The nuclear physics of neutron star mergers

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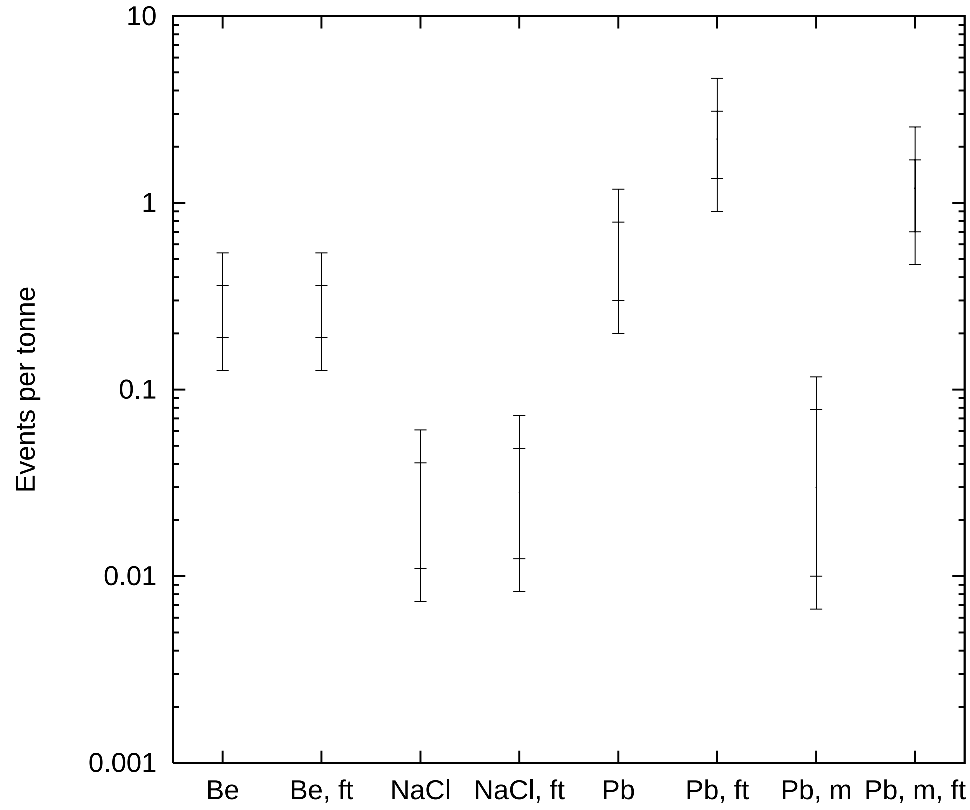
Nuclear astrophysics and Wick's influence

Example: the 90s and supernovae

- The neutrino process: discovered a new nucleosynthesis process in the outer layers of the supernova due to neutrino-induced spallation on nuclei of neutrons and protons. Woosley et al 1990
- r-process nucleosynthesis: proposed a molding of the abundance pattern due to neutrino induced spallation on nuclei. Haxton et al 1997

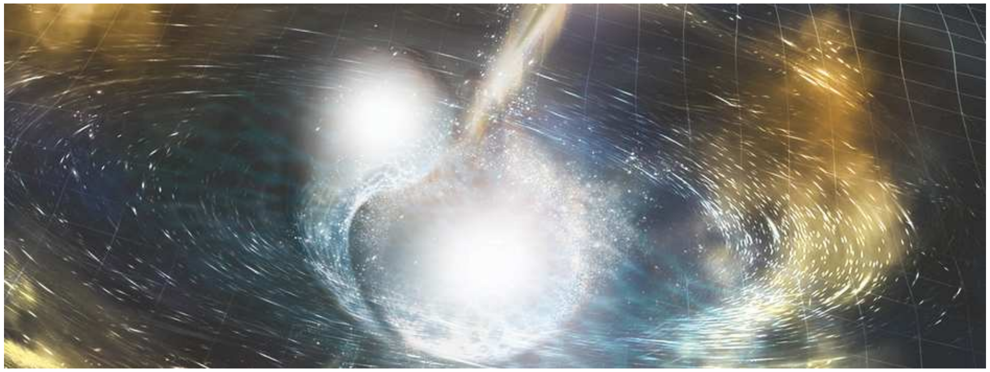
Lead as a supernova neutrino detector



Fuller, Haxton, McLaughlin 1998

A supernova lead detector now exists: HALO at SNOLAB

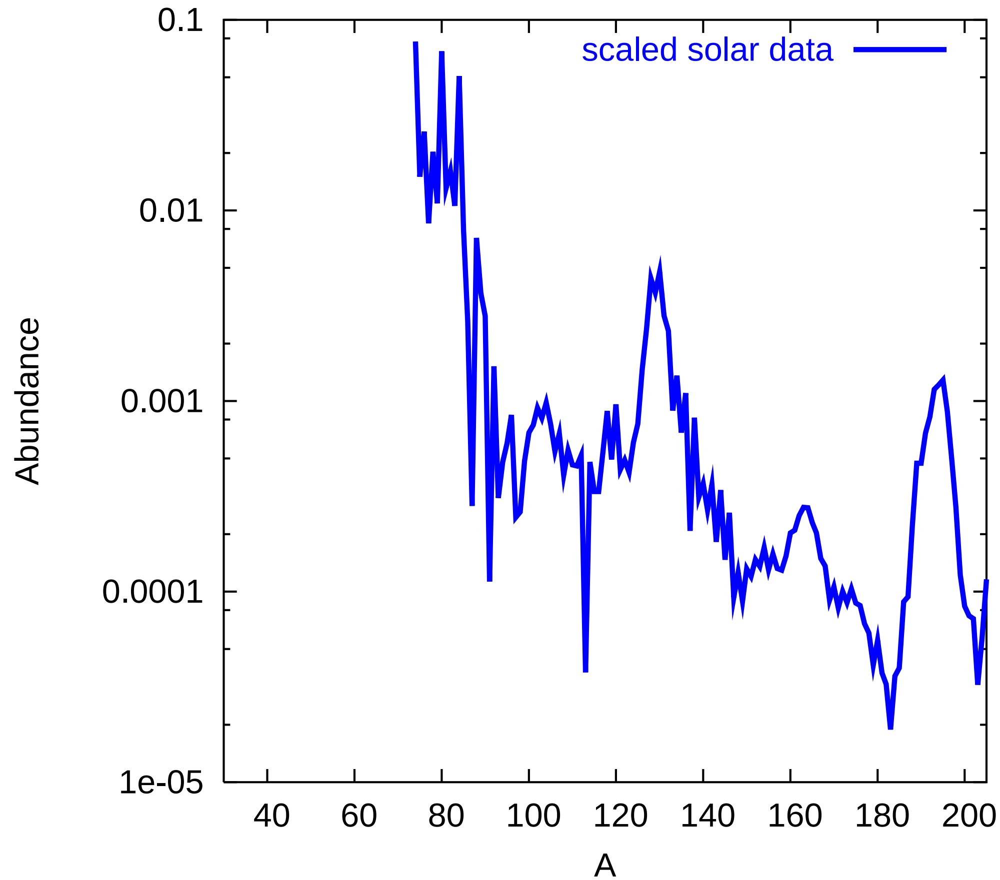
Where is the nuclear physics in neutron star mergers?



Multimessenger: electromagnetic counterpart (r-process), neutrinos, gravitational waves (equation of state)

First, some background on the r-process

solar abundances: one way to study the r-process



Choose a model of an astrophysical site (merger, supernovae), calculate elements synthesis, with available nuclear inputs, and compare with this pattern.

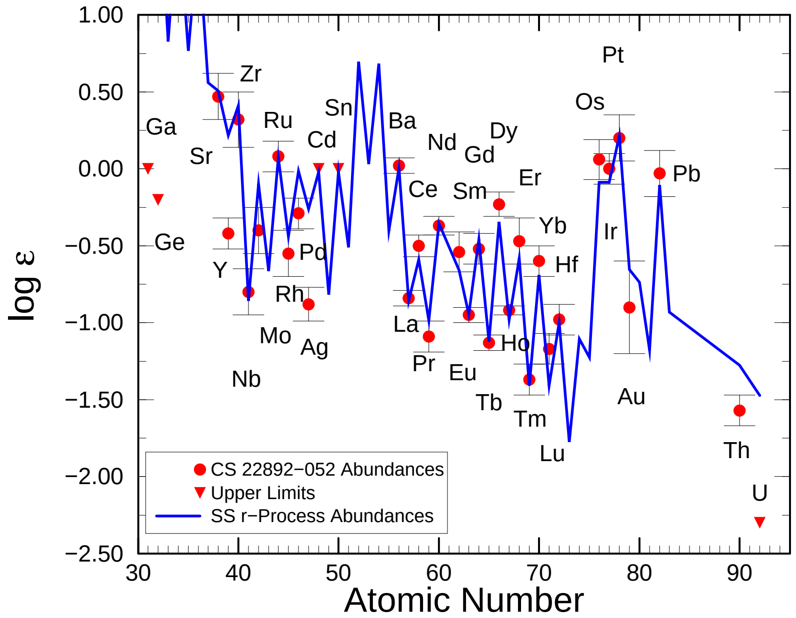
r-process in Halo Stars: a second way

Halo Stars:

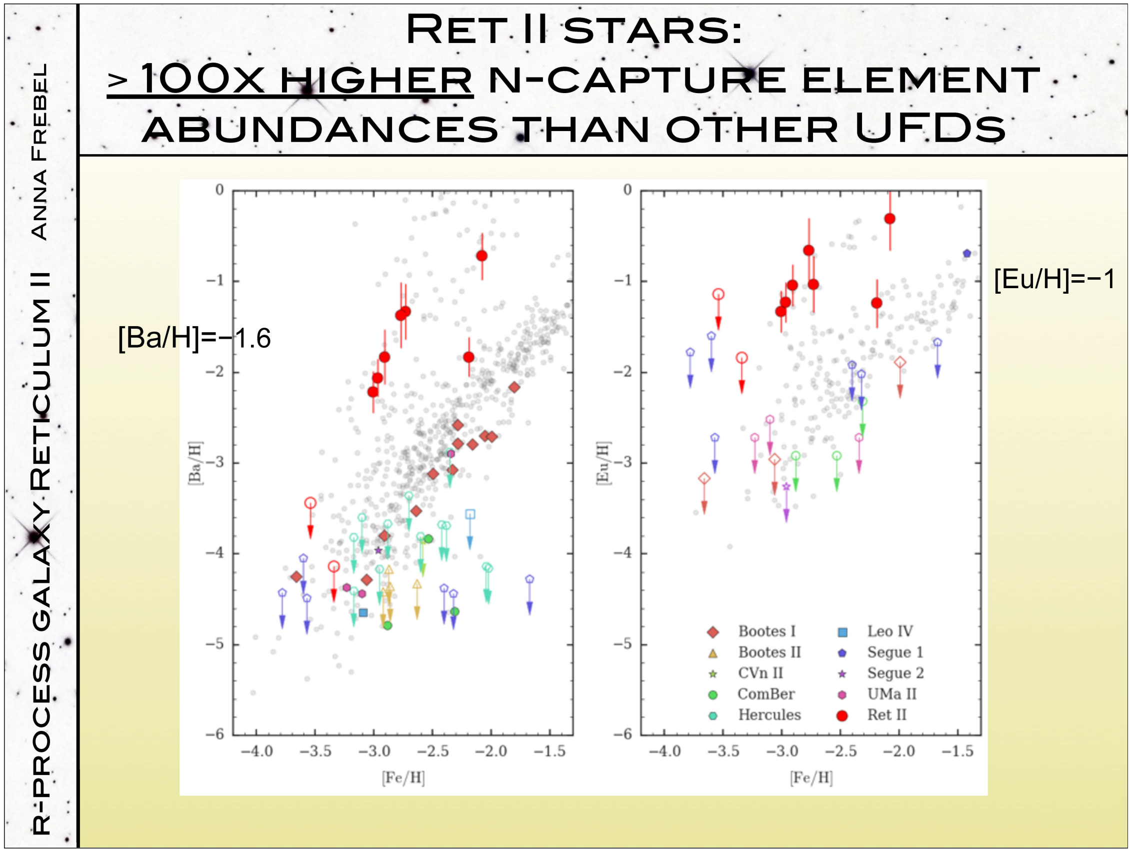
- two r-process sites

  Figure from Cowan and Sneden (2004)

