate

@ 80 Mev/u





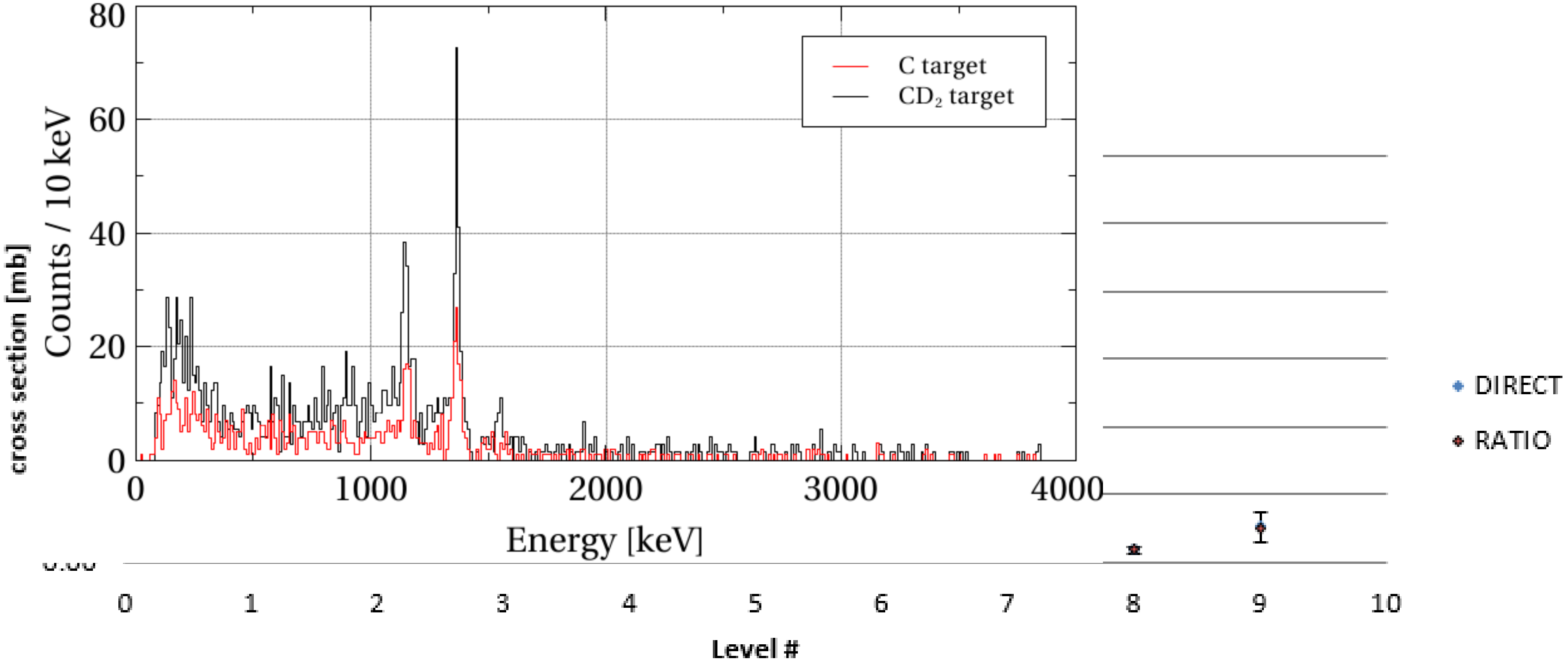
Highly reduced uncertainty! ATTENTION: Q-value uncertain 50 keV (dominant)

C. Langer et al., PRL 113 (2014)

But we have more: cross section

@ 80 Mev/u

Keep in mind: beam energy!



