Nuclear Masses in Astrophysics

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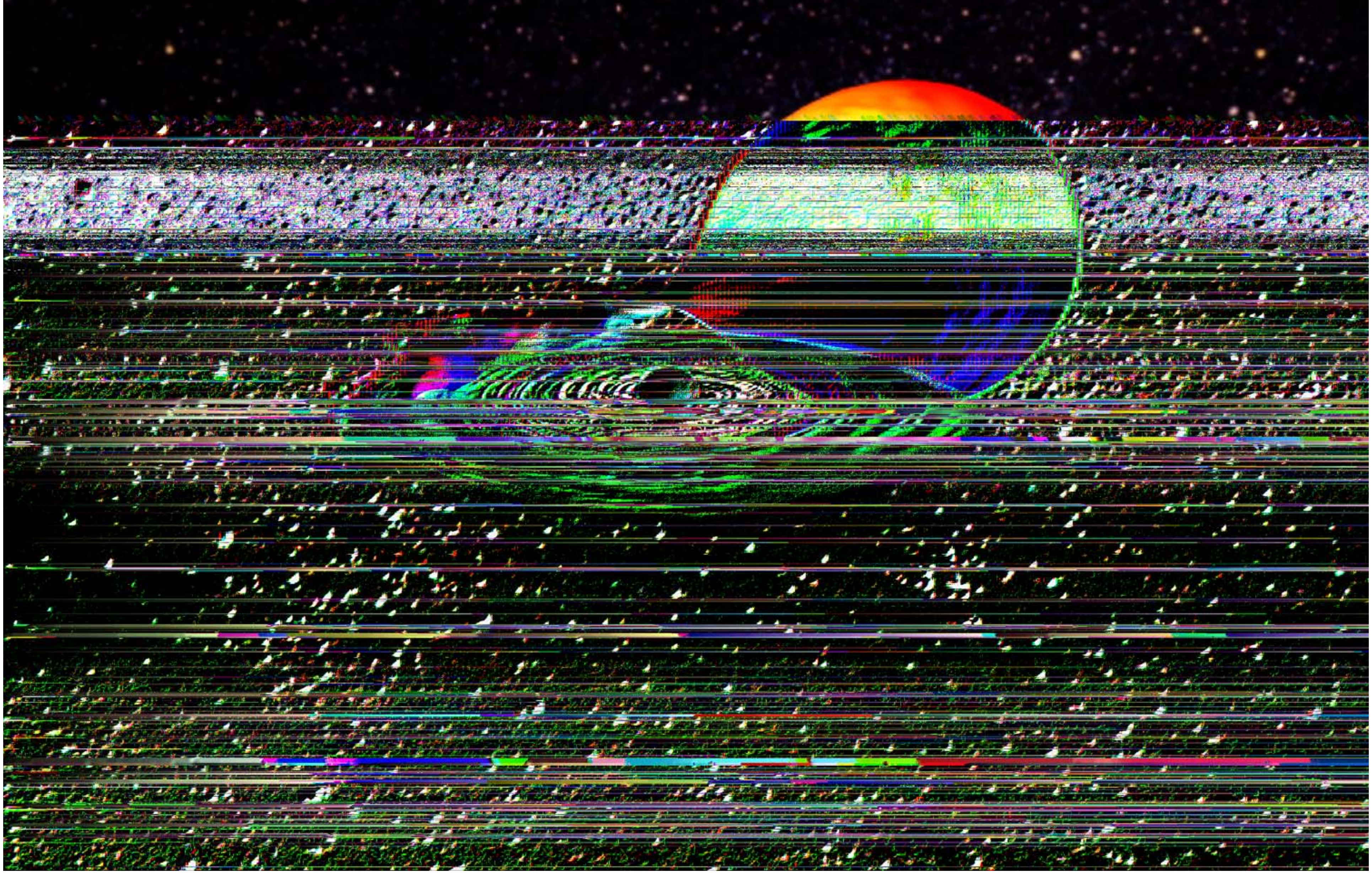
National Superconducting Cyclotron Laboratory
Joint Institute for Nuclear Astrophysics

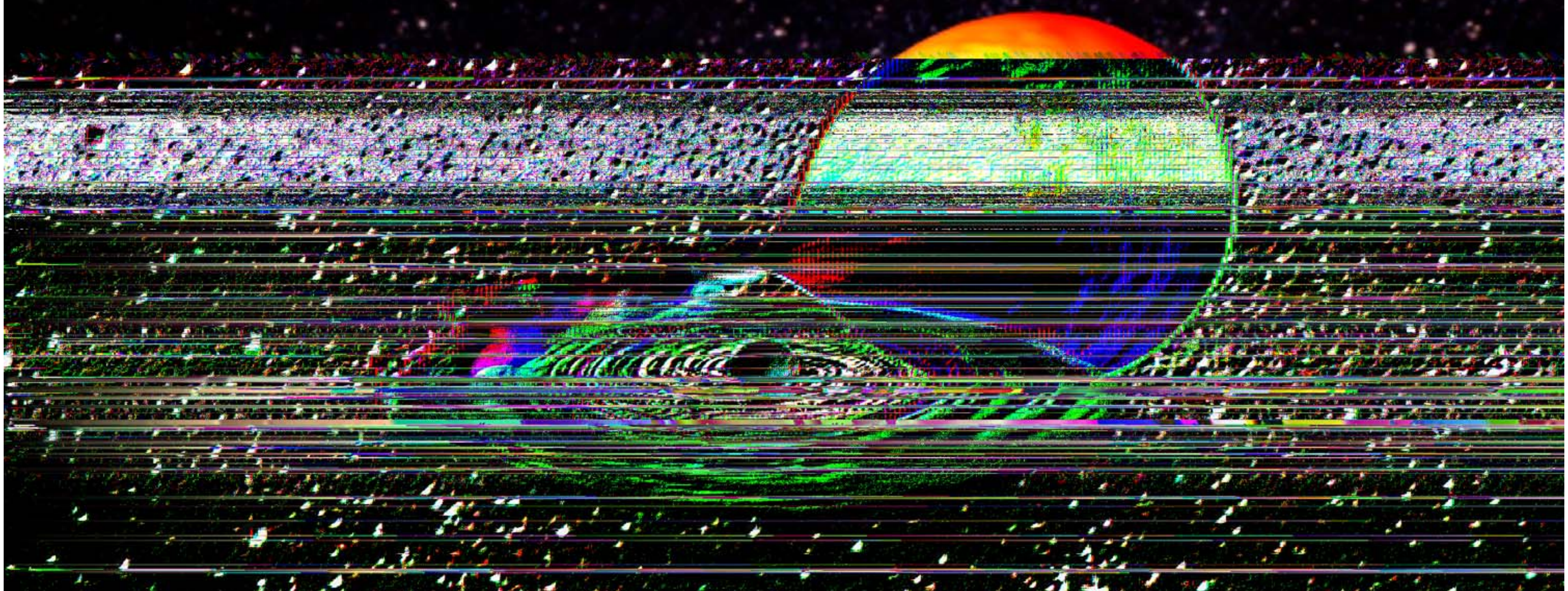
1. X-ray bursts
2. The r-process

X-ray bursts

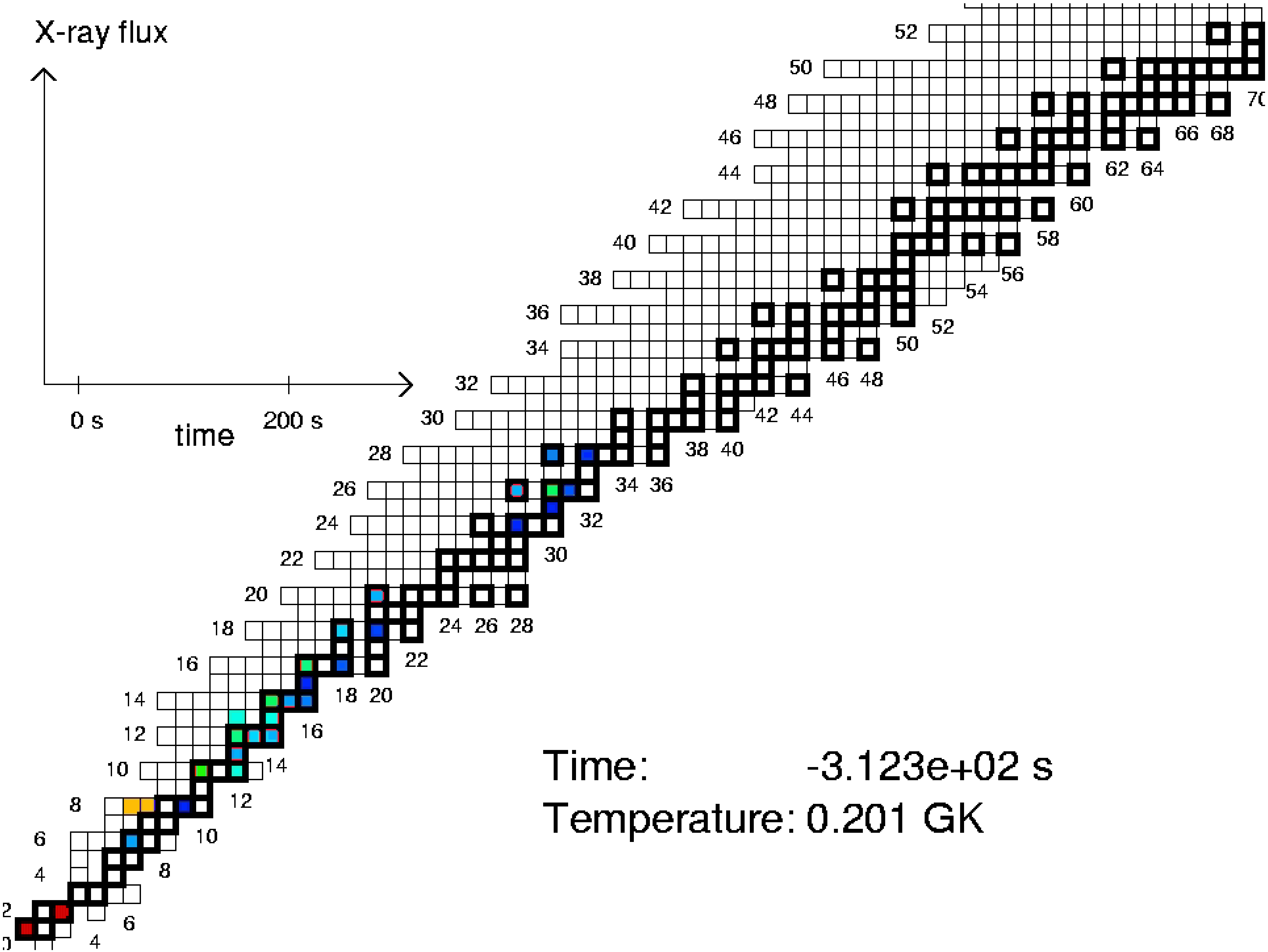


X-ray bursts

X-ray bursts



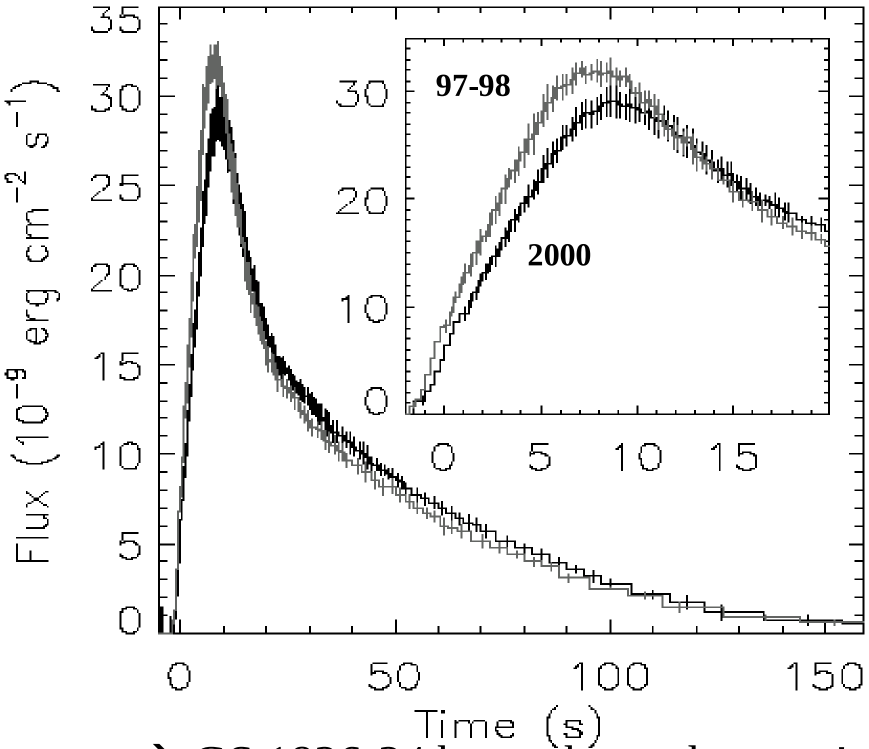
- Many new observations by Beppo-SAX, RXTE, Chandra, XMM-Newton
  → lots of open questions
- Learn about neutron stars
  - increase in mass, spin, temperature compared to isolated NS
  - many observables


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

Observables of nuclear processes in X-ray bursts: Lightcurve

Precision X-ray observations

(NASA's RXTE)



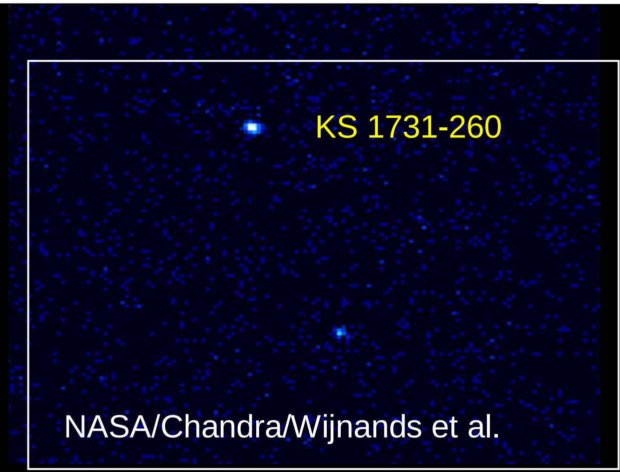
→ GS 1826-24 burst shape changes !

(Galloway 2003 astro/ph 0308122)

- Need precise nuclear data to make full use of high quality observational data

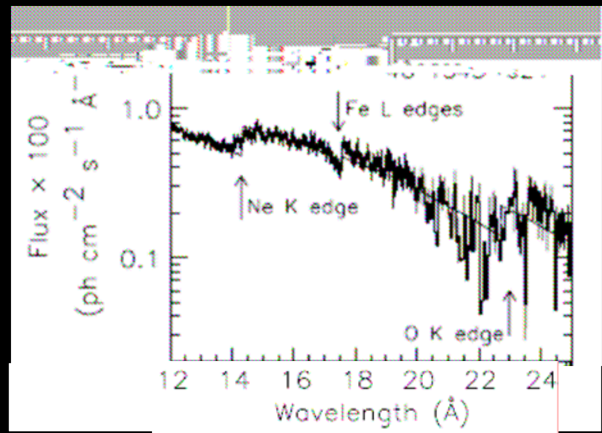
More observables – what about the produced nuclei ?

- Crust composition
  - → Crust heating (Gupta et al. 06)
    - → crust cooling
    - → superbursts



- Ejected composition (<few%)
  (Weinberg et al. 06)

?