- robust "main" r-process

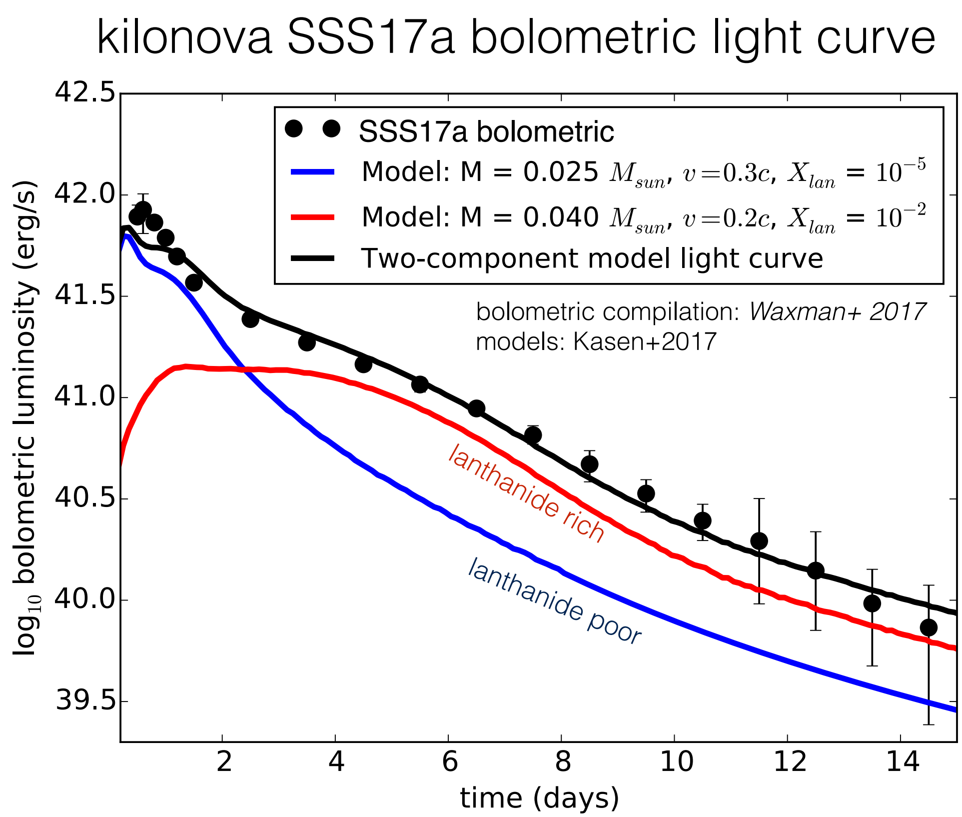


Ultra faint dwarf galaxies: a third way



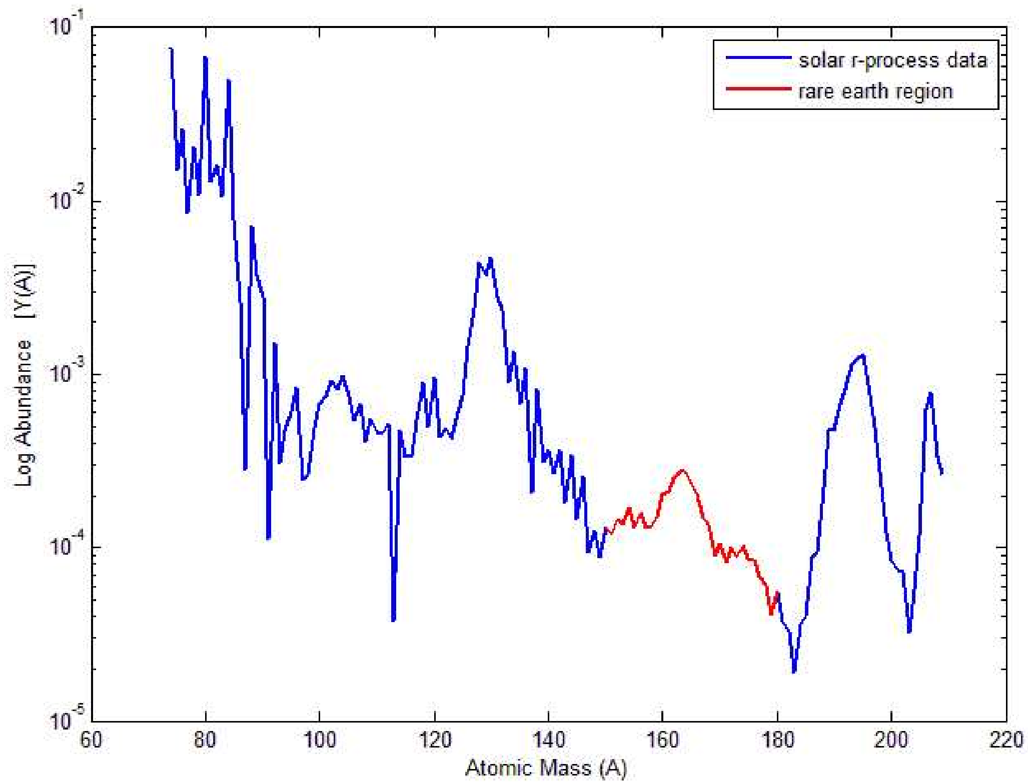
One galaxy of ten has r-process elements Slide credit: Anna Frebel

Electromagnetic counterpart to the neutron star merger GW signal

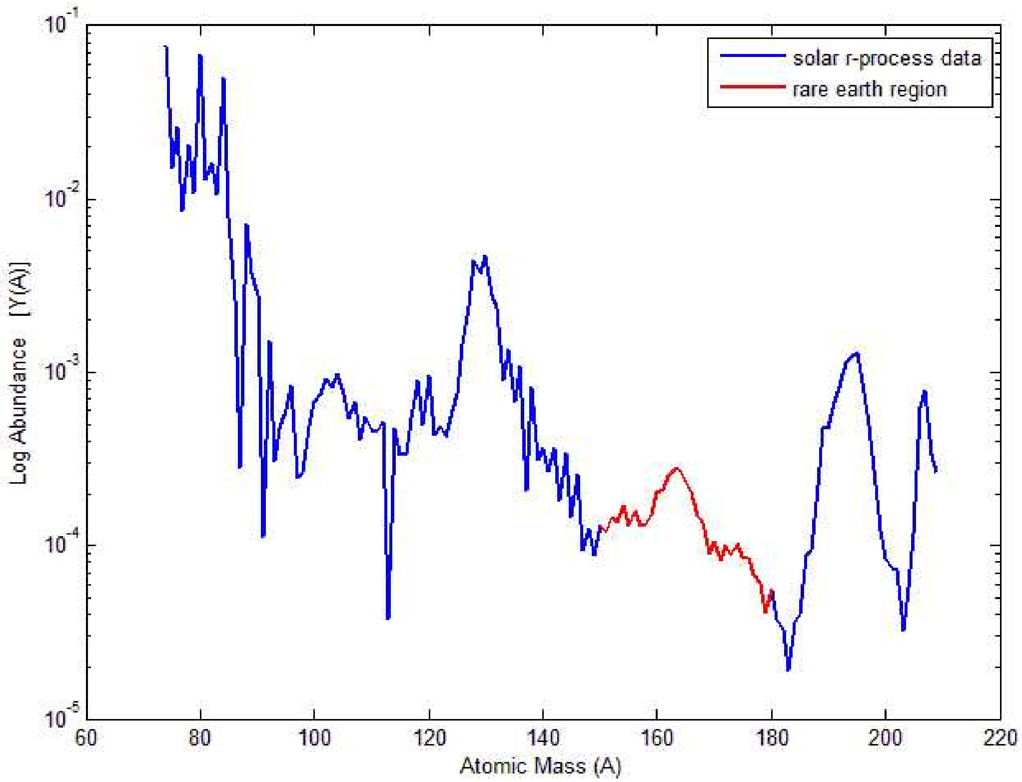


Material with significant opacity is the best fit to the data Slide credit: Dan Kasan Suggests lanthanides were made in the r-process.

Where are the lanthanides?



This gives a hint about the r-process



If lanthanides are required to fit the electromagnetic counterpart, then at least some r-process was synthesized in this merger.

Status of the interpretation of observations:

A few points

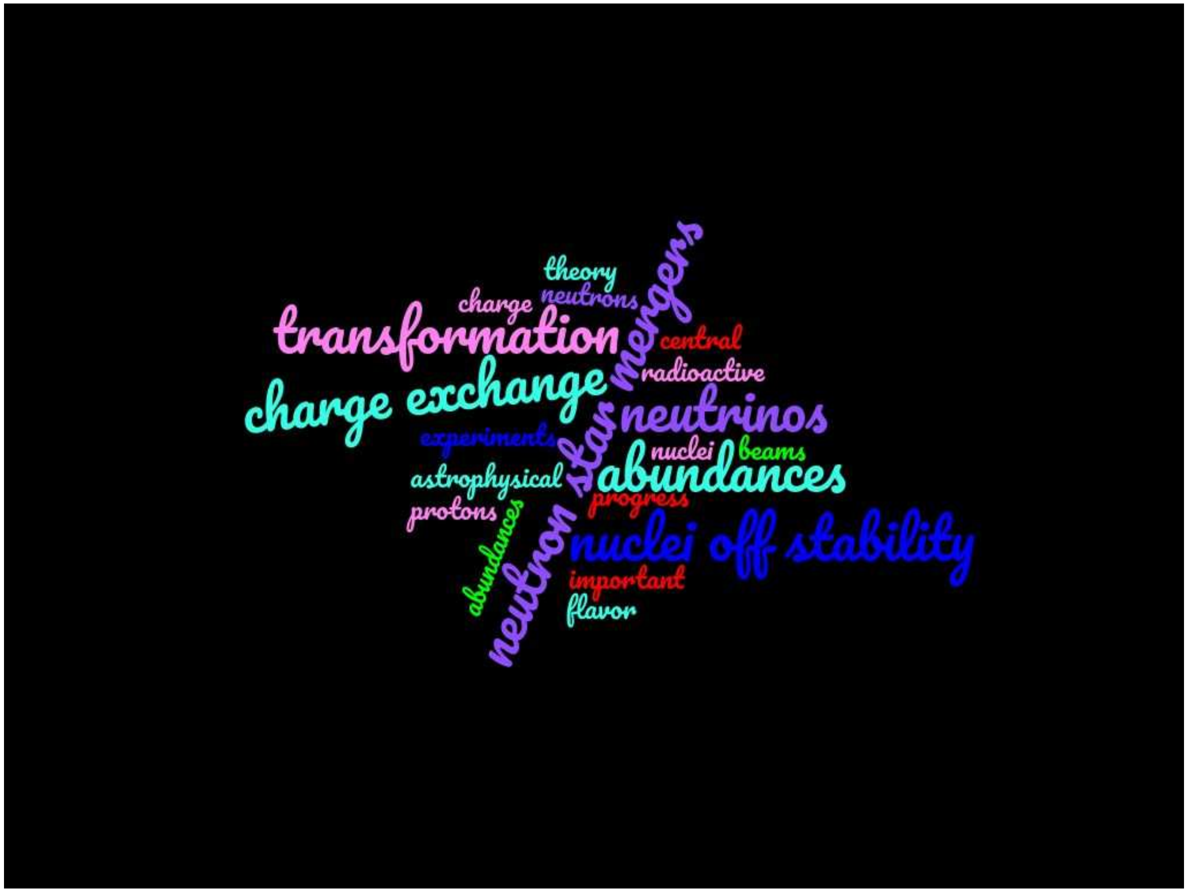
- halo star data: rare earths made with third peak (at least sometimes)
- ultra-faint dwarfs: rare earths made in a rare event (at least one)
- EM counterpart to GW: models with rare earths preferred because of opacity