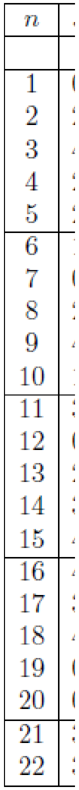
Experimentally subtract part of
the cross section from C interactions

C. Langer, preliminary and in preparation

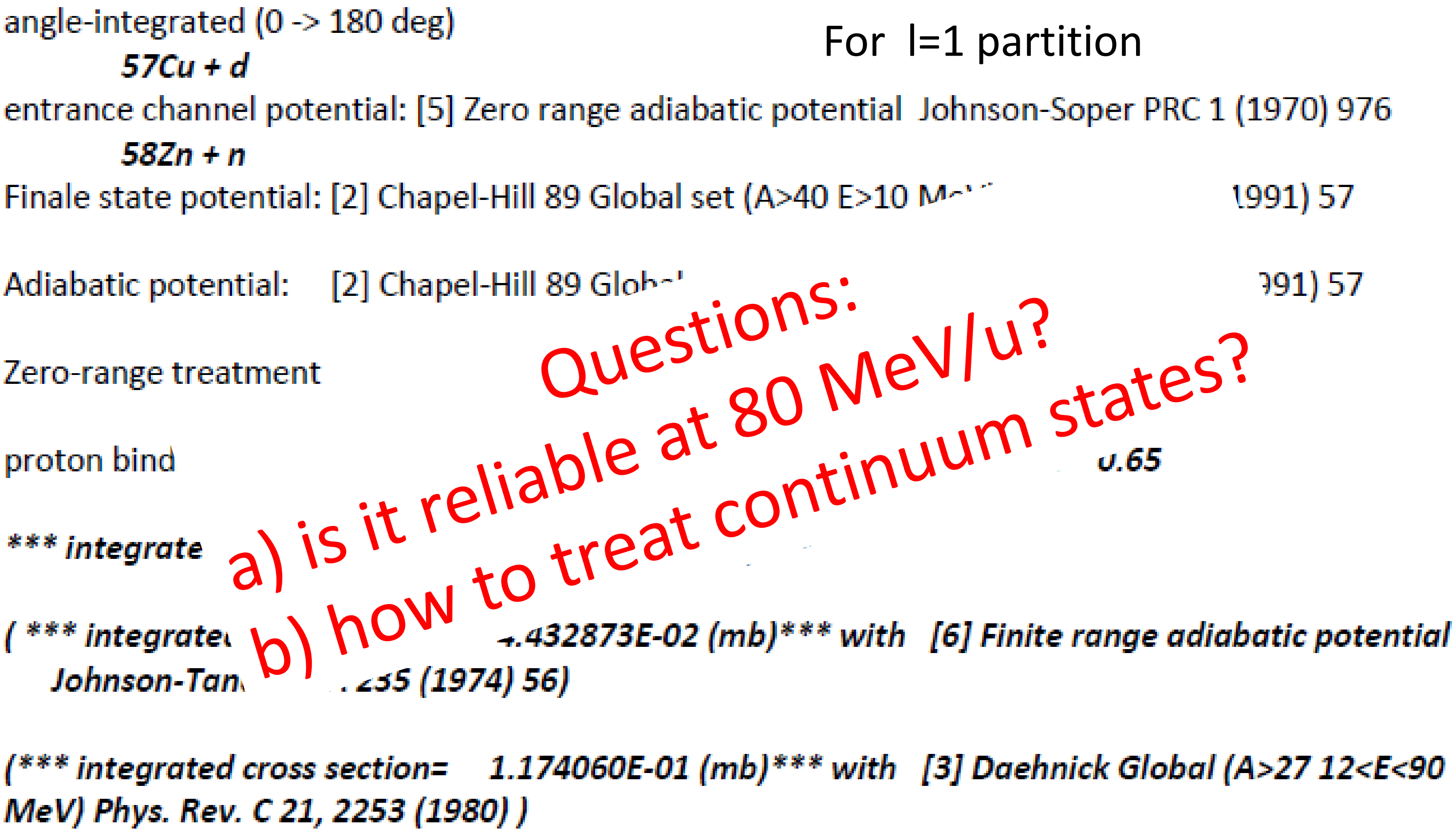
Experimentalist tries TWOFNR

@ 80 Mev/u

For l=1 partition



B.A.



