Nucleosynthesis and neutrinos in explosive astrophysical events

TRIUMF

JINA-CEE

FIRE

Fission In R-process Elements

Nicole Vassh

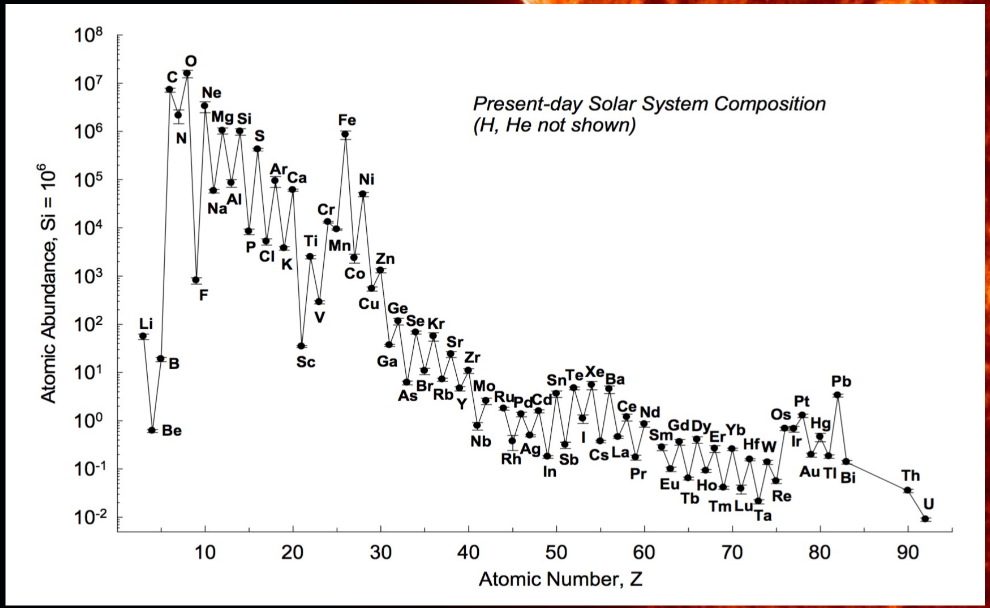
TRIUMF Theory Group

Winter Nuclear & Particle Physics Conference,

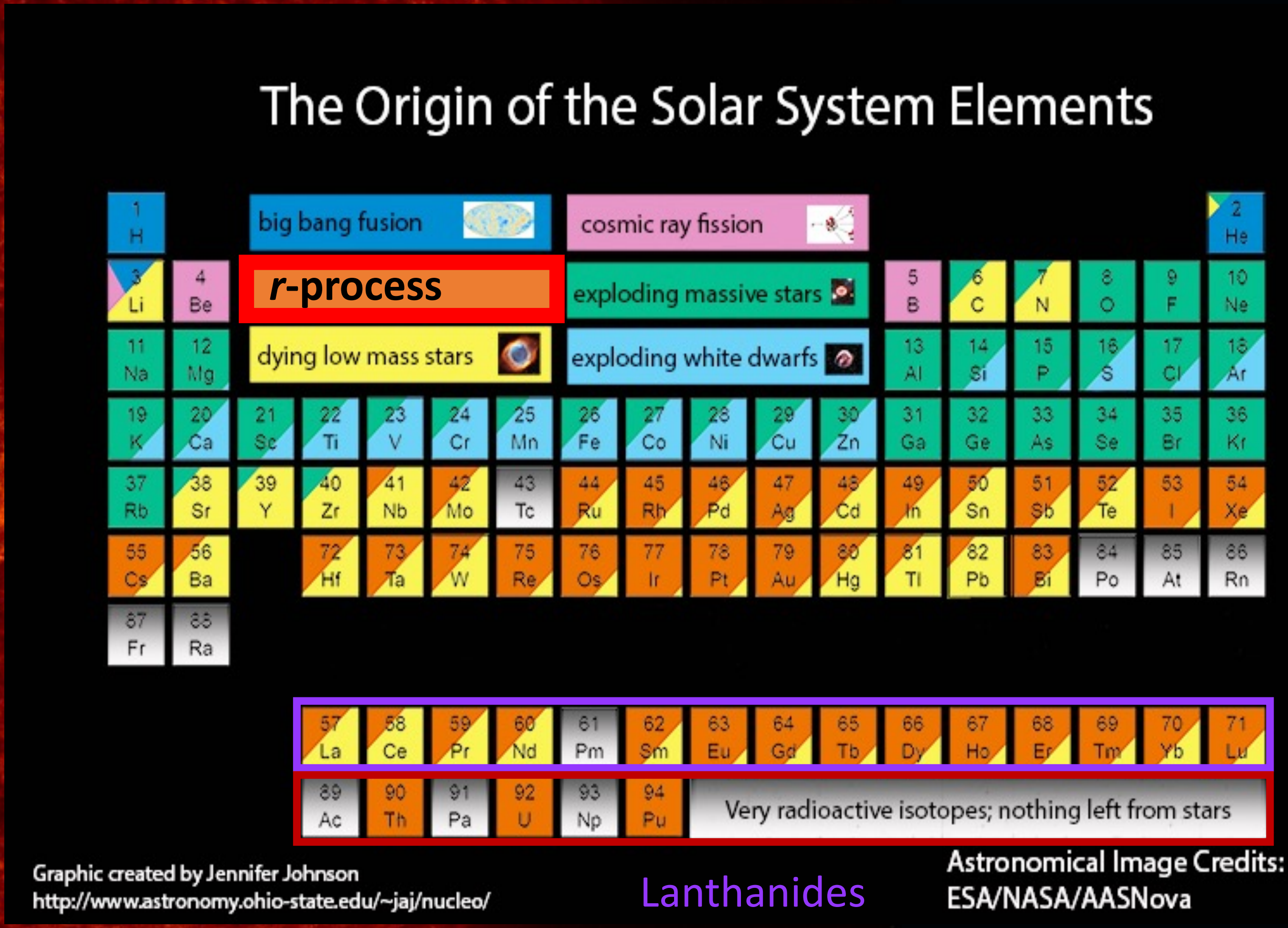
Live from Vancouver, knowing exactly what we are missing in Banff :/