rare earths = lanthanides

A couple open questions regarding the r-process

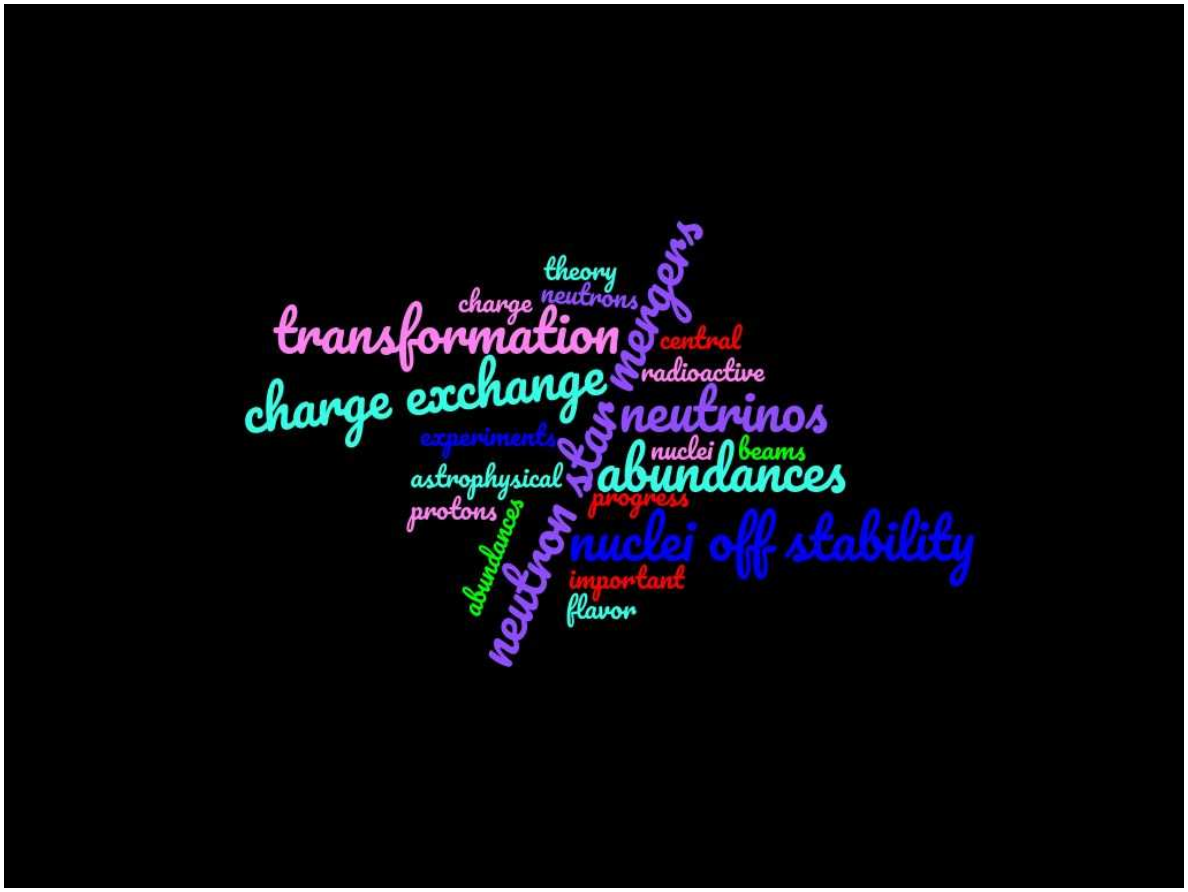
- How many r-process sites are there? Are neutron star mergers the only one? Do mergers make any material beyond the lanthanides?
- What can nuclear physics tell us?

Some roles that nuclear physics plays

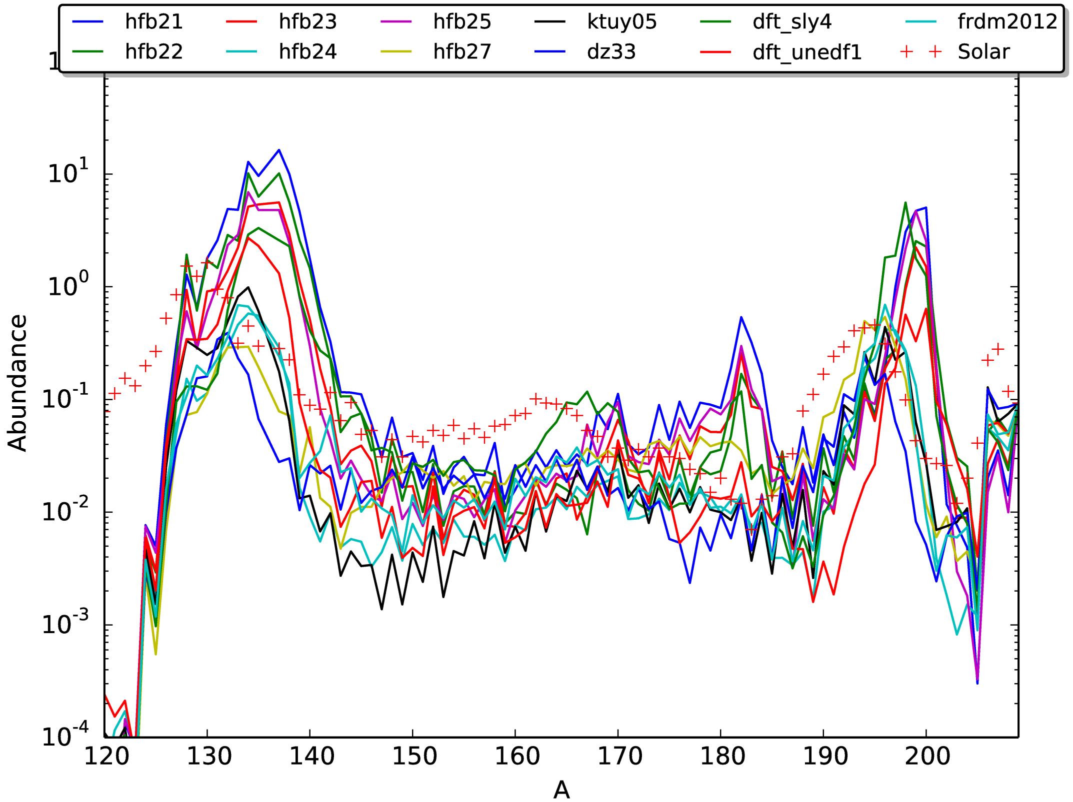


Some roles that nuclear physics plays

nuclear structure/reactions determine the abundance pattern

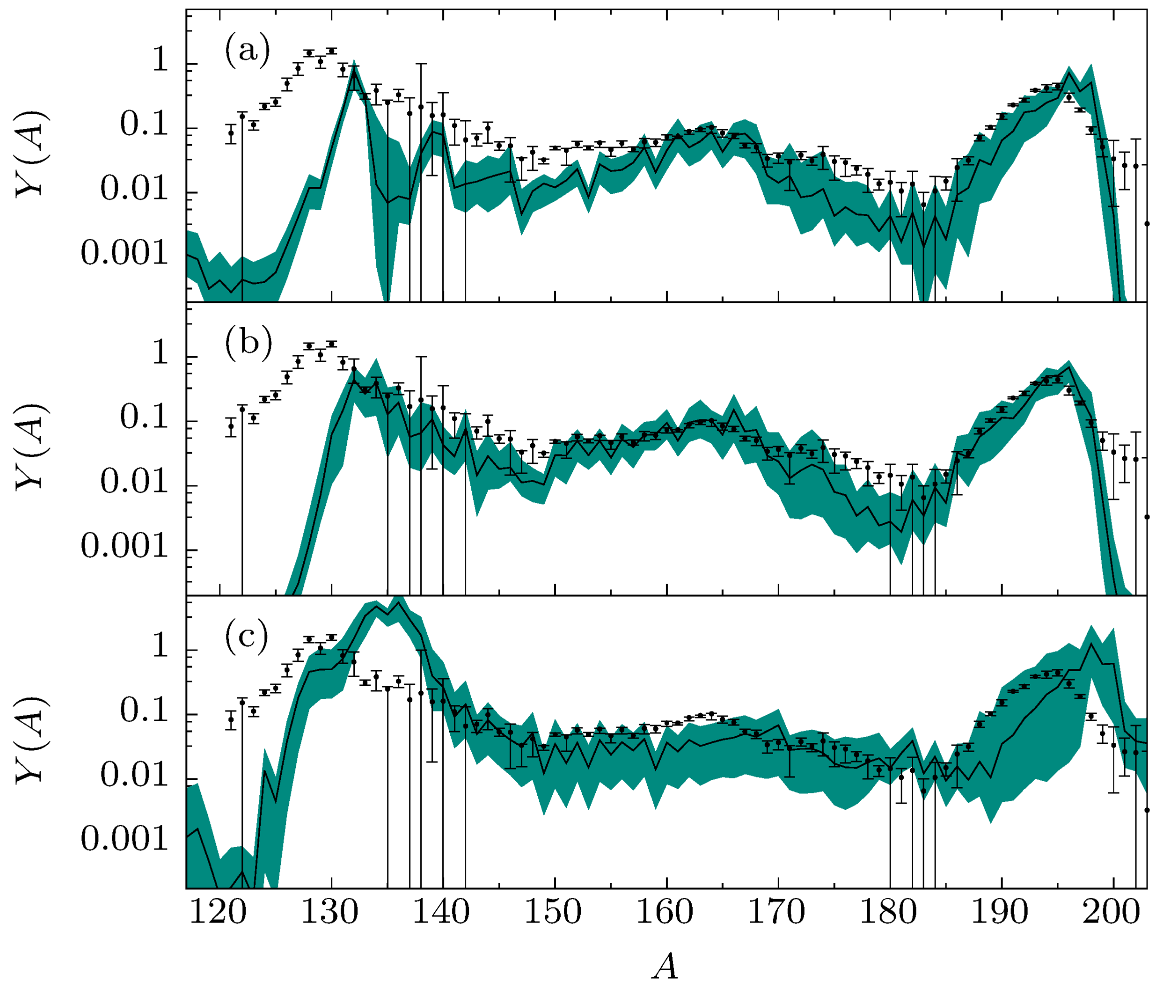


Nuclear structure, reactions determine abundances



Nuclear physics is one of the largest uncertainties in r-process predictions. Slide credit: FIRE collaboration

Uncertainty from one mass model



Shows the range of abundance patterns for 50 realizations of UNEDF1. Sprouse et al 1029