angle-integrated (0 -> 180 deg)

57Cu + d

entrance channel potential: [5] Zero range adiabatic potential Johnson-Soper PRC 1 (1970) 976

58Zn + n

Finale state potential: [2] Chapel-Hill 89 Global set (A>40 E>10 M … 991) 57

Adiabatic potential: [2] Chapel-Hill 89 Glob … 991) 57

Zero-range treatment

proton bind … .65

****** integrate***

*(*** integrate … .432873E-02 (mb)*** with [6] Finite range adiabatic potential Johnson-Tan … 235 (1974) 56)*

*(*** integrated cross section= 1.174060E-01 (mb)*** with [3] Daehnick Global (A>27 12<E<90 MeV) Phys. Rev. C 21, 2253 (1980))*

:ion

e

Questions:

a) is it reliable at 80 MeV/u?

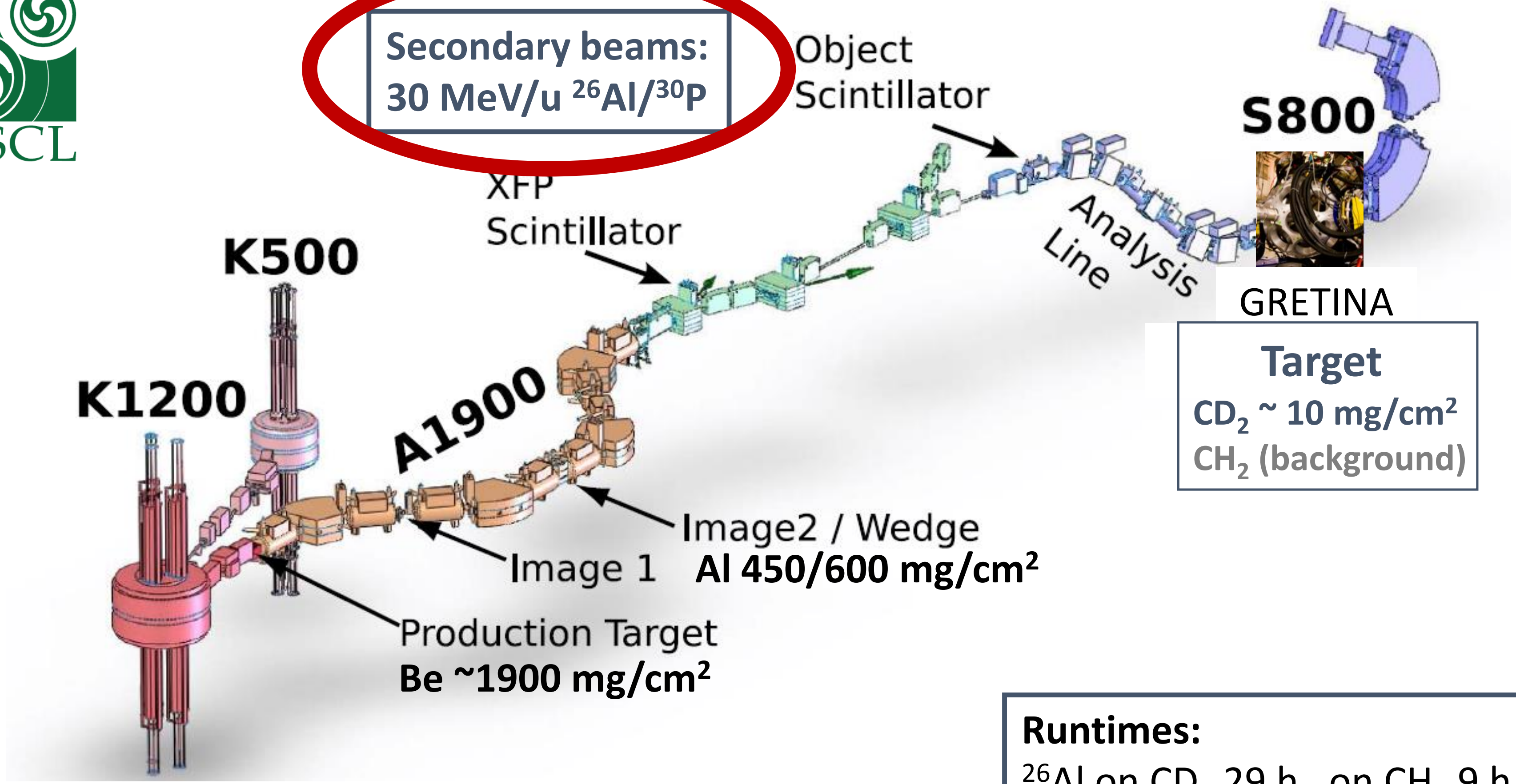
b) how to treat continuum states?

