Nuclear properties and the astrophysical *r* process

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University of Jyväskylä

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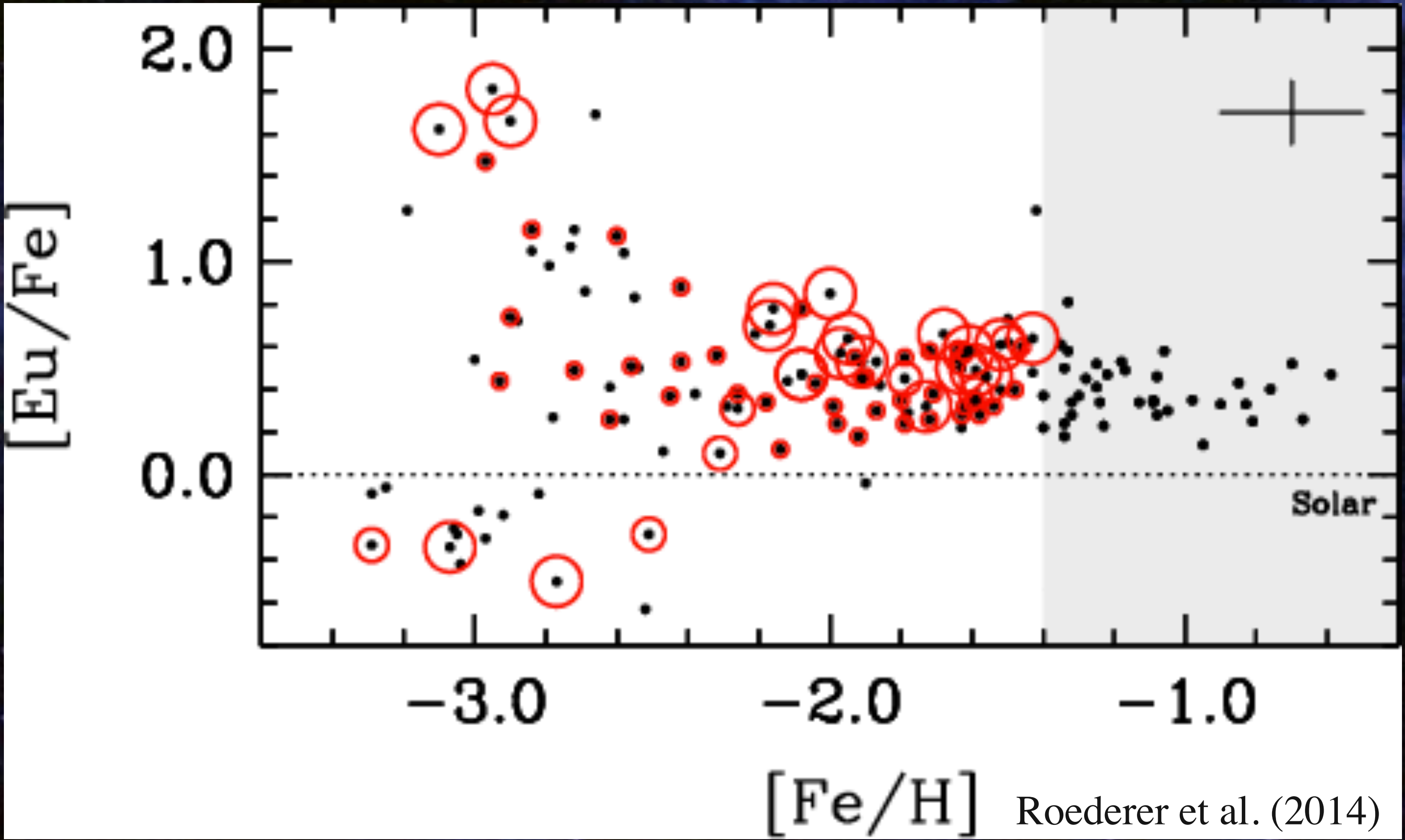
Nuclear properties and the astrophysical *r* process

What is the astrophysical origin of the heaviest elements??

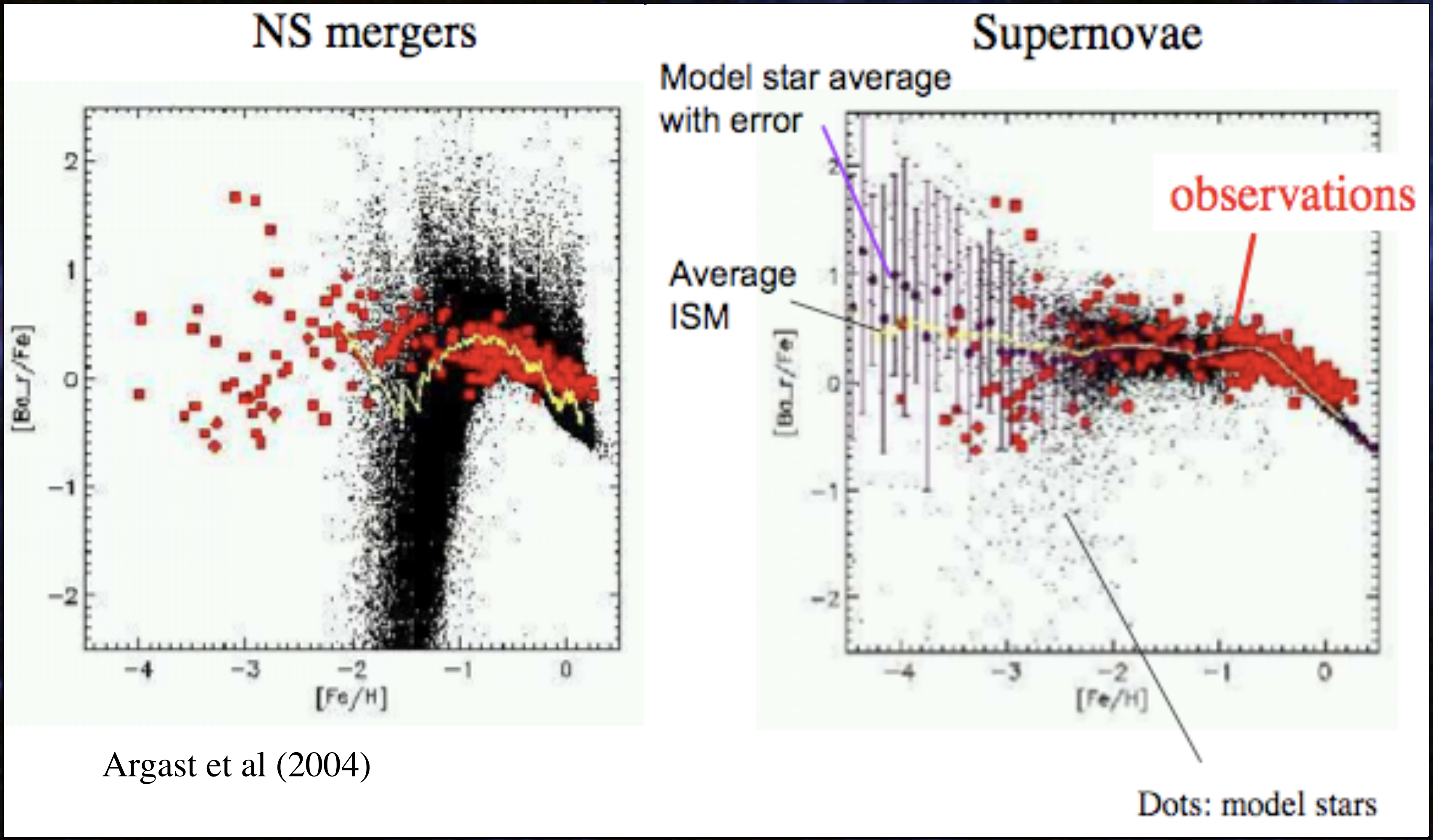
Class #	Subject
1	Introduction, chemical abundances
2	Origins of the elements up to helium
3	Origins of the elements up to iron, *r*-process dynamics
4	Astrophysical sites of the *r* process
5	Nuclear data for the *r* process

metal-poor stars and the *r* process



Roederer et al. (2014)

galactic chemical evolution and the *r* process



Mathews & Cowan (1990), Argast et al (2004): mergers do not fit observational data

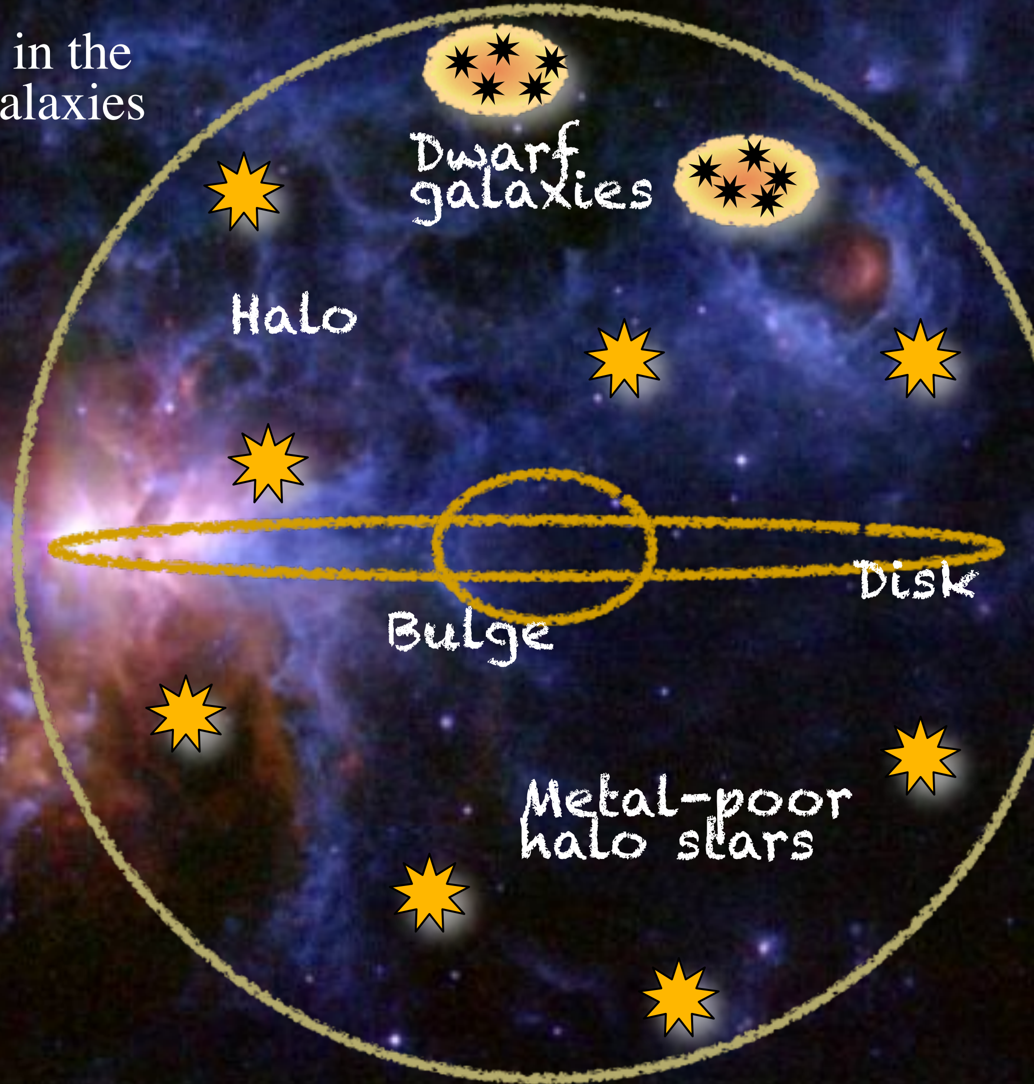
metal-poor stars and the Milky Way

Metal-poor stars are found in the halo, the bulge and in dwarf galaxies

The disk and open and globular clusters do not contain stars with [Fe/H]<−2.3

=> Origin of halo and bulge stars is actually unknown

=> Trace chemical signature of their birth gas cloud wherever they formed



ultra-faint dwarf galaxies

Low luminosity

(300 - 3,000 L_{sun})

Dark matter-dominated

(M/L > 100)

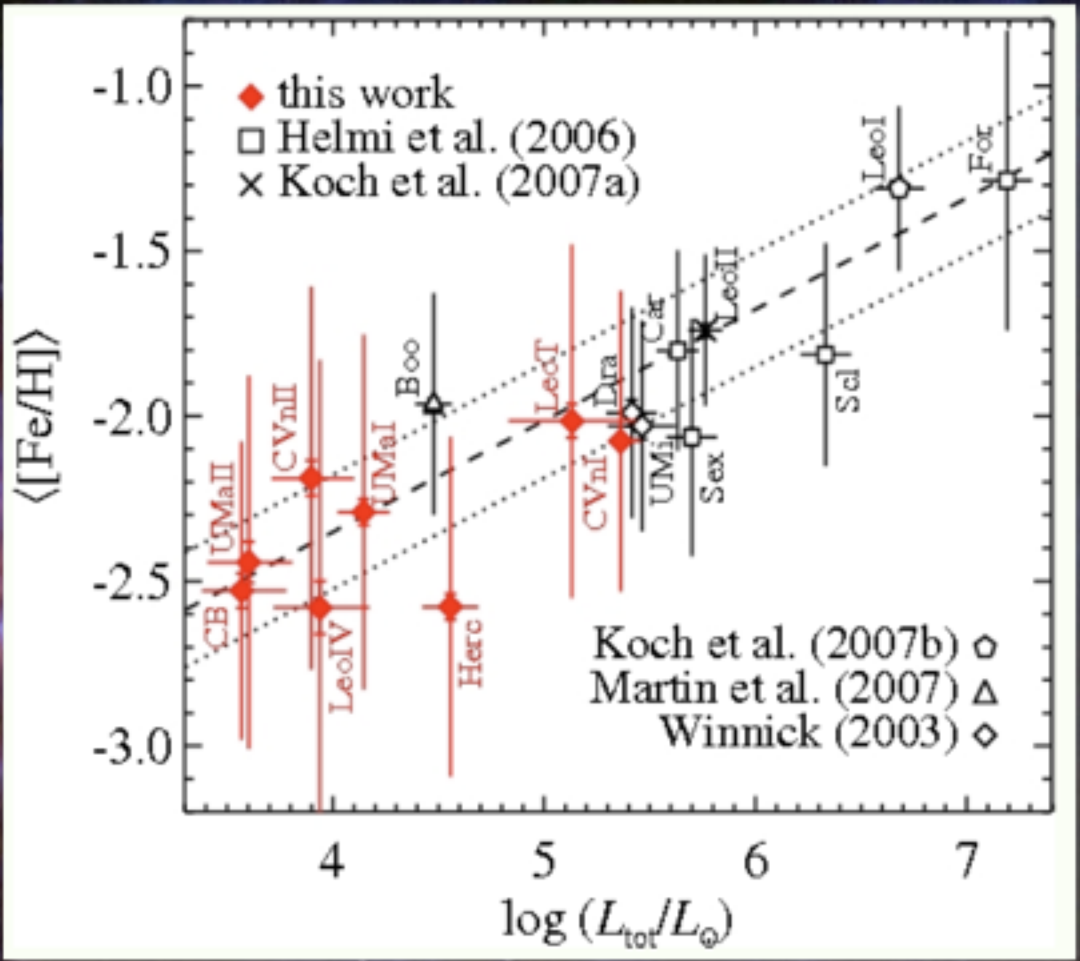
Metal-poor

(mean [Fe/H] ~ –2)

Stars are old

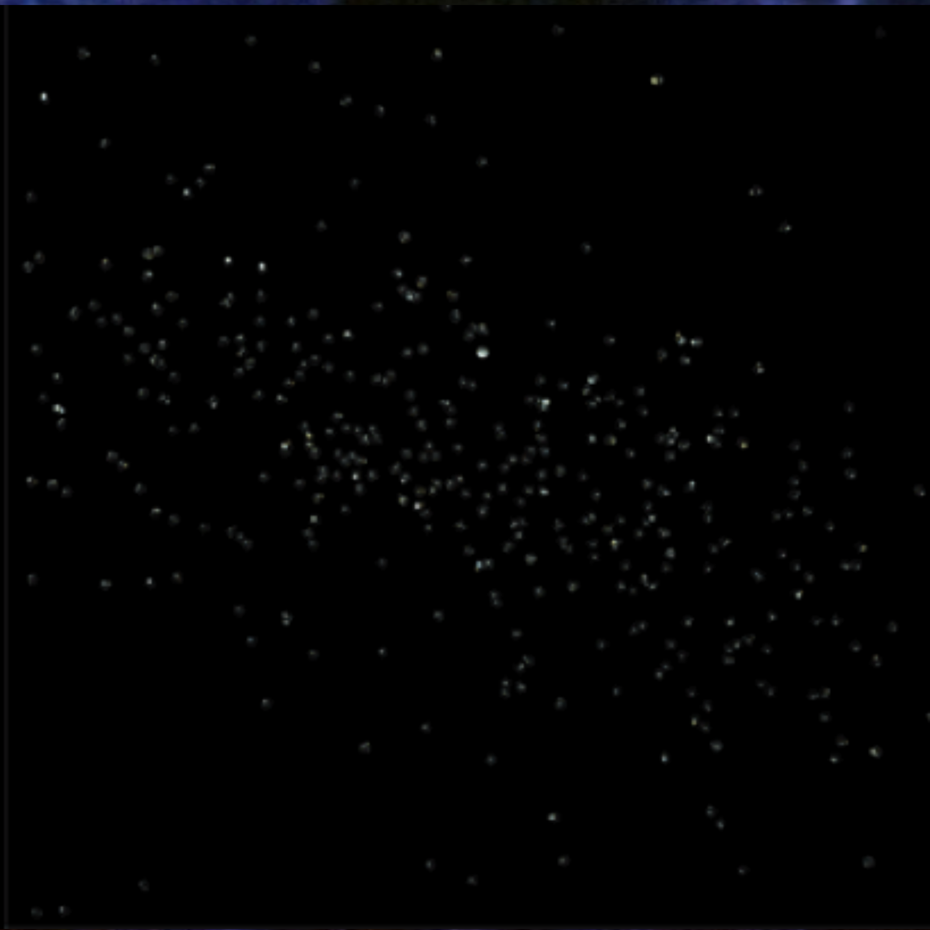
(mean age 13.3 +/– 1 Gyr)