Experimental reach

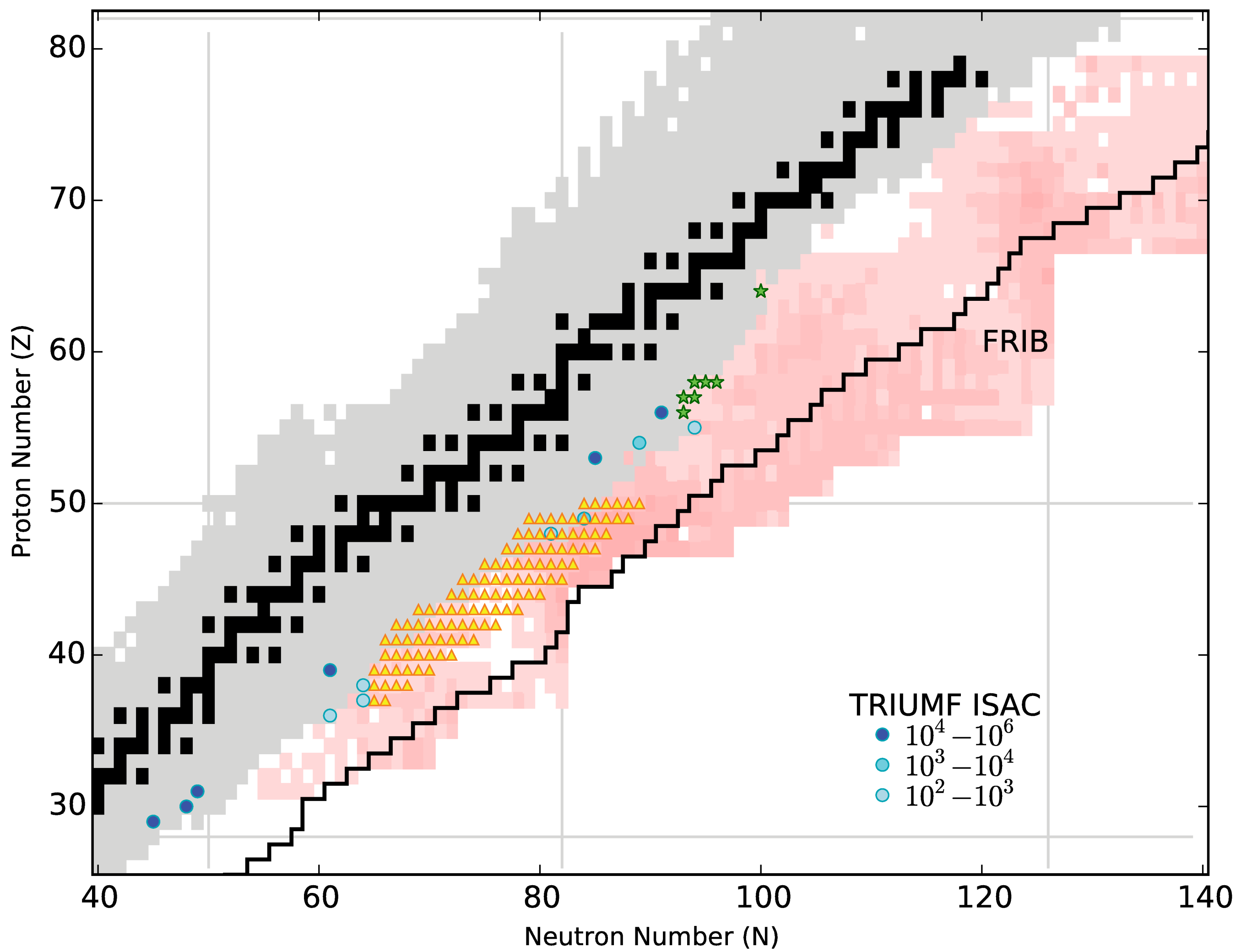
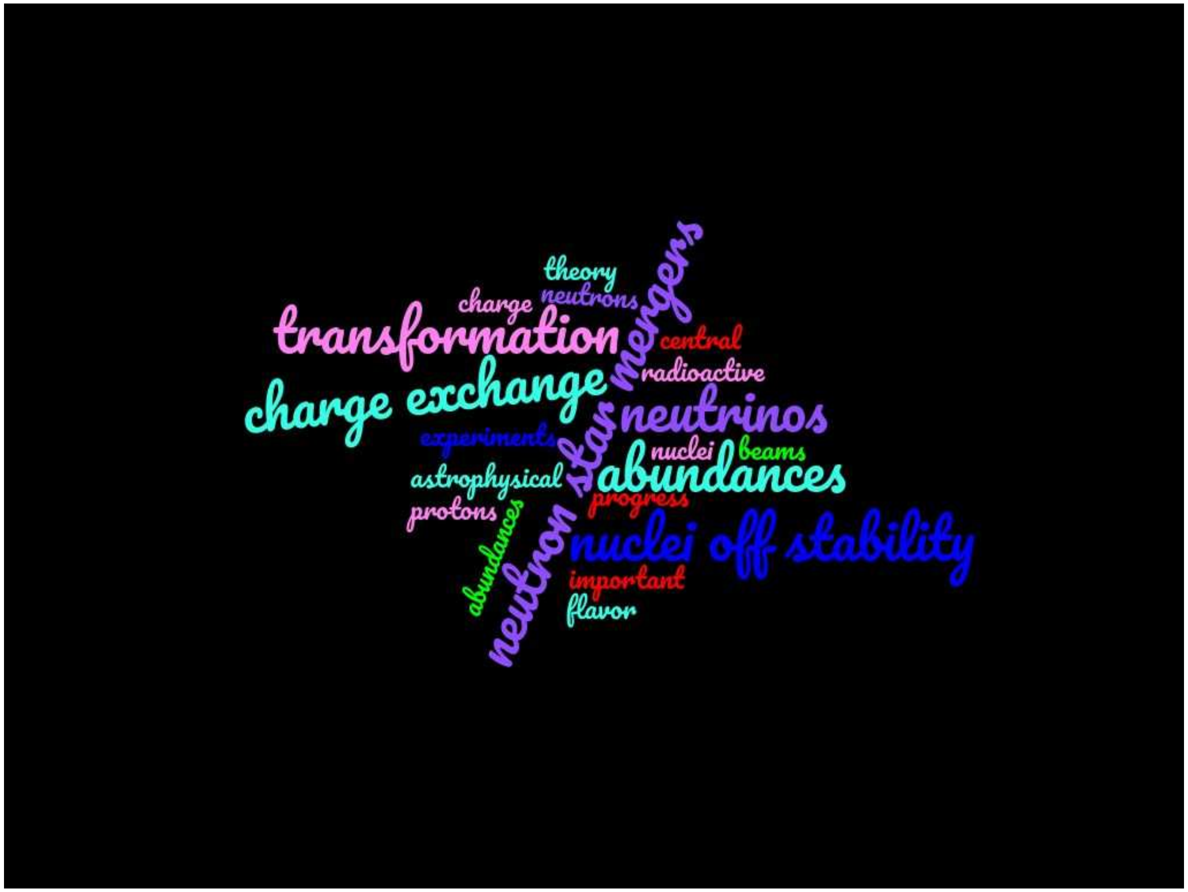