Likely no nucleosynthesis contribution
Goal: understand systems and neutron stars

Recent progress in mass measurements

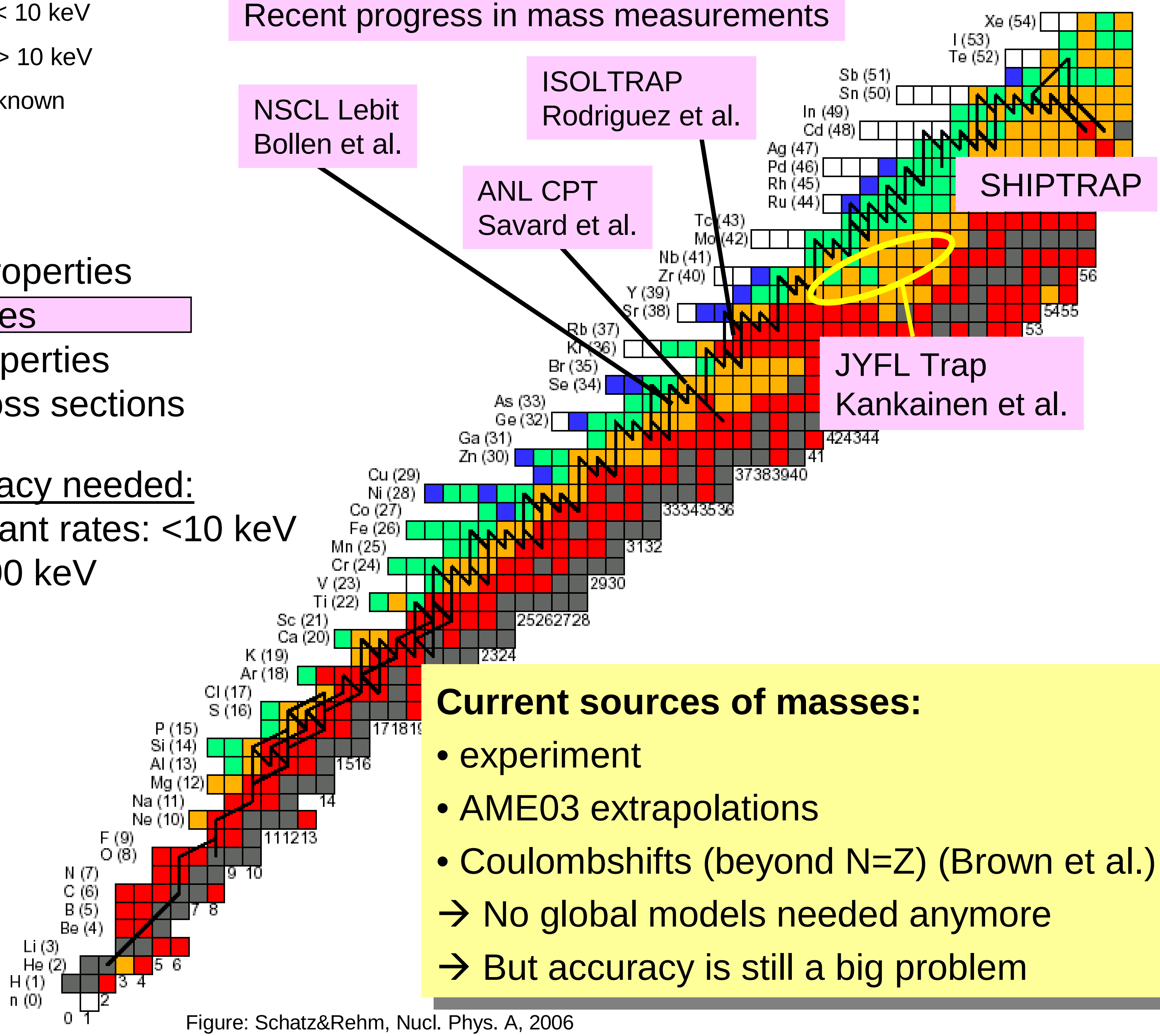
- Mass known < 10 keV
- Mass known > 10 keV
- Only half-life known
- seen

<u>Measure:</u>

→ decay properties
→ gs masses
→ level properties
→ rates/cross sections

<u>Mass accuracy needed:</u>

→ for resonant rates: <10 keV
→ else: <100 keV



Current sources of masses:

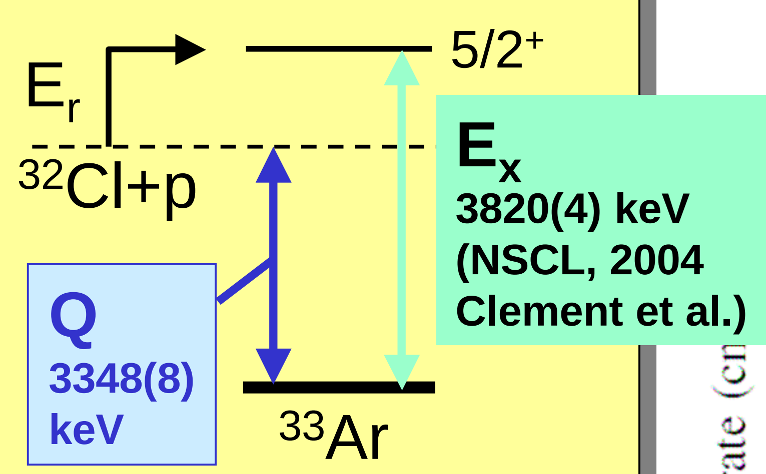
- experiment
- AME03 extrapolations
- Coulombshifts (beyond N=Z) (Brown et al.)

→ No global models needed anymore
→ But accuracy is still a big problem

Figure: Schatz&Rehm, Nucl. Phys. A, 2006

Masses for rates with isolated narrow resonances

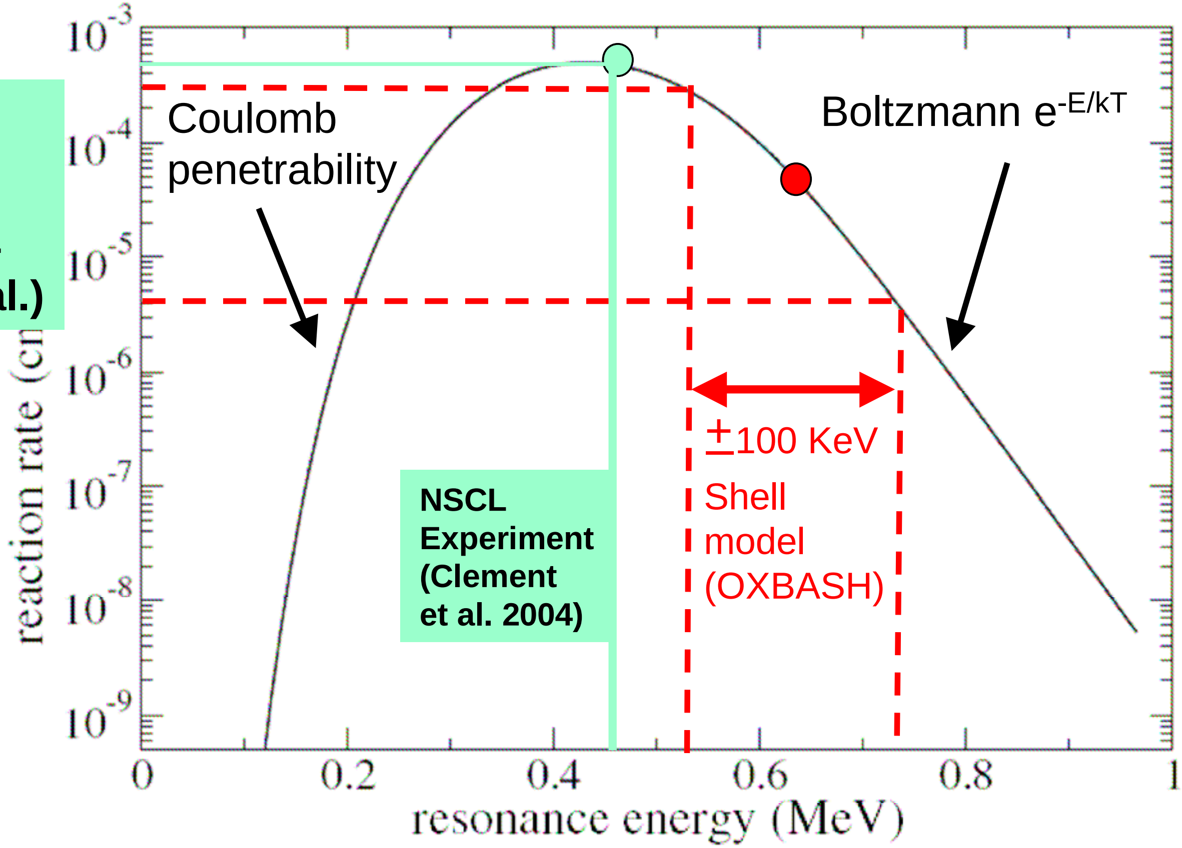
$$N_A < \sigma v > = 1.54 \cdot 10^{11} (AT_9)^{-3/2}\, \omega\gamma[\mathrm{MeV}]\, e^{\frac{-11.605\, E_r[\mathrm{MeV}]}{T_9}} \frac{\mathrm{cm}^3}{\mathrm{s\ mole}} \qquad \omega\gamma = \frac{2J_r+1}{(2J_1+1)(2J_T+1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma}$$



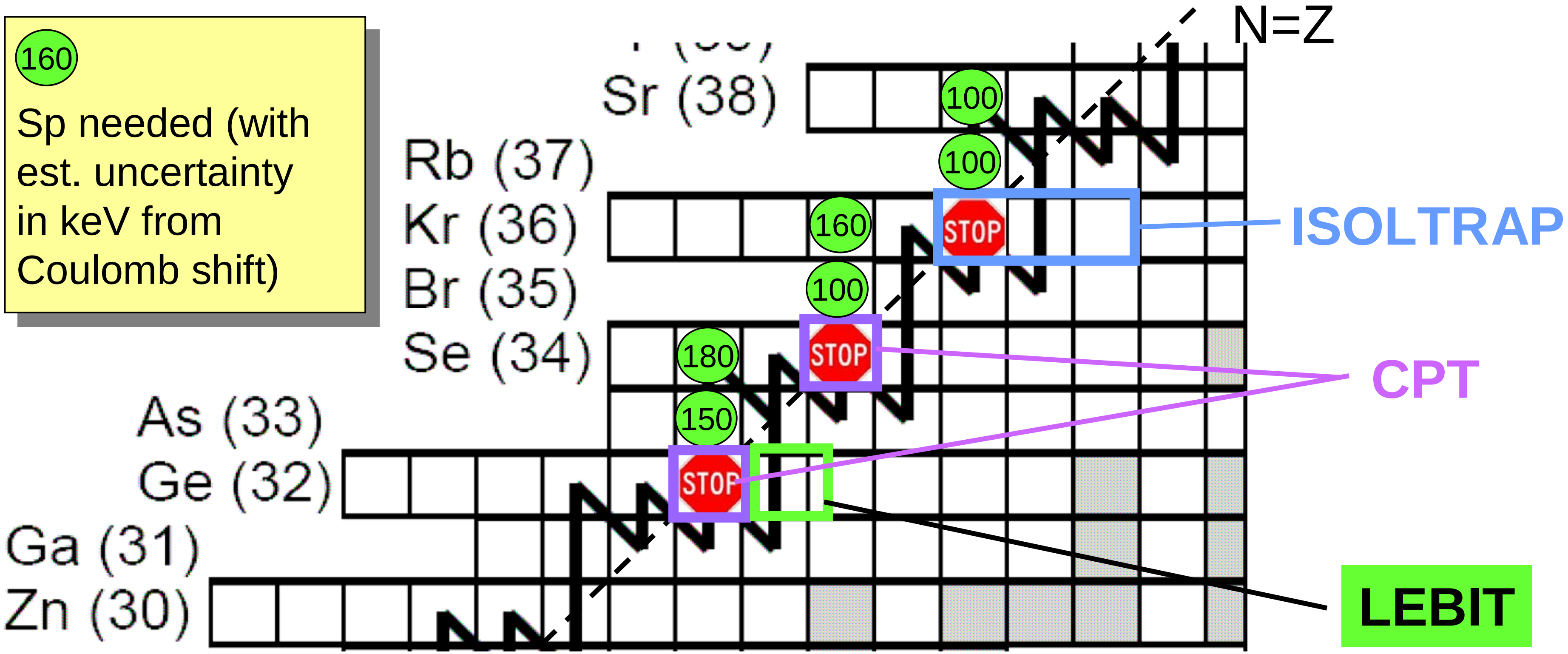
$E_r = E_x - Q = 476(9)$ keV

→ Need gs masses with <10 keV precision

^{32}Cl(p,g)^{33}Ar Reaction rate for T=0.4 x 10^9 K



Masses for key waiting points



Current effective lifetime uncertainties from masses:

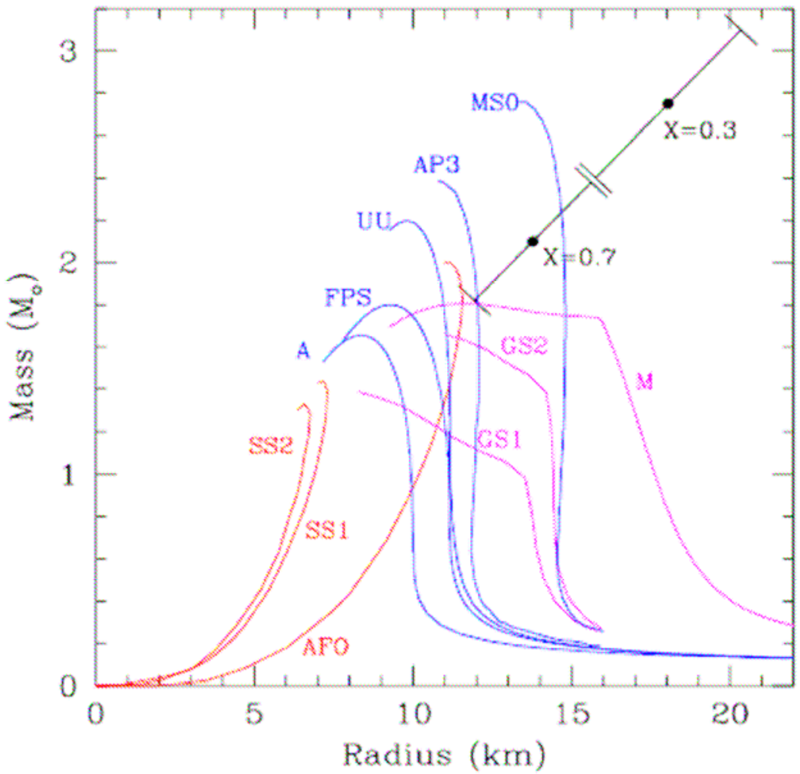
- STOP ^{64}Ge (τ_β=92s): up to x20 (as low as 0.5 s)
- STOP ^{68}Se (τ_β=51s): up to x4 (as low as 10 s)
- STOP ^{72}Kr (τ_β=25s): up to x2 (as low as 12 s)

→ Future trap measurements: ^{65}As, ^{66}Se, ^{70}Se, ^{70}Kr, ^{74}Sr

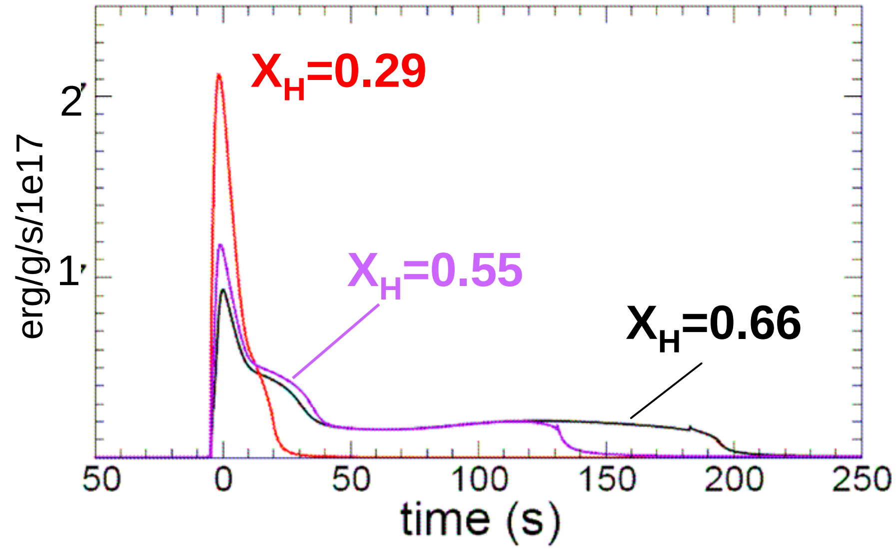
→ Mass measurements with reactions: ^{69}Br, ^{73}Rb

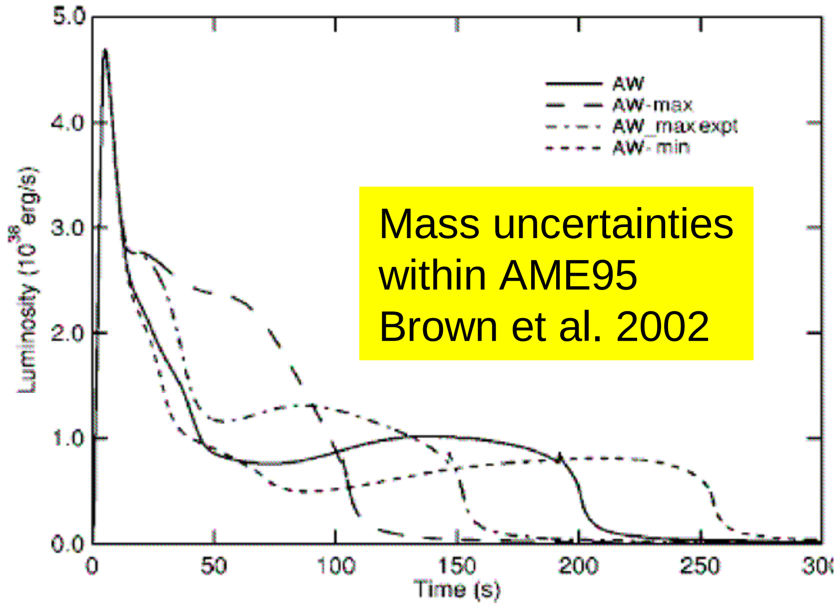
Example: understand bursts to constrain NS

X-ray bursts from EXO0748−676:
- O,Fe absorption lines (→ redshift)
- T_c/F_{cool} (→ ~surface area)
- Eddington luminosity



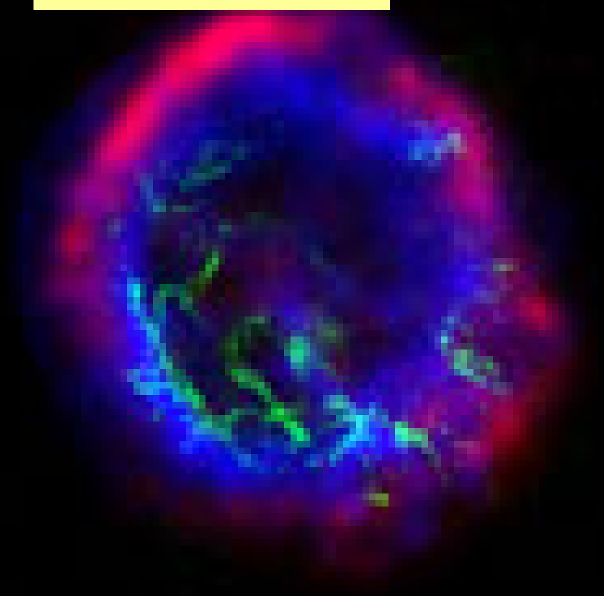
(Ozel Nature 441 (2006) 1115)





r (apid neutron capture) process

Supernovae ?