Few bursts of star formation



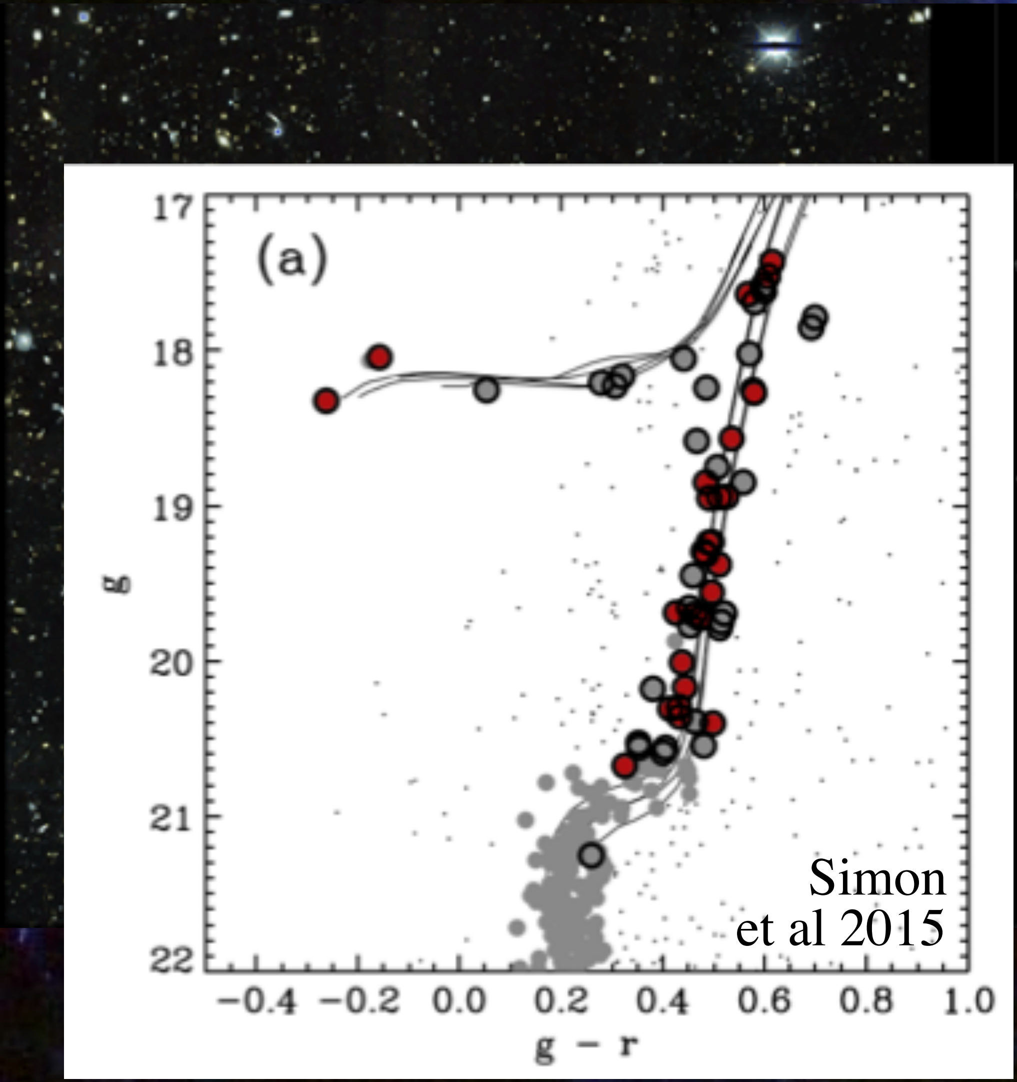
ultra-faint dwarf galaxy: Reticulum II

All stars



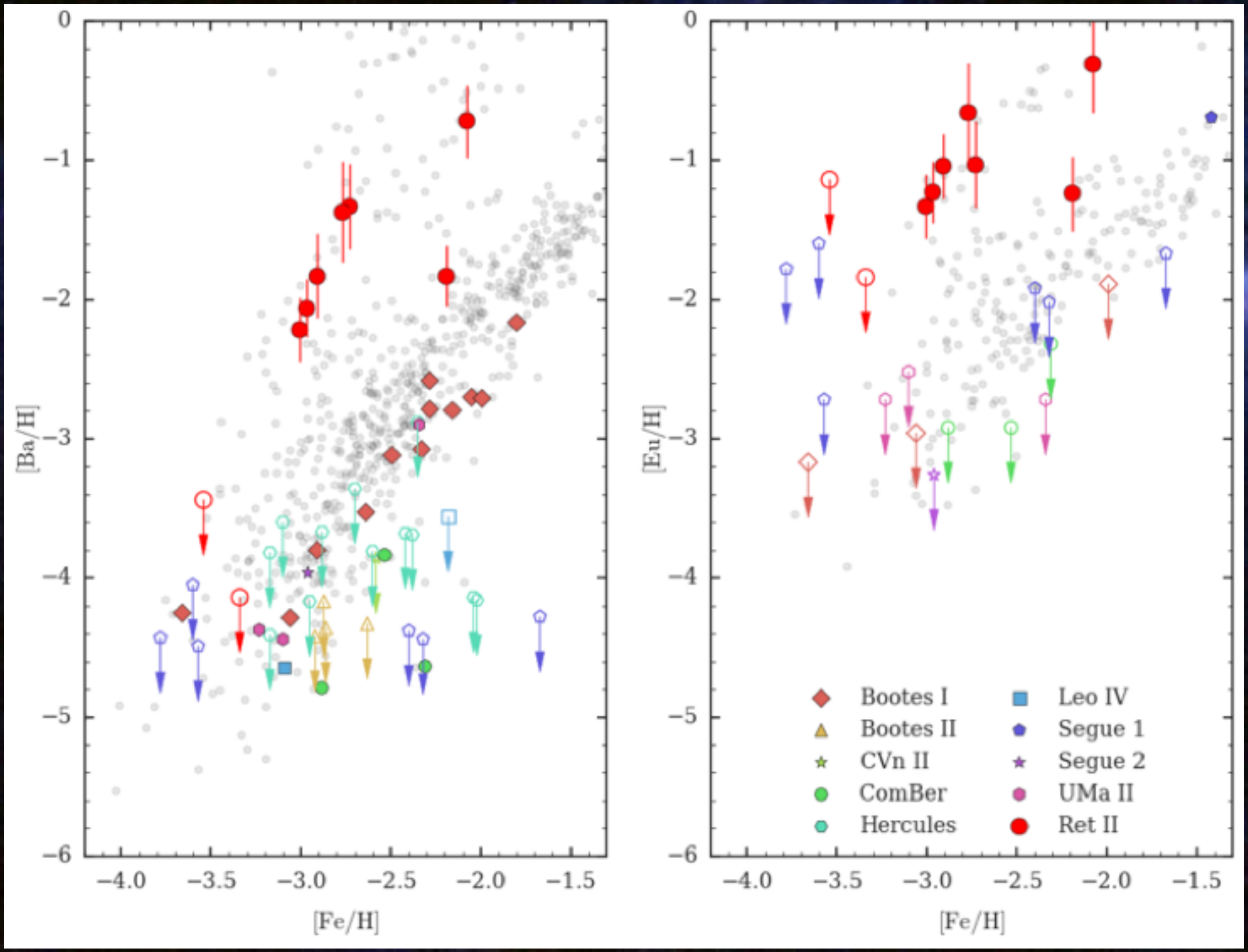
Ret II stars

ultra-faint dwarf galaxy: Reticulum II



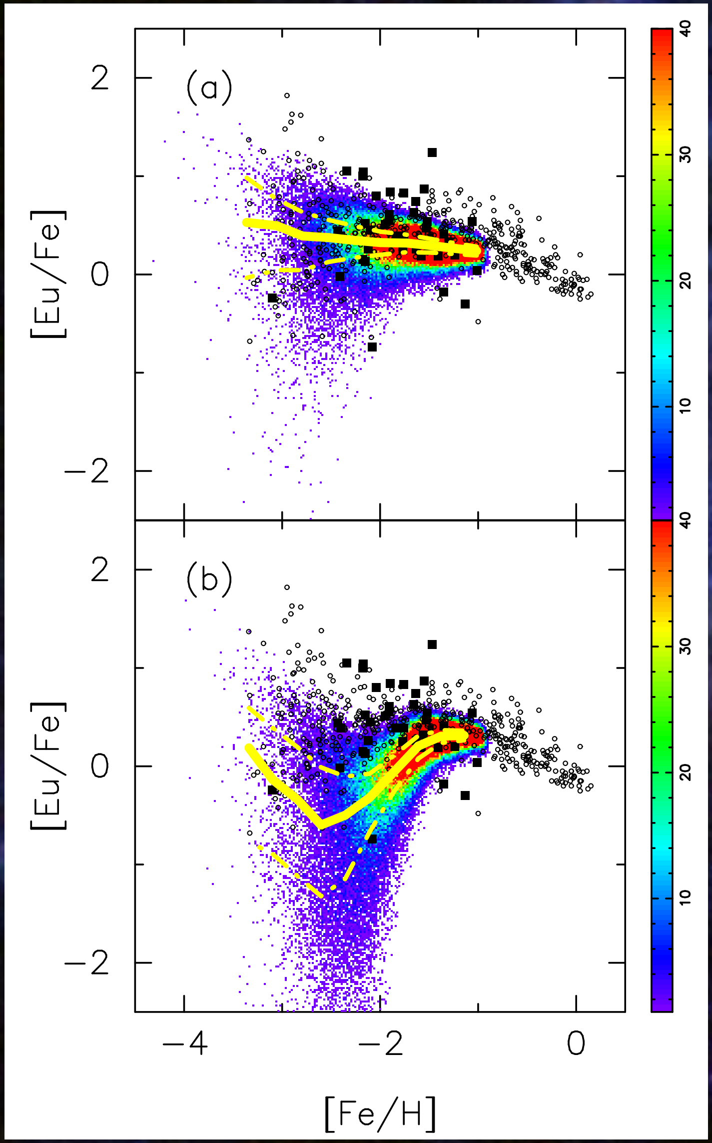
Ret II stars

ultra-faint dwarf galaxy: Reticulum II



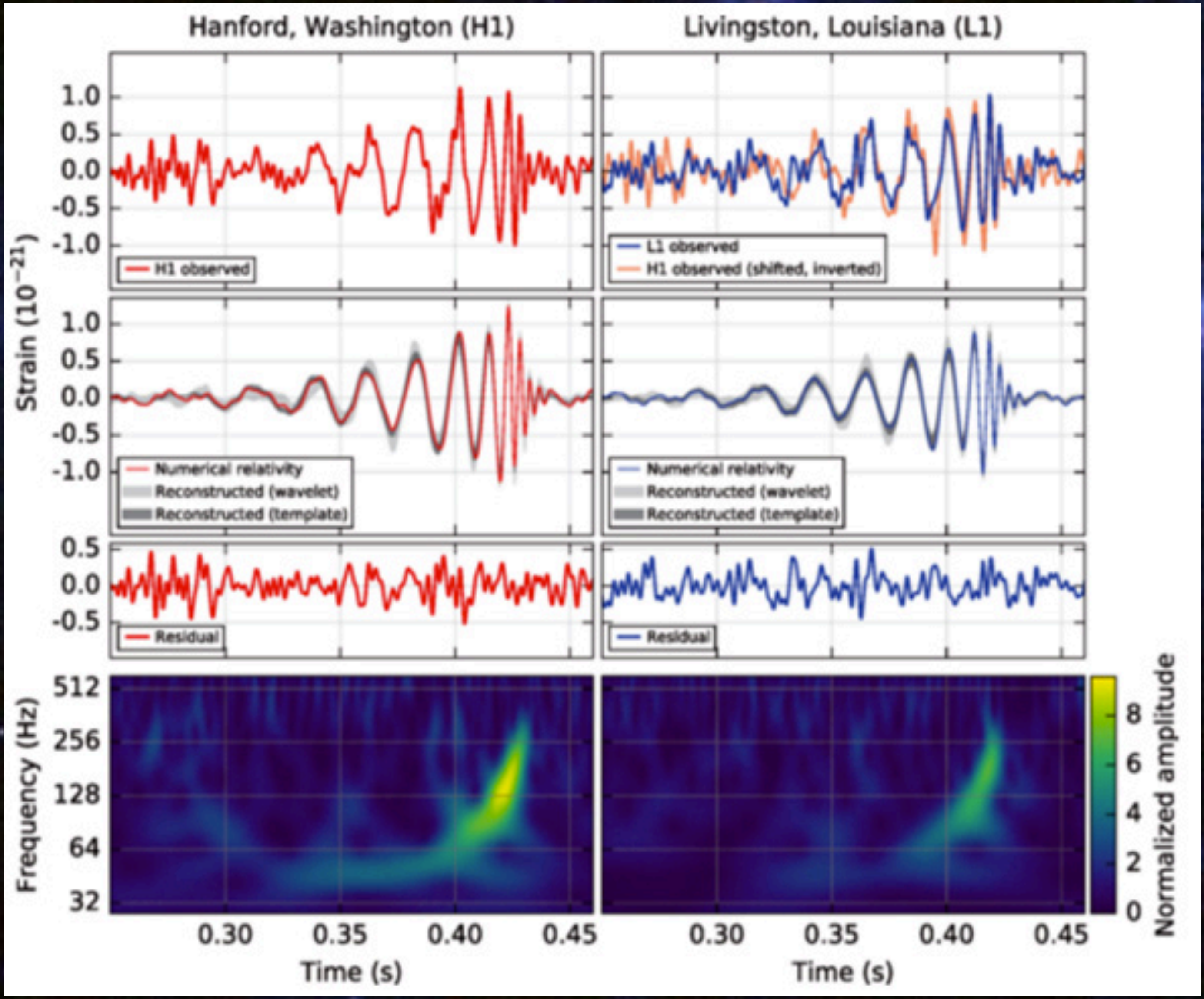
Ji et al (2016)

new GCE simulations including UFD galaxy accretion

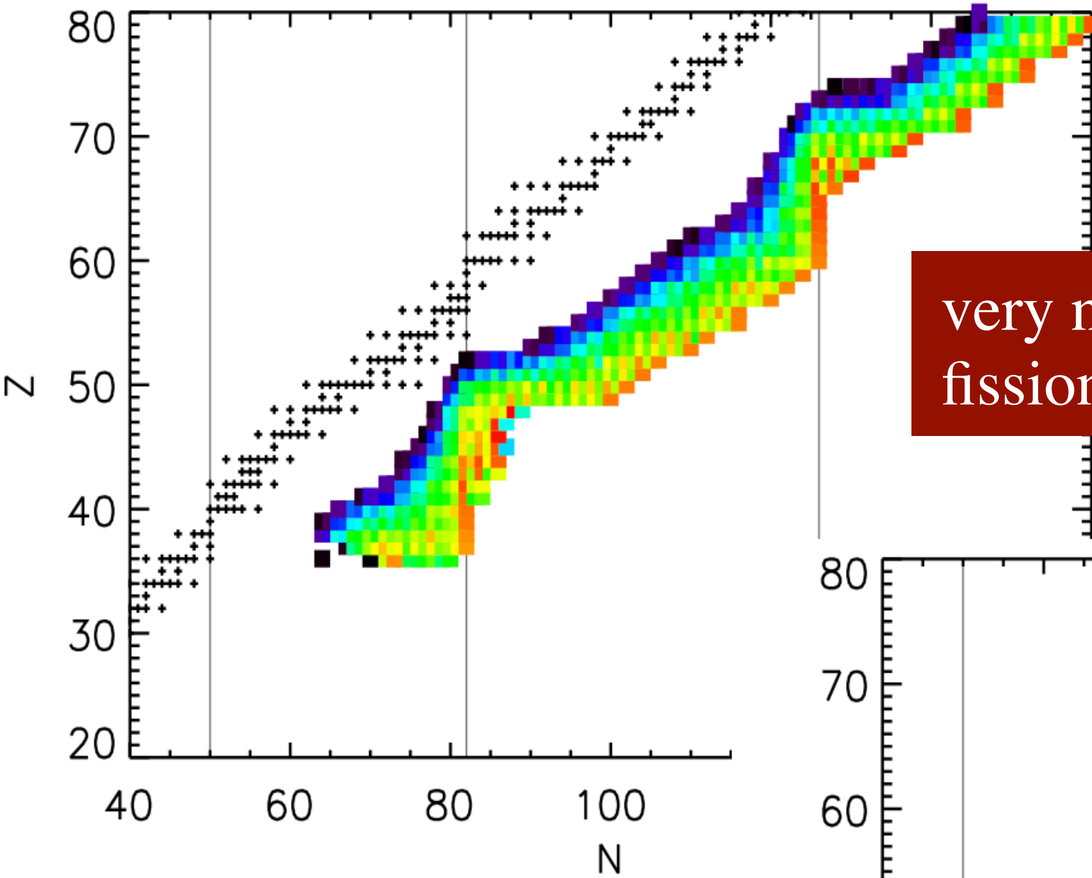


Hirai et al (2015)

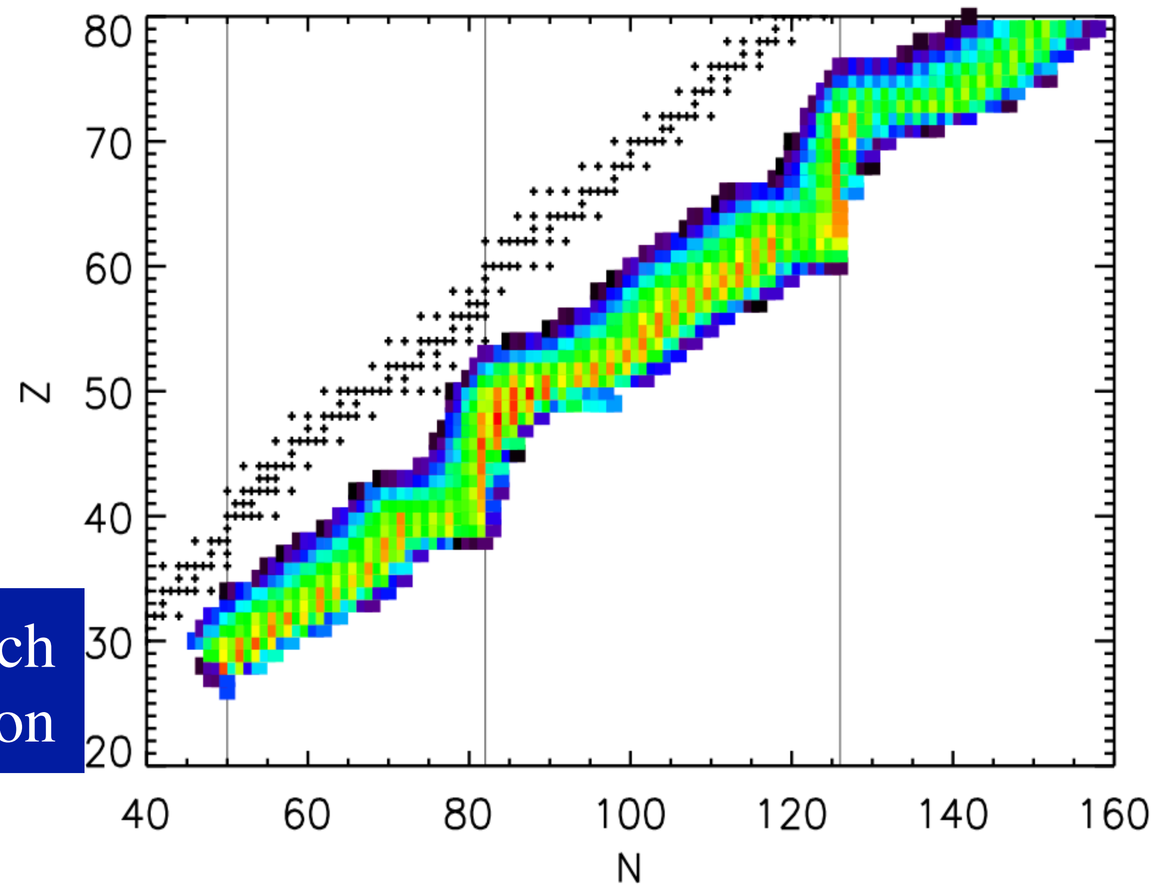
prospects: gravitational wave astrophysics



r-process pattern signatures



very neutron rich
fission cycling



barely neutron rich
limit seed production

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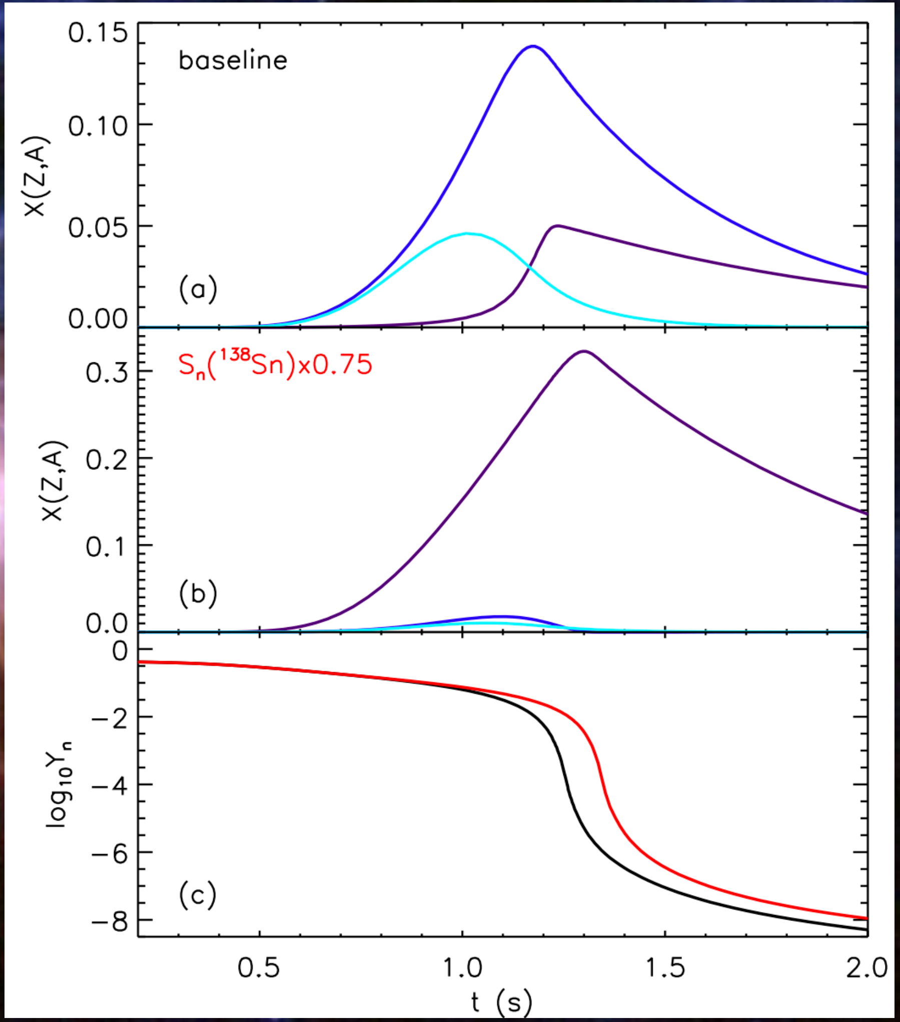
nuclear data and the *r* process

the role of masses in an equilibrium *r* process

While (n,γ)-(γ,n) equilibrium holds, the neutron separation energies determine the abundances along an isotopic chain:

$$\frac{Y_{equilibrium}(Z,A+1)}{Y_{equilibrium}(Z,A)} = \frac{G(Z,A+1)}{2G(Z,A)} n_n \left(\frac{2\pi\hbar^2 N_A}{m_n kT}\right)^{3/2} \exp\left[\frac{S_n(Z,A+1)}{kT}\right]$$