February 16, 2022

The solar composition can be decomposed into many processes → multiple nucleosynthesis sites enriched the solar system



Lodders 10



Lanthanides

Actinides

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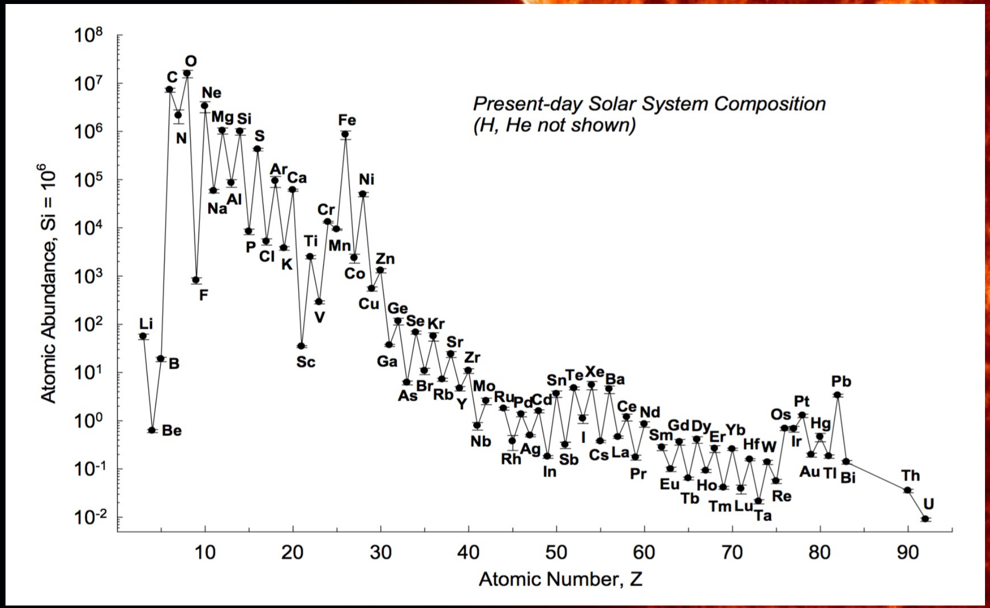