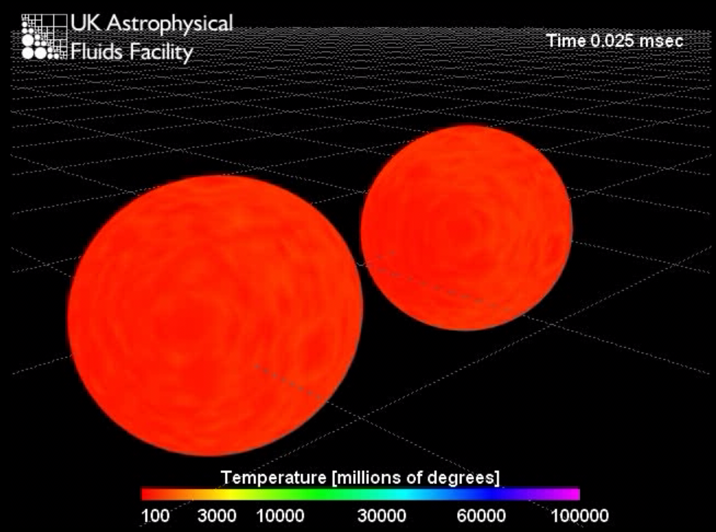


The origin of about half of elements > Fe (including Gold, Platinum, Silver, Uranium)

Open questions:

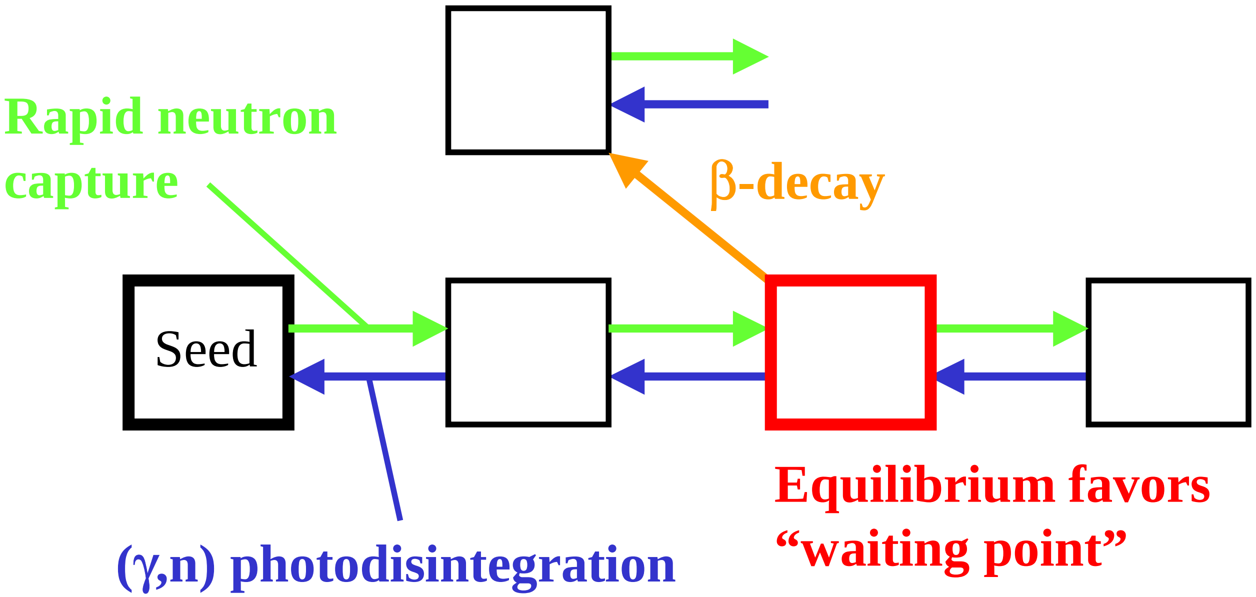
- **Where does the r process occur ?**
- **What are the actual reaction sequences ?**
- **Are there multiple r-processes and what are their individual contributions ?**
- **What can the r-process tell us about the physics of extreme environments ?**

Neutron star mergers ?



r-process and masses

10-100 g/cm^3 neutrons →neutron capture timescale: ~ 0.2 μs

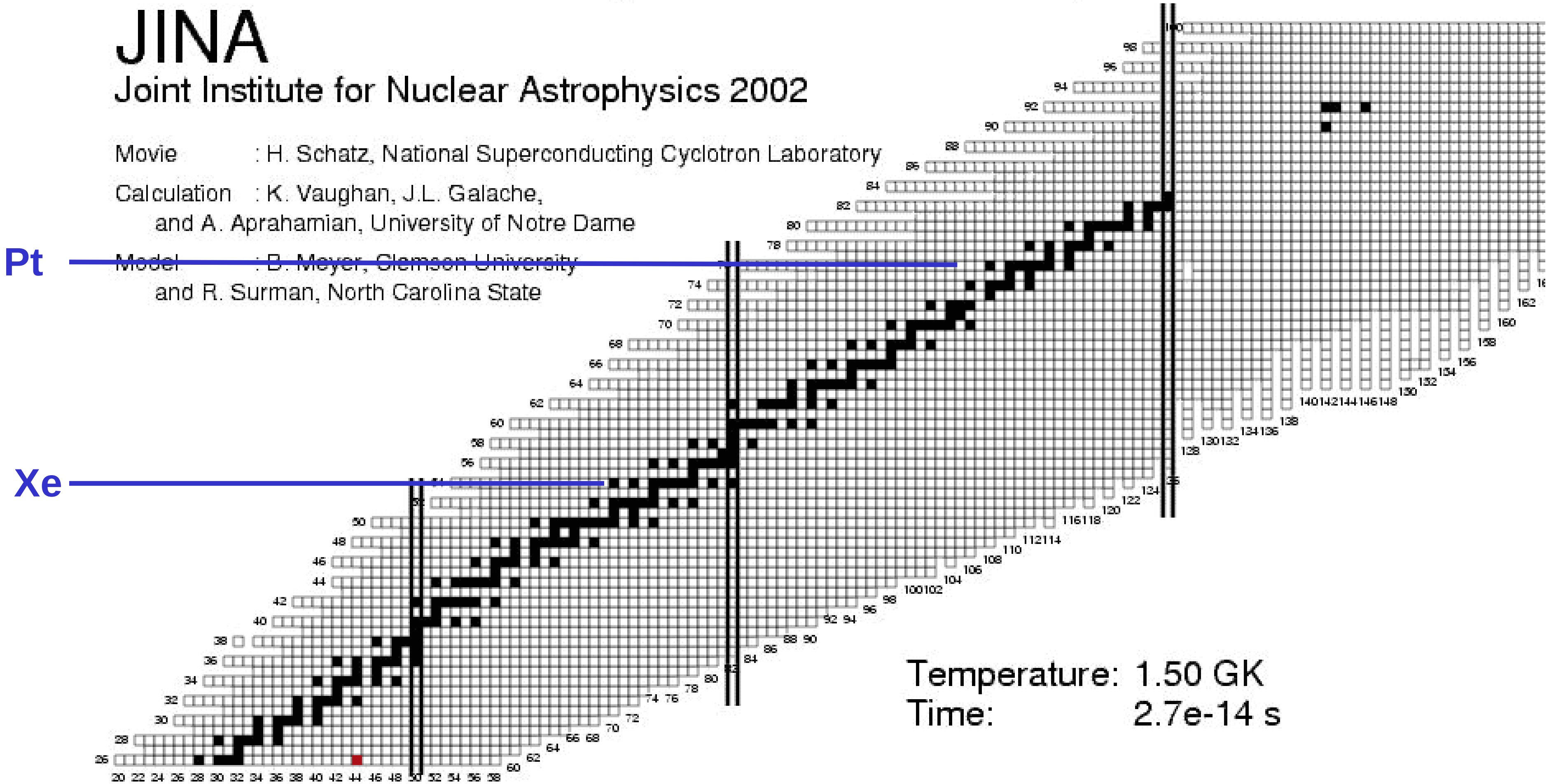


Location of path: $S_n = T_9/5.04 \times (34.08 + 1.5 \log T_9 - 1.5 \log n_n) = 2\text{-}4$ MeV

Questions:
- actual path ?
- beginning (seed) and end (fission) ?
- neutrino induced processes ?

Origin of the heavy elements in nature ?

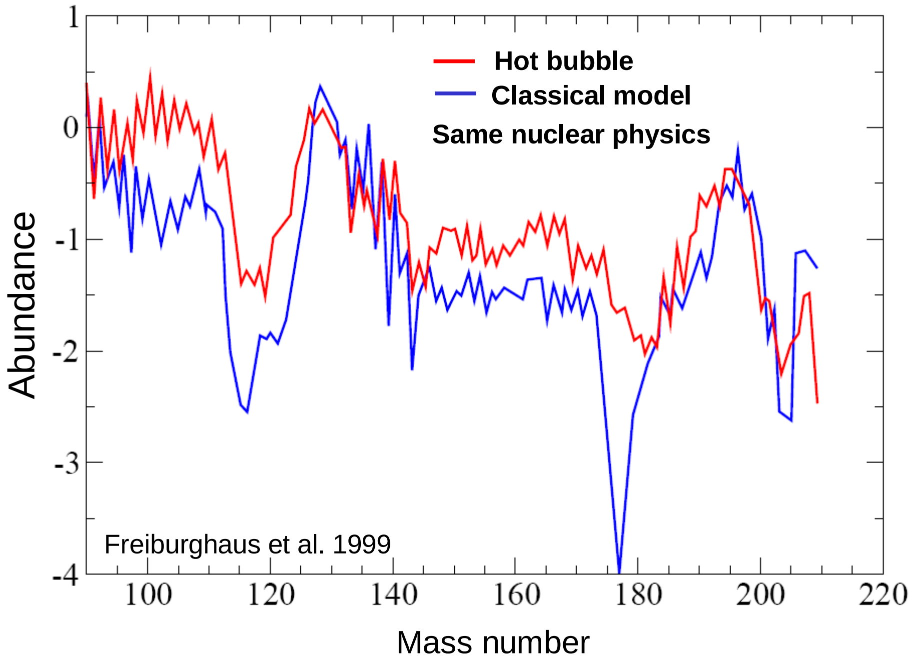
Nucleosynthesis in the r-process



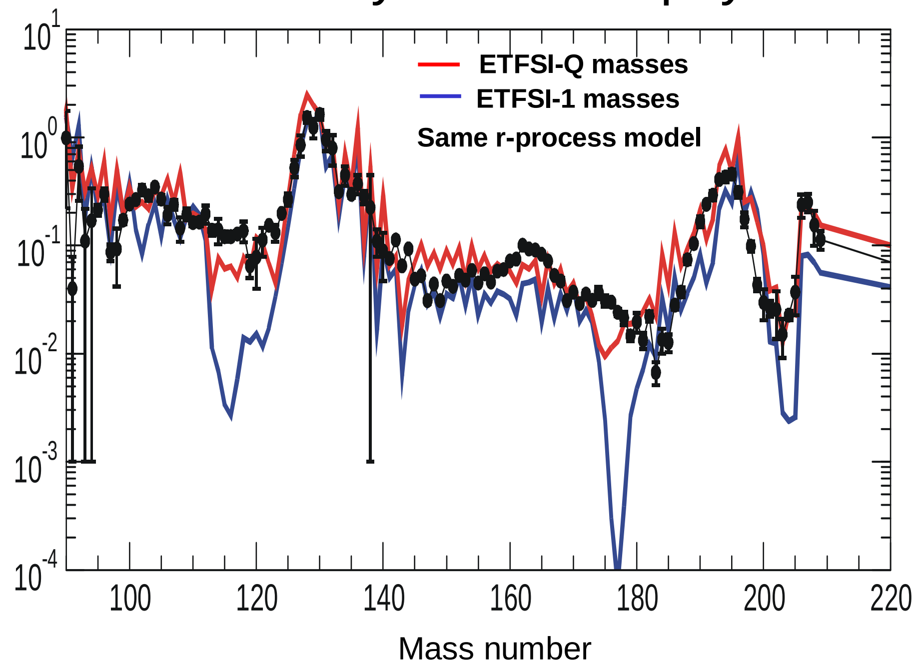
Compare calculated results with many precision abundance observations ?
→ Masses and half-lives of very unstable, exotic nuclei need to be known
so that one can calculate the produced abundances for a given model

Sensitivity of r-process to astro and nuclear physics

Sensitivity to astrophysics



Sensitivity to nuclear physics



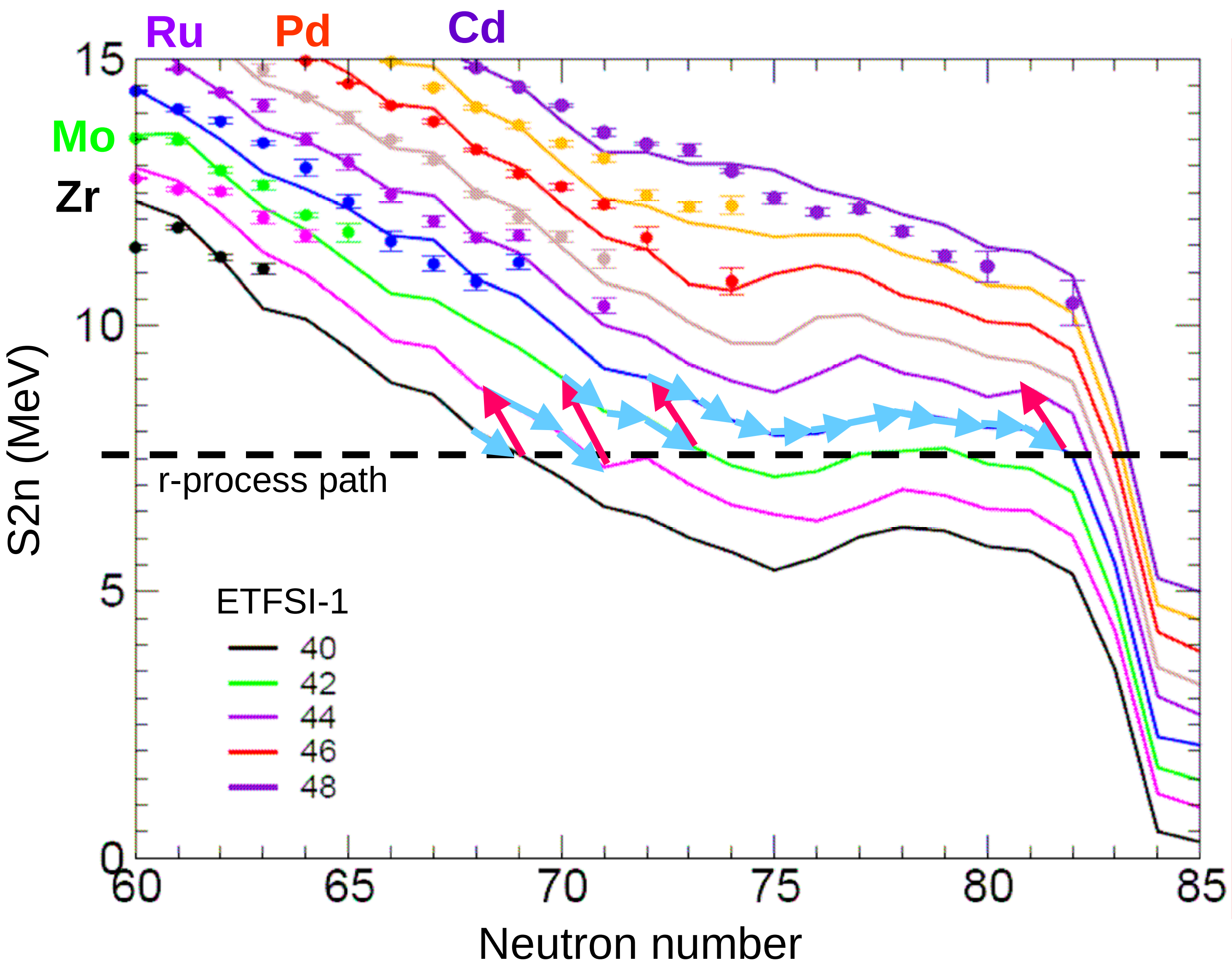
Contains information about:

- n-density, T, time (fission signatures)
- freezeout
- neutrino presence
- which model is correct

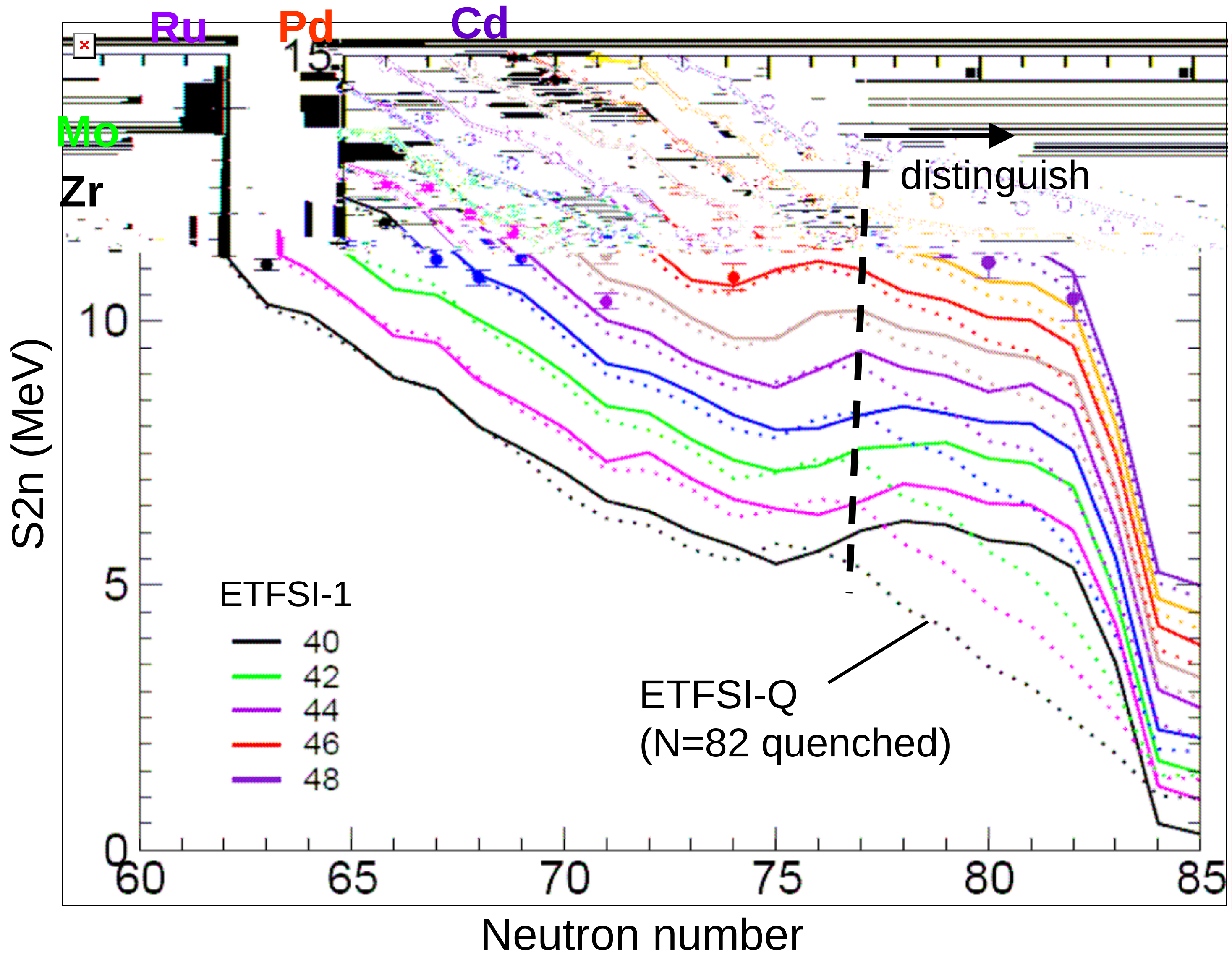
But convoluted with nuclear physics:

- masses (set path)
- $T_{1/2}$, Pn (Y ~ $T_{1/2(prog)}$, key waiting points set timescale)
- n-capture rates
- fission barriers and fragments

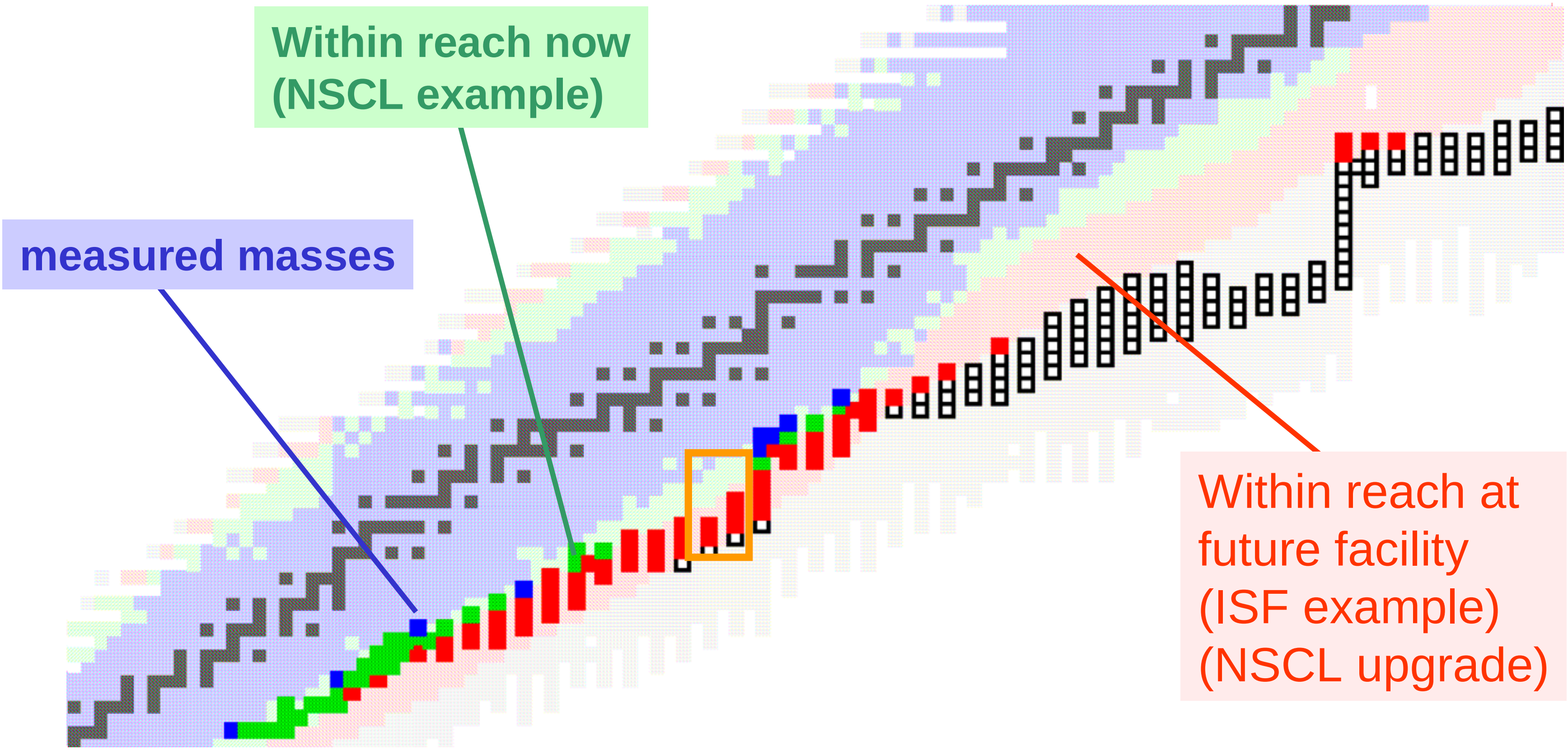
Shell quenching effect on masses/r-process



Shell quenching effect on masses/r-process



Facilities reach for mass measurements (TOF)



→ Lower part of r-process on solid nuclear physics bases
→ Influence of shell quenching unambiguously resolved
→ Some data on heavier r-process, incl. N=126

Conclusions

Masses of unstable nuclei play a role in many astrophysical scenarios:

X-ray bursts

→ Reaction rate calculations (and to guide experiments)
→ Effective lifetimes of waiting points (Sp around drip lines)

Neutron star crust processes

→ odd-even staggering of QEC from stability to n-drip → heating (Gupta et al. **astro-ph/0609828**)

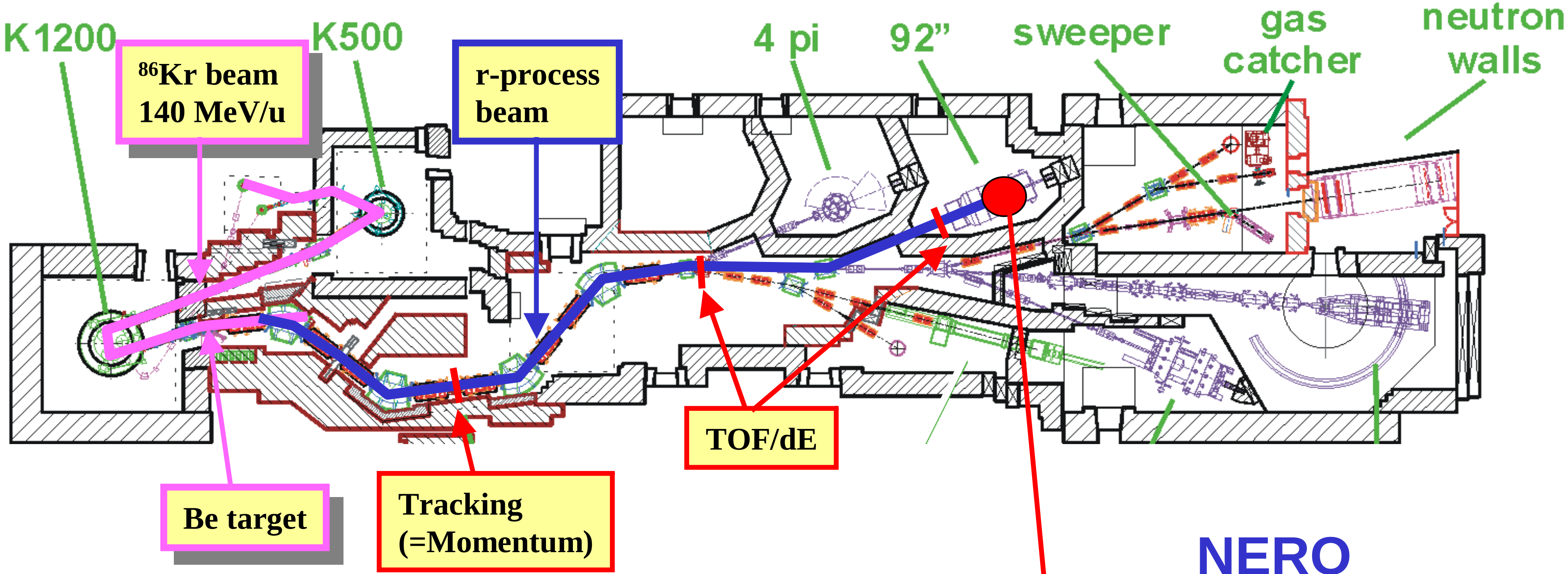
r-process

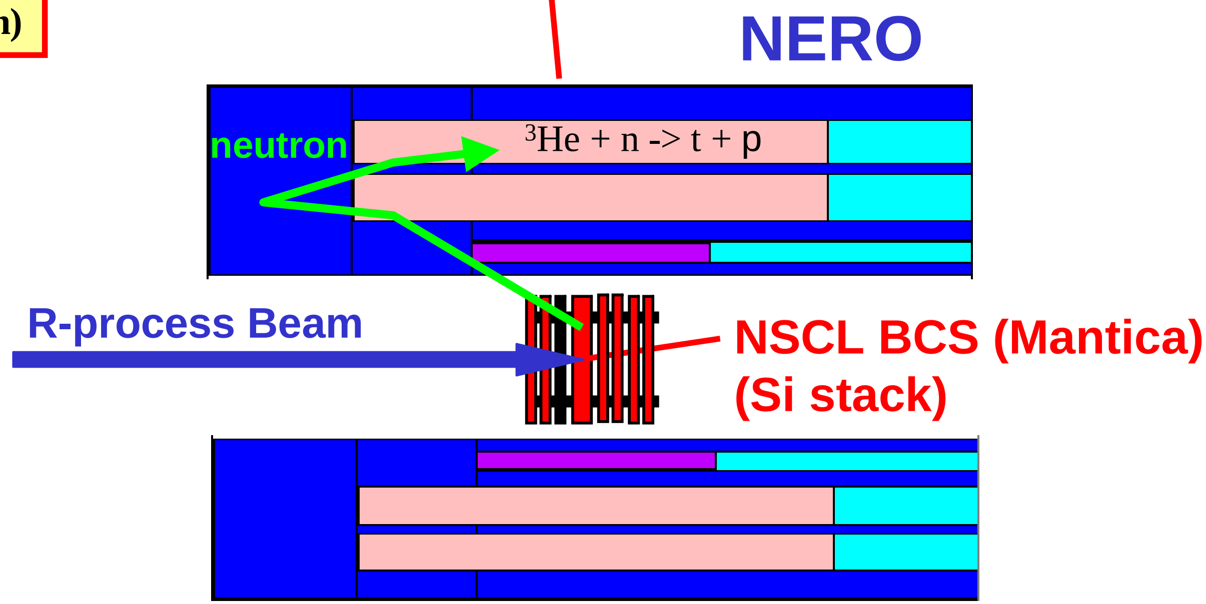
→ Location of the path for given set of astro conditions
→ Masses manifest themselves directly in observed abundances

- Experimental masses (δ < 10-100 keV) needed for progress in the field
  → Need next generation rare isotope facilities

- Theoretical global model for n-rich nuclei (crusts, r-process)
  (also beyond Pb … to and beyond N~184)

r-process beams at the NSCL Coupled Cyclotron Facility

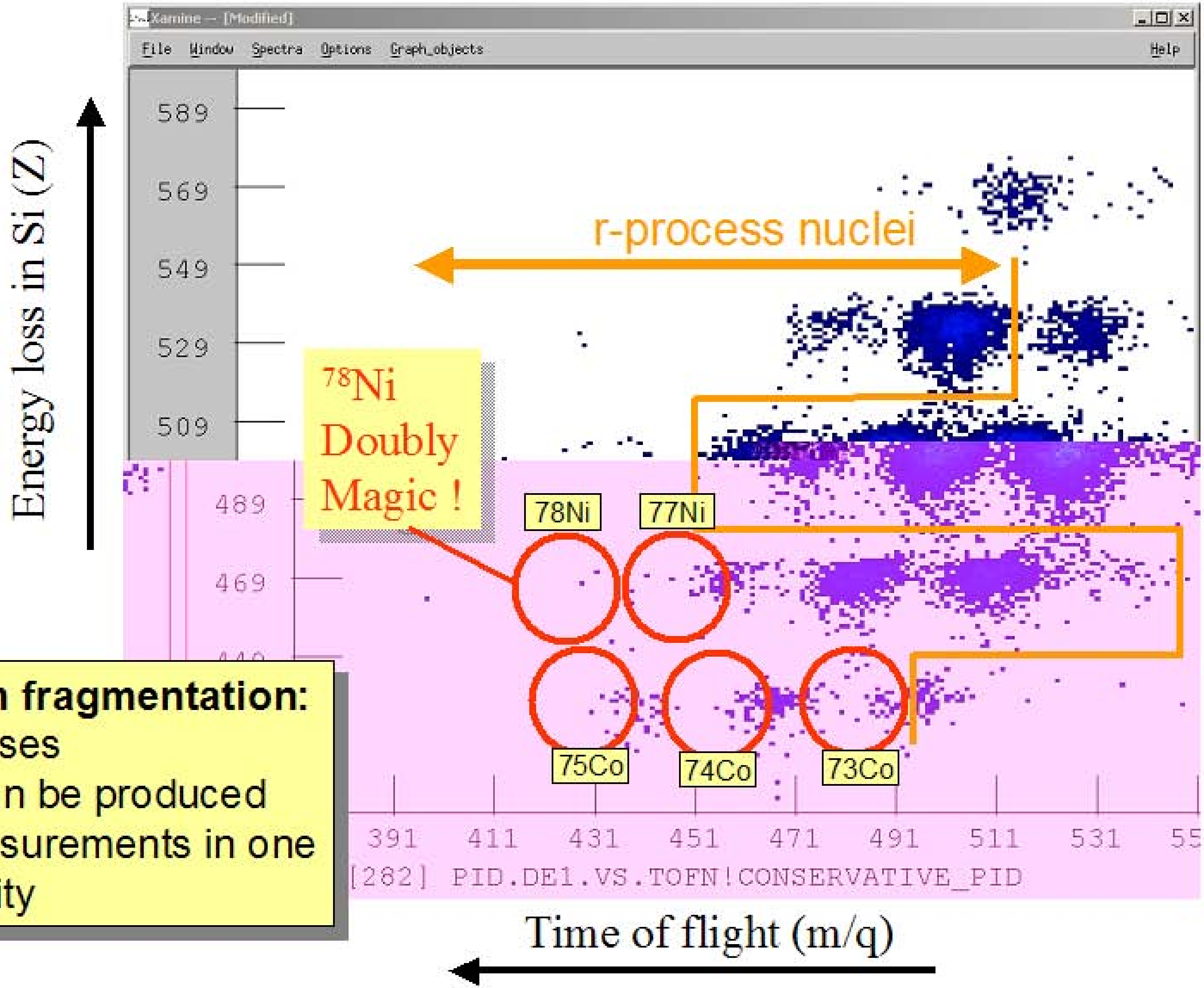




Detect:

- β decay time
- β-n coincidences

Particle Identification

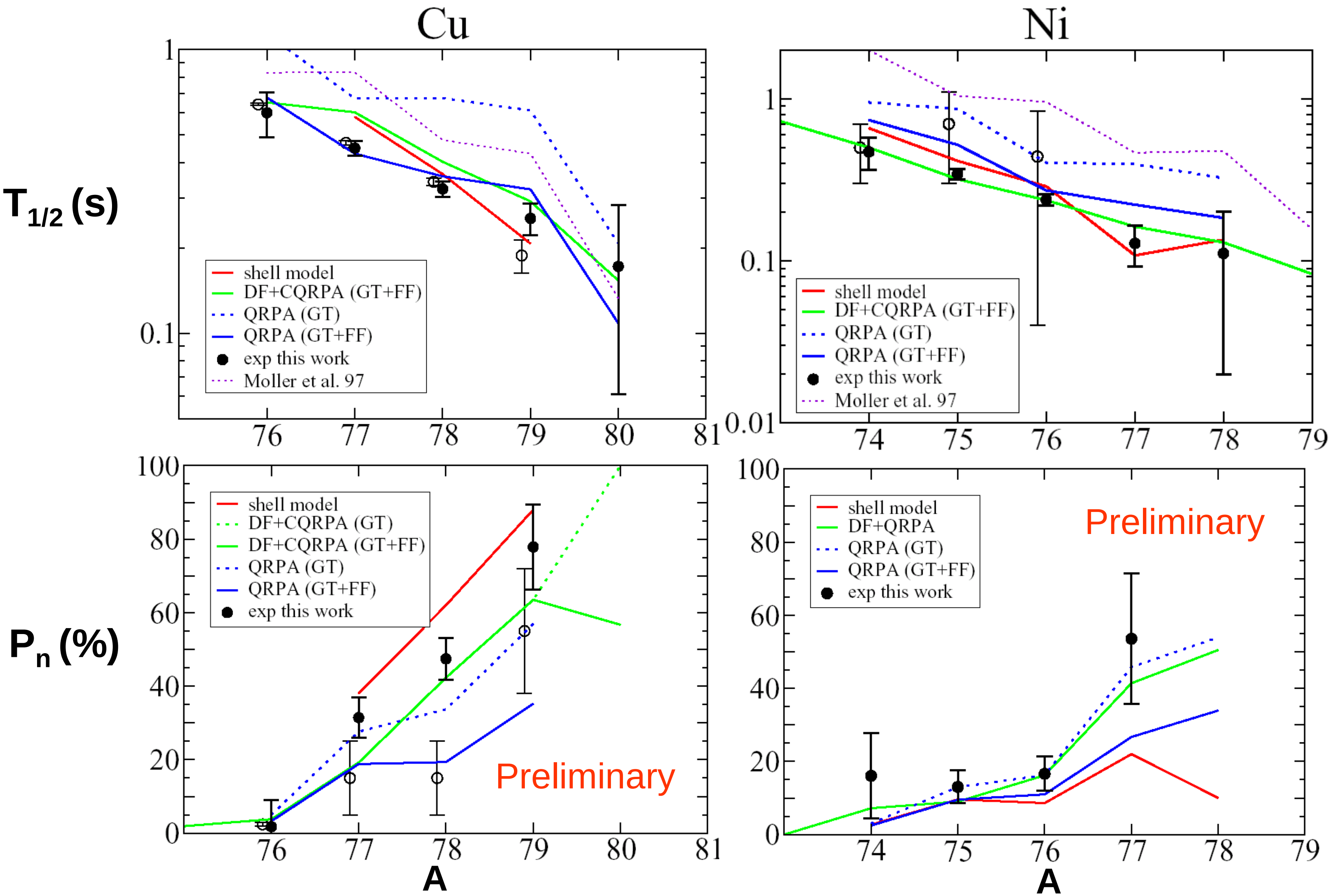


Fast RIB from fragmentation:

- no decay losses
- any beam can be produced
- multiple measurements in one
- high sensitivity

Results (Hosmer et al.)

DF+CQRPA Borzov et al. 2005, QRPA: Moller et al. 2003, Shell model: Lisetzky & Brown 2005

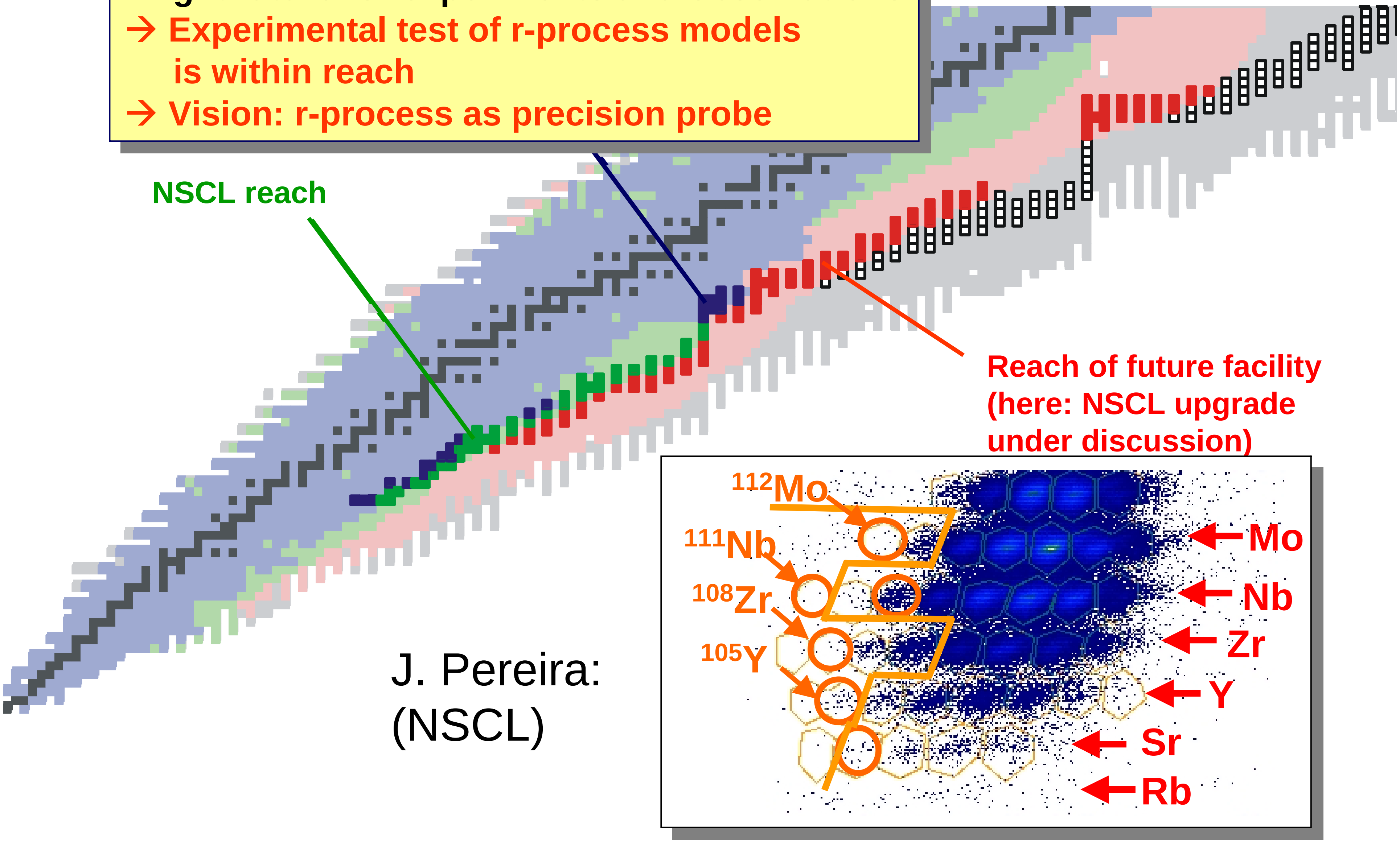


NSCL and future facilities reach

Bright future for experiments and observations

→ Experimental test of r-process models is within reach

→ Vision: r-process as precision probe

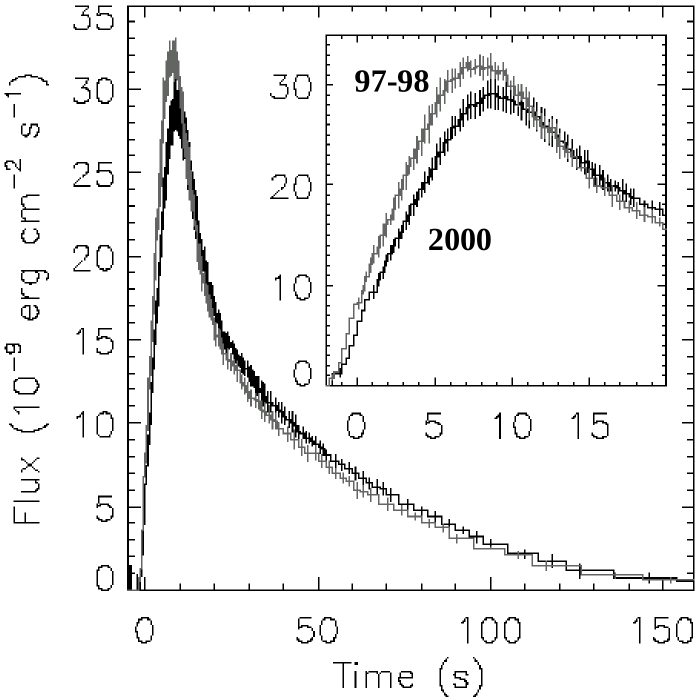


J. Pereira:
(NSCL)

Reality check: Burst comparison with observations

Precision X-ray observations

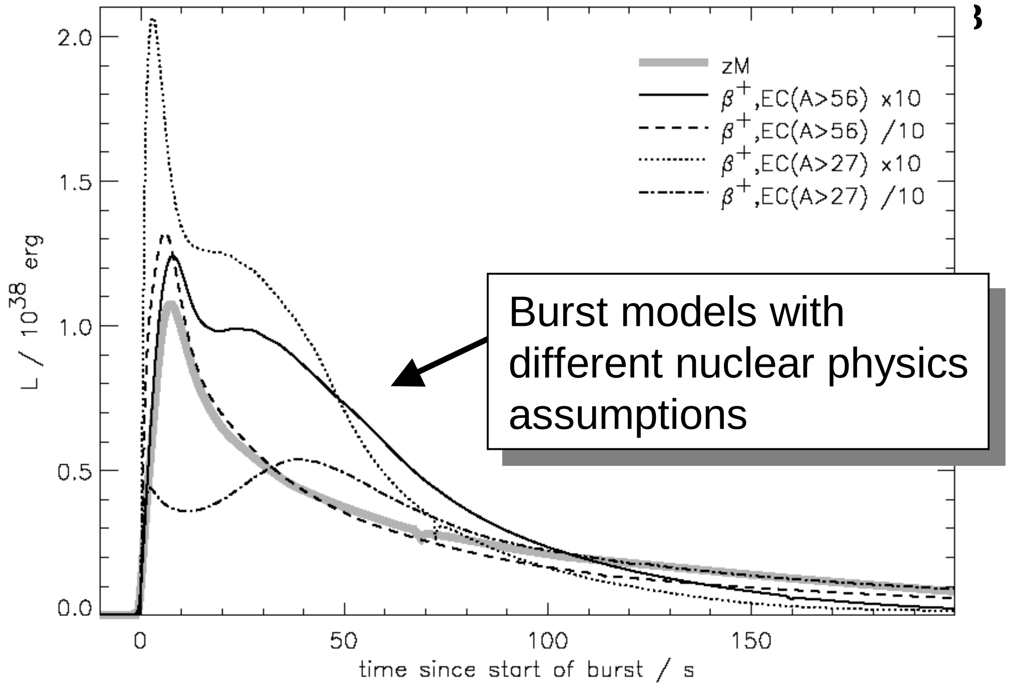
(NASA's RXTE)



→ GS 1826-24 burst shape changes !

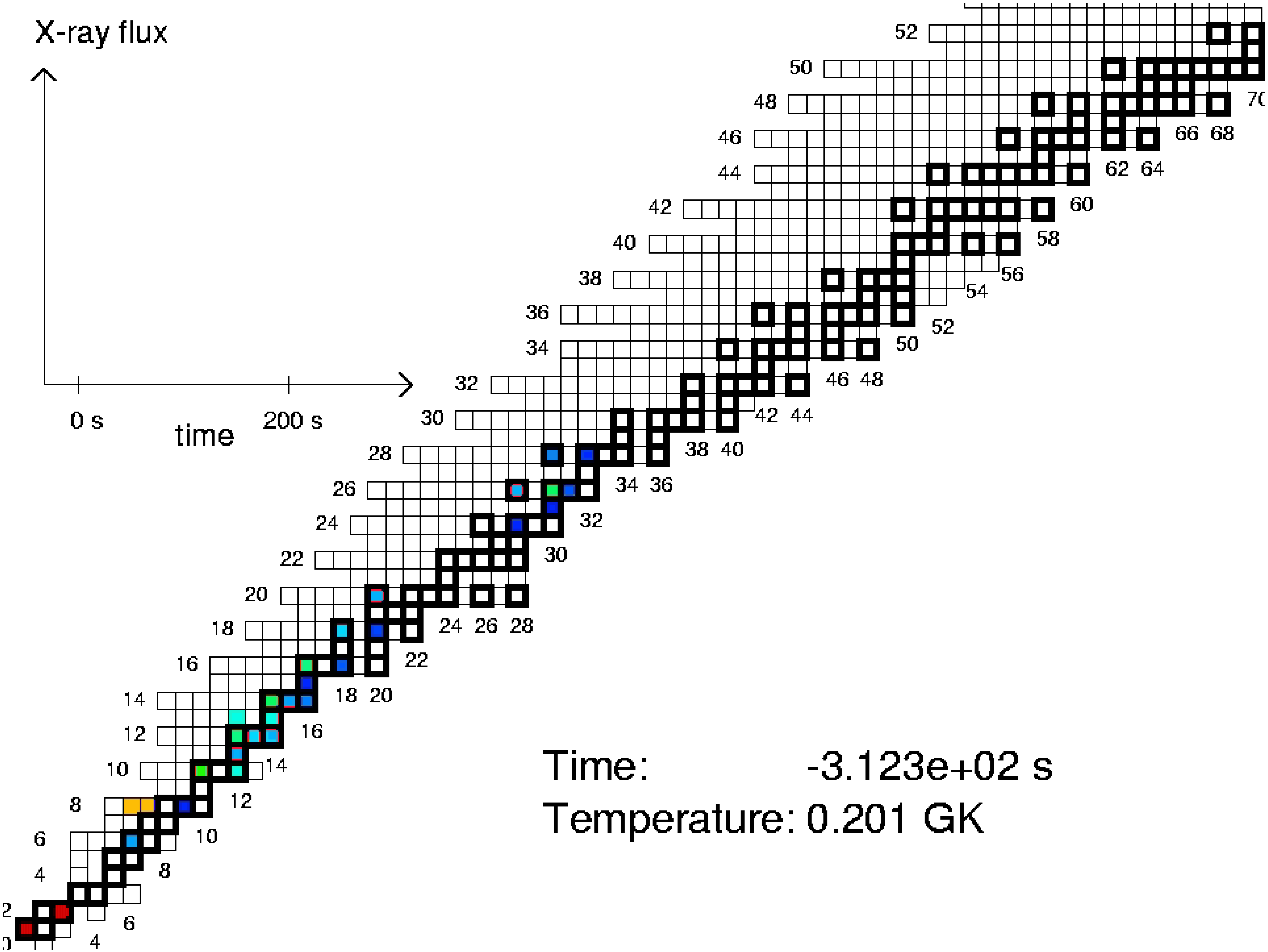
(Galloway 2003 astro/ph 0308122)