^{136}Sn
^{138}Sn
^{140}Sn

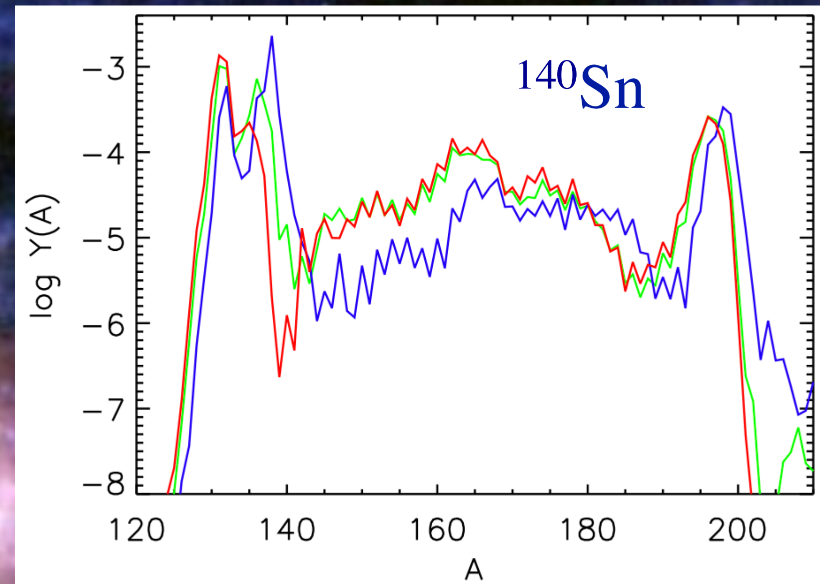


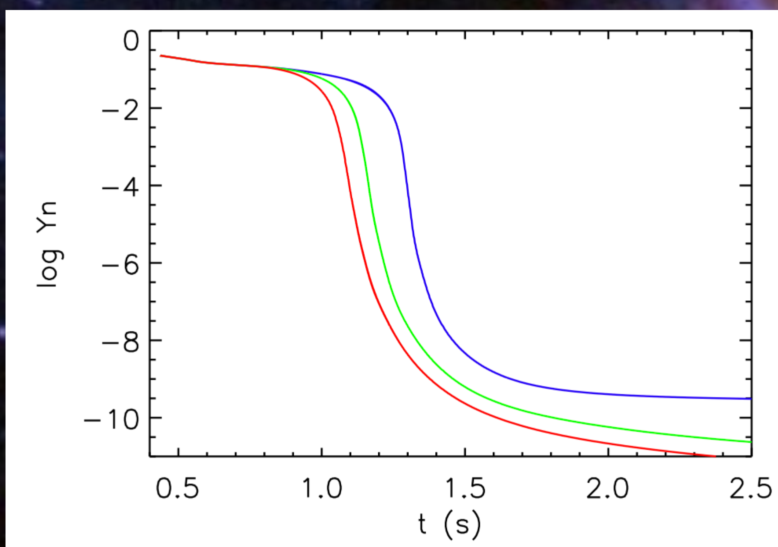
Brett, Bentley, Paul, Surman, Aprahamian (2012)

the role of β decay rates in an equilibrium *r* process

The beta decay rates determine the relative abundances of the isotopic chains through the steady beta flow condition:

$$\lambda_\beta(Z,A_{path})Y(Z,A_{path}) \sim \text{constant}$$





baseline

$\lambda_\beta(Z,A)\times 10$

$\lambda_\beta(Z,A) \div 10$

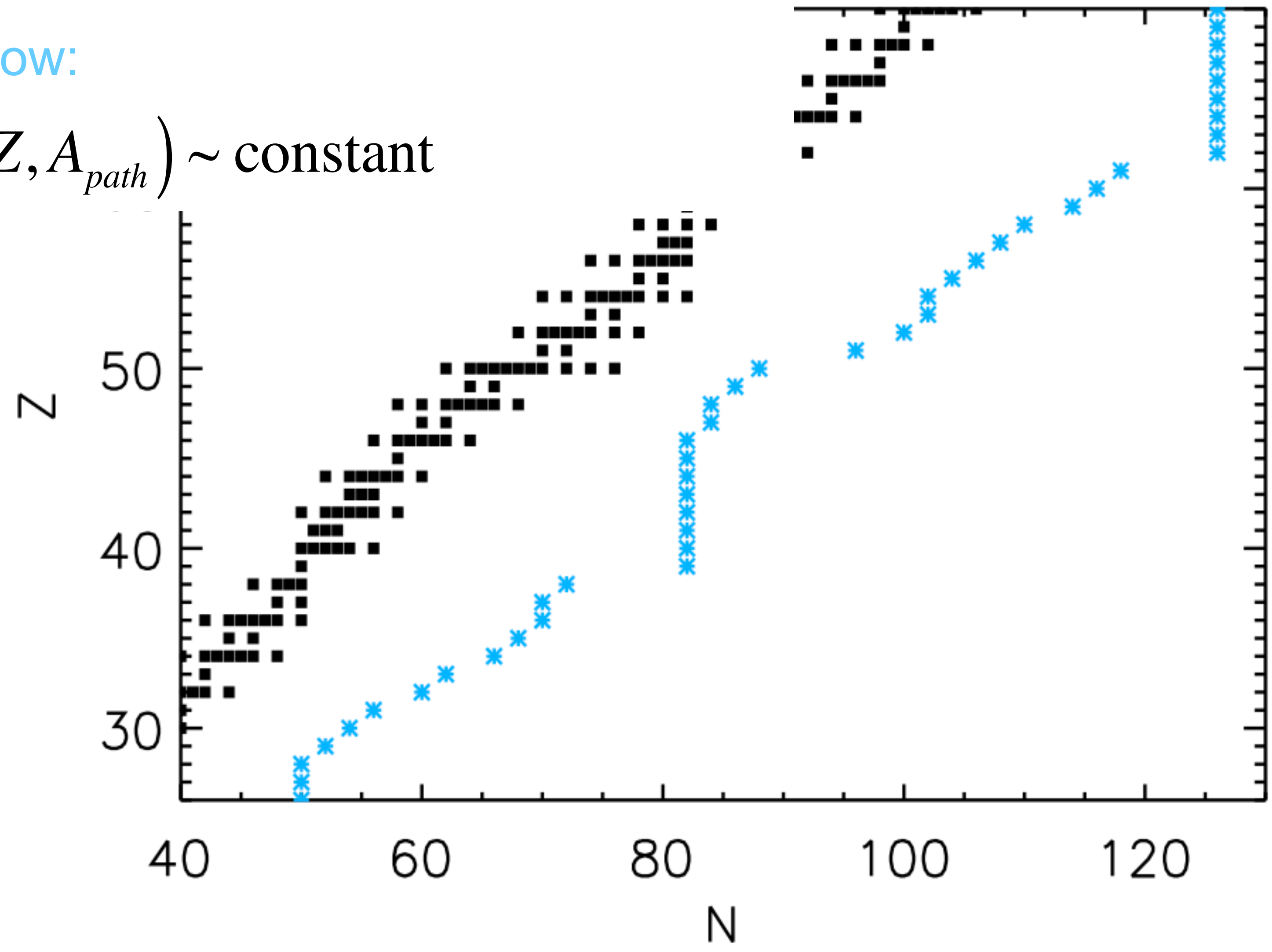
Cass, Passucci, Surman, Aprahamian (2012) equilibrium path from Saha eqn:

$$\frac{N_{A+1}}{N_A} \sim \frac{N_n}{2}(\hbar c)^3\left(\frac{A}{A+1}\right)^{3/2}\left(\frac{2\pi\hbar^2}{m_n c^2 kT}\right)^{3/2} e^{S_n(Z,A+1)/kT}$$

steady beta flow:

$$\lambda_\beta\left(Z,A_{path}\right)Y\left(Z,A_{path}\right) \sim \text{constant}$$

(n,γ)-(γ,n) equlibrium *r*-process



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r-process sensitivity studies

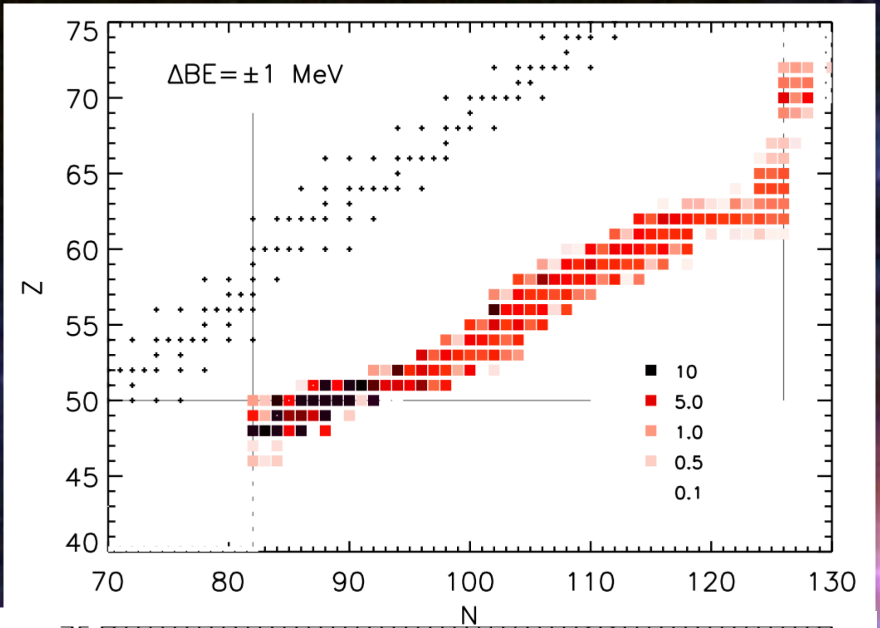
Choose a baseline simulation

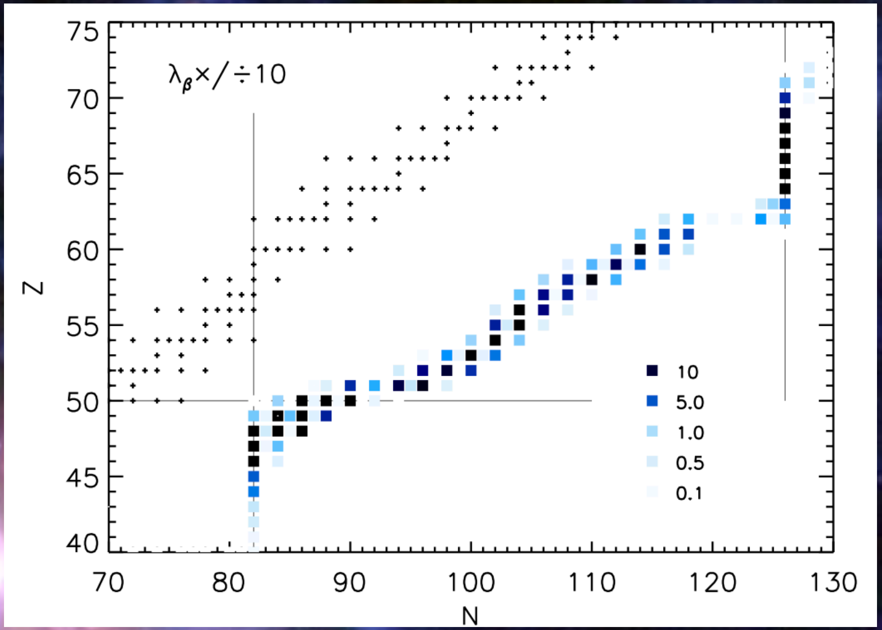
Vary one piece of nuclear data by a set amount, rerun the simulation, and compare the final abundance pattern to the baseline:

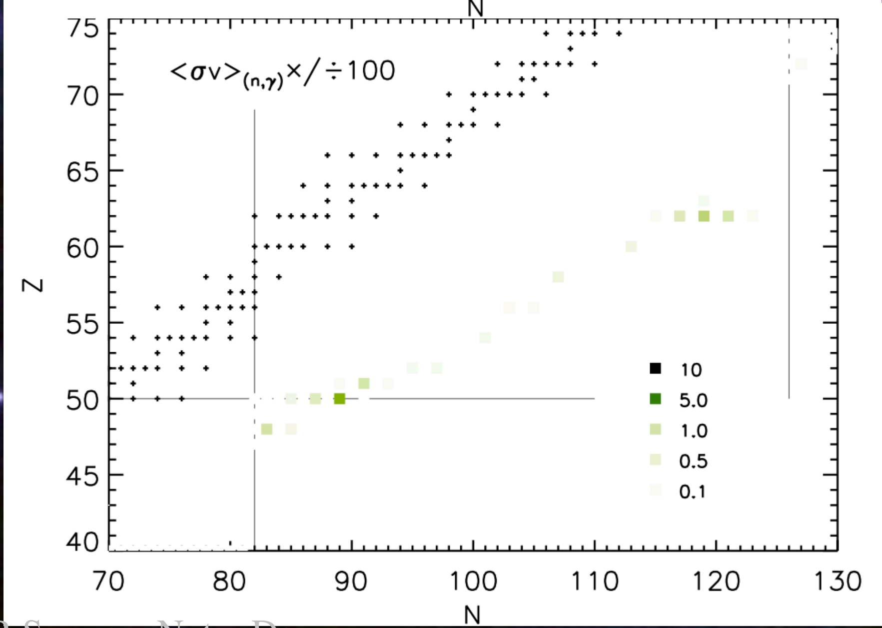
$$F = 100 \times \sum_A \left| X_{baseline}(A) - X(A) \right|$$