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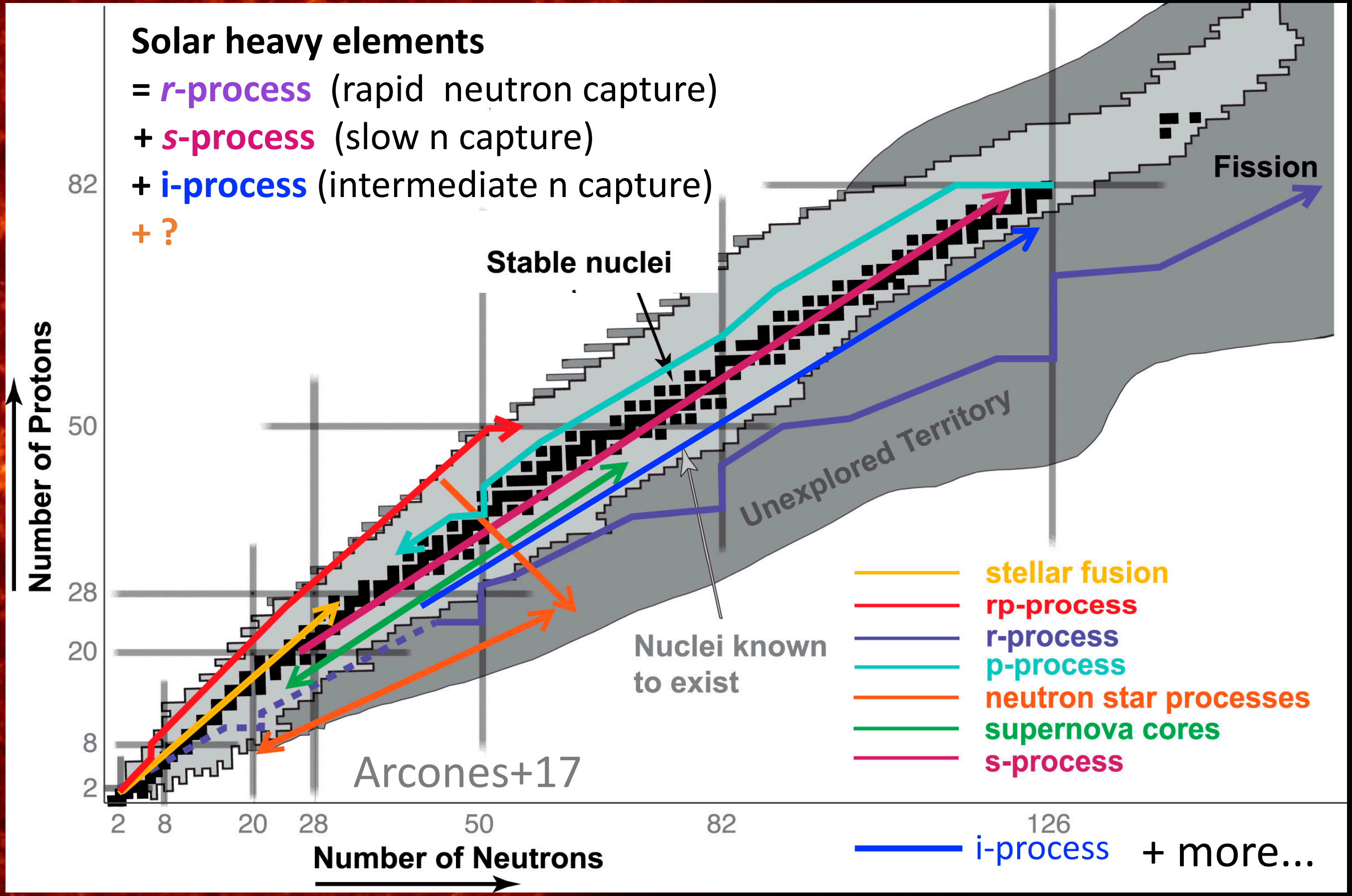

* i-process talk by Falk in this session

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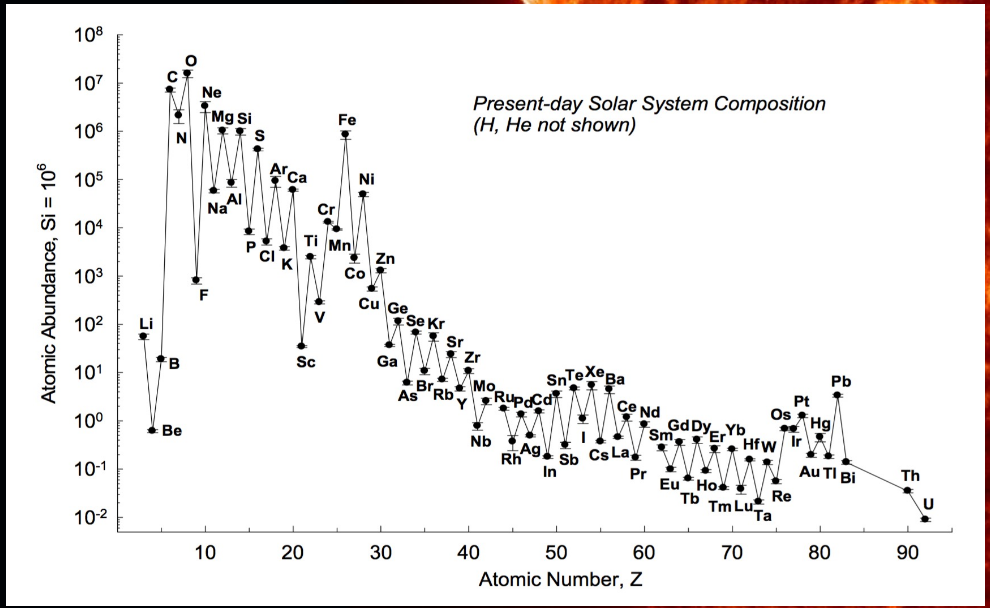