Uncertain models due to nuclear physics

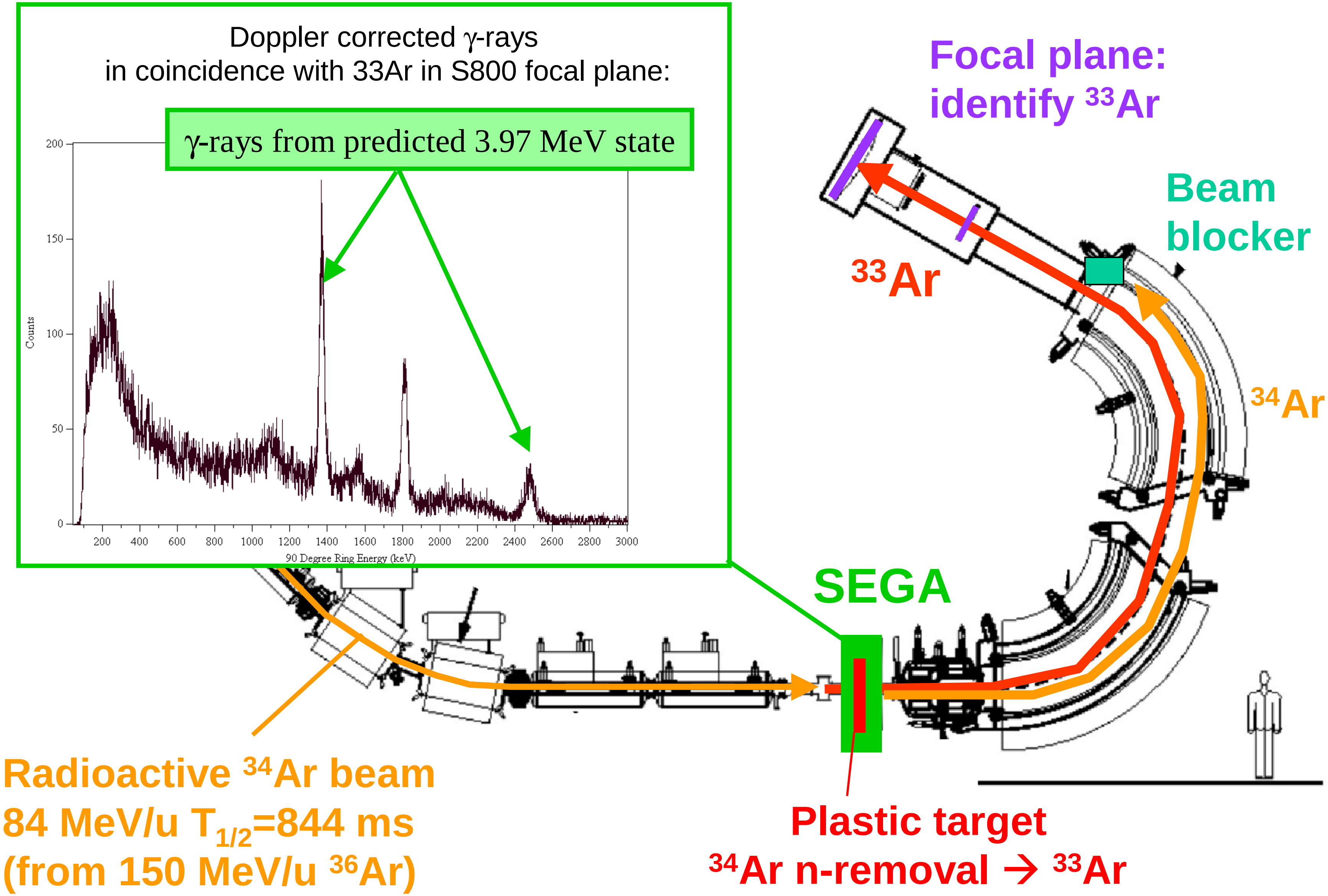


Woosley et al. 2003 astro/ph 0307425

- Need precise nuclear data to make full use of high quality observational data


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

n-removal related to astrophysical ^{32}Cl+p → ^{33}Ar+γ rate



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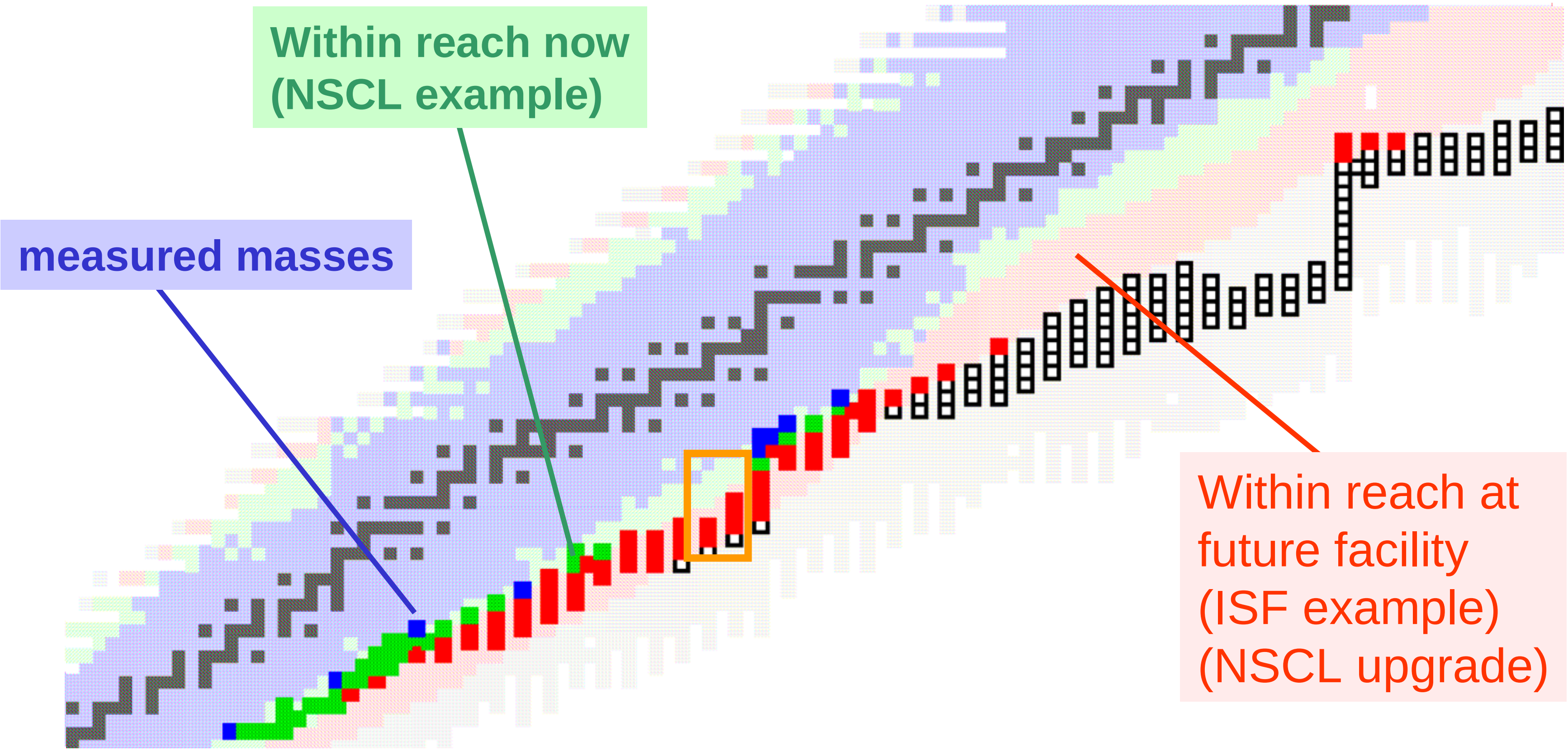
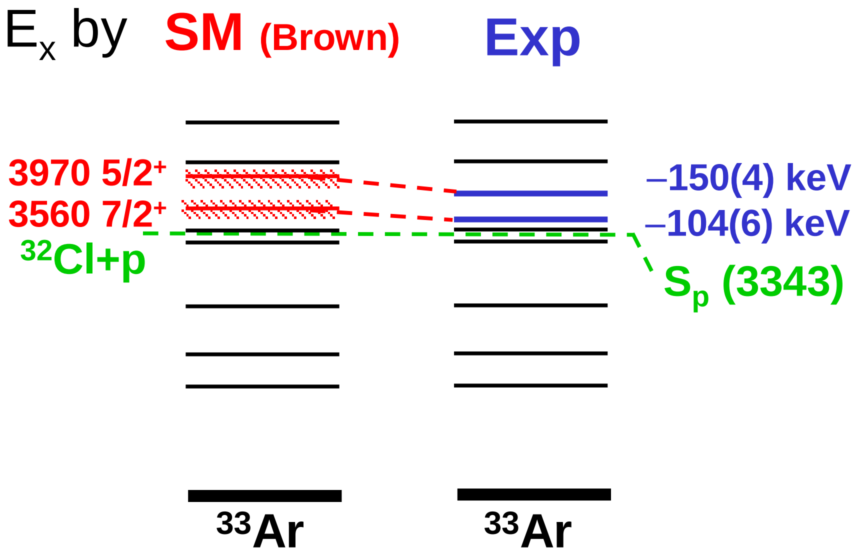
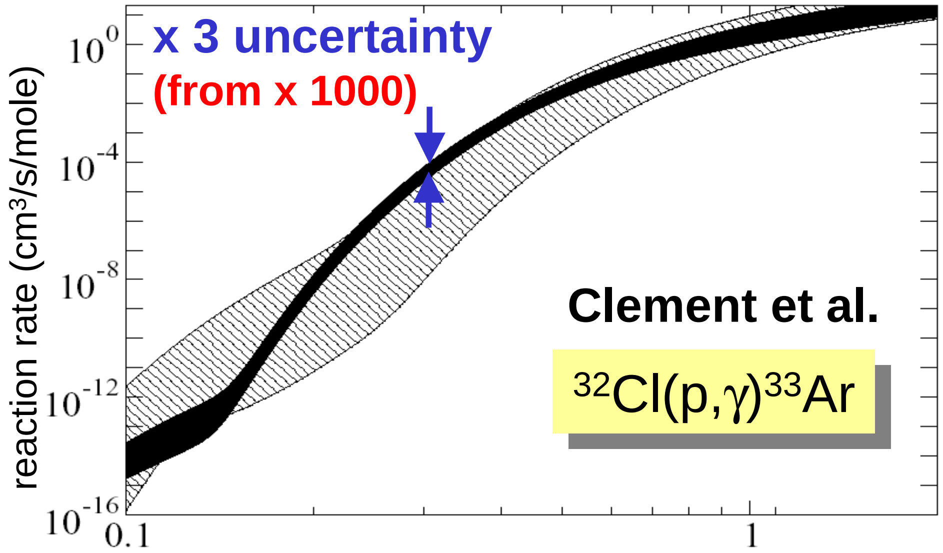
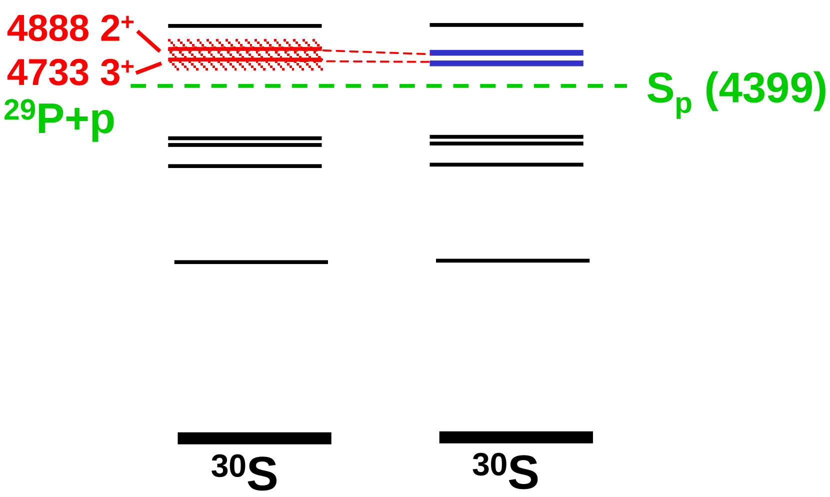


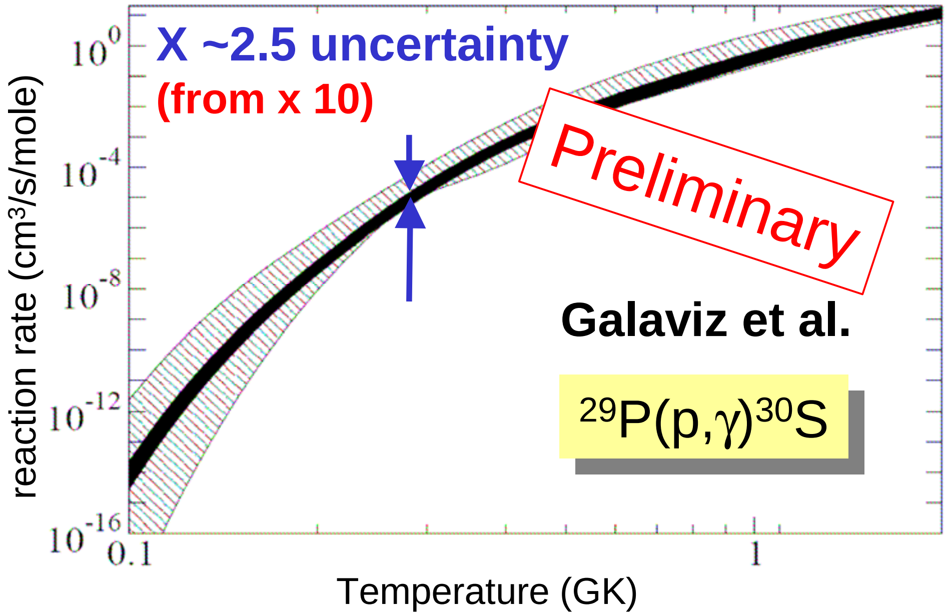
→ Lower part of r-process on solid nuclear physics bases
→ Influence of shell quenching unambiguously resolved
→ Some data on heavier r-process, incl. N=126

New rates: Clement et al. PRL 92 (2004) 2502, Galaviz et al.









→ Other reactions in preparation

Summary

- **Fast beams are important tool for nuclear astrophysics**
  → especially when reach to most exotic nuclei is required
  → Key questions: origin of r-process elements, X-ray bursts, supernovae

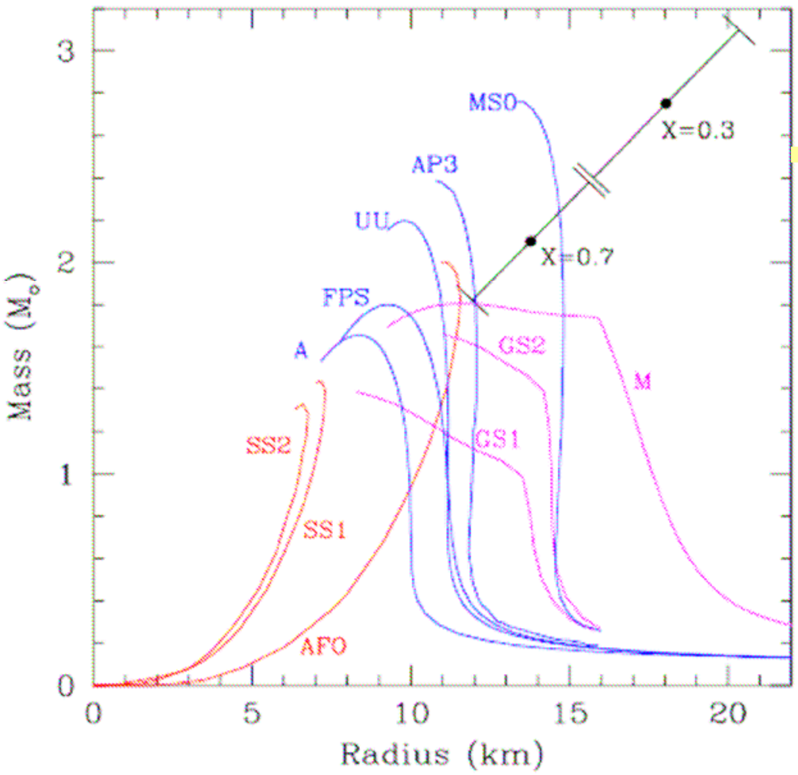
- **Observations drive the field – nuclear physics needs to keep up**
  → New generation of radioactive beam facilities are needed

- **Other tools are also needed**
  → low energy beams for direct rate measurements
  New facility at MSU/NSCL is planned
  (gas stopping and reacceleration to astrophysical energies)
  → stable beams
  → interdisciplinary environment
  Joint Institute for Nuclear Astrophysics (NSF PFC)
  (www.jinaweb.org)

→ **Collaboration**

Example: understand bursts to constrain NS

Constrain NS from observations

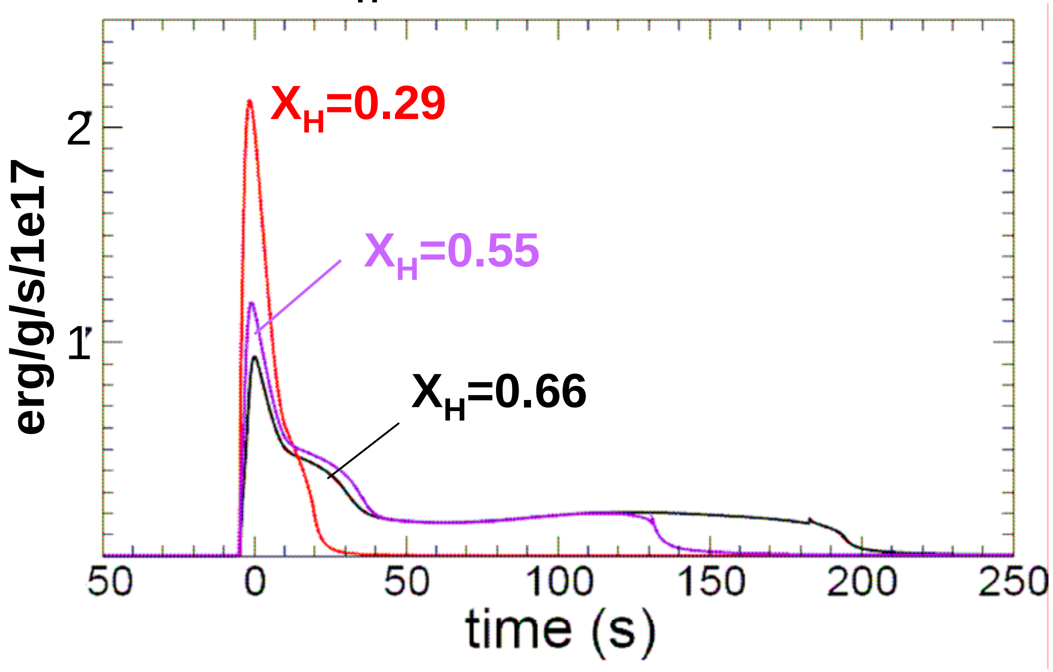


(Ozel Nature 441 (2006) 1115)

Observe in X-ray bursts from EXO0748−676:

- O,Fe absorption lines (→ redshift)
- T_c/F_{cool} (→ ~surface area)
- Eddington luminosity

Need X_H – use burst diagnostics ?