Repeat for each nucleus in the network

r-process sensitivity studies: (n,γ)-(γ,n) equilibrium only

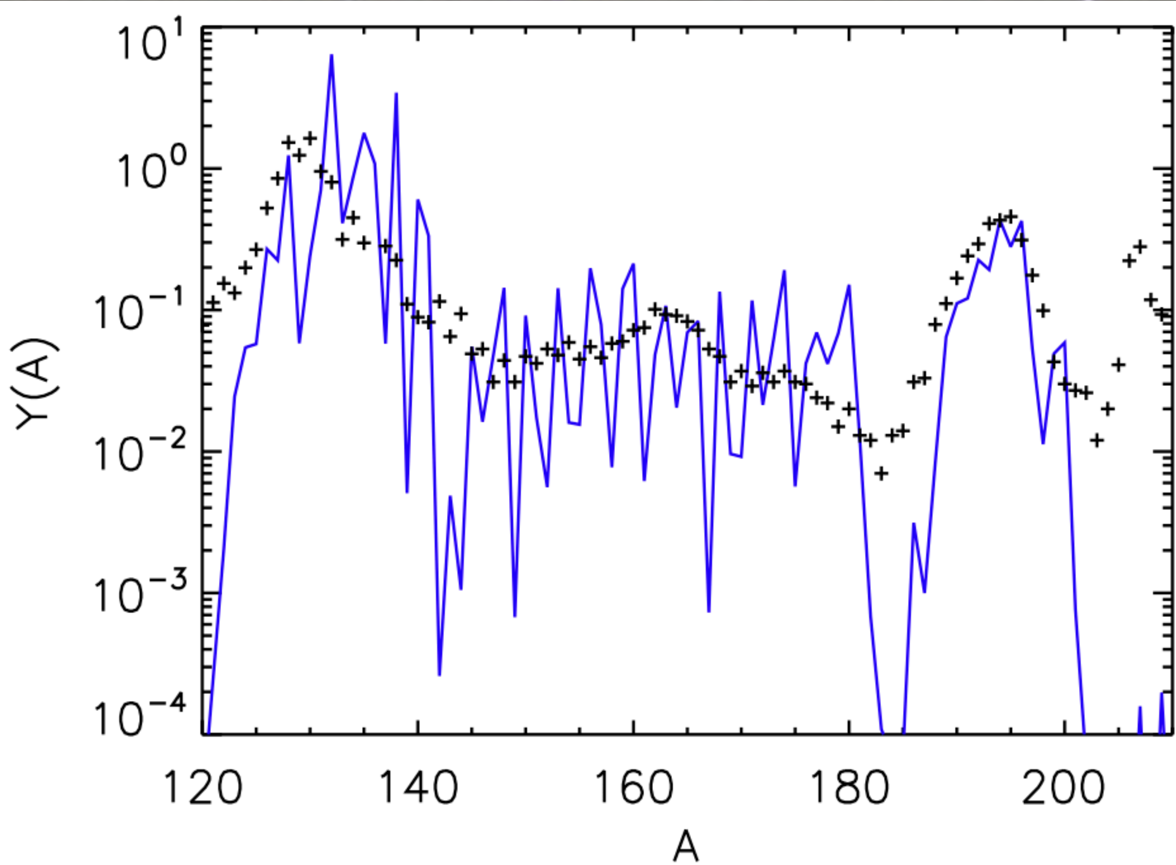


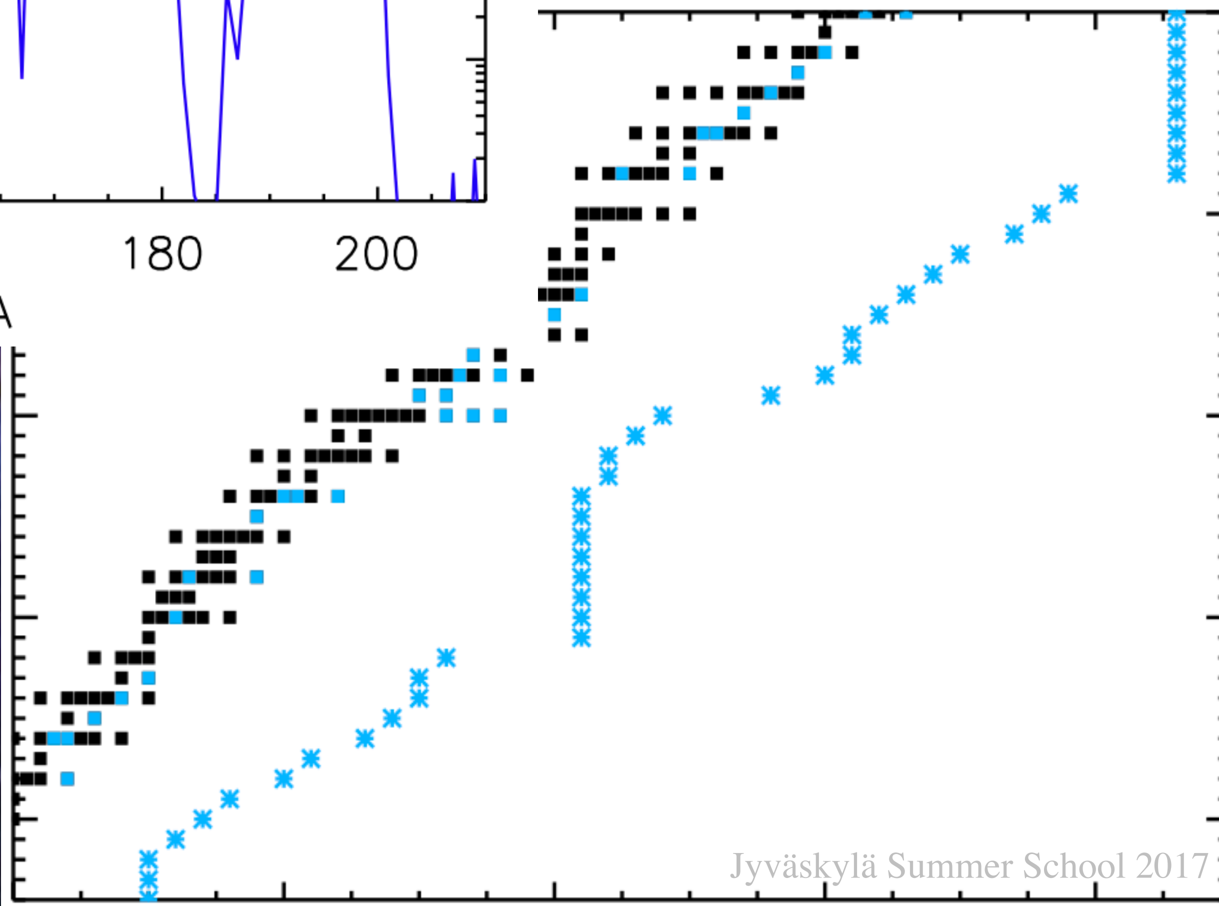




wind parameterized as Meyer (2002) with $s/k = 100$, $Y_e = 0.25$

(n,γ)-(γ,n) equlibrium *r*-process





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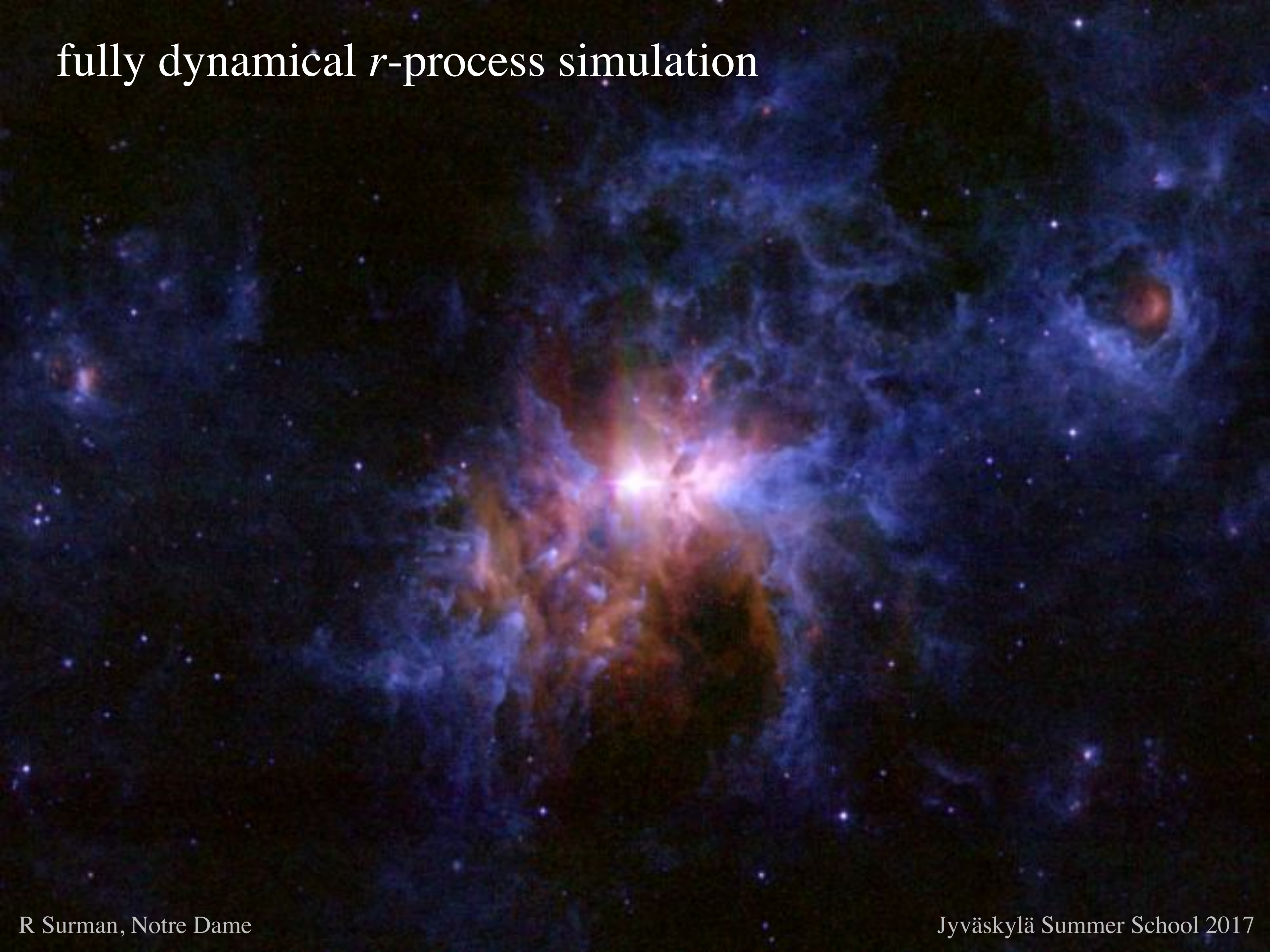
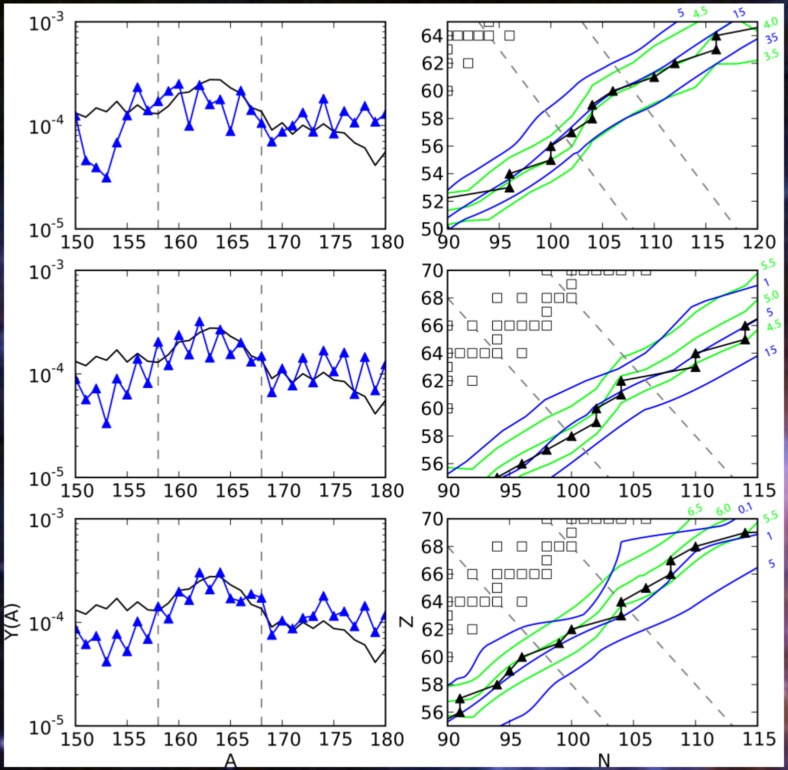
fully dynamical *r*-process simulation

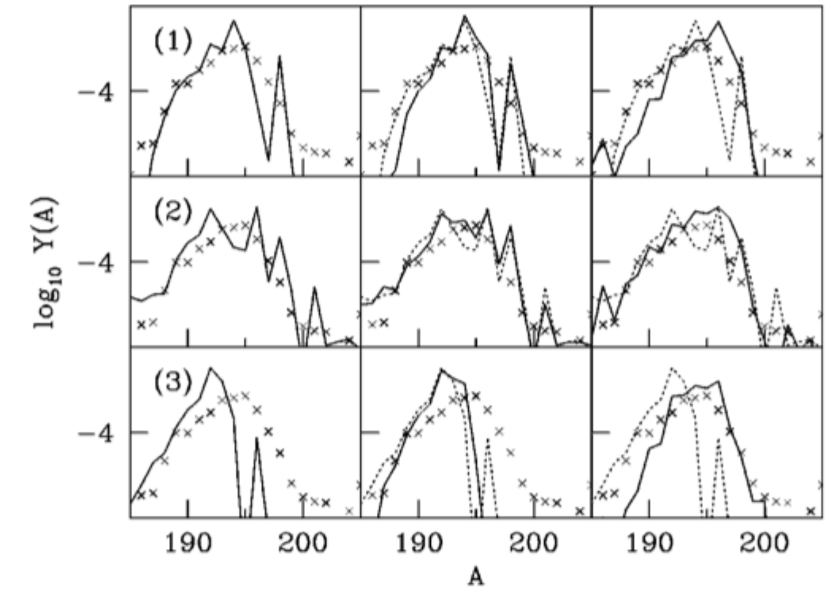


freezeout from (n,γ)-(γ,n) equilibrium



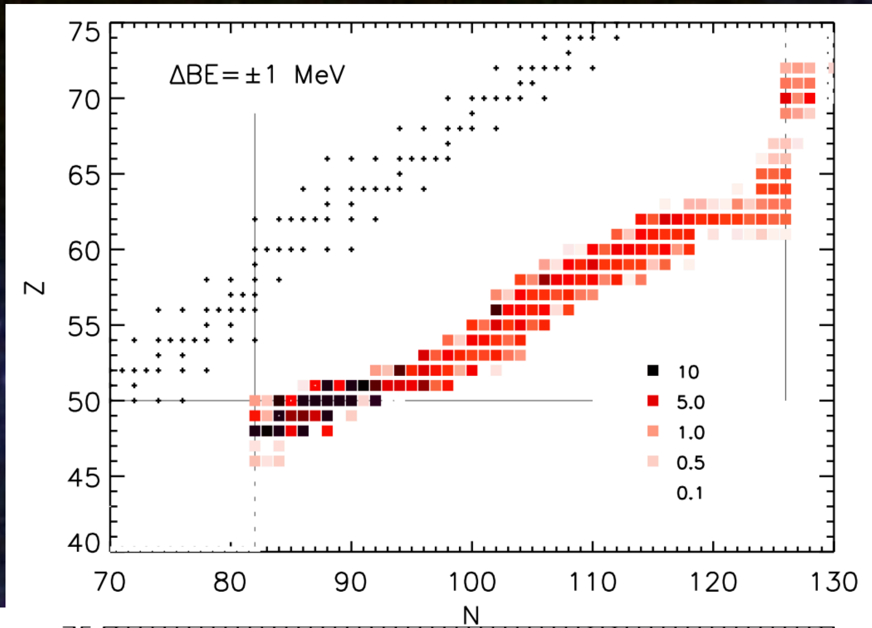
Mumpower, McLaughlin, Surman (2012)

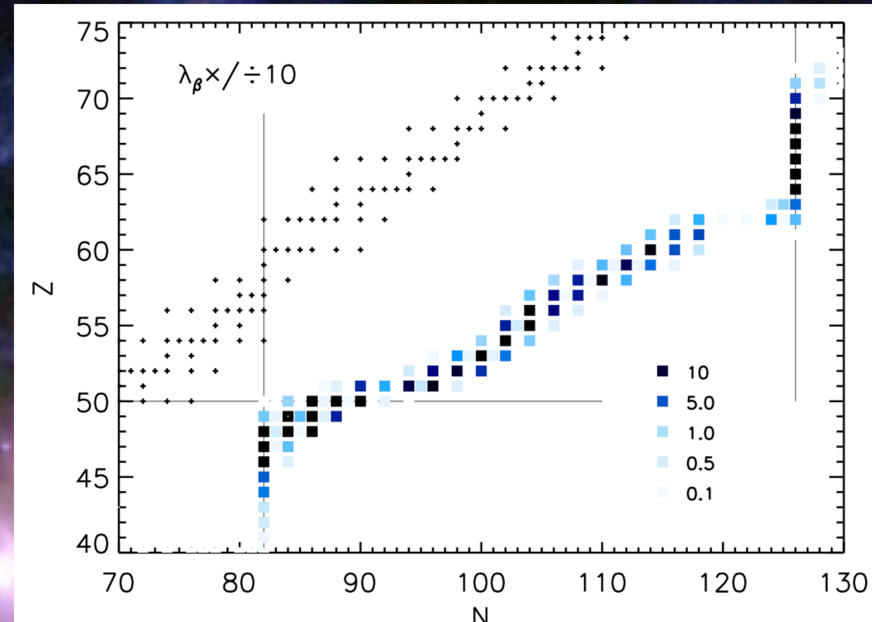
- rare earth peak forms
- main peaks can shift, spread, or narrow
- abundance pattern details finalized

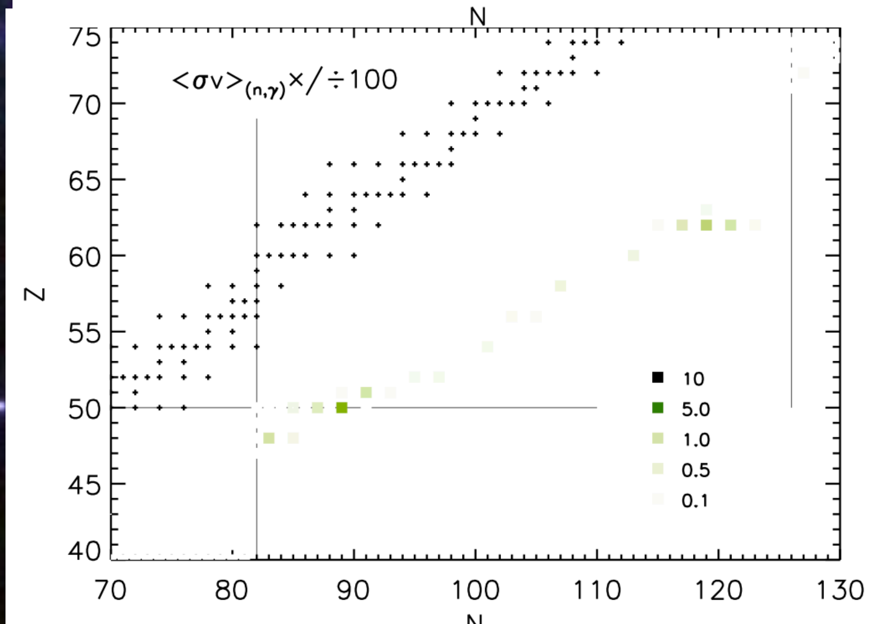


Surman & Engel (2001)

r-process sensitivity studies: (n,γ)-(γ,n) equilibrium only

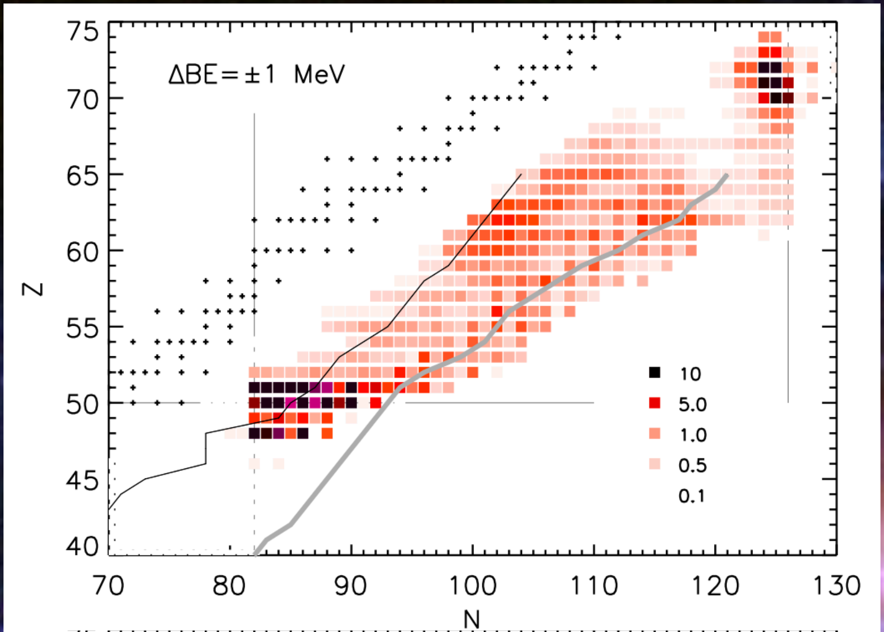


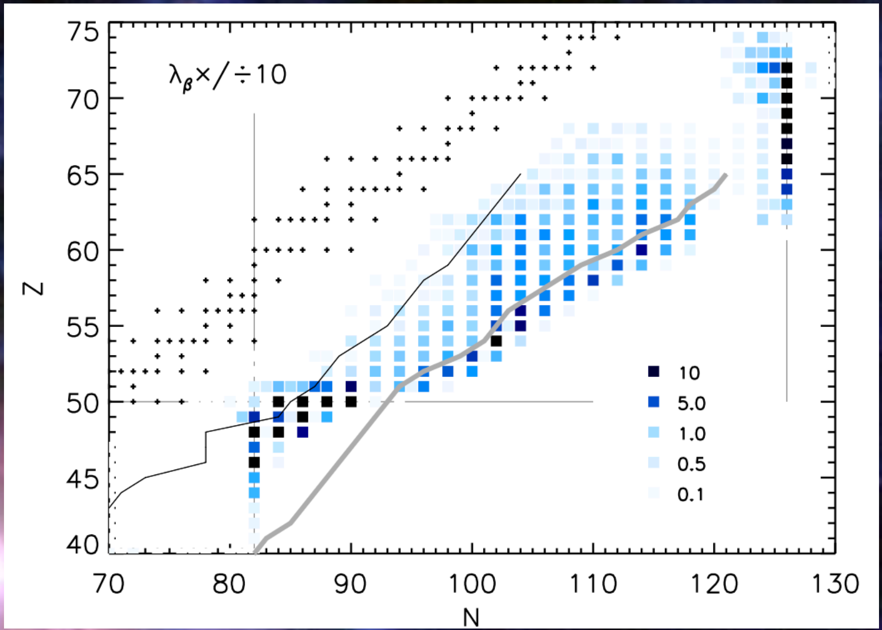


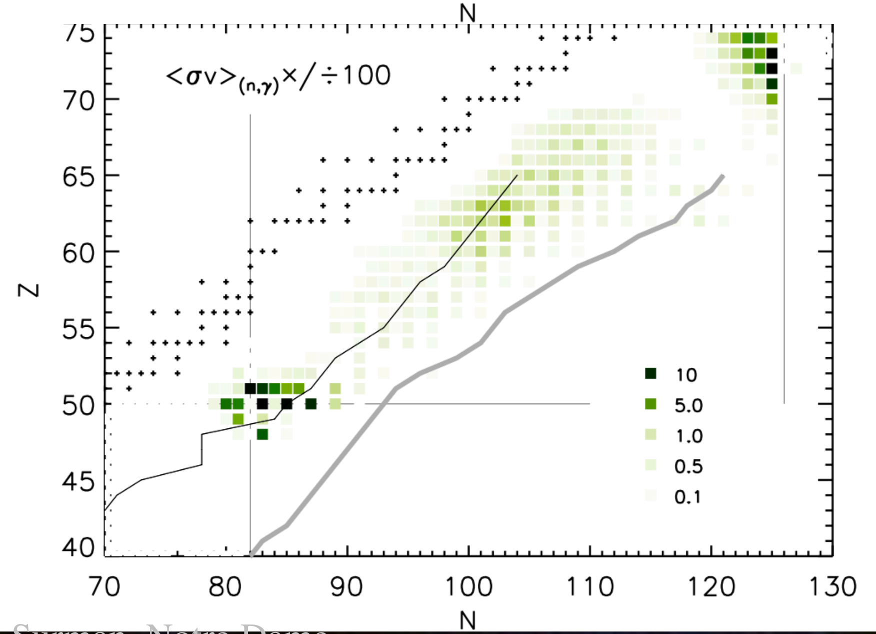


wind parameterized as Meyer (2002) with $s/k = 100$, $Y_e = 0.25$

r-process sensitivity studies: fully dynamical simulation







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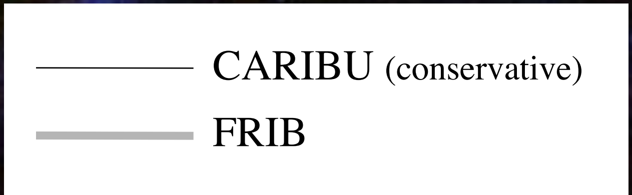
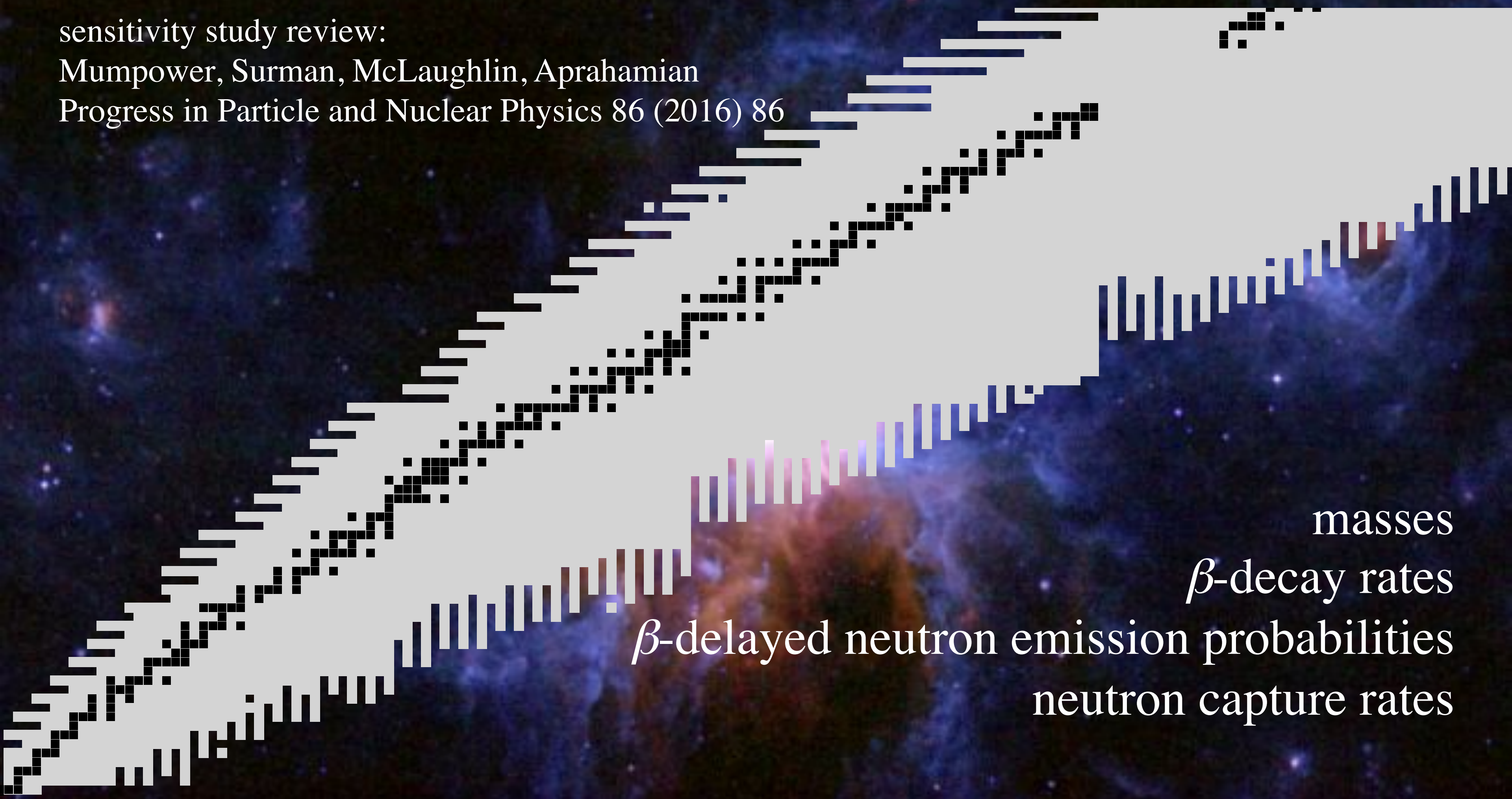