Total TWOFNR cross section for this state (after using C2S):	$6\text{x}10^{-2}$ mb
Experiment:	$5(1)\text{x}10^{-2}$ mb

C. Langer, preliminary and in preparation

Constraining important nova reactions

Secondary beams:
30 MeV/u $^{26}Al/^{30}P$



Target
CD_2 ~ 10 mg/cm^2
CH_2 (background)

Primary beam:
150 MeV/u $^{36}Ar^{18+}$

Runtimes:
^{26}Al on CD_2 29 h, on CH_2 9 h
^{30}P on CD_2 48 h, on CH_2 25 h

Following slides from A. Kankainen – Experiment of P. Woods et al. – Thanks!

Using an indirect method (direct reaction not possible at the moment)

Rate: $$\boxed{\langle \sigma v \rangle = \left(\frac{2\pi}{\mu kT}\right)^{3/2} \sum_i (\omega\gamma)_i e^{-E_{r_i}/kT}}$$

Resonance Energy: $E_r = E_x - Q$

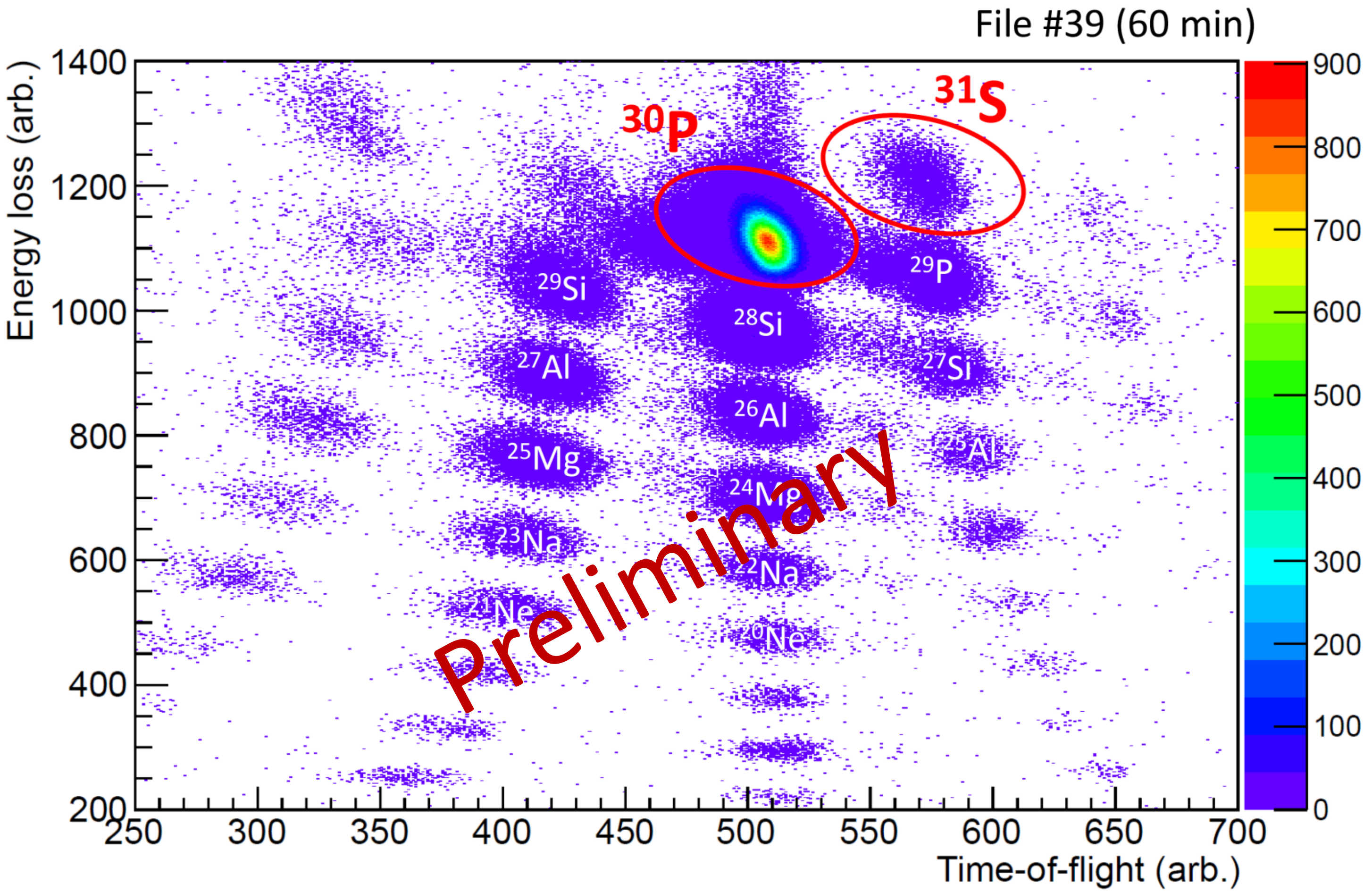
Reaction Q-value: $Q = \Delta \mathrm{M_H} - \Delta \mathrm{M}(^{55}\mathrm{Ni}) - \Delta \mathrm{M}(^{56}\mathrm{Cu})$