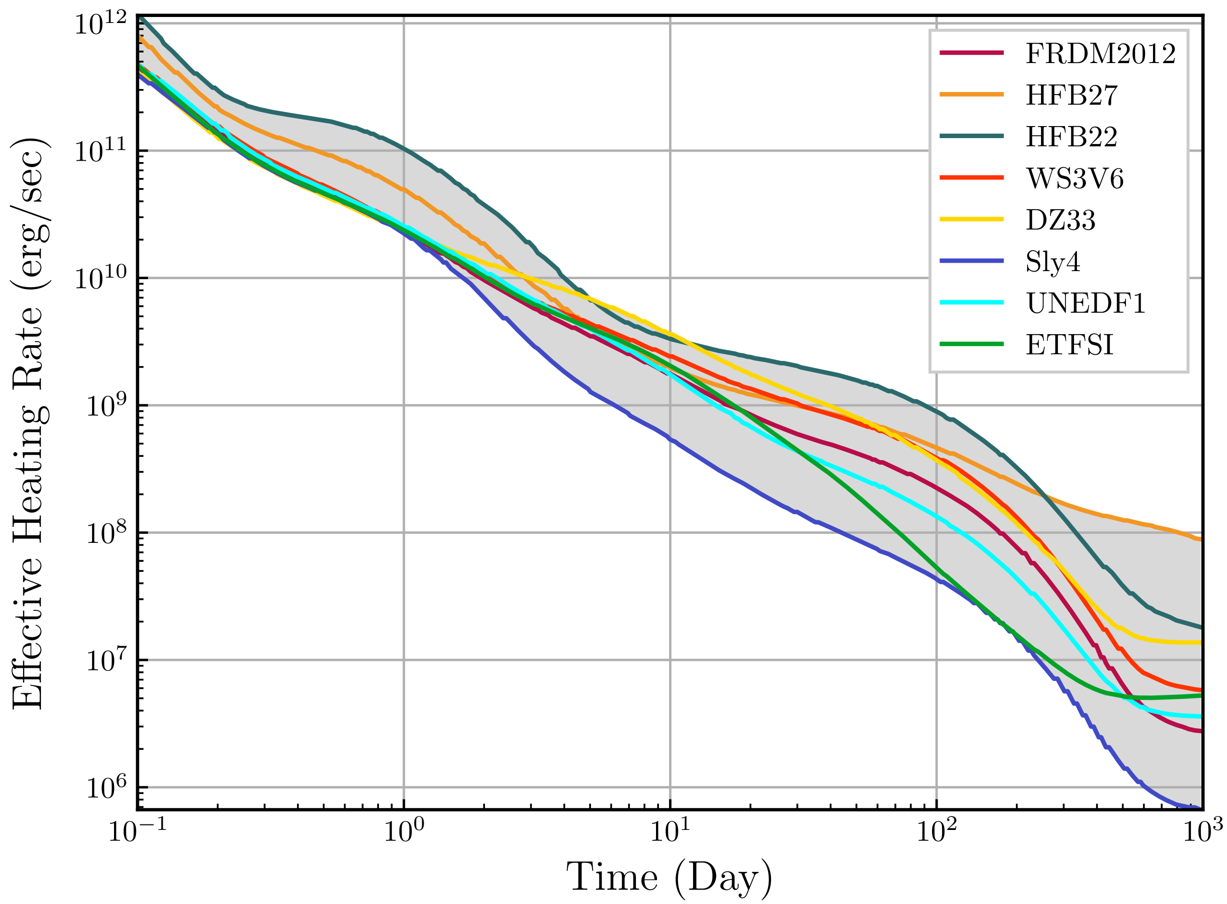
Fig. from Mumpower et al 2016

Some roles that nuclear physics plays

nuclear structure/reactions determine the heating for the EM counterpart



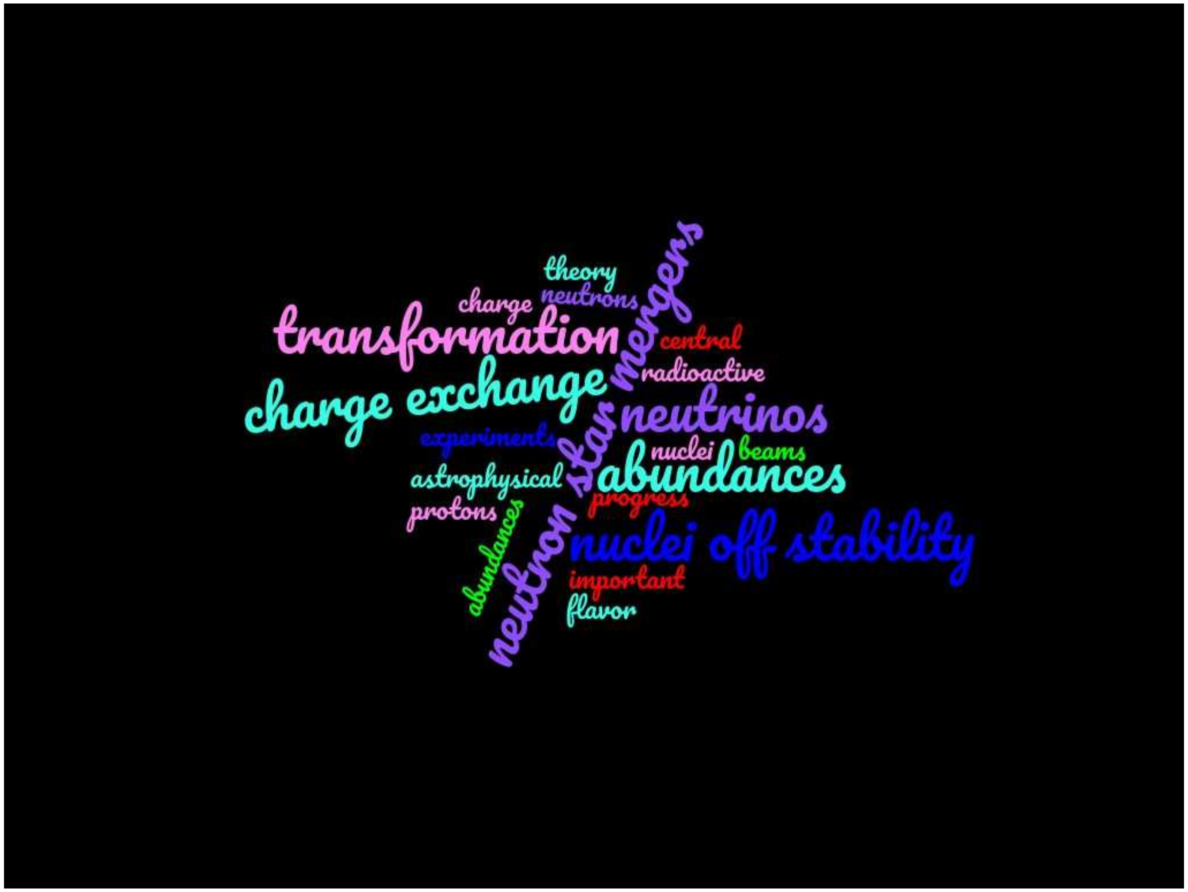
Nuclear reactions determine energy release



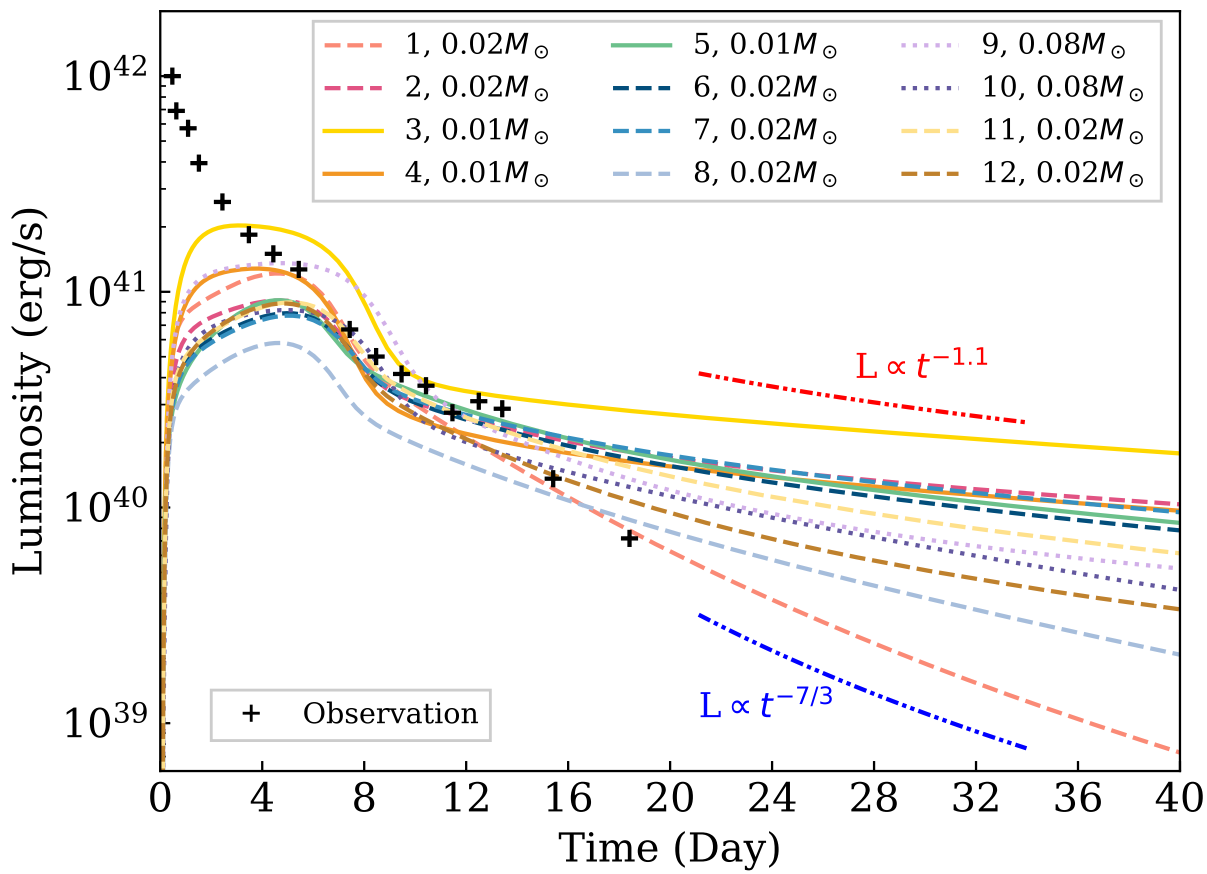
Zhu et al., in prep. Shows the influence of nuclear mass model on the nuclear heating, uncertainties on fission prescriptions, electron fraction, ejecta mass and ejecta velocity not taken into account.

Some roles that nuclear physics plays

Nuclear physics influences the light curve



Nuclear physics uncertainty propagates to deduced ejecta mass



Zhu et al., in prep. Shows the influence of nuclear model and electron fraction on the light curve, uncertainties in ejecta velocity not taken into account.

Some roles that nuclear physics plays

decays of particular nuclei influence the light curve in an observable way

Fission of 254Cf changes the heating curve

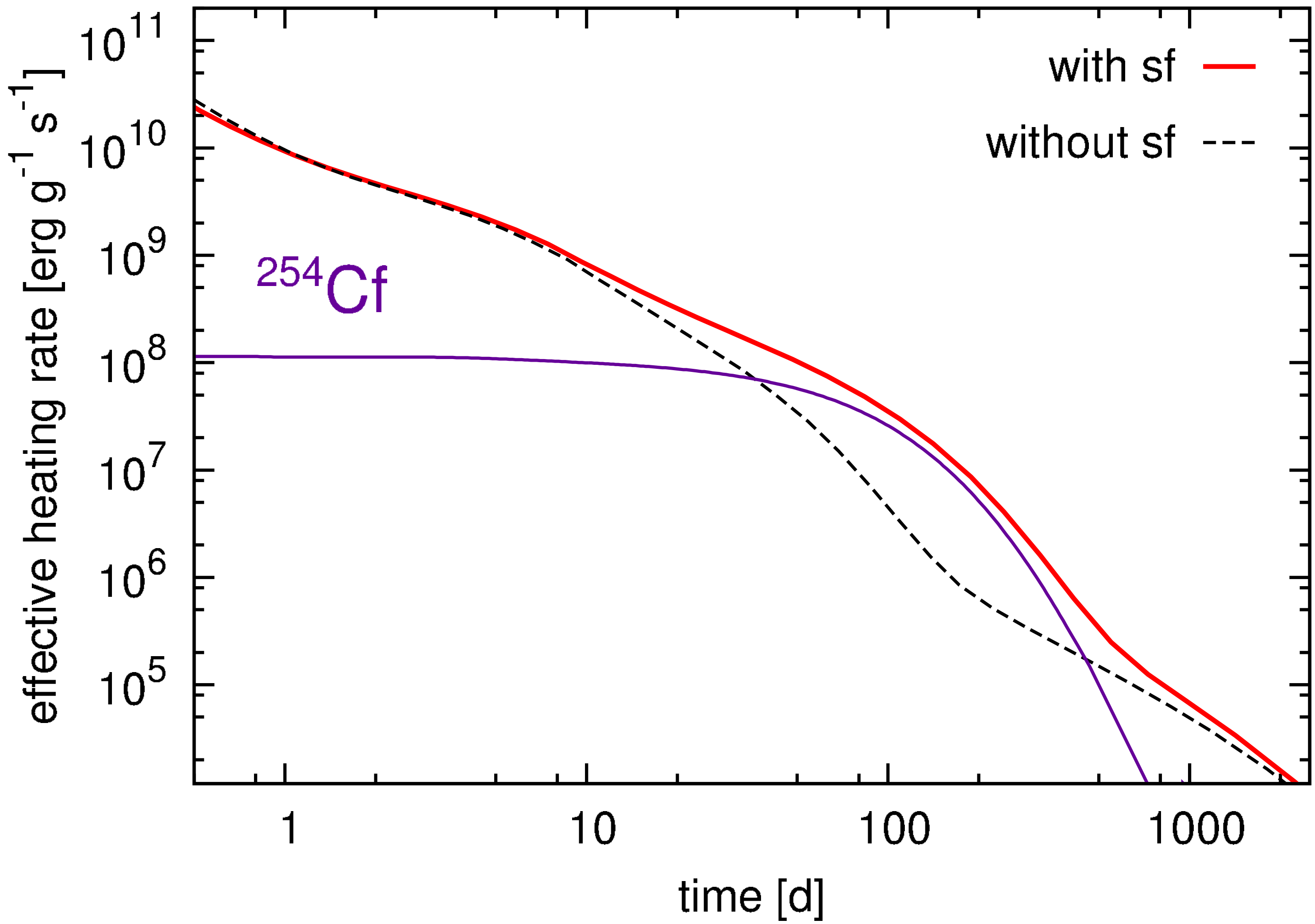


fig. from Zhu et al 2018. The FIRE collaboration isolated the extra heating to come largely from a single nucleus.