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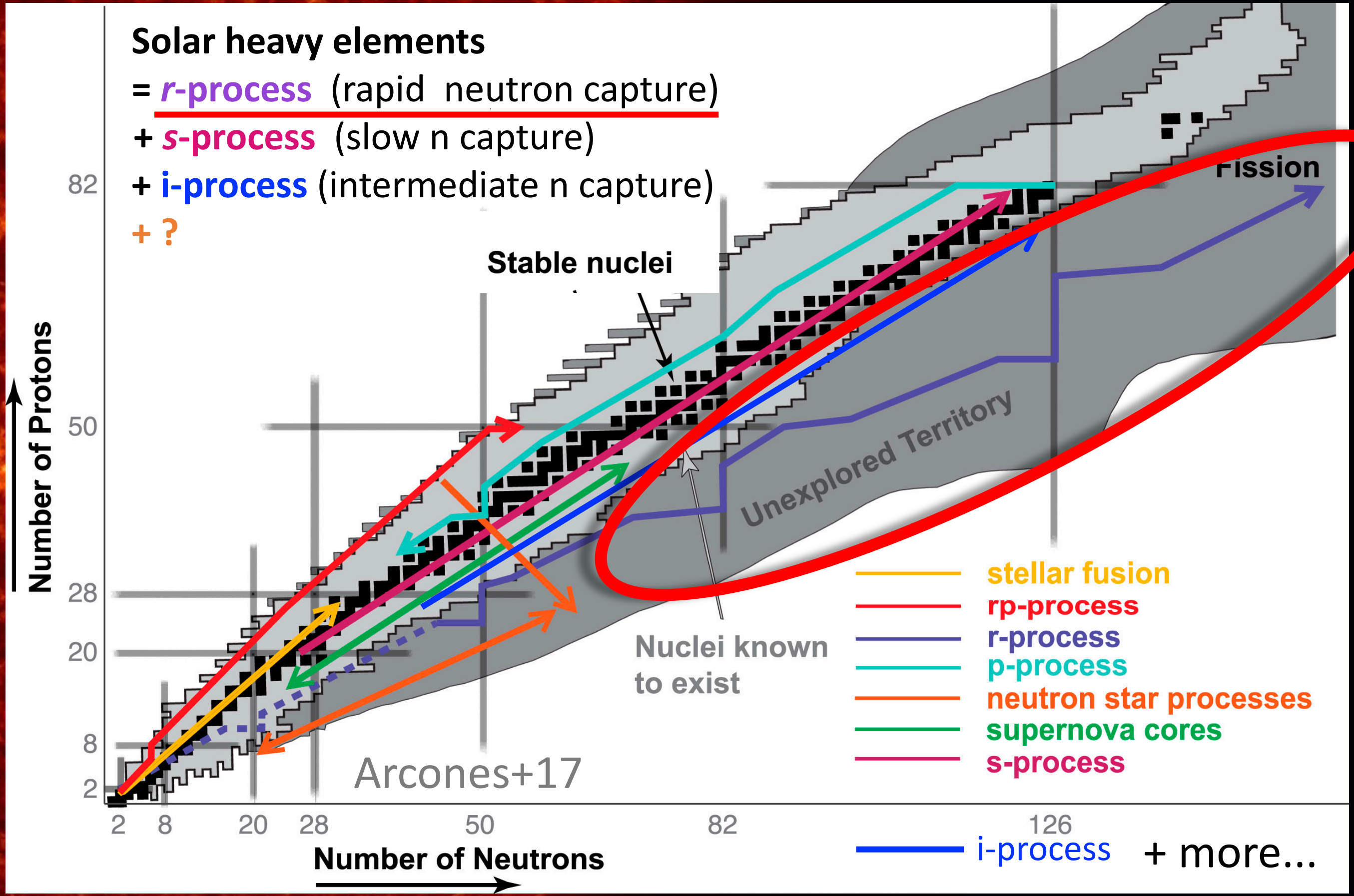

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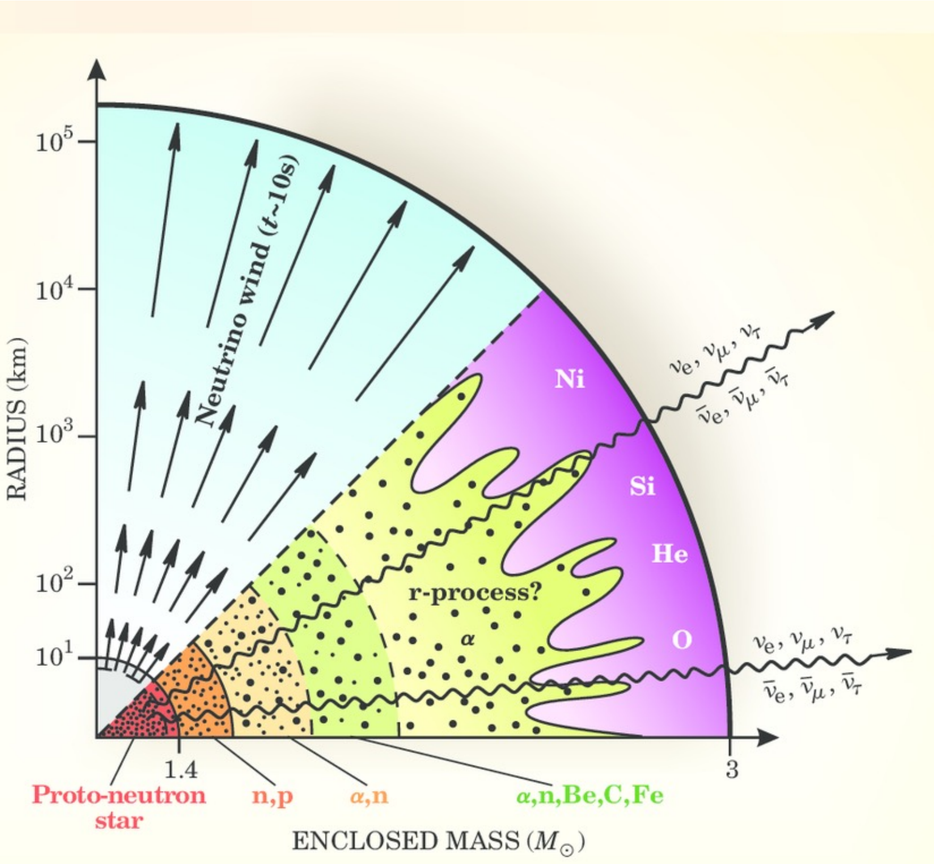
Supernovae as the *r*-process source? Simulations and neutrino-driven winds (NDWs)