Resonance Strength: $\omega\gamma = \frac{2J_R+1}{(2J_S+1)(2J_p+1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma}$

Particle identification in the S800

@ 30 Mev/u

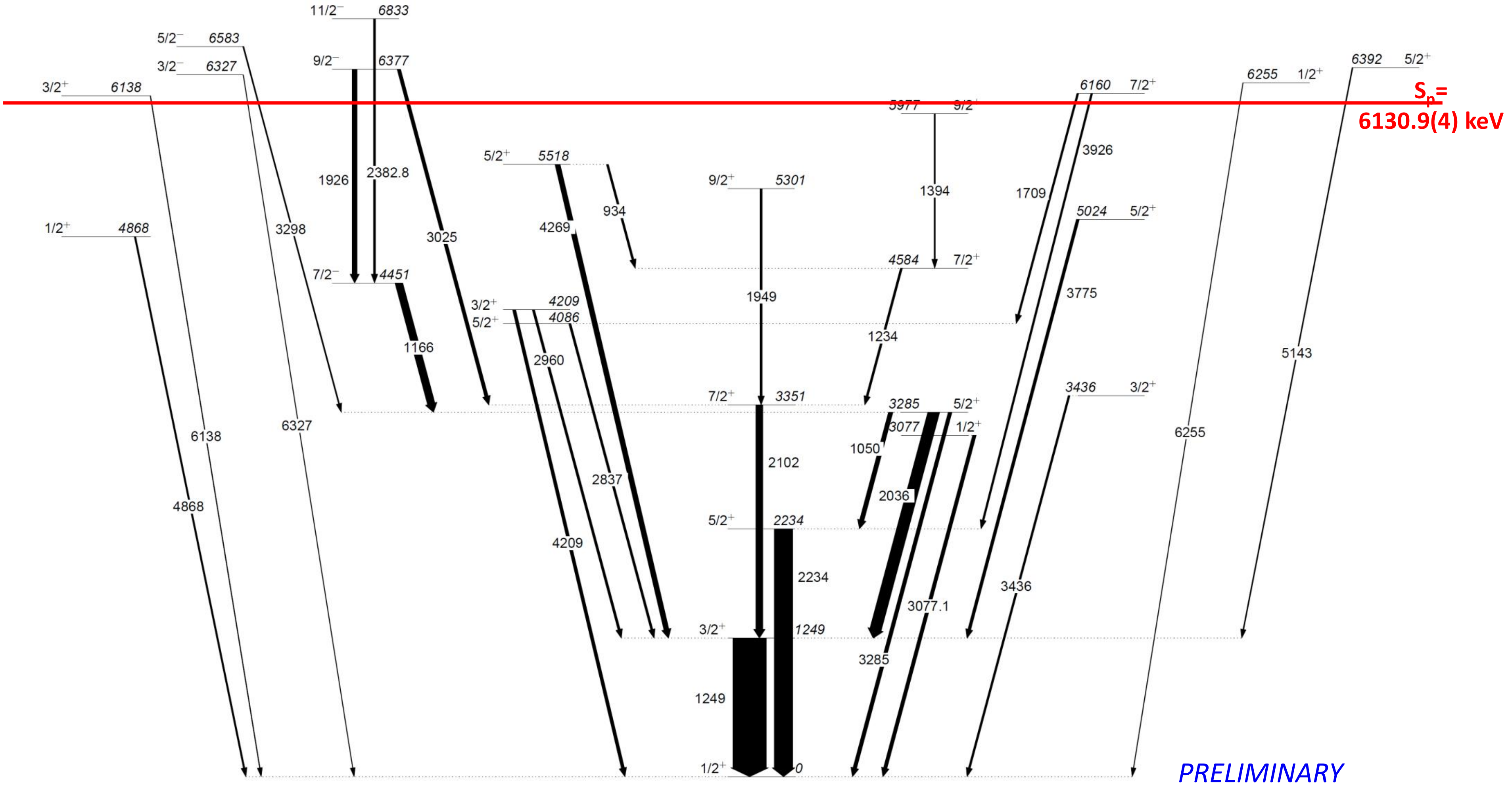
Ion chamber



OBJ → FP

Slide by A. Kankainen – thanks!

A few important states for astrophysics @ 30 Mev/u



PRELIMINARY
(bg subtracted, no add-back)

Slide by A. Kankainen – thanks!

@ 30 Mev/u

- States quite evenly populated
- Upper limits for non-observed states close to the observed
- Note! $9/2^-$ has a high spectroscopic factor $C^2S=0.39$ [Brown et al., PRC 89 (2014) 062801(R)]

$$\boxed{\sigma(d,n) \rightarrow \text{DWBA} \rightarrow \Gamma p}$$

Bound states:

- Assume transition matrix element small (peripheral reaction) →1st-order perturbation theory

Resonant states :

- Resonant wave function large and different channels coupled in nuclear interior
- Details: A. M. Mukhamedzhanov, PRC 84, 044616 (2011)

Forward-peaked
Peripheral

$\sigma \rightarrow \Gamma_p$

^{30}P (1^+) + d (1^+)

^{31}S (J^π) + n($1/2^+$)

Slide by A. Kankainen – thanks!