Collaboration

β-decay

MSU:
J. Pereira
P. Hosmer
F. Montes
P. Santi
A. Becerril
R.R.C. Clement
A. Estrade
G. Lorusso
P.F. Mantica
M. Matos
C. Morton
W.F. Mueller
M. Ouellette
E. Pellegrini
H. Schatz
M. Steiner
A. Stolz
B.E. Tomlin

Mainz:
S. Hennrich
O. Arndt
K.-L. Kratz
B. Pfeiffer

PNL
P. Reeder

Notre Dame:
M. Quinn
A. Aprahamian
A. Woehr

Maryland:
W.B. Walters

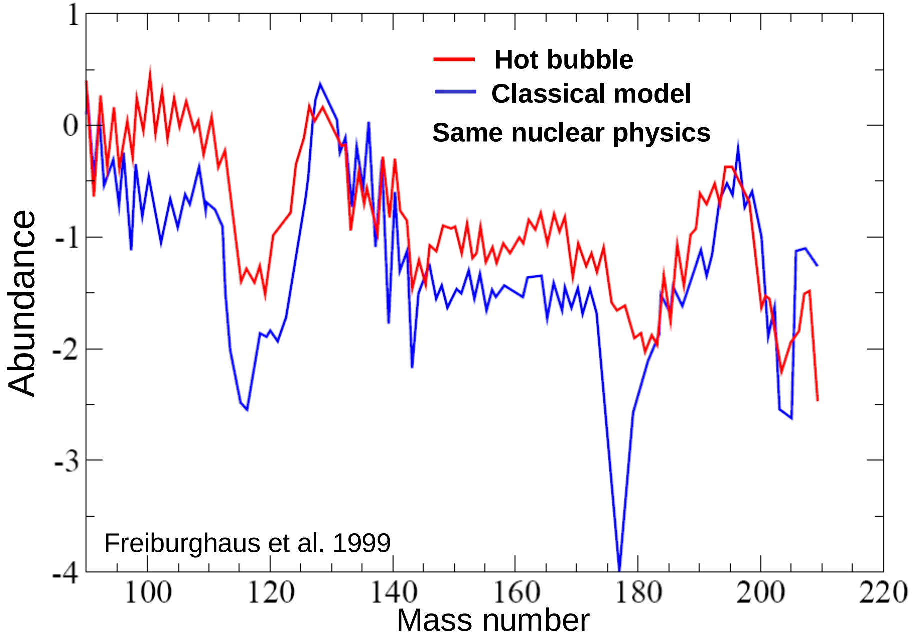
n-removal

MSU
D. Galaviz
R.R.C. Clement
M. Amthor
D. Bazin
C. Bertulani
A. Brown
A. Cole
A. Gade
T. Glasmacher
B. Lynch
M. Matos
W. Mueller
J. Pereira
H. Schatz
B. Sherrill
M. VanGoethem
M. Wallace

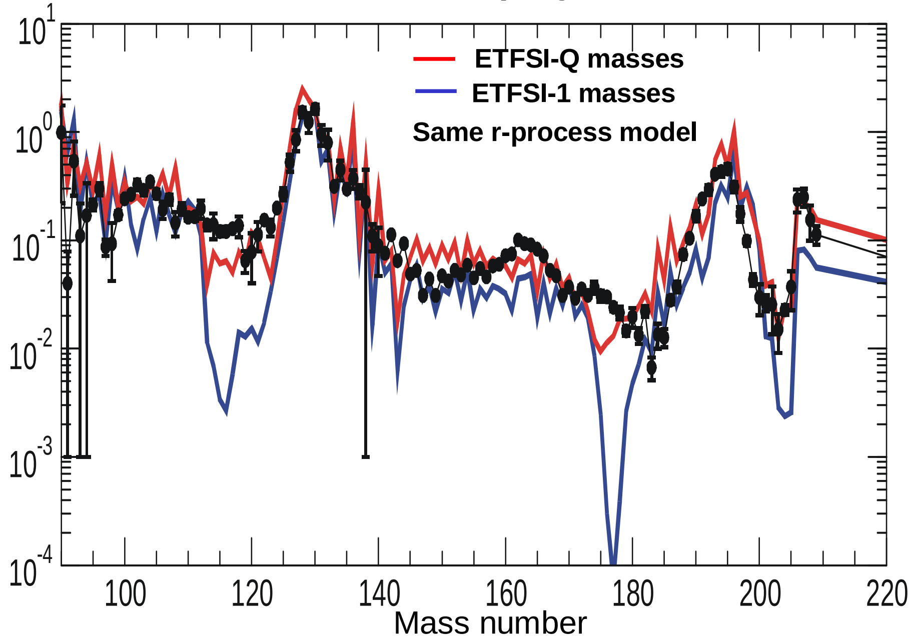
Sensitivity of r-process abundances

r-process abundances are determined by

Astrophysics



Nuclear physics



Contains information about:

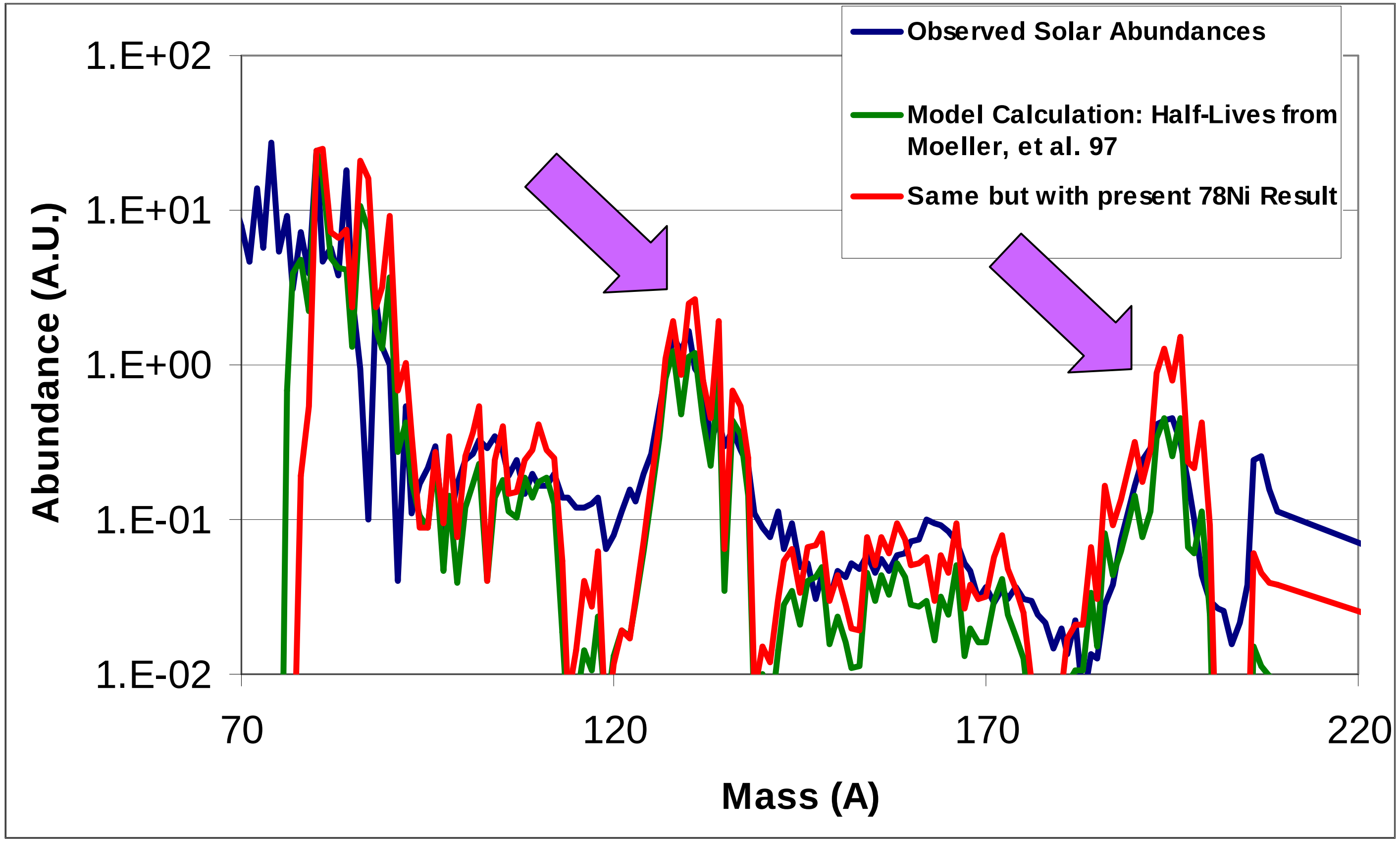
- n-density, T, time (fission signatures)
- freezeout
- neutrino presence
- which model is correct

Convoluted with unknown nuclear physics:

- masses (set path)
- $T_{1/2}$, Pn ($Y \sim T_{1/2(prog)}$, key waiting points set timescale)
- n-capture rates
- fission barriers and fragments

H. Schatz

Impact of ^{78}Ni half-life on r-process models



→need to readjust r-process model parameters

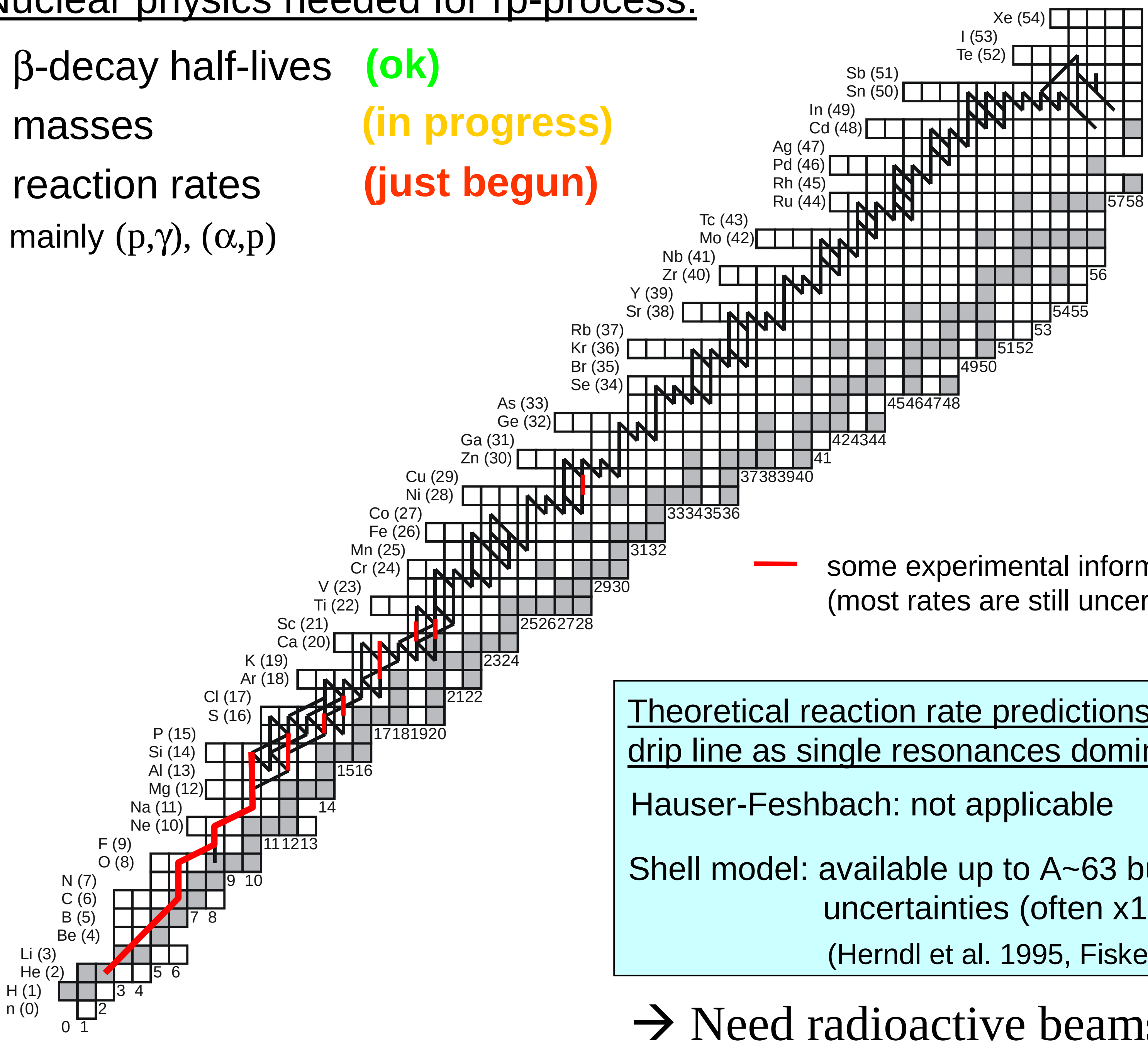
→Can obtain Experimental constraints for r-process models from observations and solid nuclear physics

→ remainig discrepancies – nuclear physics ? Environment ? Neutrinos ? Need more data

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)

Theoretical reaction rate predictions difficult near drip line as single resonances dominate rate:

Hauser-Feshbach: not applicable

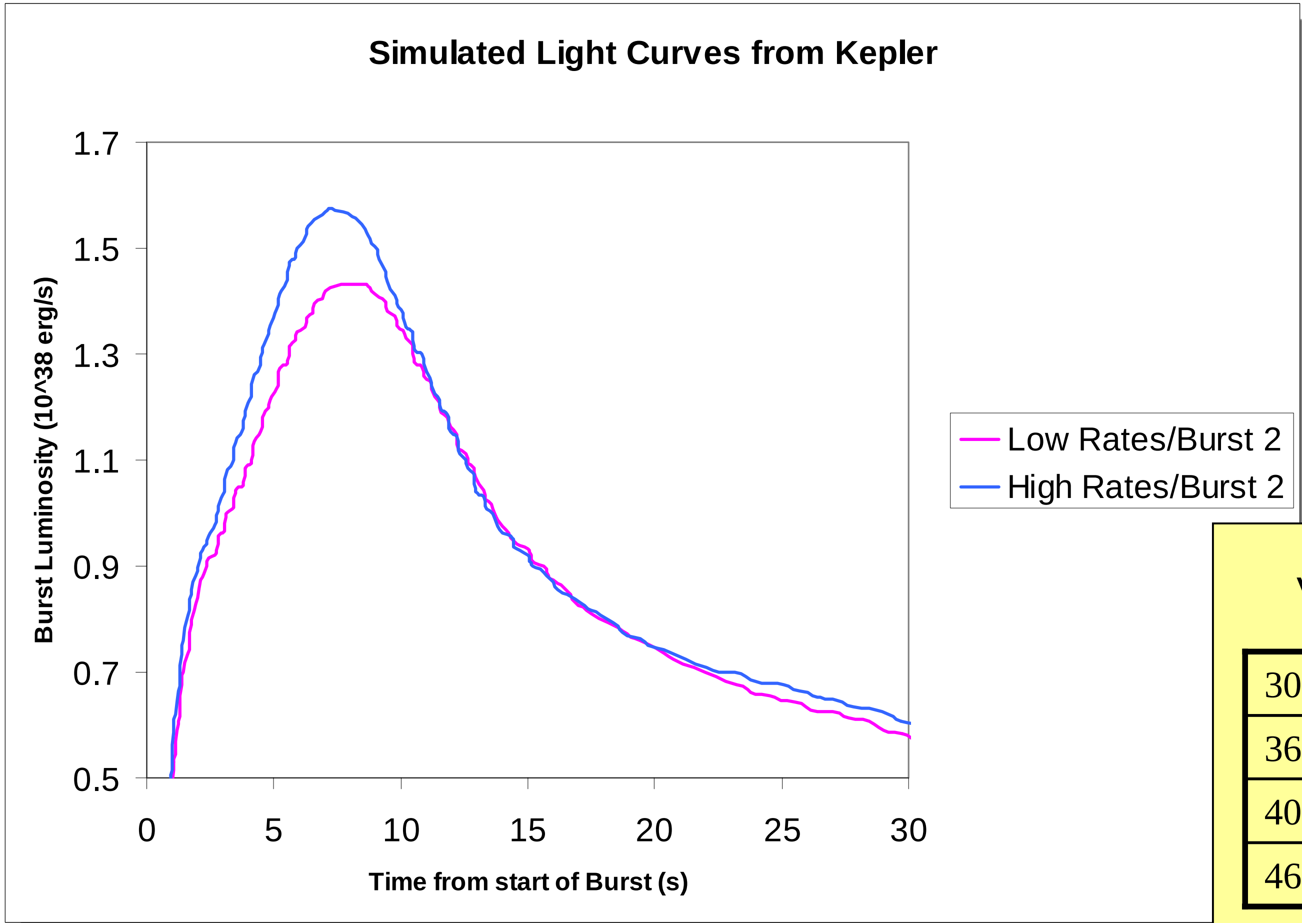
Shell model: available up to A~63 but large uncertainties (often x1000 - x10000)