Woosley&Janka 06; see also Panov&Janka 08

Neutrinos set the neutron to proton ratio

$$Y_e = \frac{n_p}{n_p + n_n}$$

via weak interactions

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

and the influence of these reactions depends on the neutrino luminosities and average energies

Supernovae as the *r*-process source?
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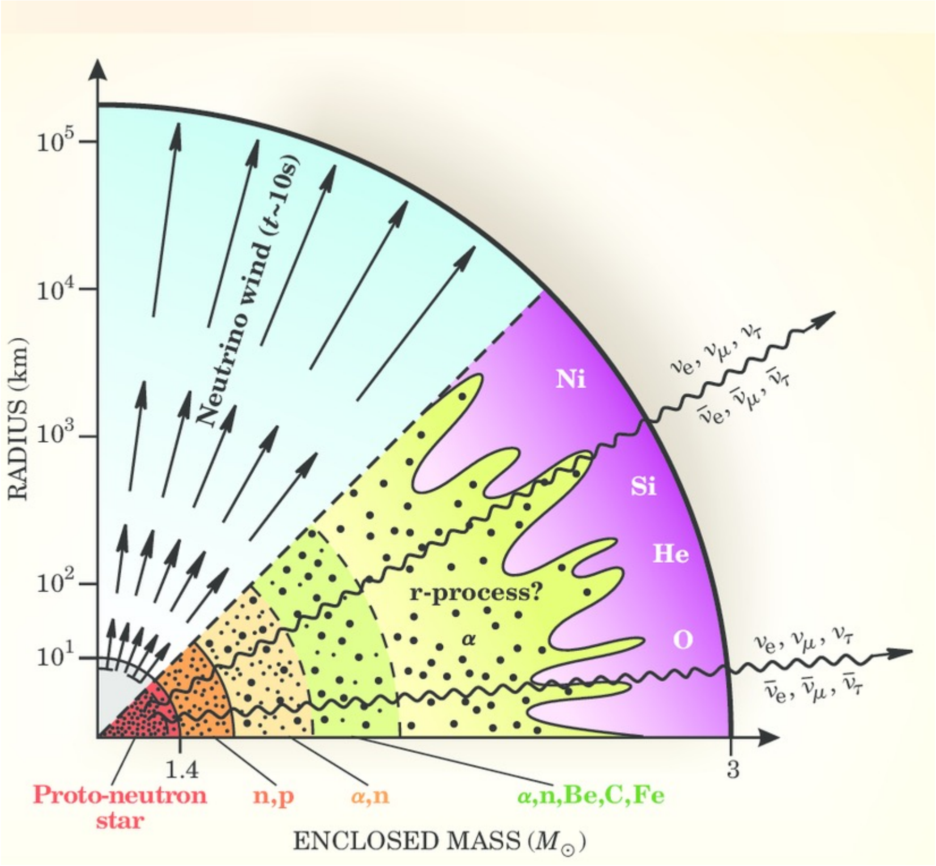

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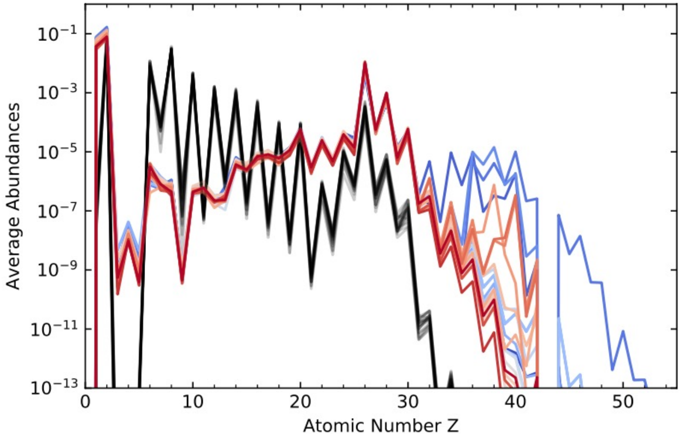
Conditions which synthesize A>130 are not found by most modern core-collapse SNe simulations (e.g. Arcones+07, Wanajo+09, Fischer+10, Hüdepohl+10)

In such events other processes such as (α,n) and νp process could reach up to A~100 (e.g. Pruet+06, Fröhlich+06, Bliss+18)

Recent simulations find some cases develop NDWs but not standard feature for successful explosions