Observable consequence

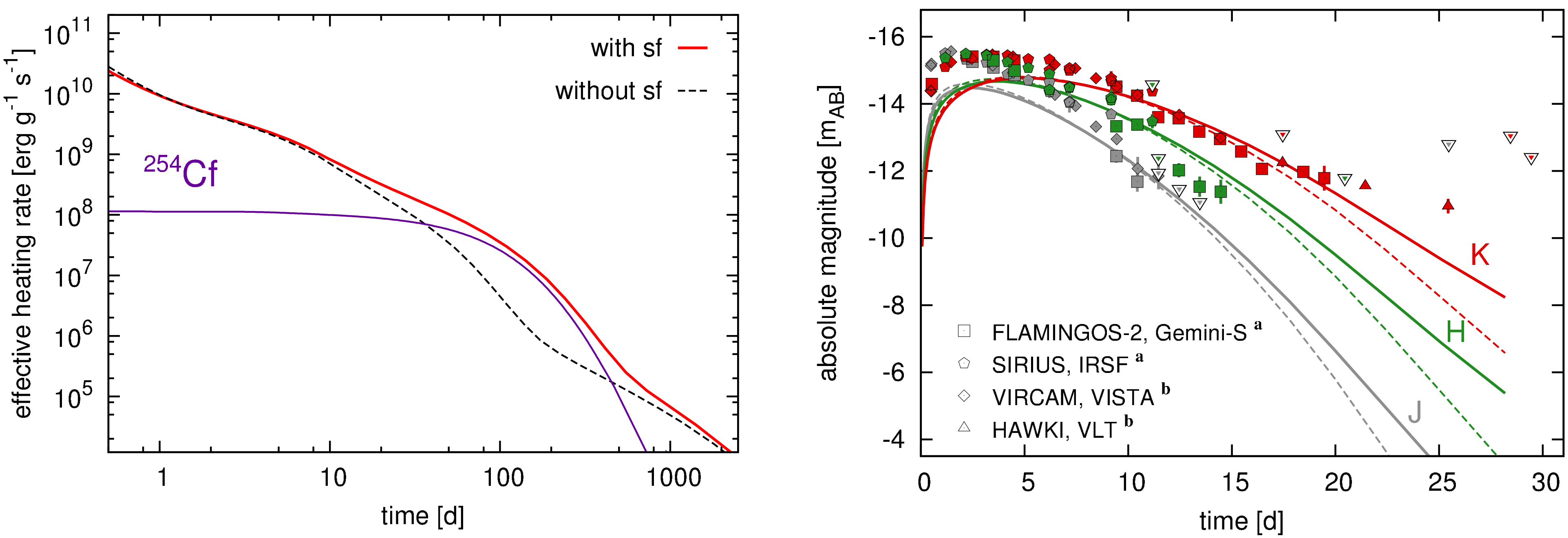


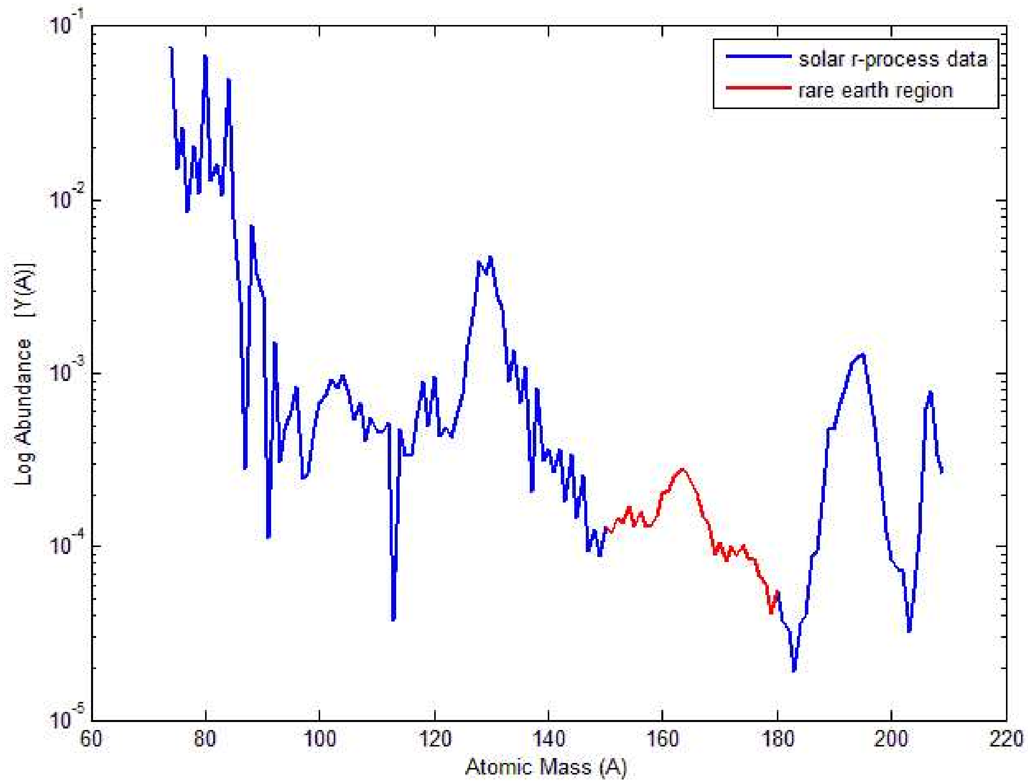
fig. from Zhu et al 2018.

Some roles that nuclear physics plays

most of the relevant nuclei are unmeasured/off stability, but we have new opportunities on the horizon

experiment-theory collaboration

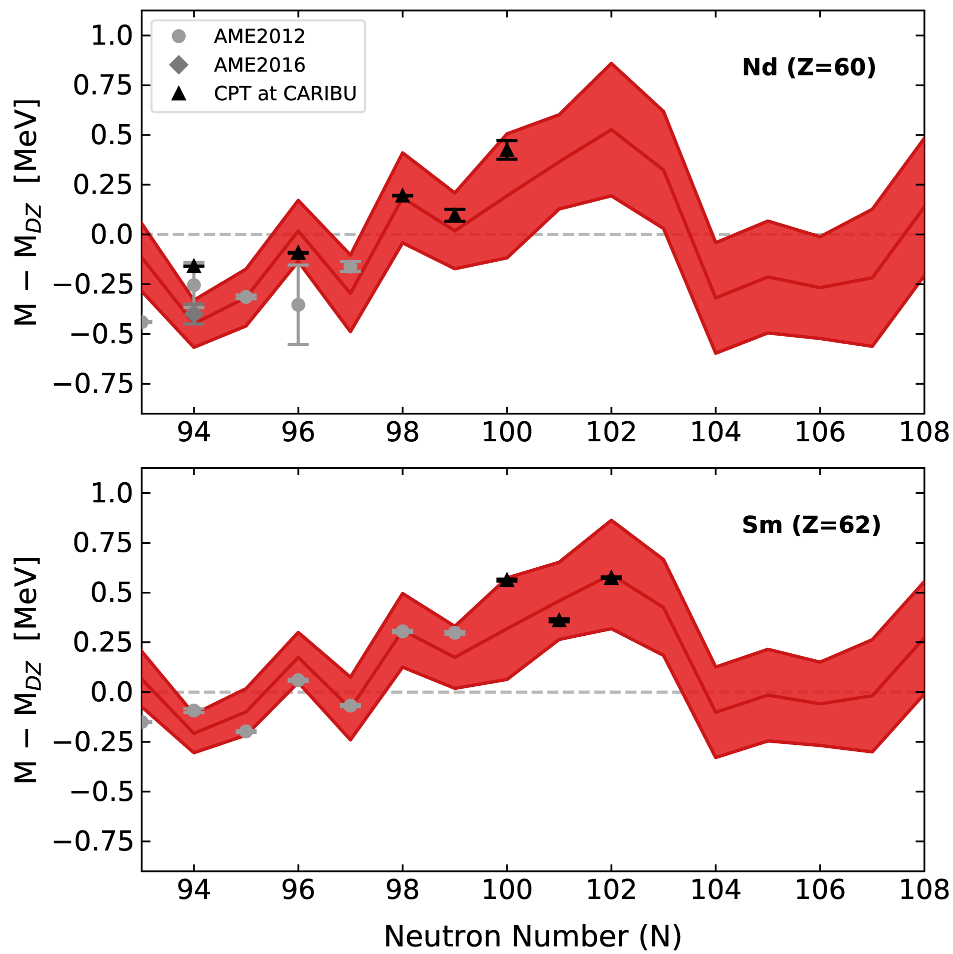
Which nuclear measurements, working in concert with theory, will provide the maximum information about the site of the r-process?



Example: solar abundance data with the rare earth peak in red. The rare earth peak is created by a nuclear physics feature. We predict this feature, and find different results for different astrophysical conditions.