nuclear data required for *r*-process simulations

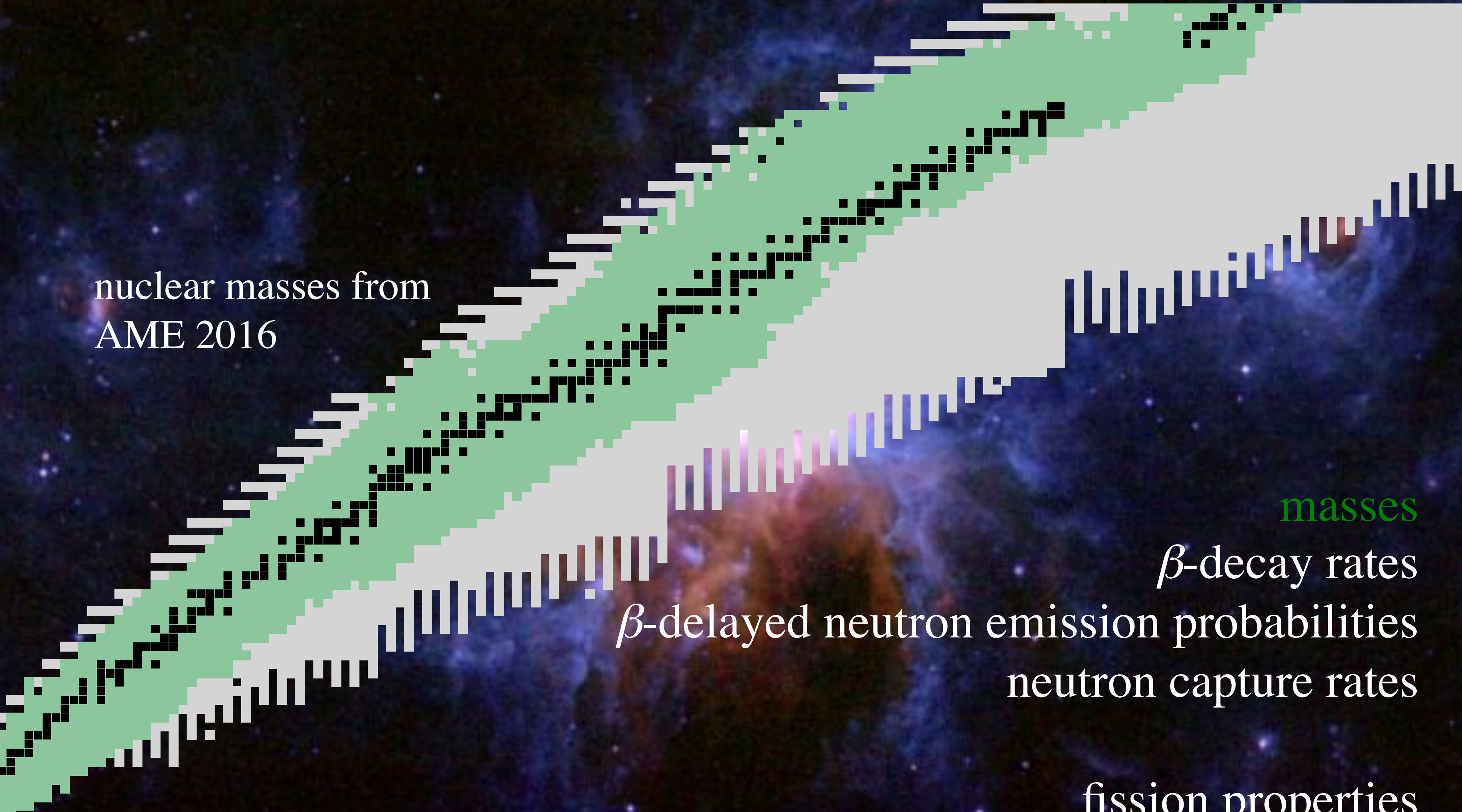
sensitivity study review:
Mumpower, Surman, McLaughlin, Aprahamian
Progress in Particle and Nuclear Physics 86 (2016) 86



masses
β-decay rates
β-delayed neutron emission probabilities
neutron capture rates

fission properties
neutrino interactions

nuclear data required for *r*-process simulations: masses



nuclear masses from
AME 2016

masses
β-decay rates
β-delayed neutron emission probabilities
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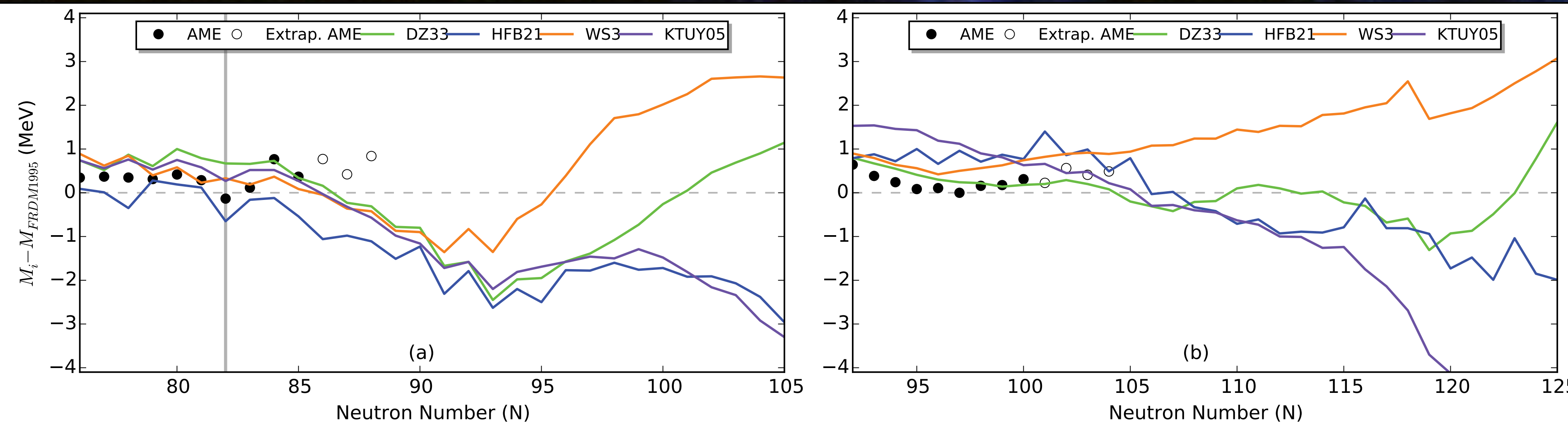
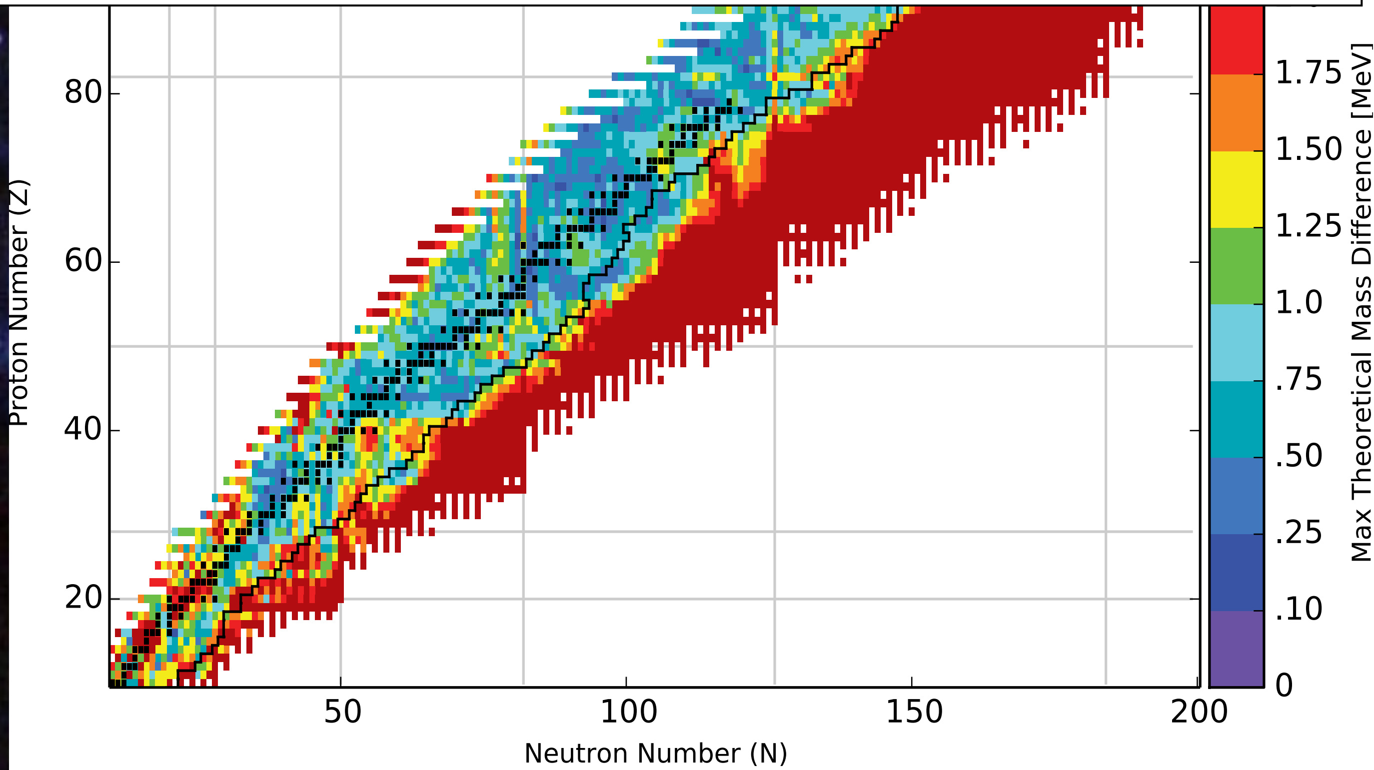
r-process uncertainties: masses





Mumpower, Surman, McLaughlin, Aprahamian 2016

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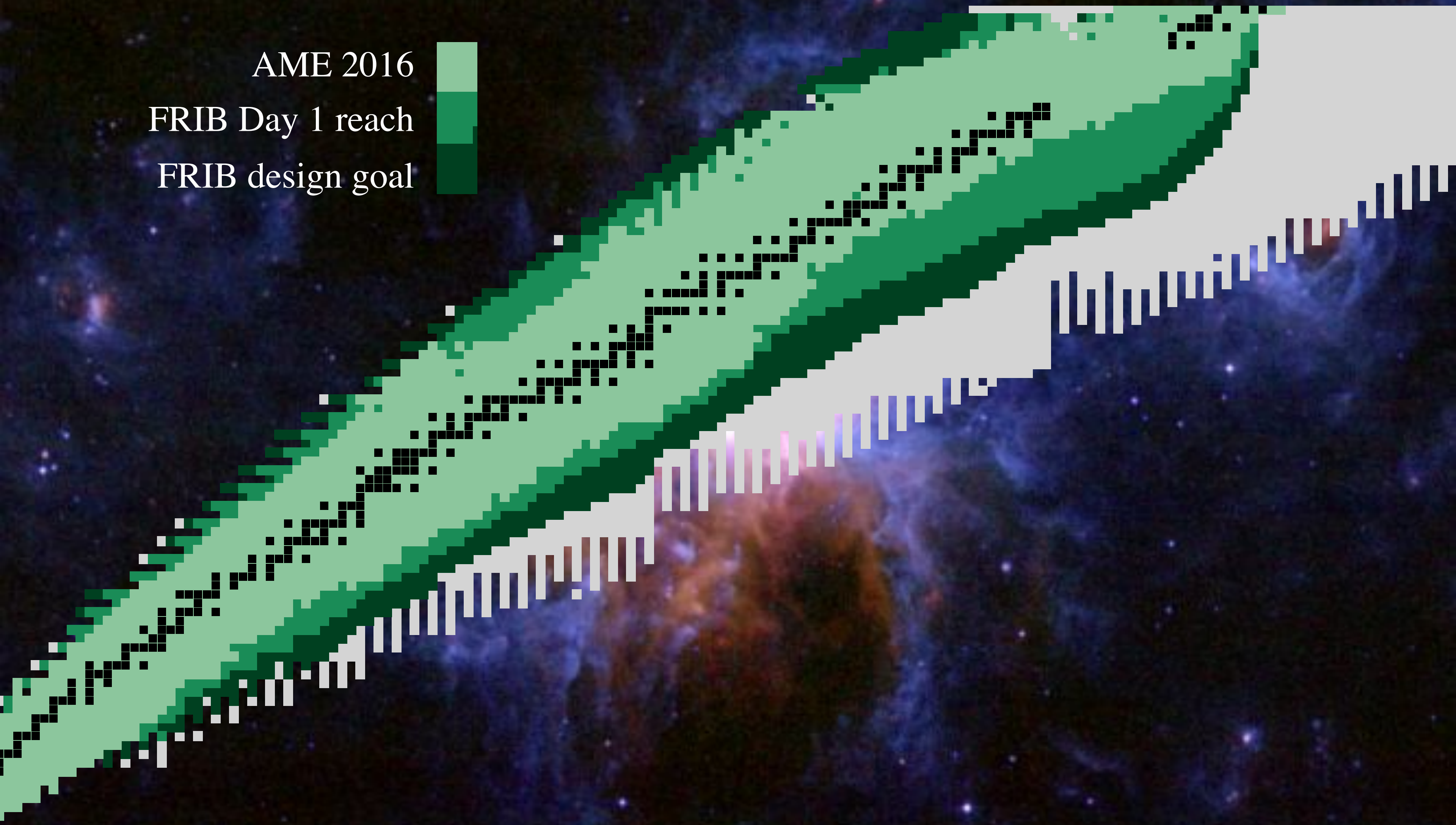
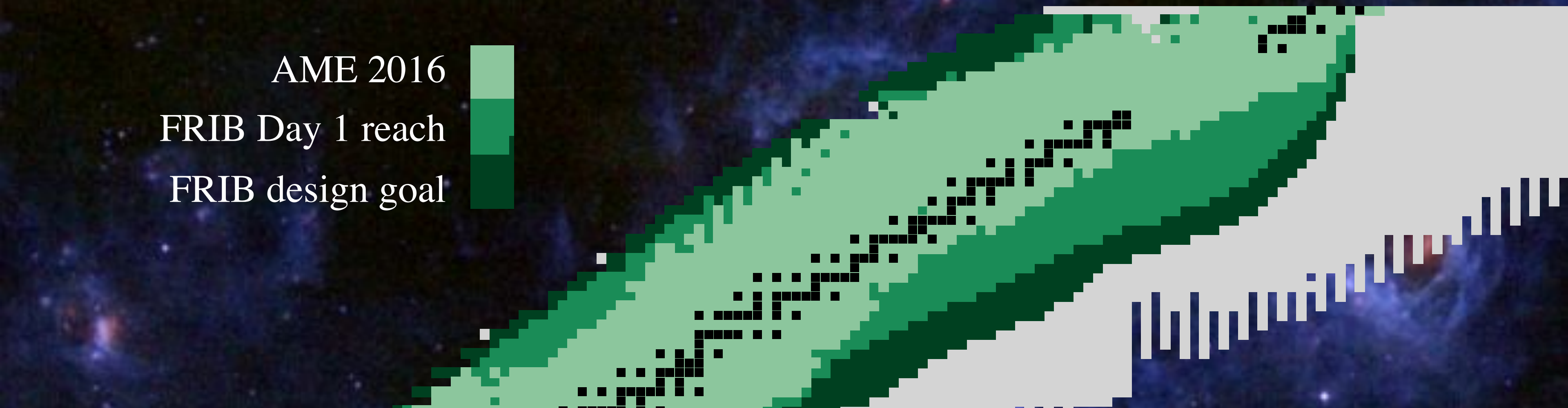
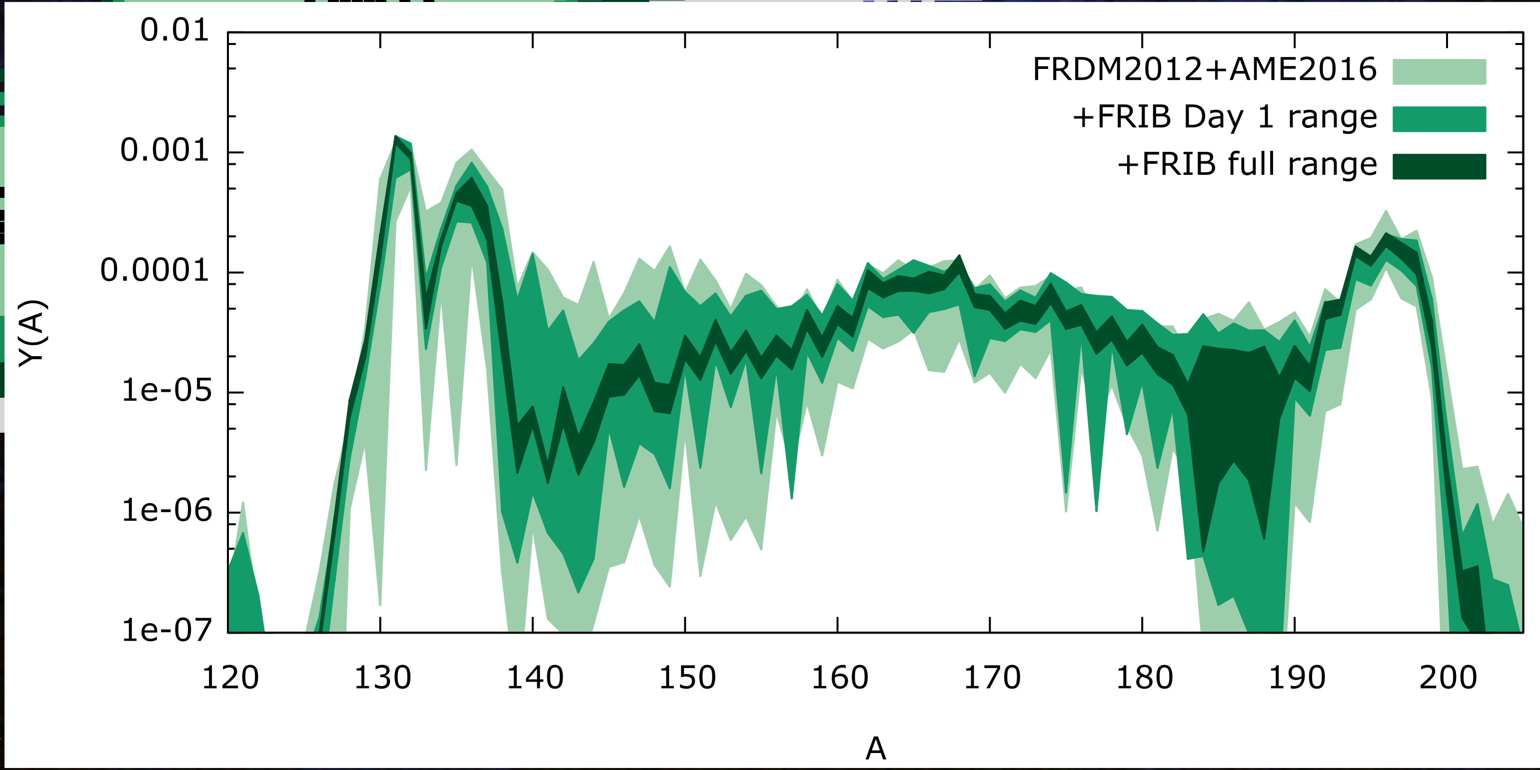
experimental prospects: masses