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

→ Need radioactive beams

Opportunities for students

Summer research project of NSCL graduate student Matt Amthor at LANL prior to his NSCL thesis experiment to determine rp-process reaction rates



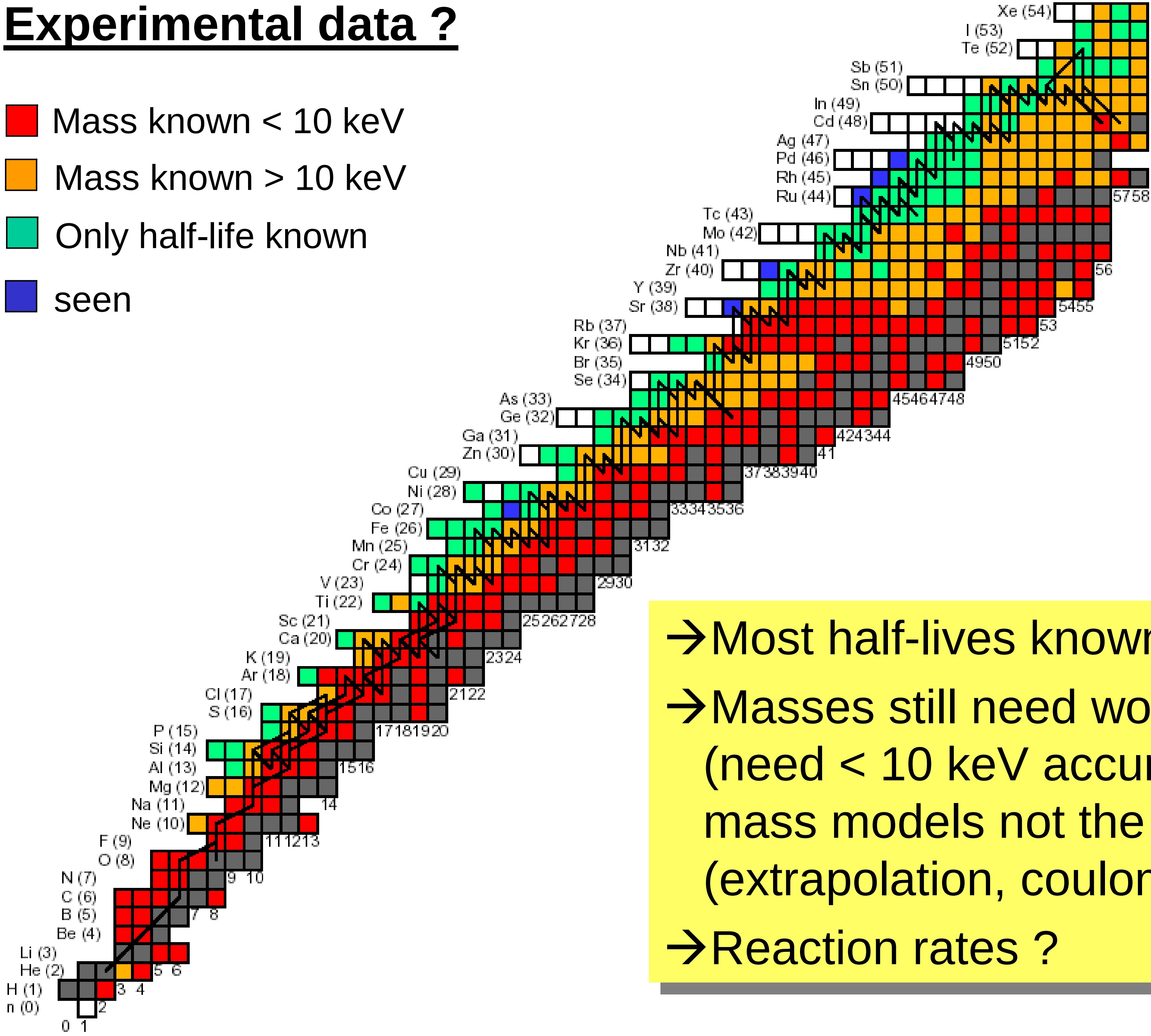
→ Comparable to observed differences

Vary by factor 100

30S(p,g)*	31Cl
36K(p,g)**	37Ca
40Sc(p,g)	41Ti
46Cr(p,g)	47Mn

M. Amthor, A. Heger, H. Schatz, B. Sherrill

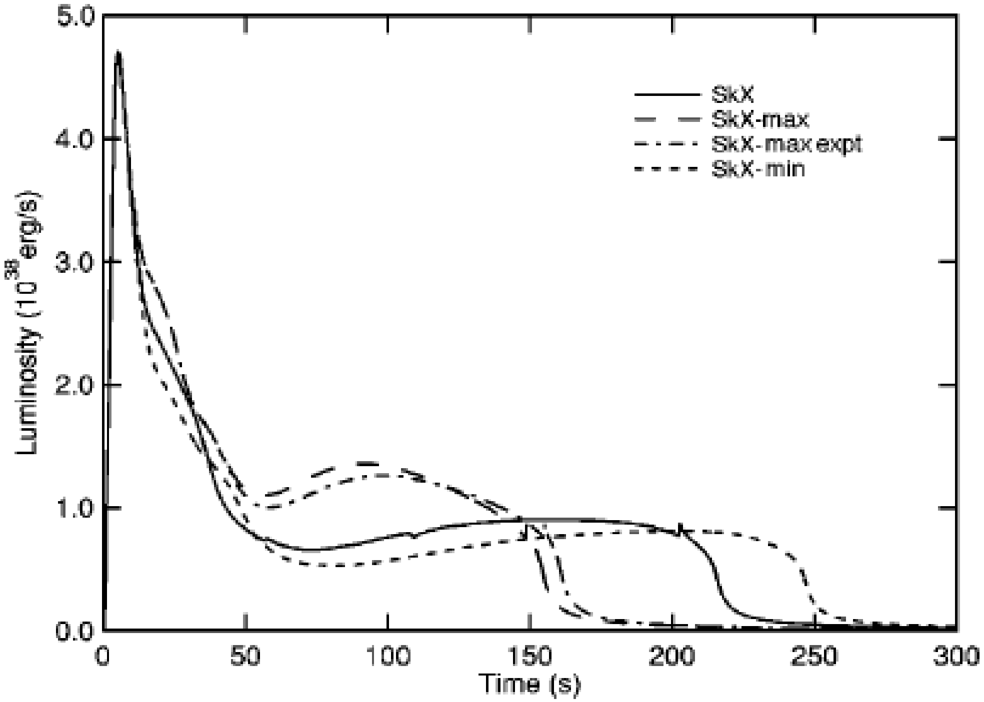
Experimental data ?



→Most half-lives known

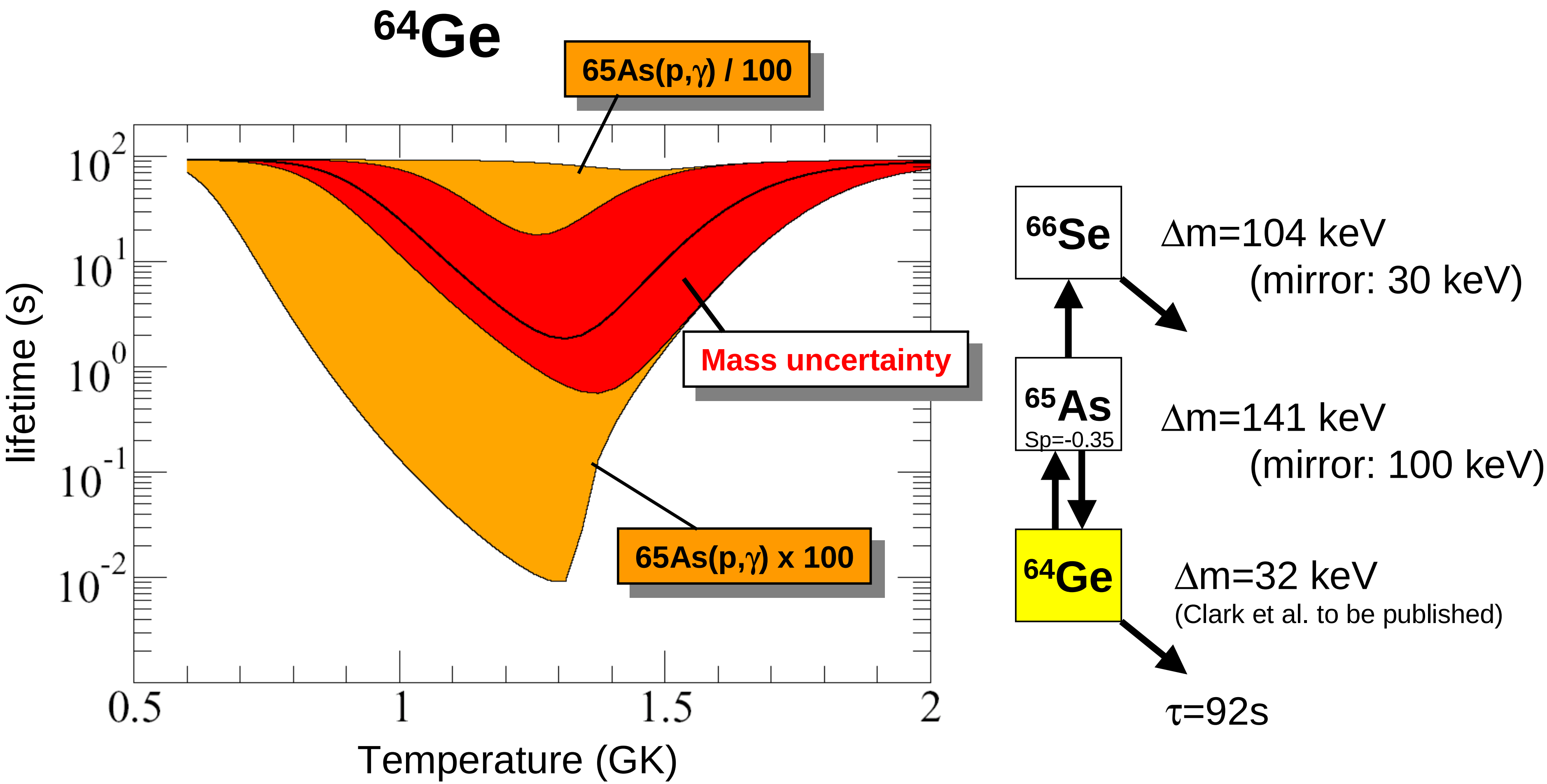
→Masses still need work
(need < 10 keV accuracy)
mass models not the issue
(extrapolation, coulomb shift)

→Reaction rates ?



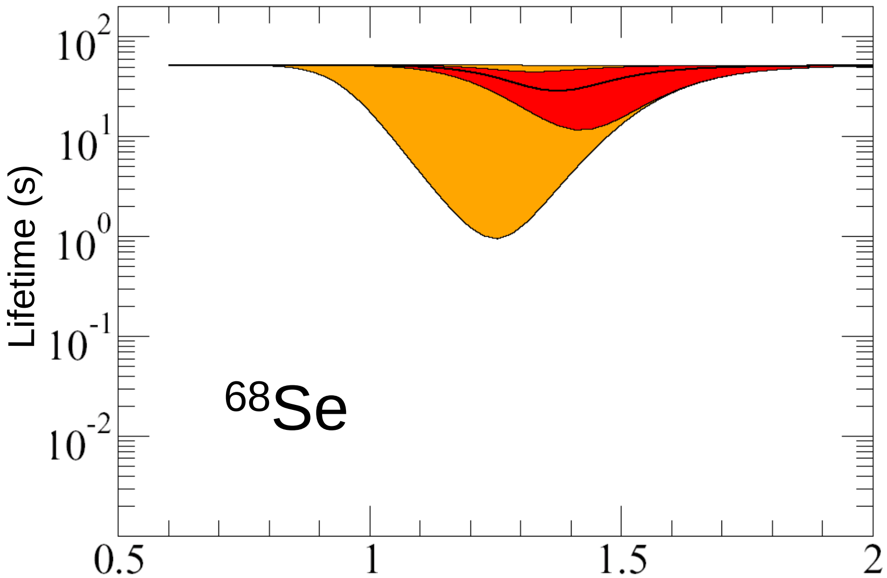
SkX
SkX-max
SkX-max expt
SkX-min
Luminosity (10^{38}erg/s)
Time (s)
0.0
1.0
2.0
3.0
4.0
5.0
0
50
100
150
200
250
300

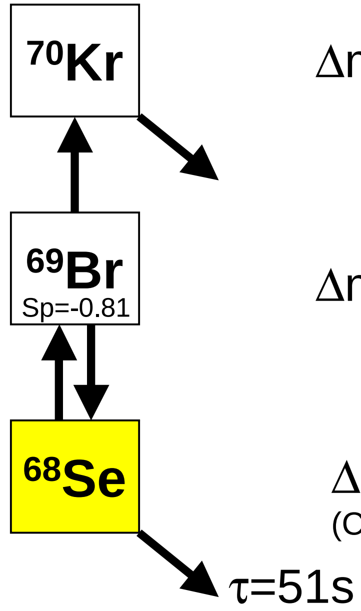
^{64}Ge Waiting point current uncertainty



H. Schatz

^{68}Se and ^{72}Kr Waiting point current uncertainty

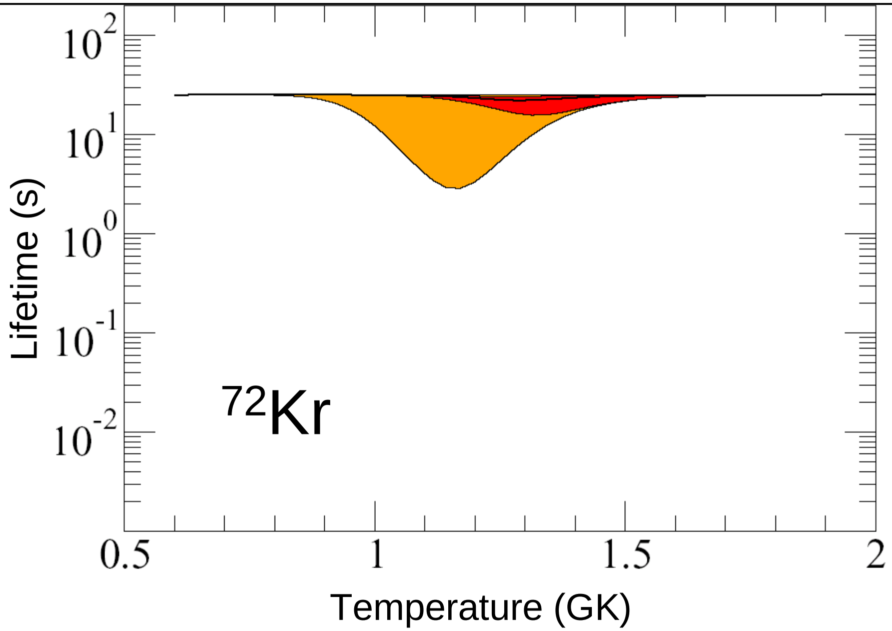


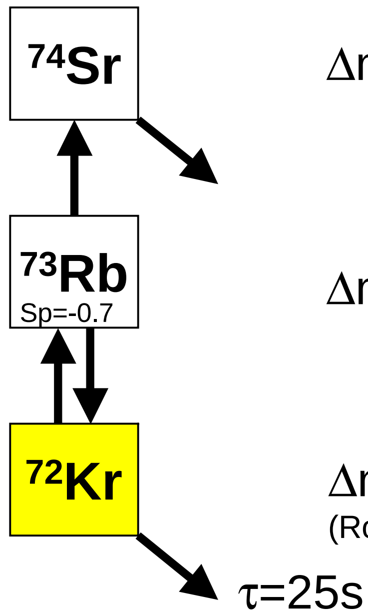


Δm=120 keV
(mirror: 62 keV)

Δm=110 keV
(mirror: 34 keV)

Δm=19 keV
(Clark et al. 2004)





Δm=100 keV
(mirror: 2.1 keV)
(Rodriguez et al. 2004)

Δm=100 keV
(mirror: 6.6 keV)
(Rodriguez et al. 2004)

Δm=8.0 keV
(Rodriguez et al. 2004)