Using MCMC to predict the feature

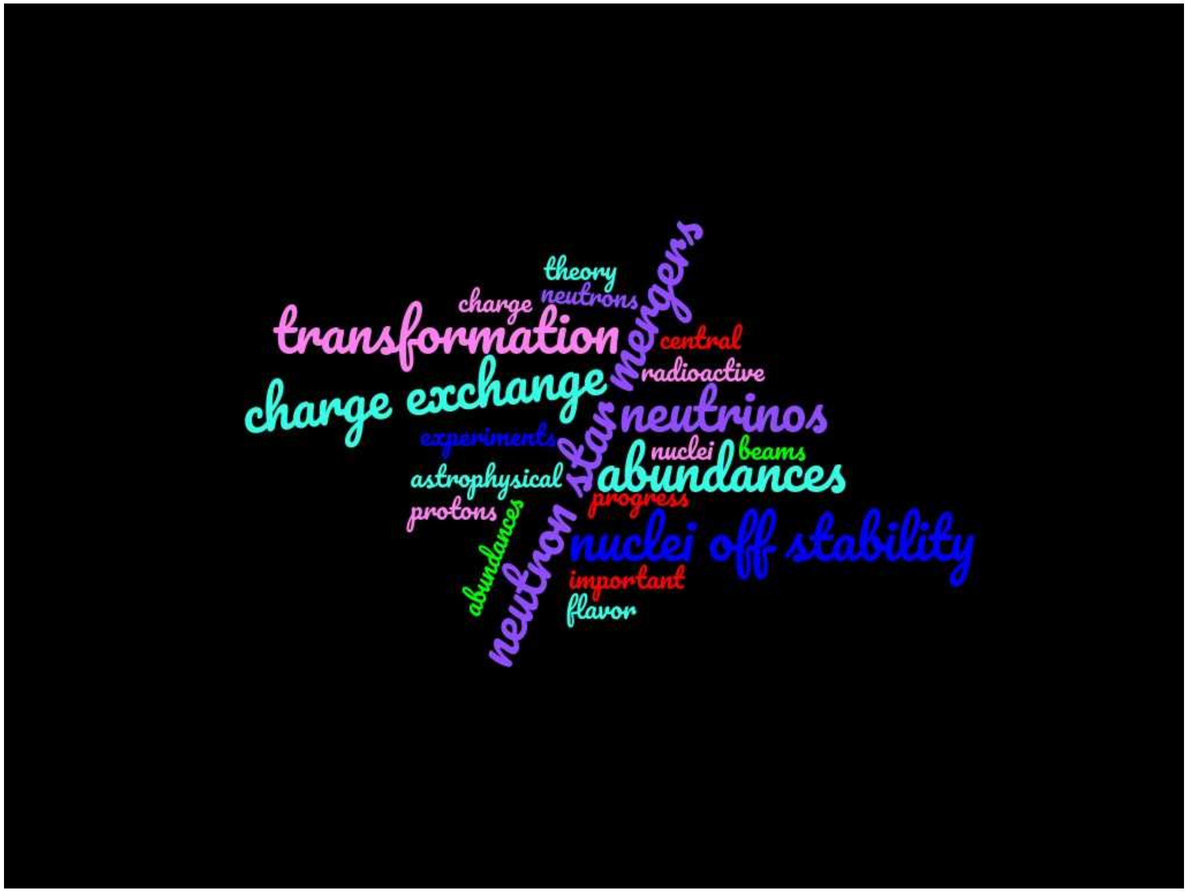
Mass surface for "hot" conditions



Orford, Vaash, et al PRL 2018

Some roles that nuclear physics plays

neutrinos influence the ratio of neutrons to protons



Nucleosynthesis from neutron star mergers

- tidal ejecta
- collisional ejecta

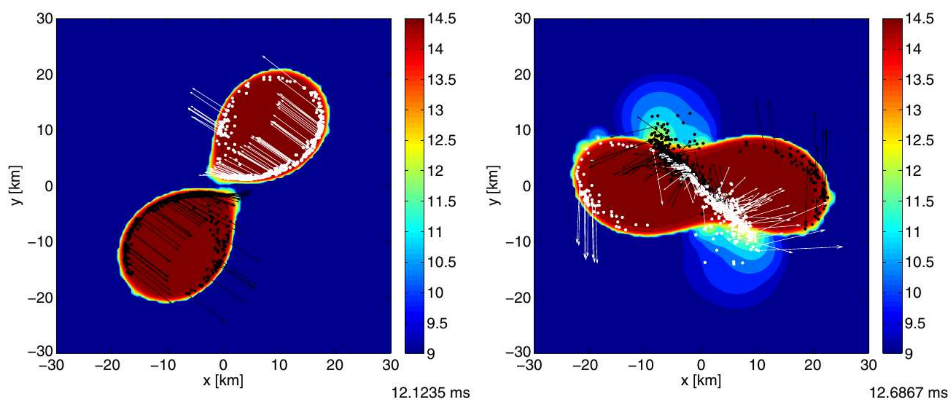


fig. from Bauswein et al 2013

- disk/hypermassive NS outflow
- outflow from viscous heating

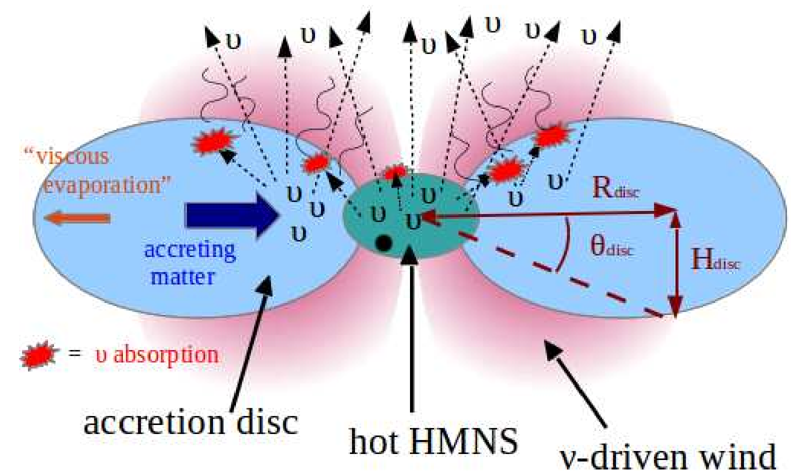


fig. from Perego et al 2014

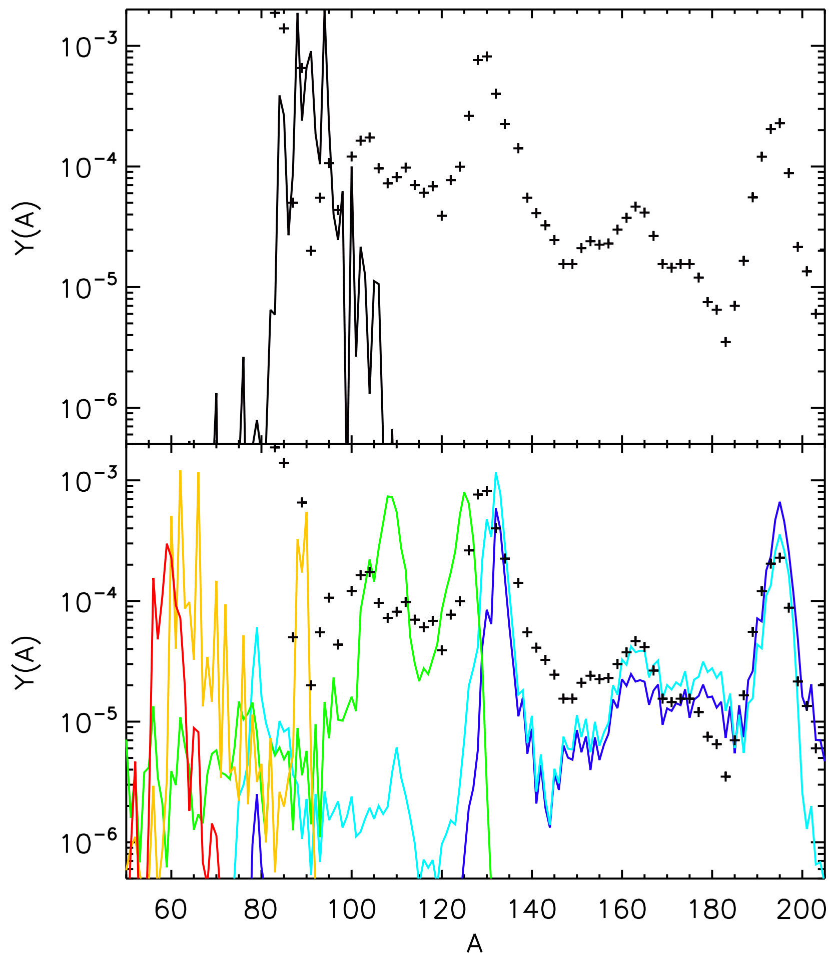
How neutrinos influence nucleosynthesis

Neutrinos change the ratio of neutrons to protons

$$\nu_e + n \rightarrow p + e^-$$

$$\bar{\nu}_e + p \rightarrow n + e^+$$

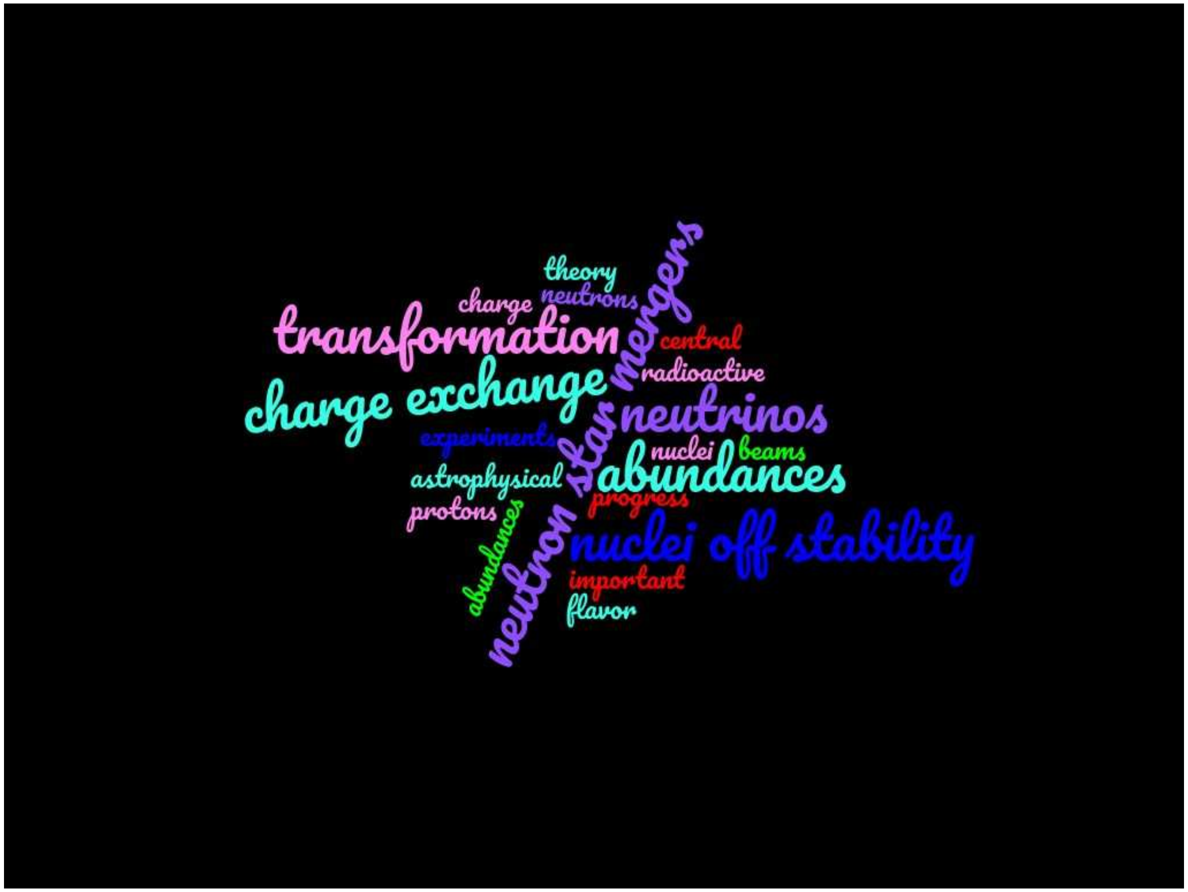
So different neutrino spectra affects the elements produced



Accretion disk wind nucleosynthesis, Malkus et al '16

Some roles that nuclear/neutrino physics plays

neutrinos flavor transform



Neutrino flavor transformation

alters the numbers of neutrons and protons

Neutrinos change the ratio of neutrons to protons

$$\nu_e + n \to p + e^-$$

$$\bar{\nu}_e + p \to n + e^+$$

Oscillations change the spectra of ν_es and $\bar{\nu}_e$s

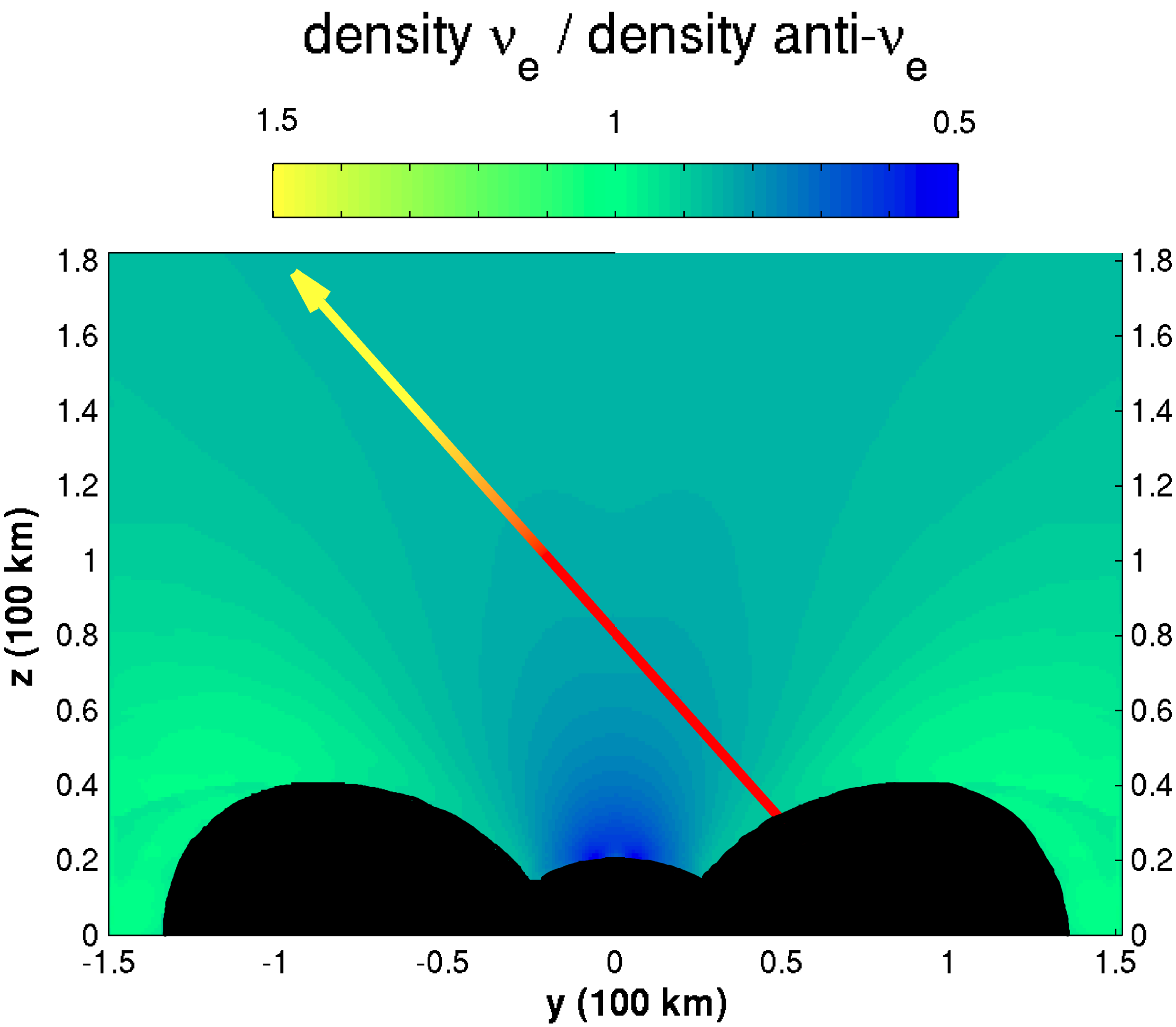
$$\nu_e \leftrightarrow \nu_\mu, \nu_\tau$$

$$\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu, \bar{\nu}_\tau$$

Mergers have less ν_μ, ν_τ than ν_e and $\bar{\nu}_e$

$\to$ oscillation reduces numbers of ν_e, $\bar{\nu}_e$

Neutrino flavor transformation in mergers



Zhu et al 2016

Three new developments on neutrino flavor transformation in mergers

1. GR estimates of neutrino fields
2. Multiangle techniques
3. Quantum kinetics: collisions

Merger oscillations: survival probabilities

Using general relativistic ray-tracing to generate more accurate neutrino fields, with angular information, above two merging neutron stars