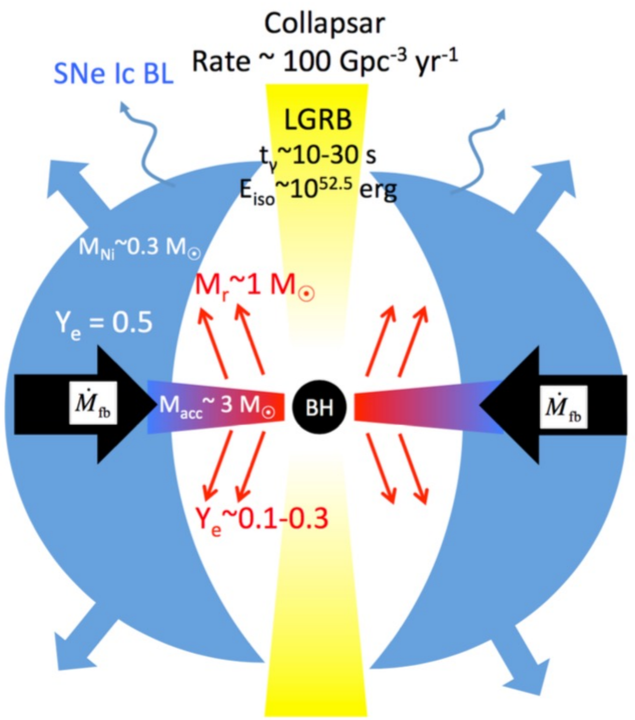
All exploding 15 $M_\odot$ models

Witt+21

Some candidate sites for *r*-process element production

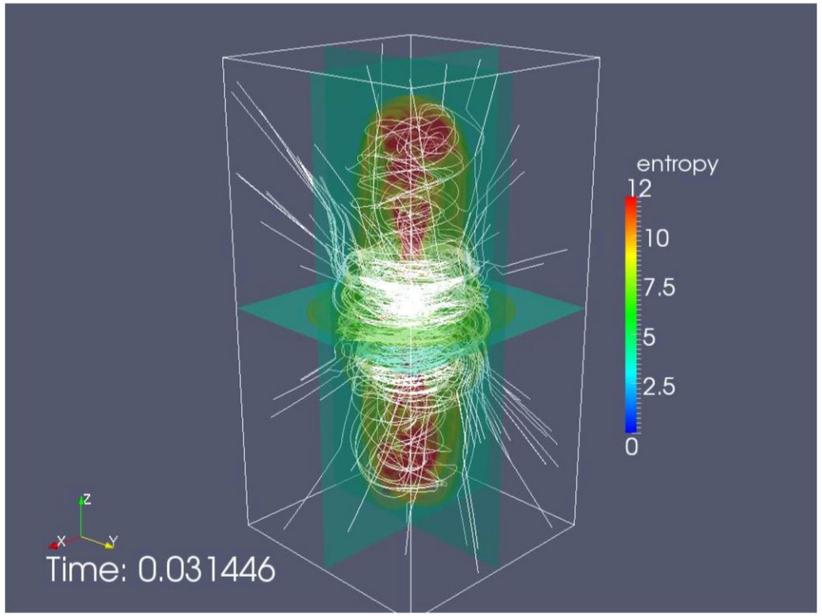
Neutron star mergers

Collapsar disk winds



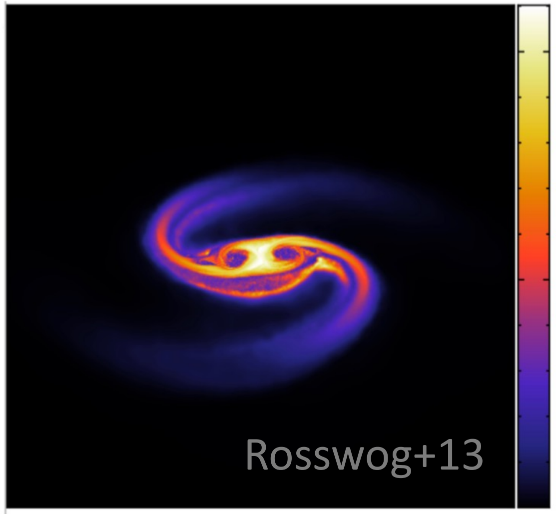
Siegel+18; see also McLaughlin&Surman 05, Miller+19

Magneto-rotationally driven (MHD) supernovae



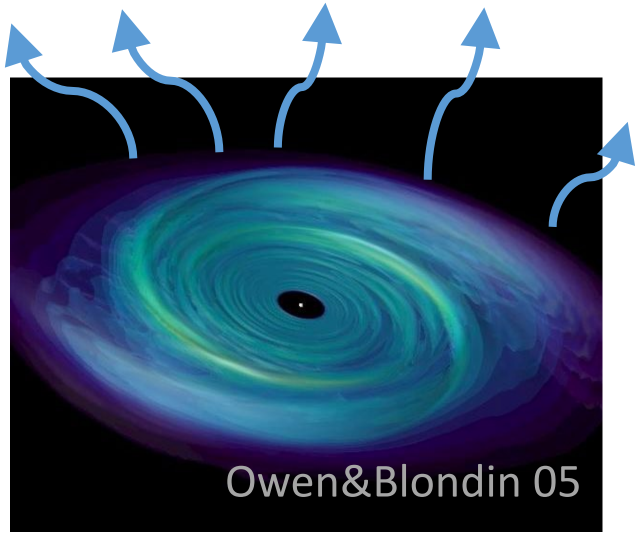
Winteler+12; see also Mosta+17, Reichert+21