experimental prospects: masses





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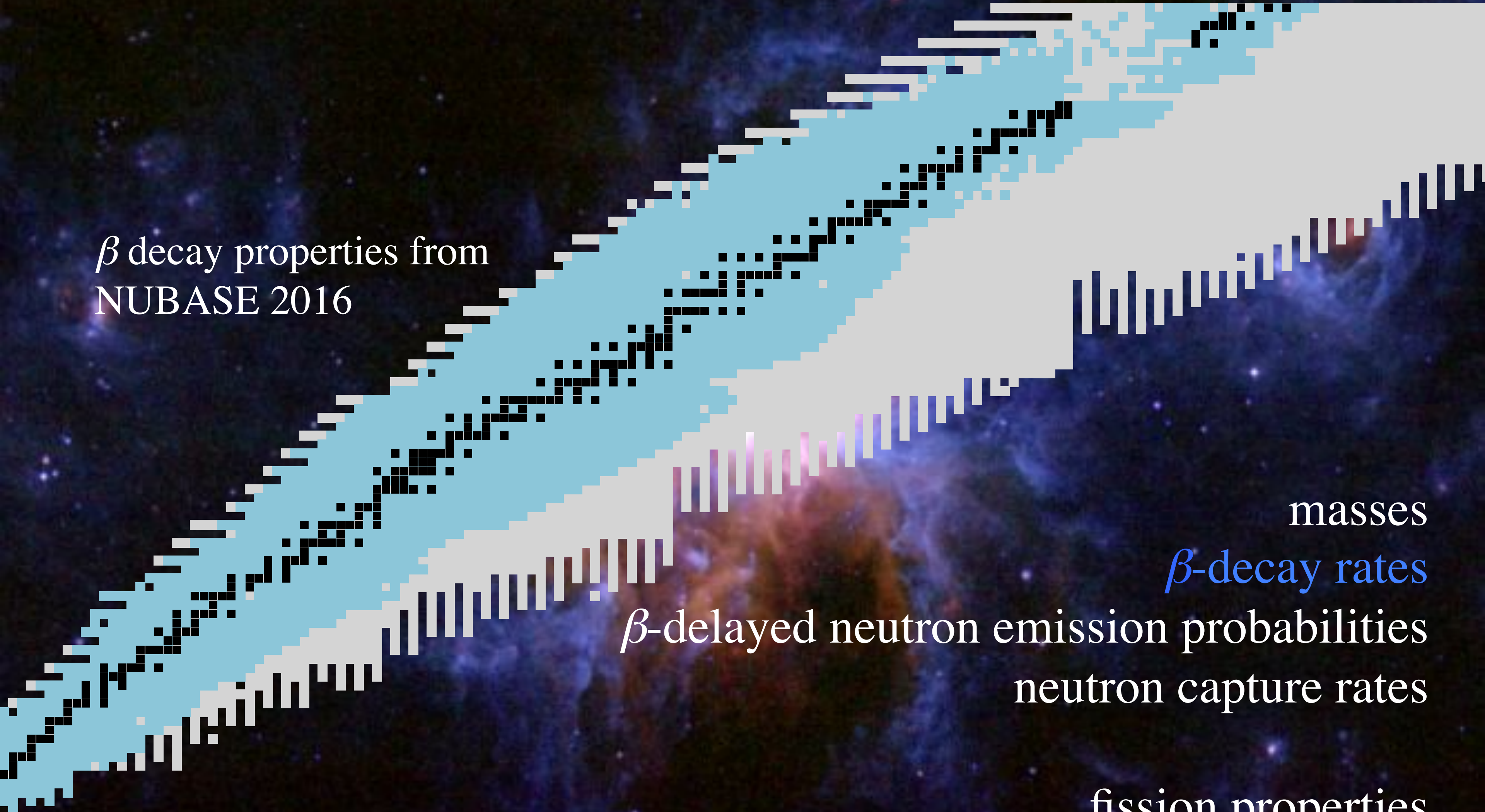
nuclear data required for *r*-process simulations: β decay

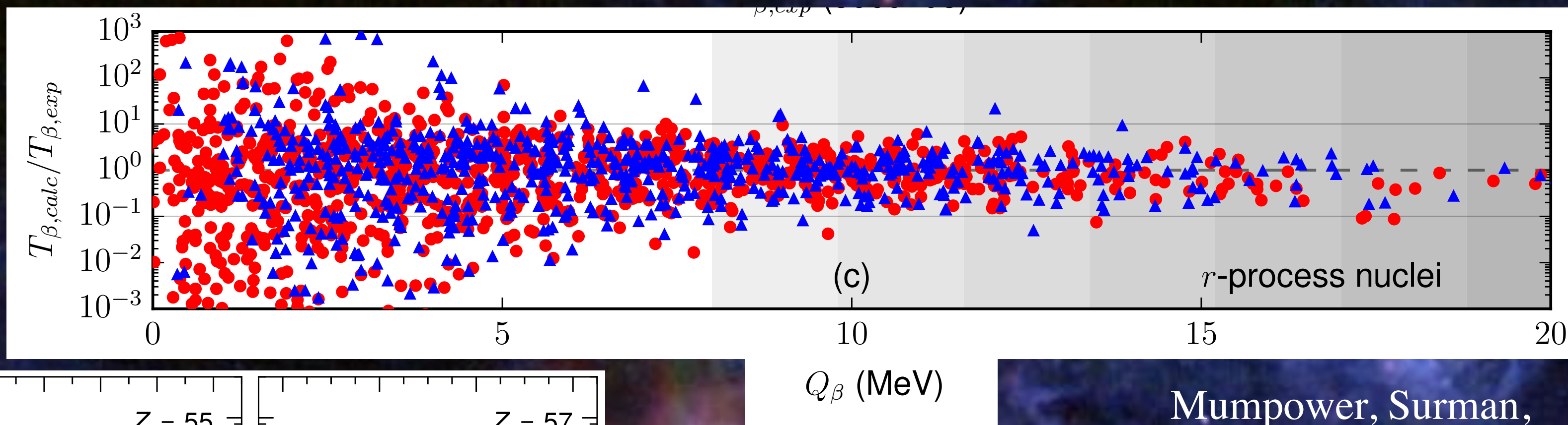


β decay properties from
NUBASE 2016

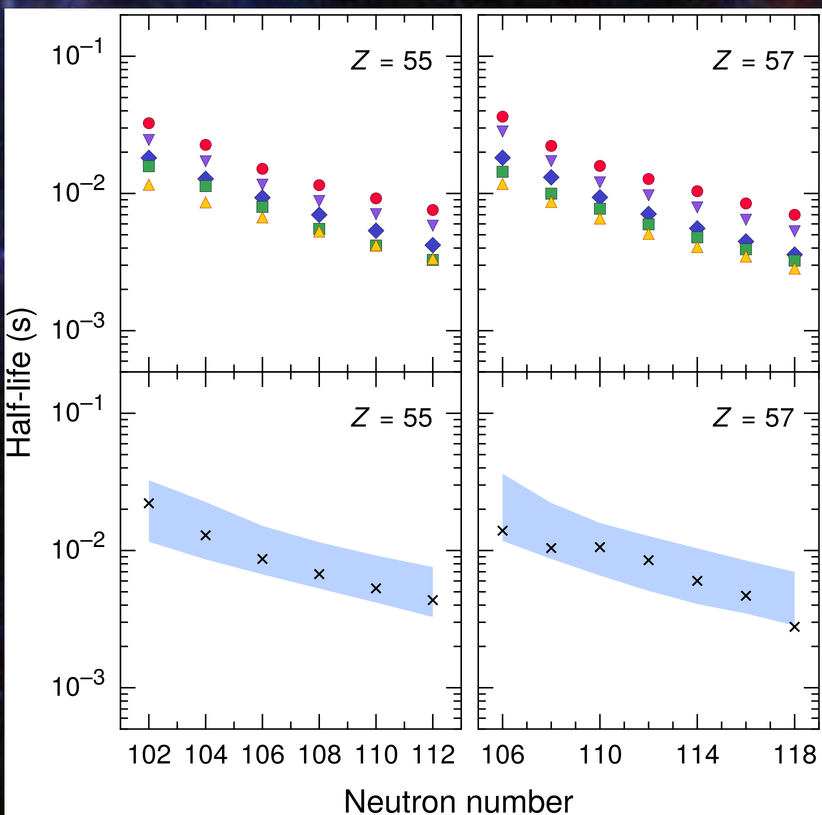
masses
β-decay rates
β-delayed neutron emission probabilities
neutron capture rates

fission properties
neutrino interactions

r-process uncertainties: β decay



Mumpower, Surman, McLaughlin, Aprahamian 2016



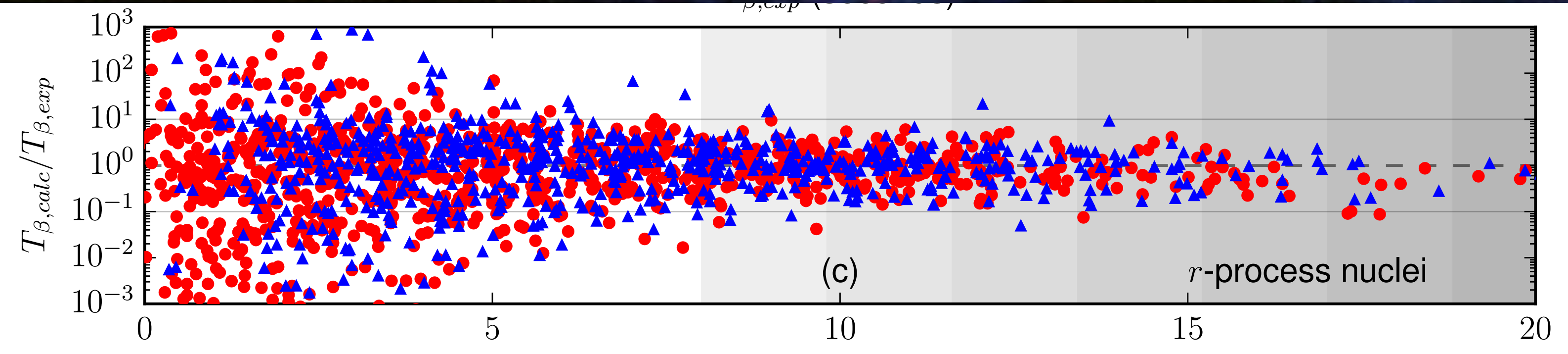
Fermi's 'Golden Rule'

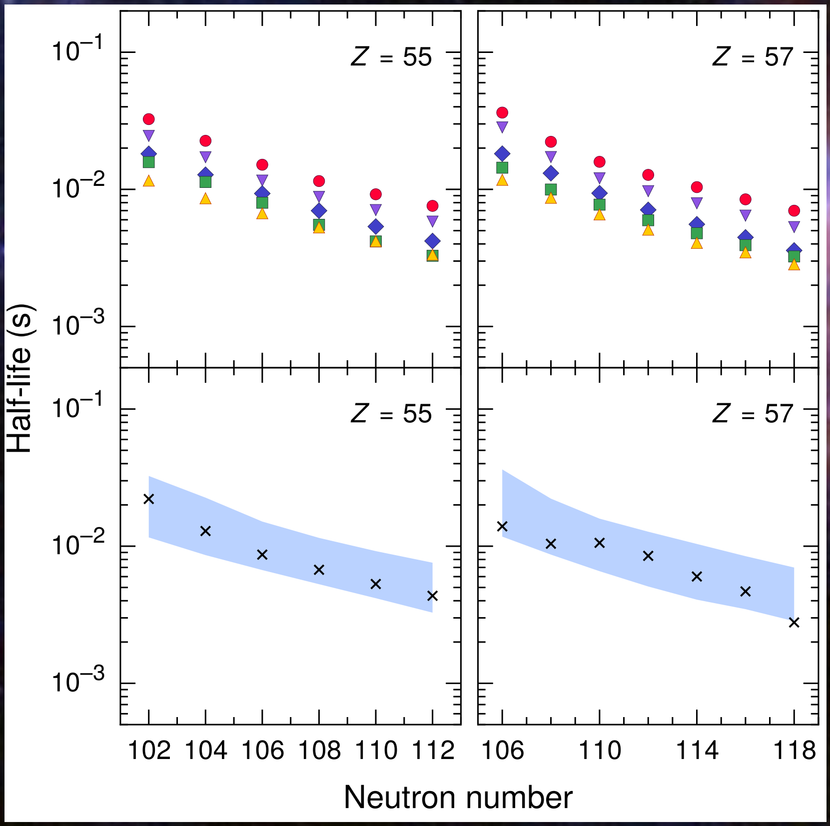
$$\lambda = \frac{2\pi}{\hbar} \left| \langle f | H_{\text{int}} | i \rangle \right|^2 \rho(E)$$

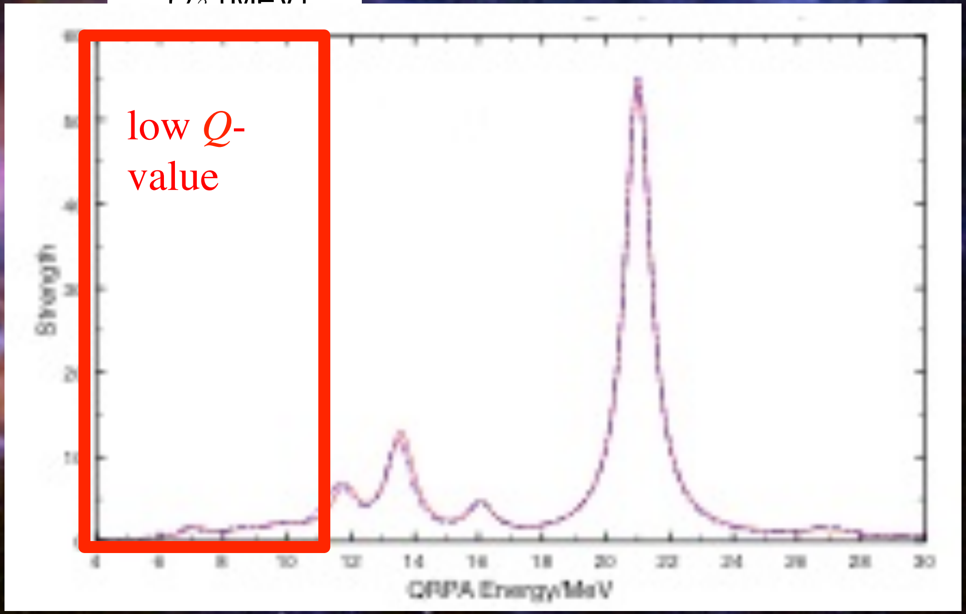
f, i	final and initial state wavefunctions
H_{int}	weak interaction Hamiltonian
$\rho(E)$	density of states for the final particles