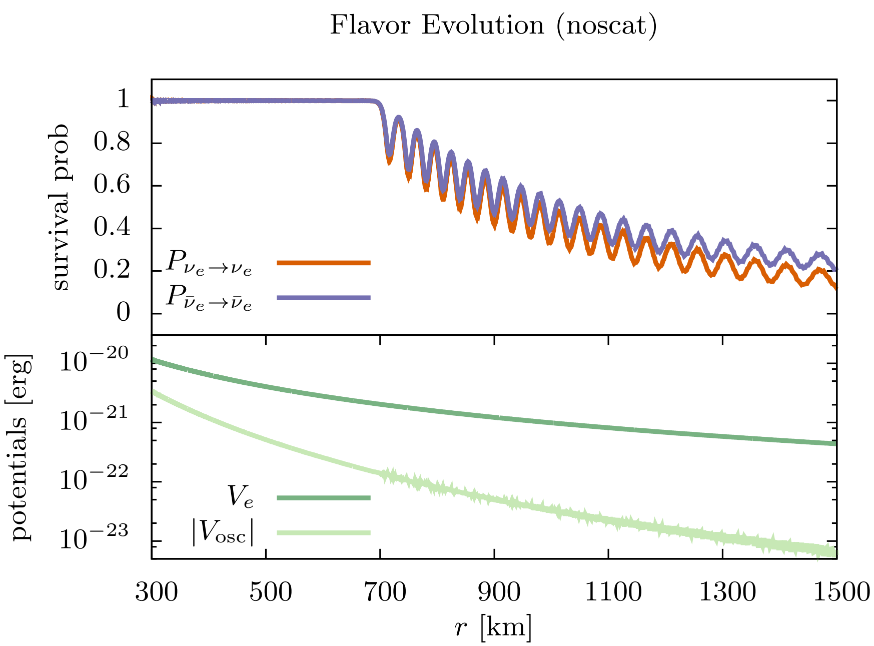


fig. from Deaton et al 2018

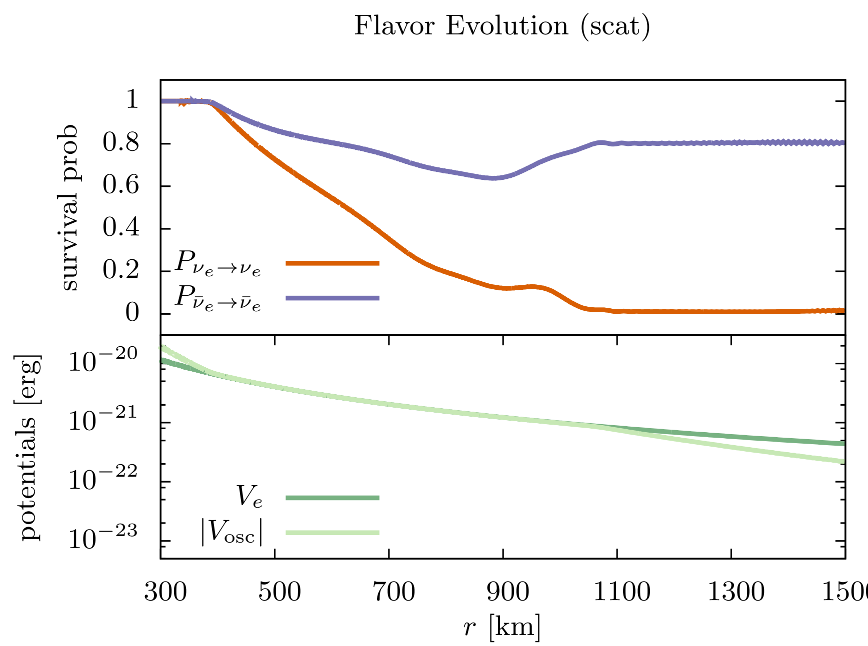
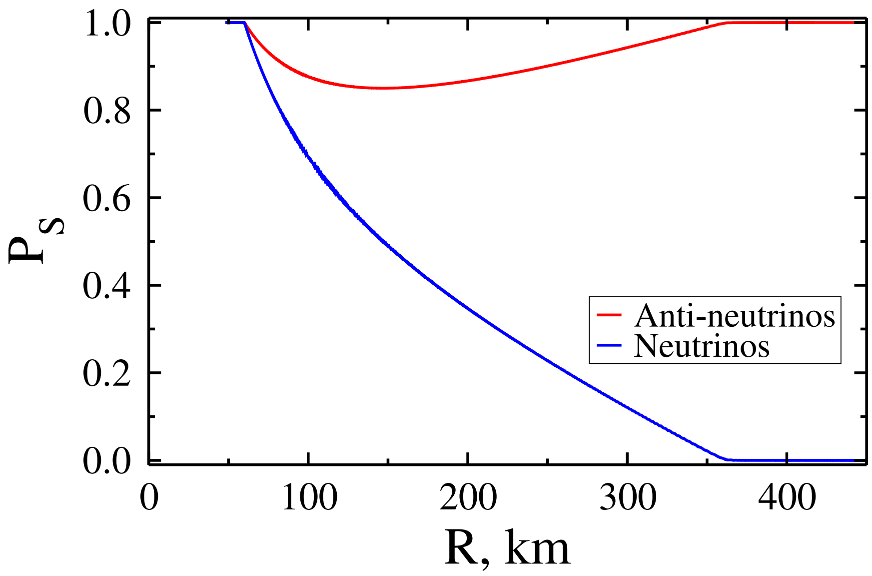


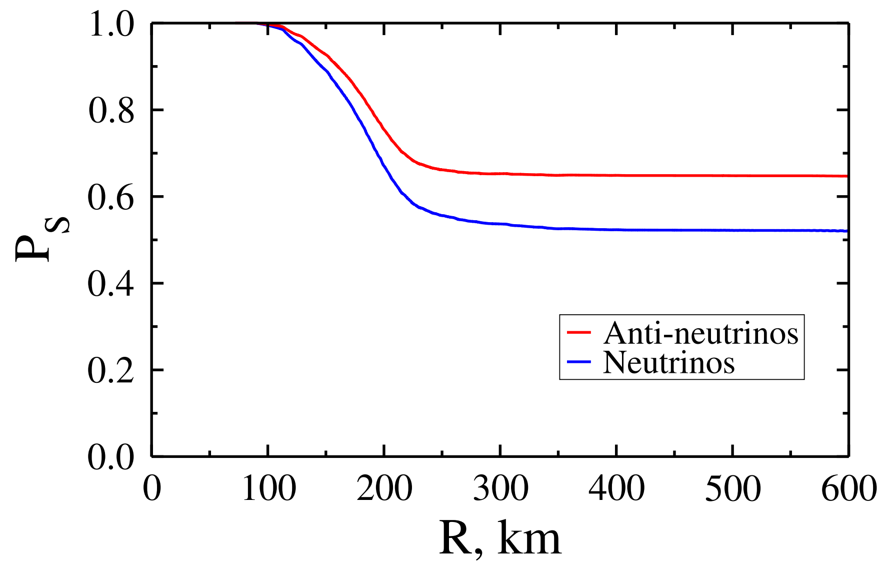
fig. from Deaton et al 2018

Multi-angle survival probabilities

First multi-angle calculations of merger-type distributions in a bulb model



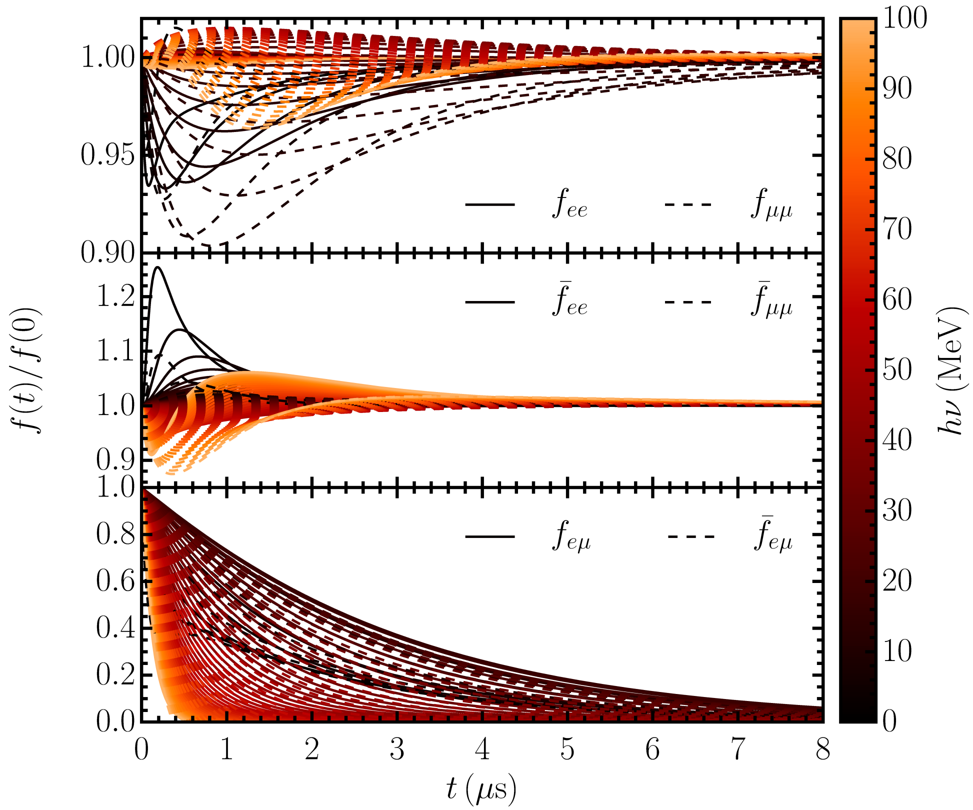
single angle, Vlasenko et al 2018



multi-angle Vlasenko et al 2018

First evolution of quantum kinetic equations

Isotropic homogeneous slab, neutrinos begin in mixed initial state, collisions reduce, redistribute phase. QKE collision terms now in NuLib.



Richers et al 2019

Conclusions

Observations of neutron star mergers are a cutting edge tool for enriching nuclear physics.

- r-process: theory and experiment
- neutrinos: quantum kinetics
- equation of state constraints

There is a community that recognizes this opportunity, and many in this community were strongy influenced by Wick's leadership in nuclear astrophysics.