Dynamical ejecta



Increasingly n-rich

Post-merger disk winds



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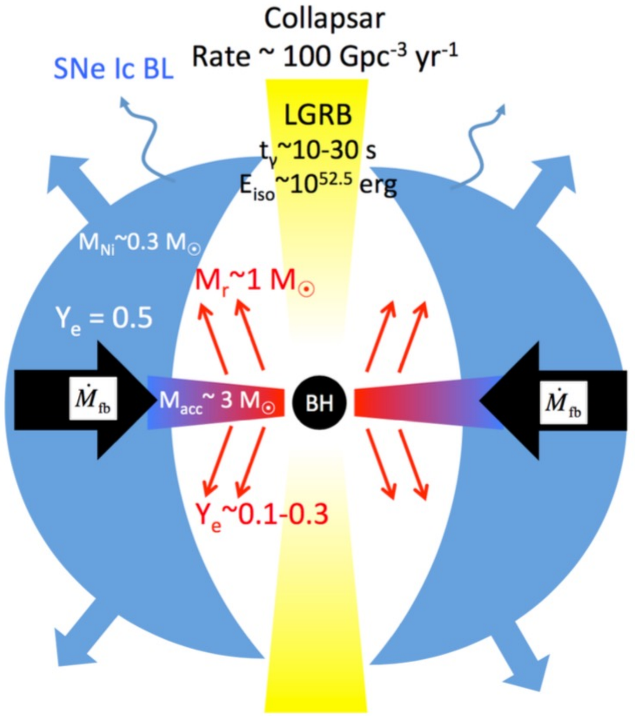

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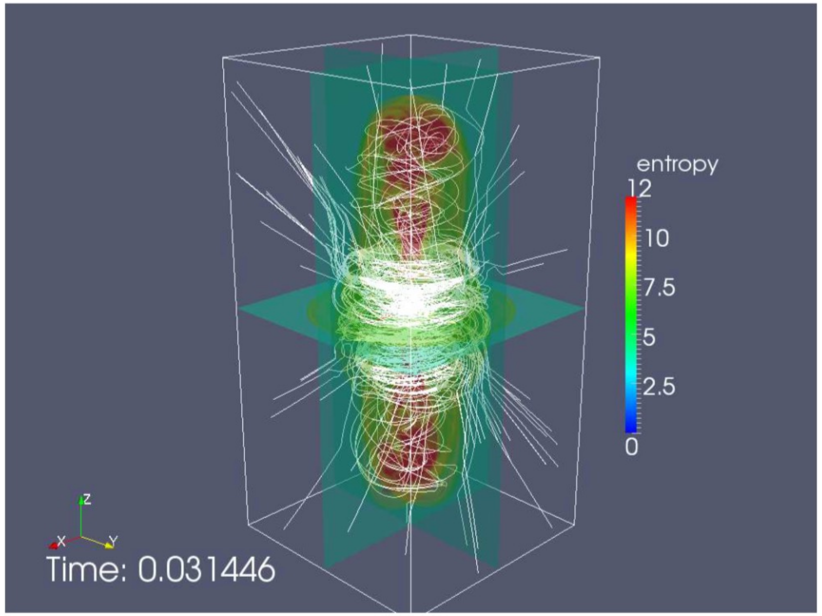

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Neutron star mergers

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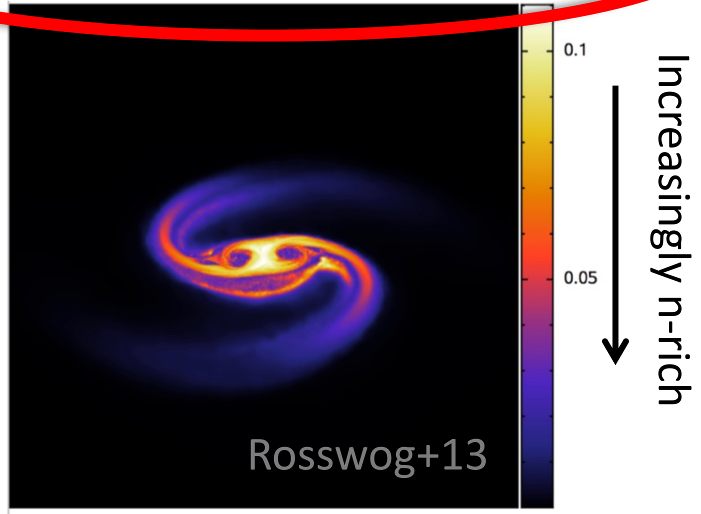