Shafer, Engel, Fröhlich, McLaughlin, Mumpower, Surman 2016

r-process uncertainties: β decay

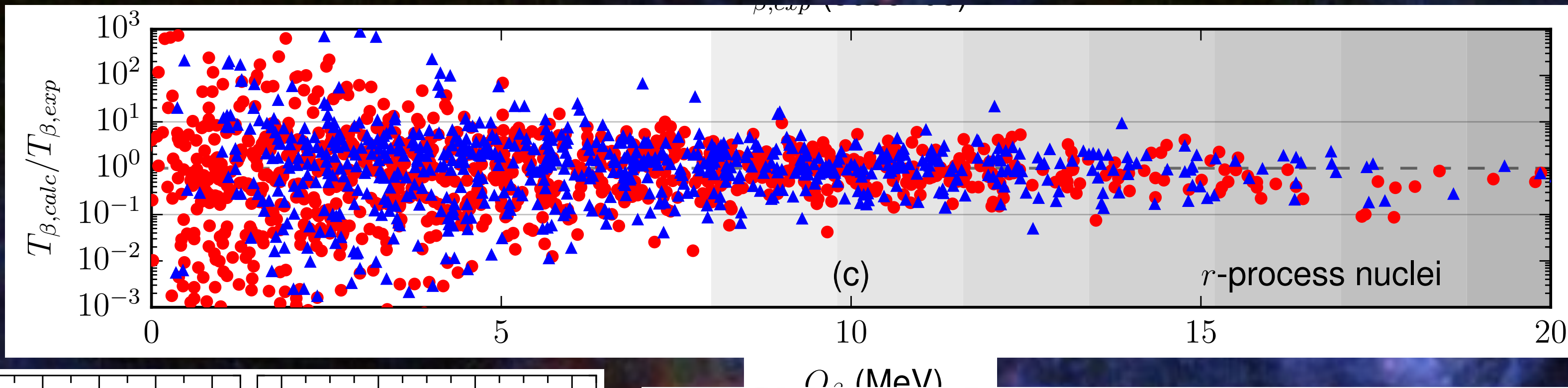


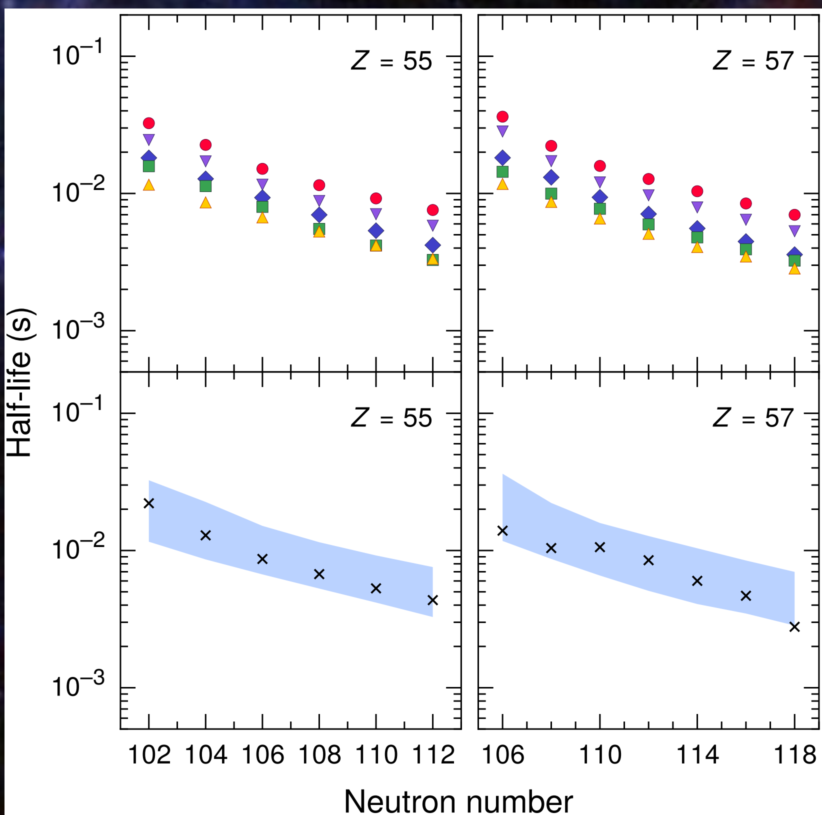


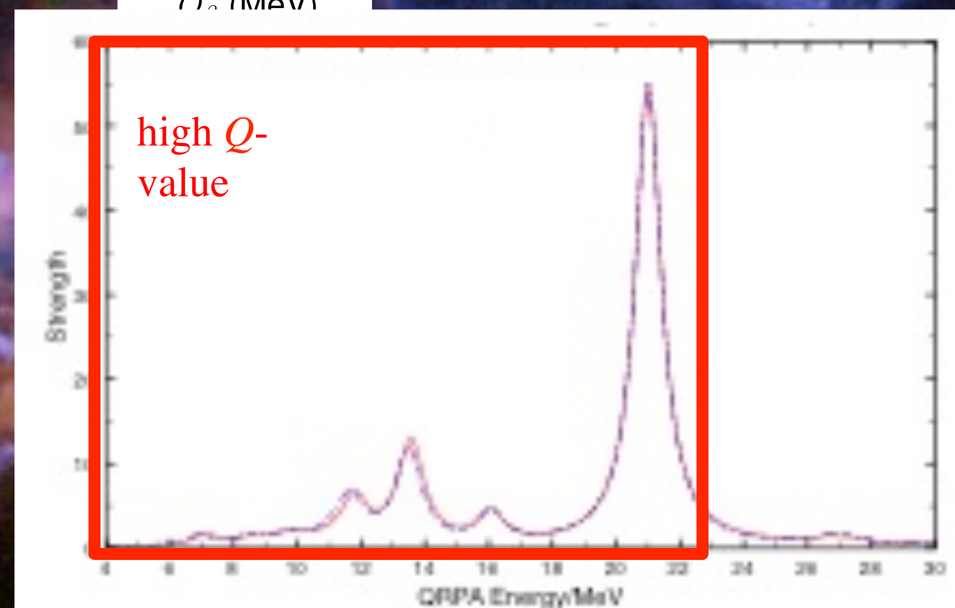


Shafer, Engel, Fröhlich, McLaughlin, Mumpower, Surman 2016

r-process uncertainties: β decay

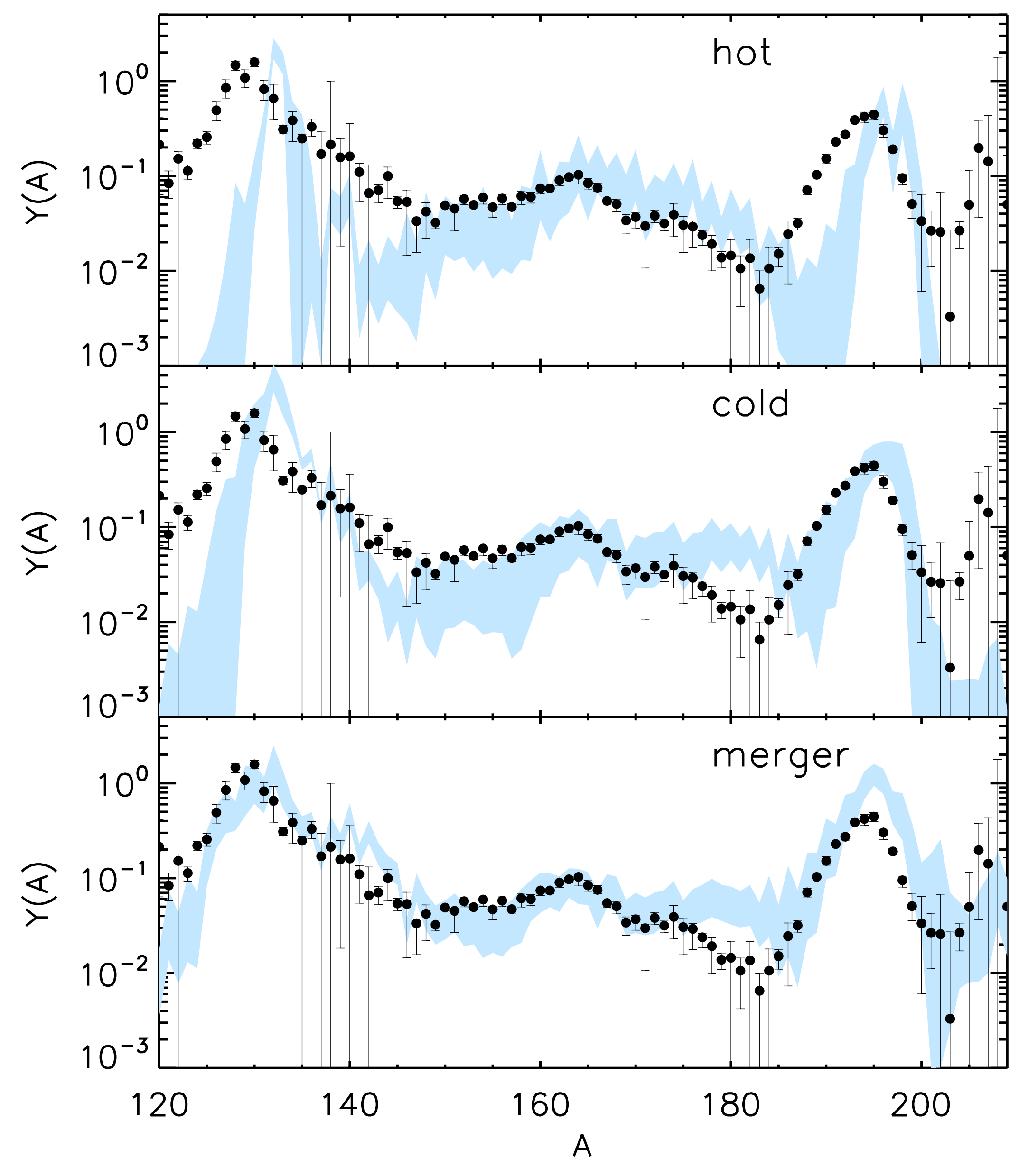






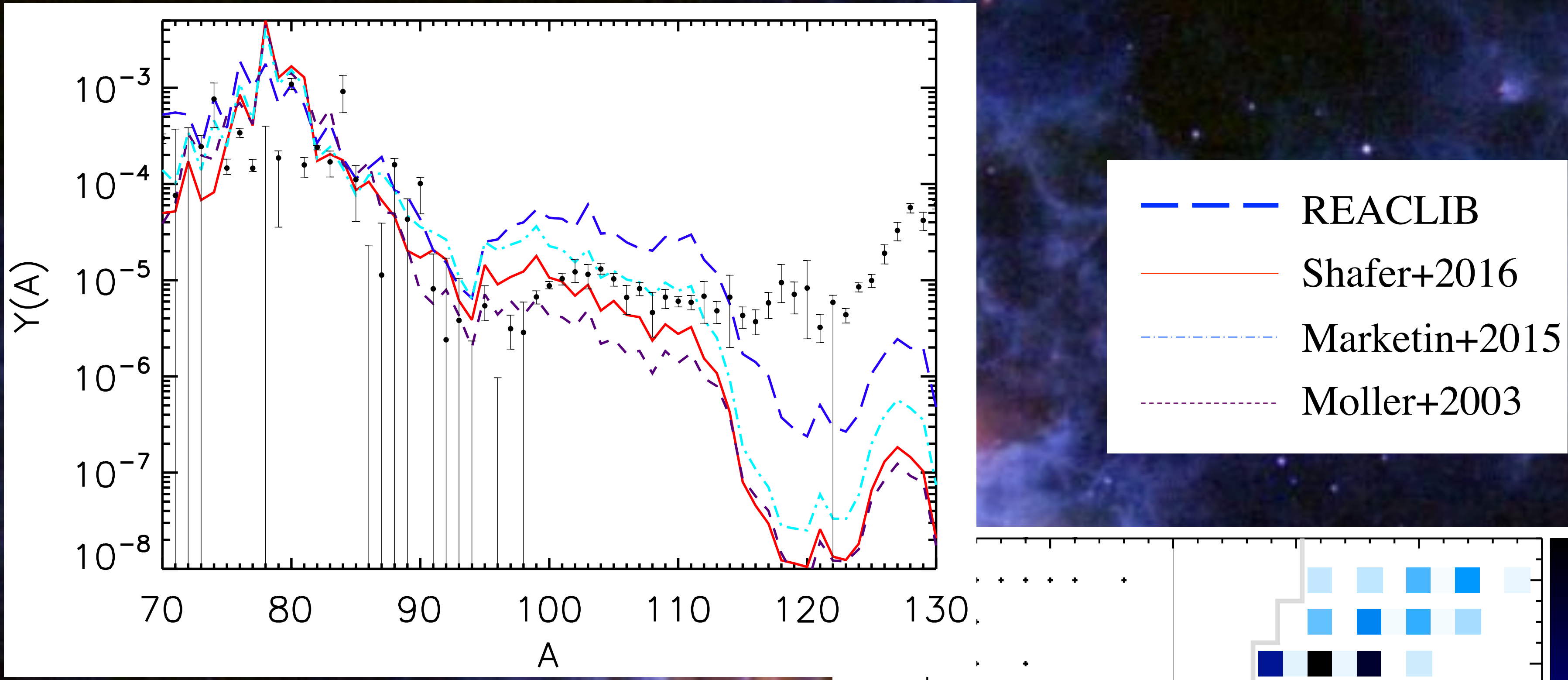
Shafer, Engel, Fröhlich, McLaughlin, Mumpower, Surman 2016

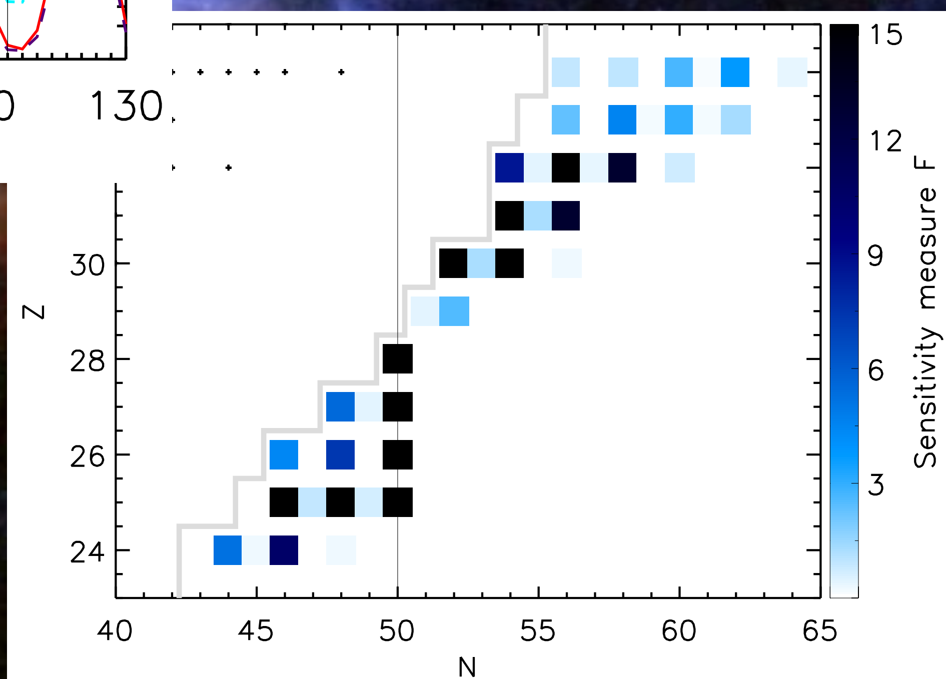
r-process uncertainties: β decay



Shafer, Engel, Fröhlich, McLaughlin, Mumpower, Surman 2016

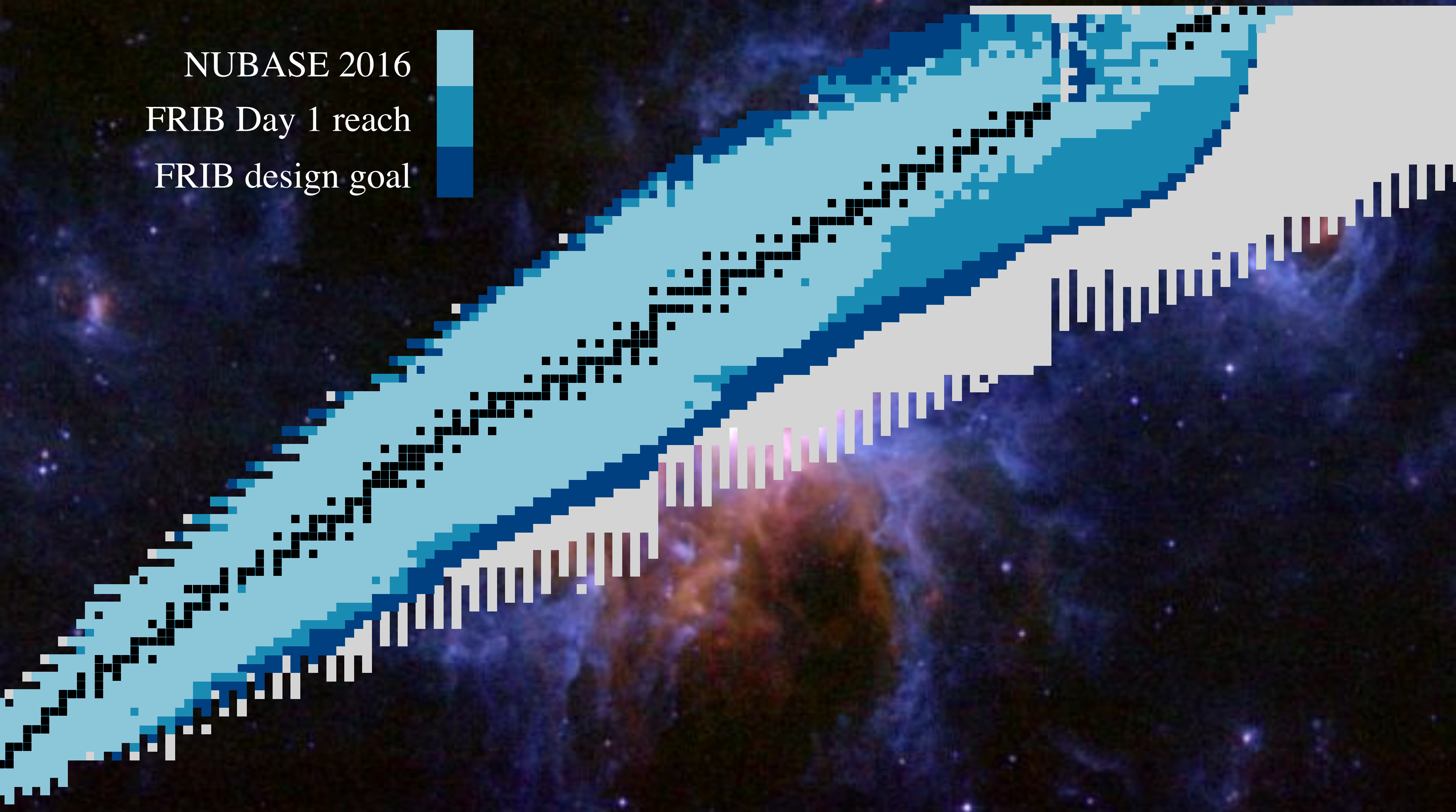
r-process uncertainties: β decay



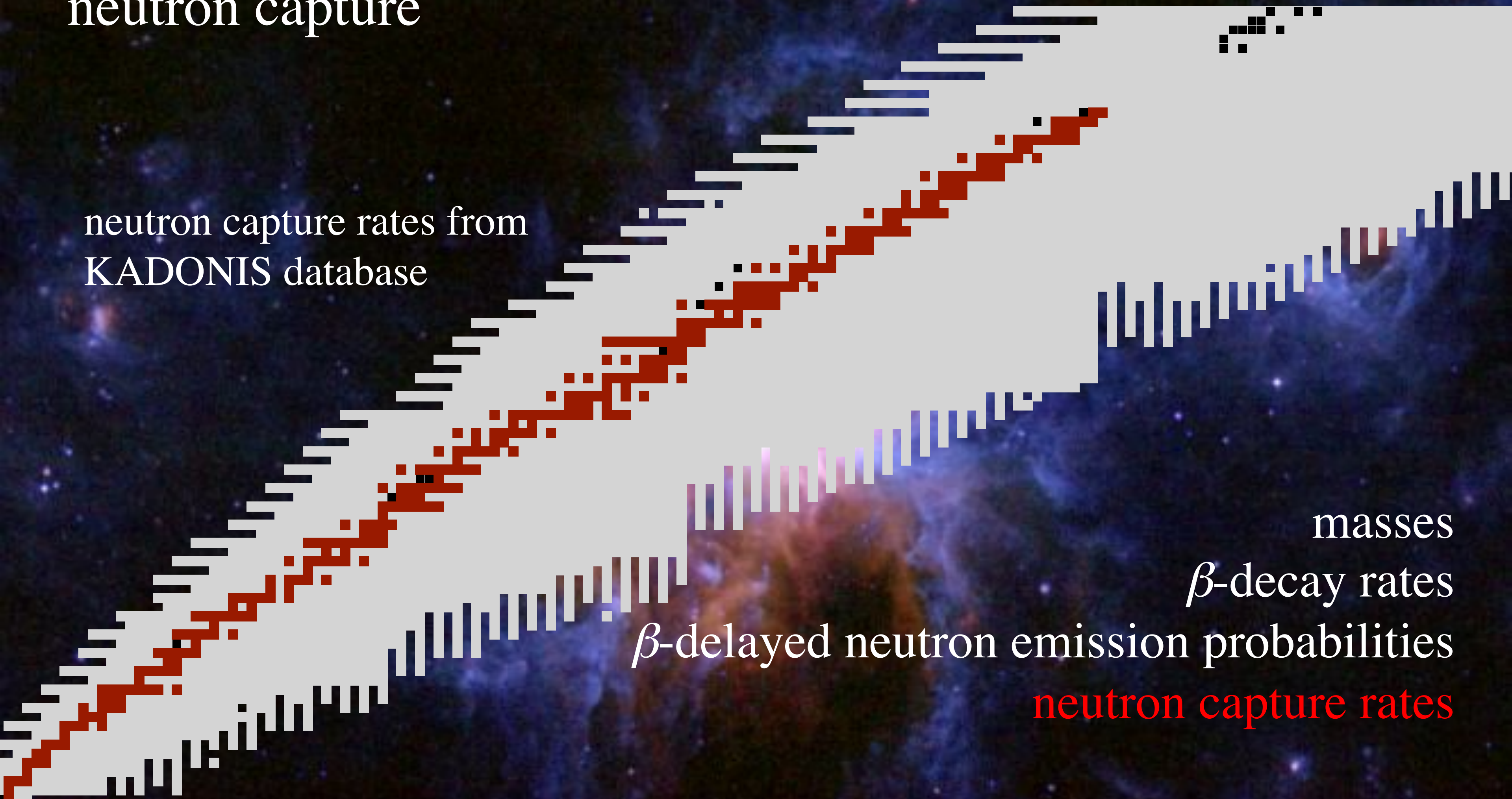


Shafer, Engel, Fröhlich, McLaughlin, Mumpower, Surman 2016

experimental prospects: β decay



nuclear data required for *r*-process simulations: neutron capture



neutron capture rates from
KADONIS database

masses

β-decay rates

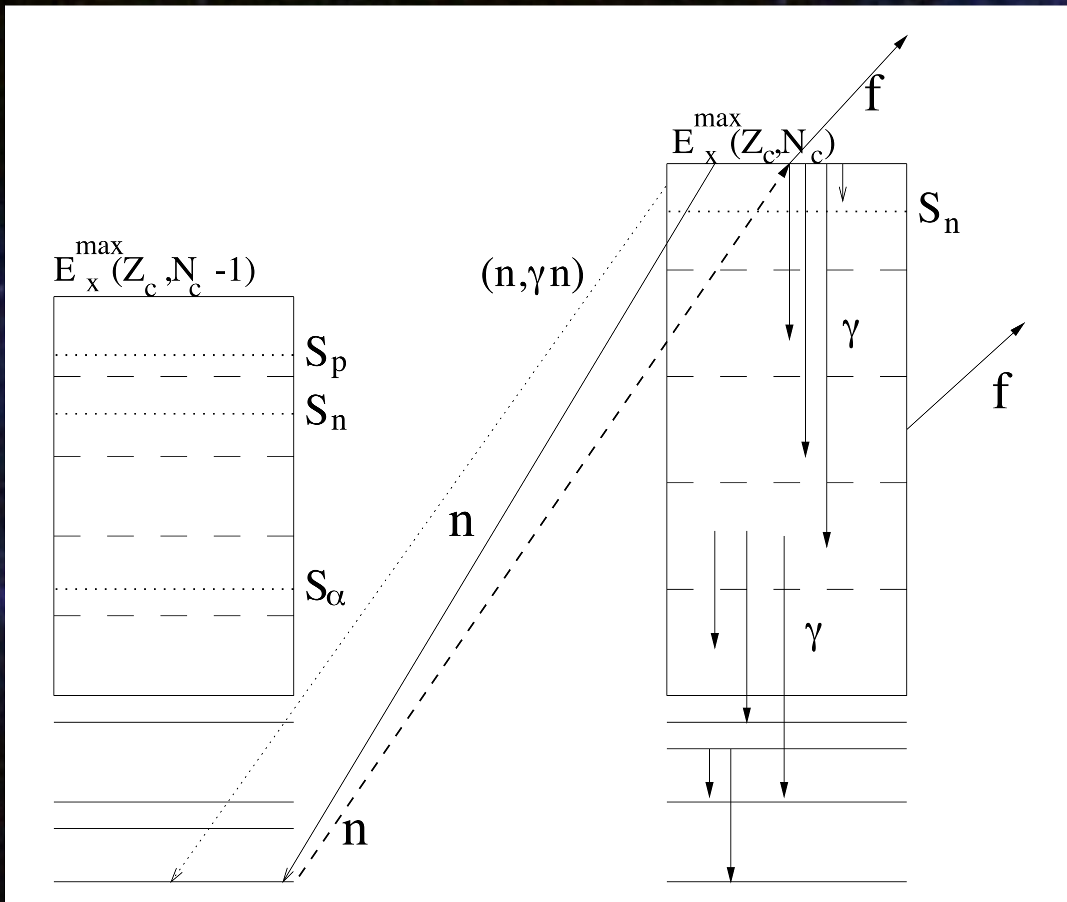
β-delayed neutron emission probabilities

neutron capture rates

fission properties

neutrino interactions

Hauser-Feshbach neutron capture rate calculations

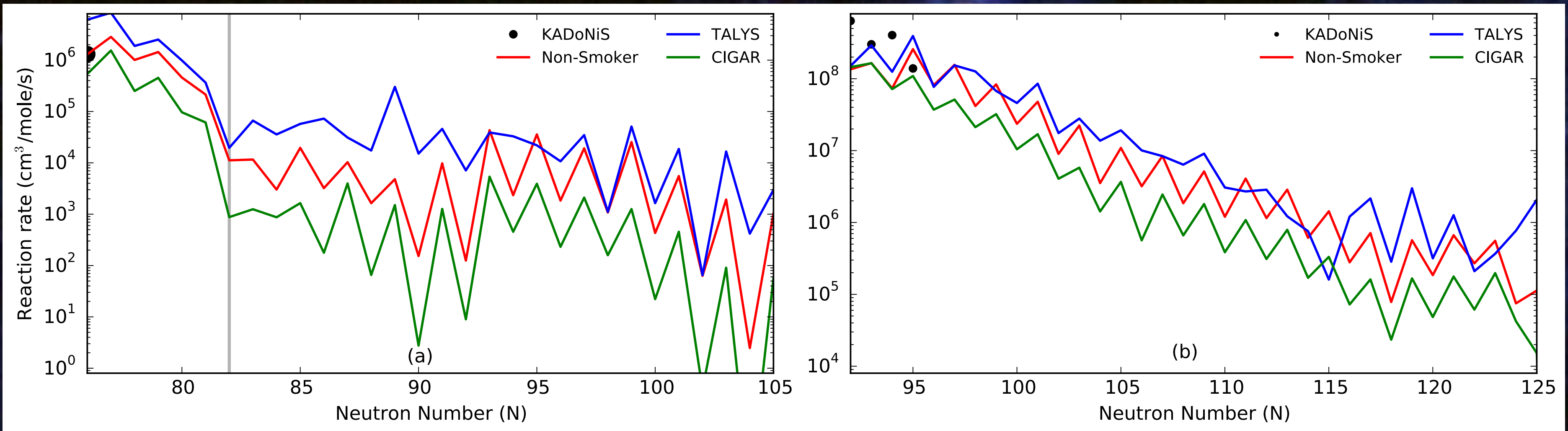


Nuclear physics ingredients:

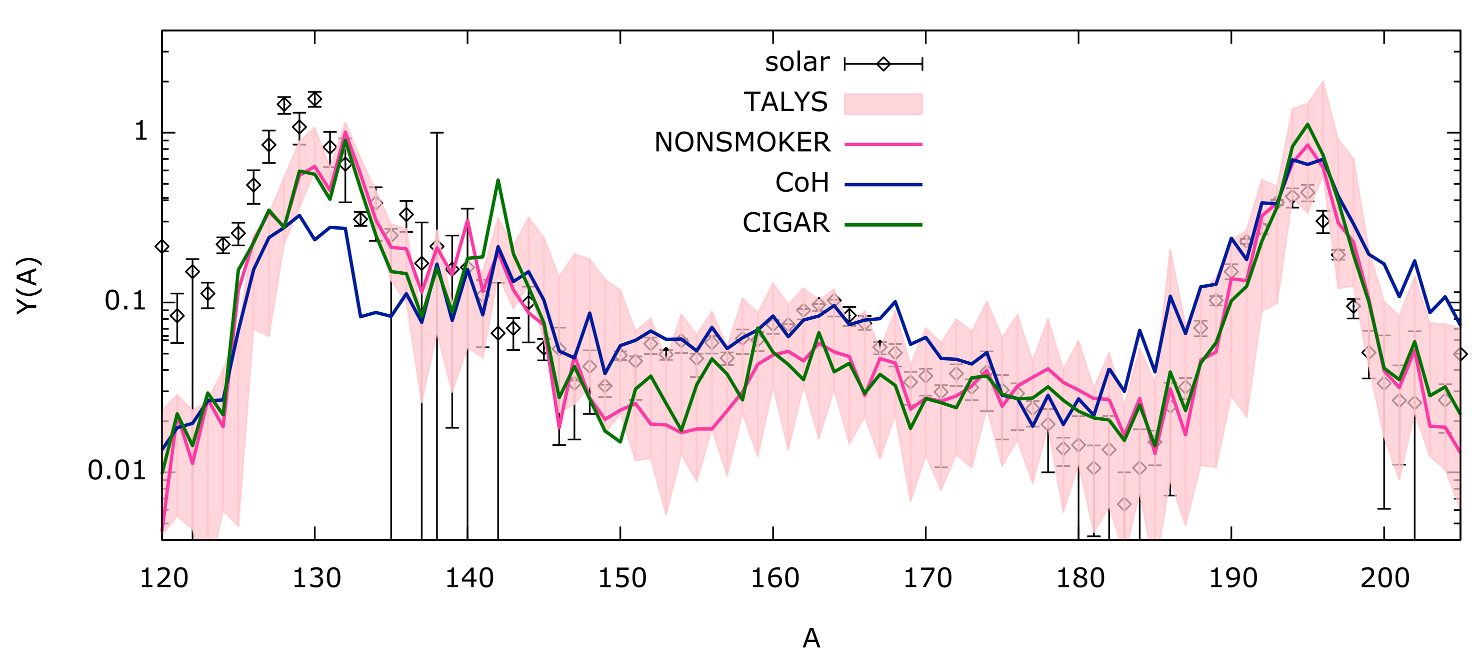
- neutron separation energies
- optical potential
- level densities
- gamma strength functions

$$\sigma^{\mu}_{n,\gamma}(E) \propto \sum_{J^\pi} (2J+1) \frac{T^{\mu}_{n}(J^\pi) T_\gamma(J^\pi)}{T_{tot}(J^\pi)}$$

r-process uncertainties: neutron capture

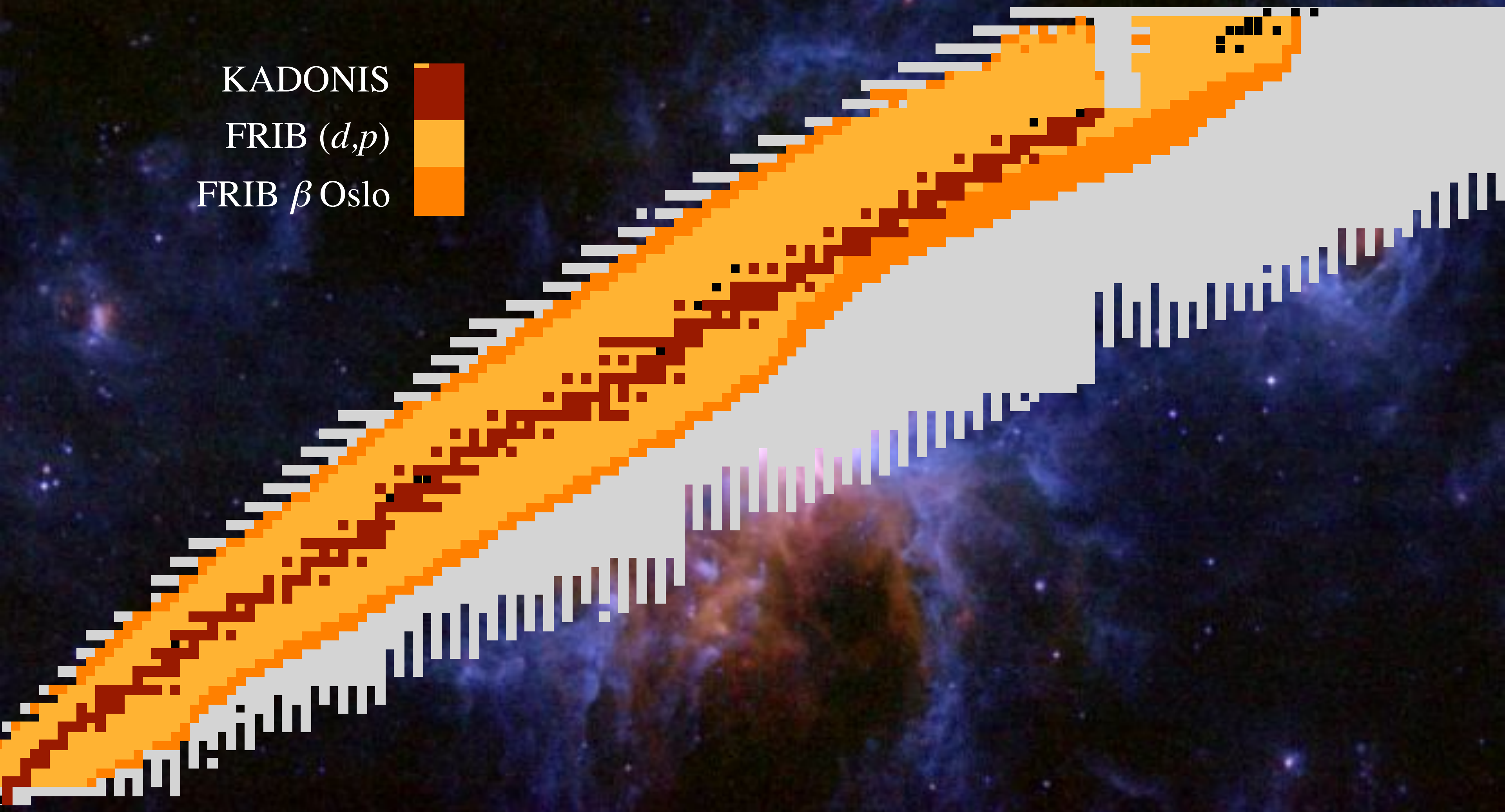


Mumpower, Surman, McLaughlin, Aprahamian 2016

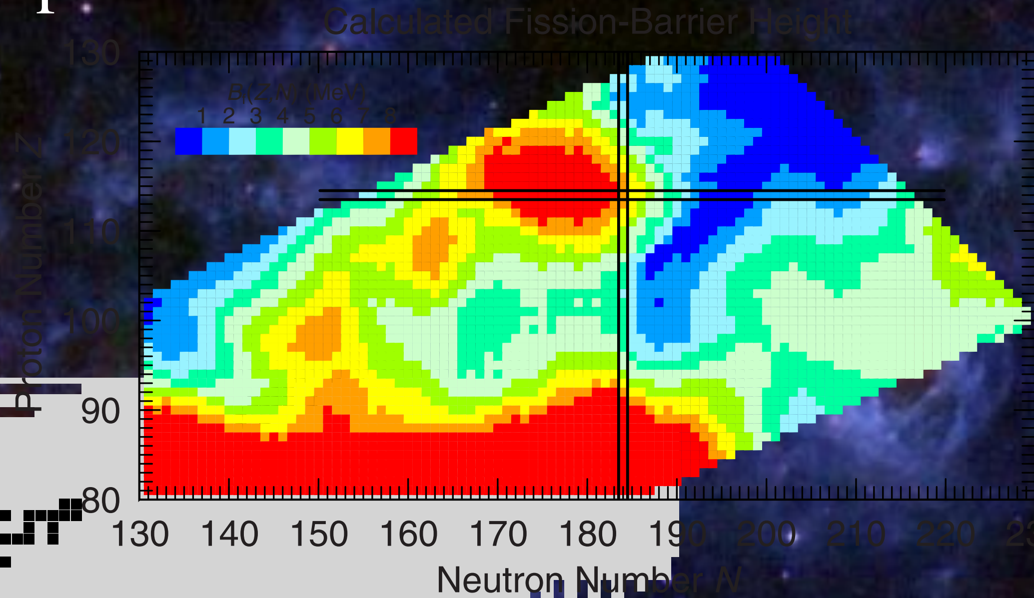


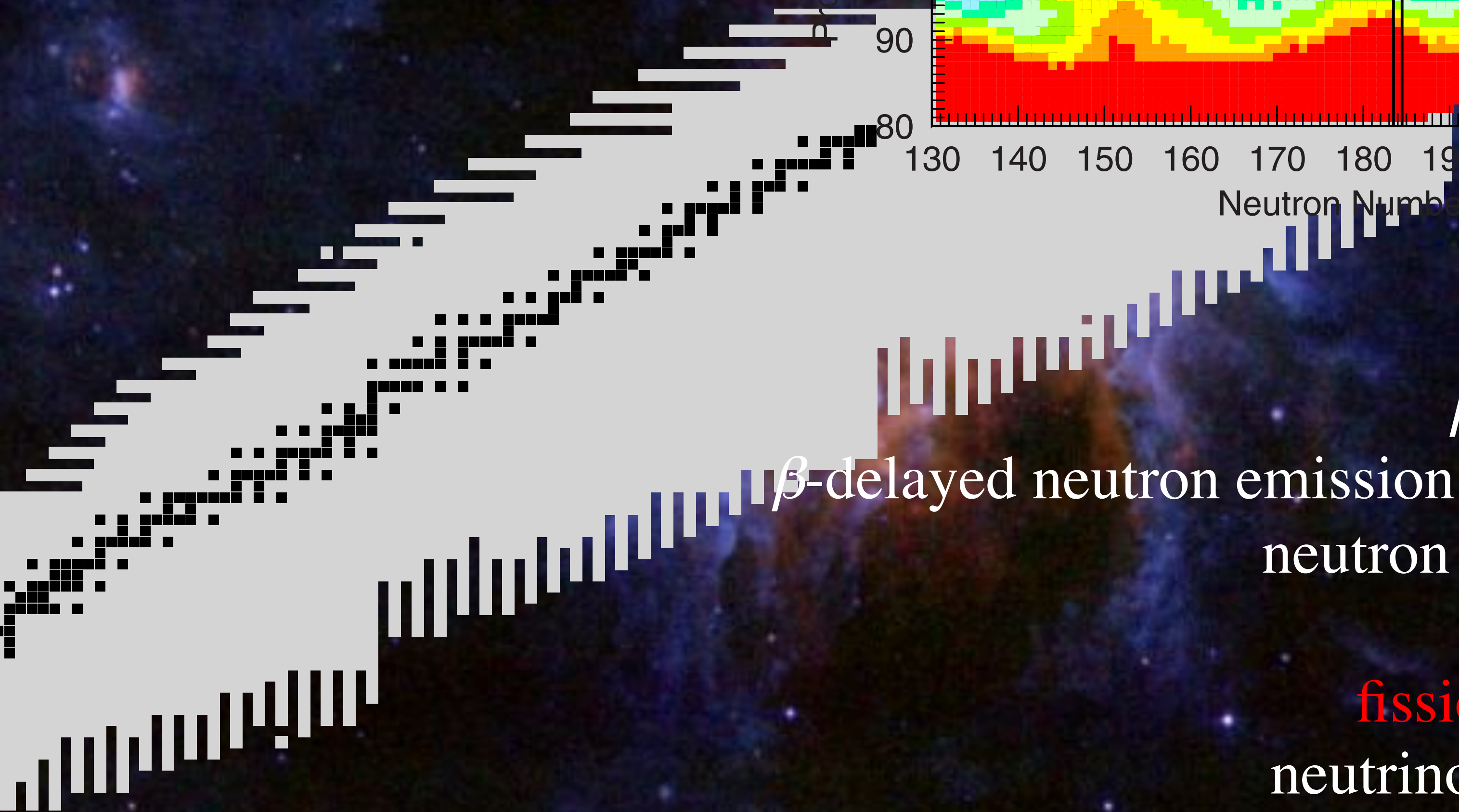
Nikas, Perdikakis, Beard, Mumpower, Surman, in preparation

experimental prospects: neutron capture



nuclear data required for *r*-process simulations: fission properties





masses

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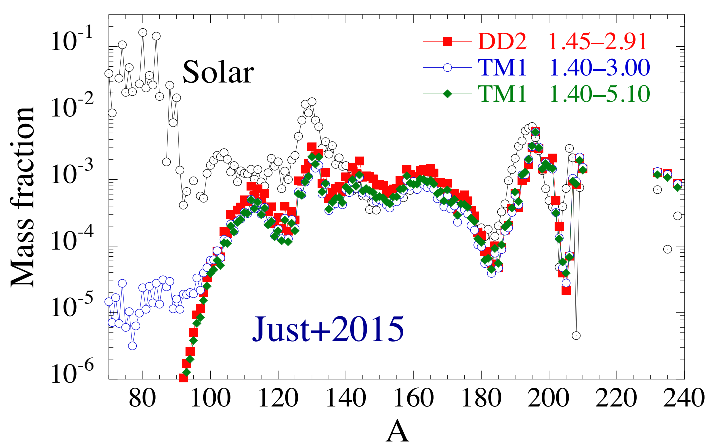
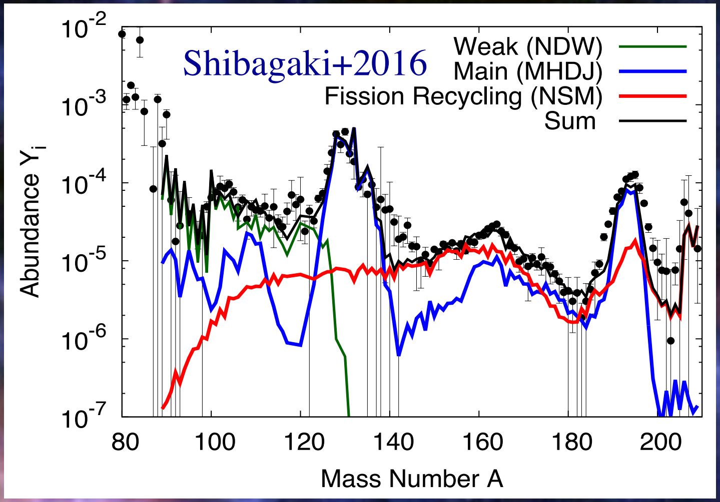
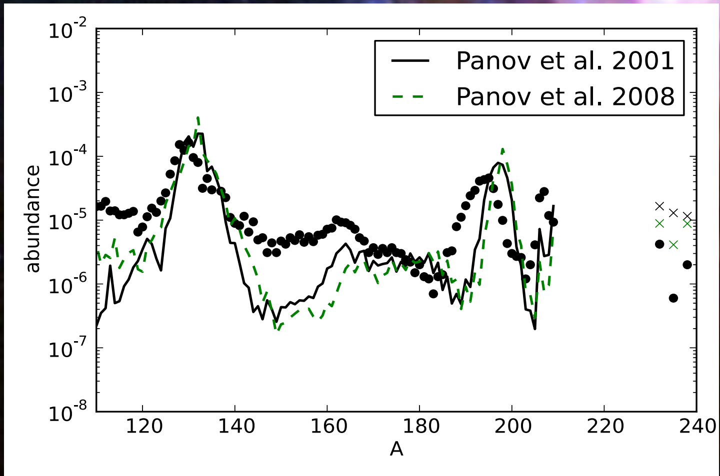
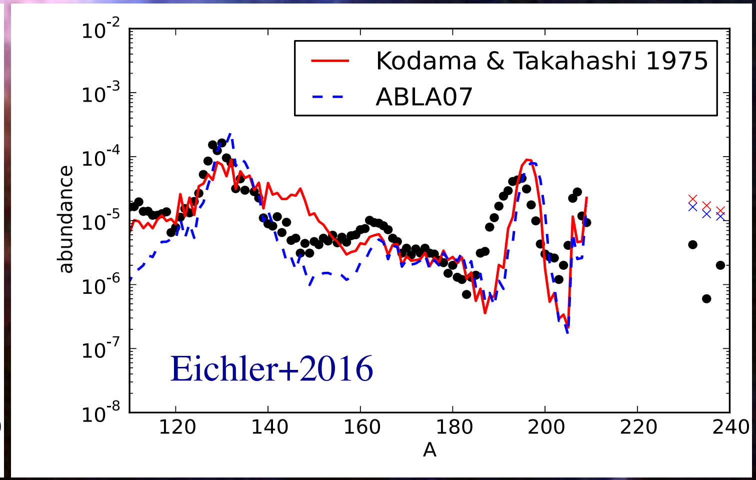
r-process uncertainties: fission properties









r-process summary

The roles of supernovae and compact object mergers in the synthesis of the heaviest elements is under investigation from many directions.

One such avenue is through nuclear physics, where current and next-generation radioactive beam facilities will continue to push the boundaries of our knowledge of extremely neutron-rich nuclei. Crucial data for *r*-process simulations includes masses, β-decay properties, neutron capture rates, and fission rates and fragment distributions.

Once nuclear physics uncertainties are reduced, we can exploit details of the *r*-process abundance pattern to explore the nature of the *r*-process site.