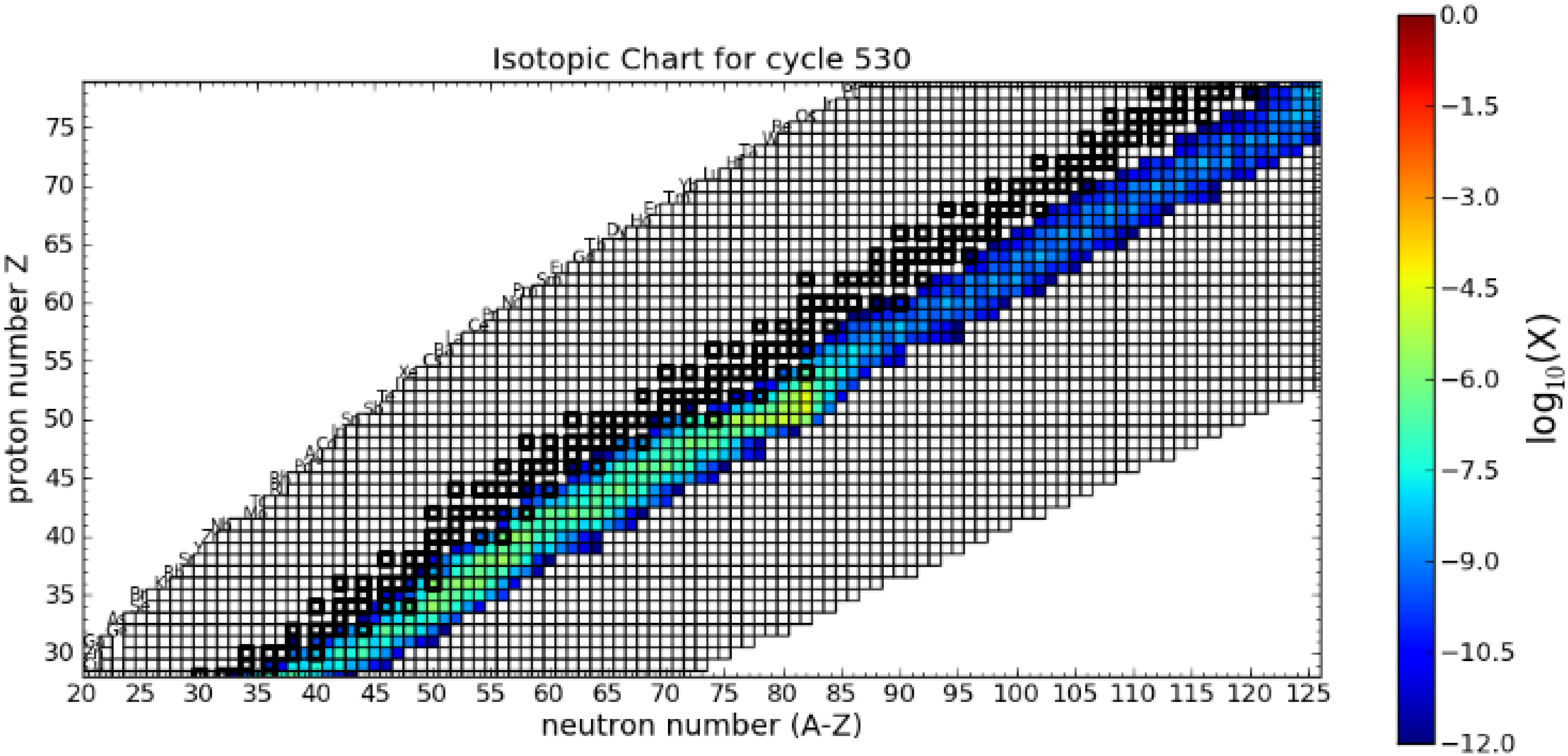
Summary

1. Constraining important nuclear reactions is important for detailed modeling of astrophysical scenarios and for stellar evolution (see talk from Rebecca and George)

2. Angle-integrated measurements in inverse kinematics at high and intermediate beam energies deliver excellent spectroscopic information (often the only way to get access to exotic systems)

3. Theoretical questions still open – can we continue with this program in the future to measure important reaction rates?

The i(ntermediate) neutron capture process



F. Herwig et al. (2014)

Future program input needs

Constraining astrophysical neutron direct-capture rates at intermediate energies via (d,p):

- for 30 MeV/u (NSCL energies) → extraction of direct capture possible (ANC)?
- how about resonant captures in the continuum?

Proton capture reactions:

- using (d,n) to extract spectroscopic factor (what energies are optimal)?
- treat the continuum in this process?

In general: any access to errors of the theory, which is very important for rate calculations?