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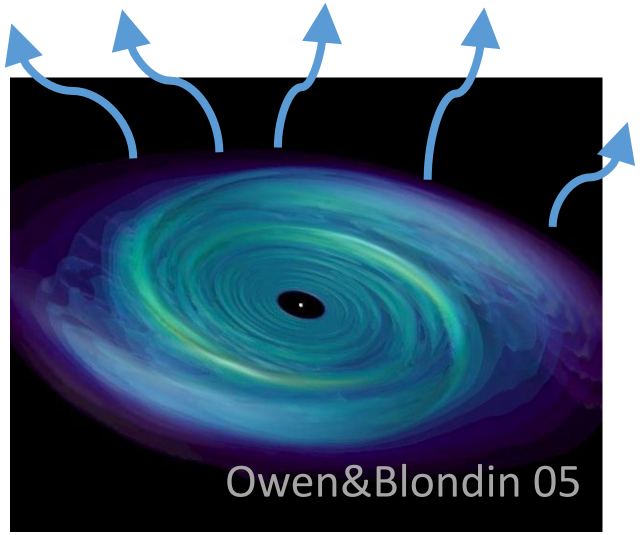
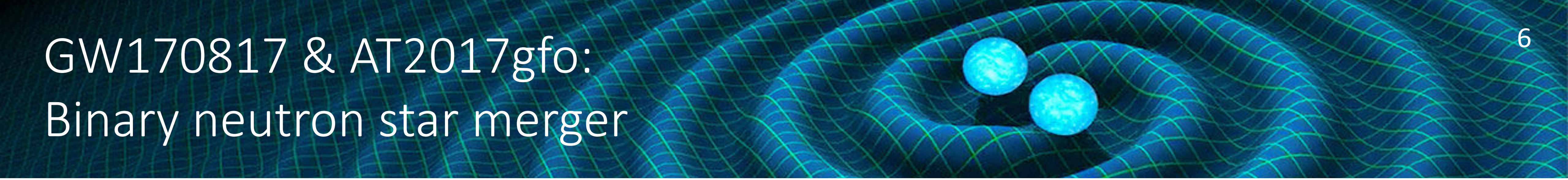
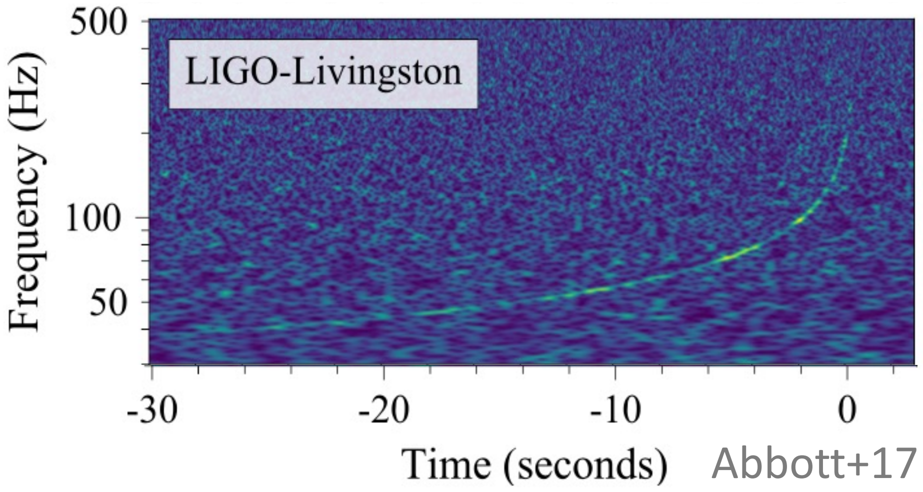




GW170817 & AT2017gfo: Binary neutron star merger

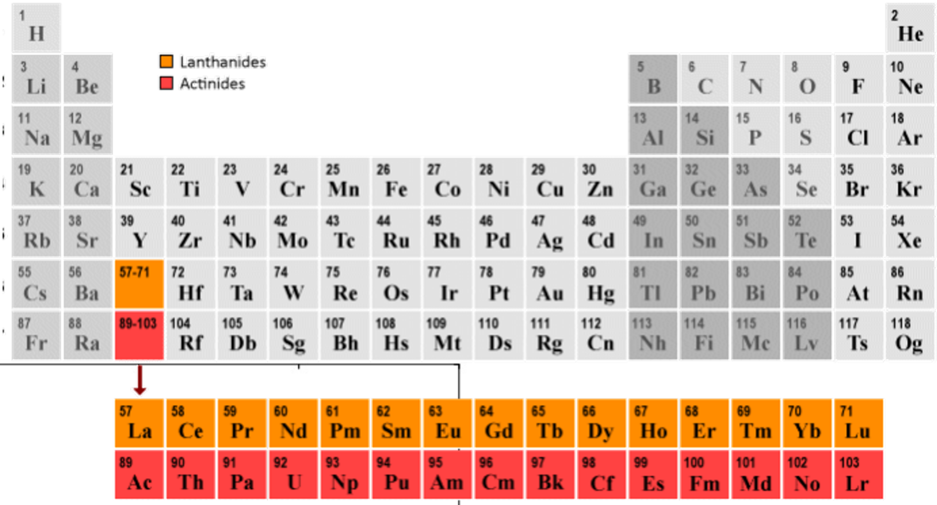
Gravitational wave signal



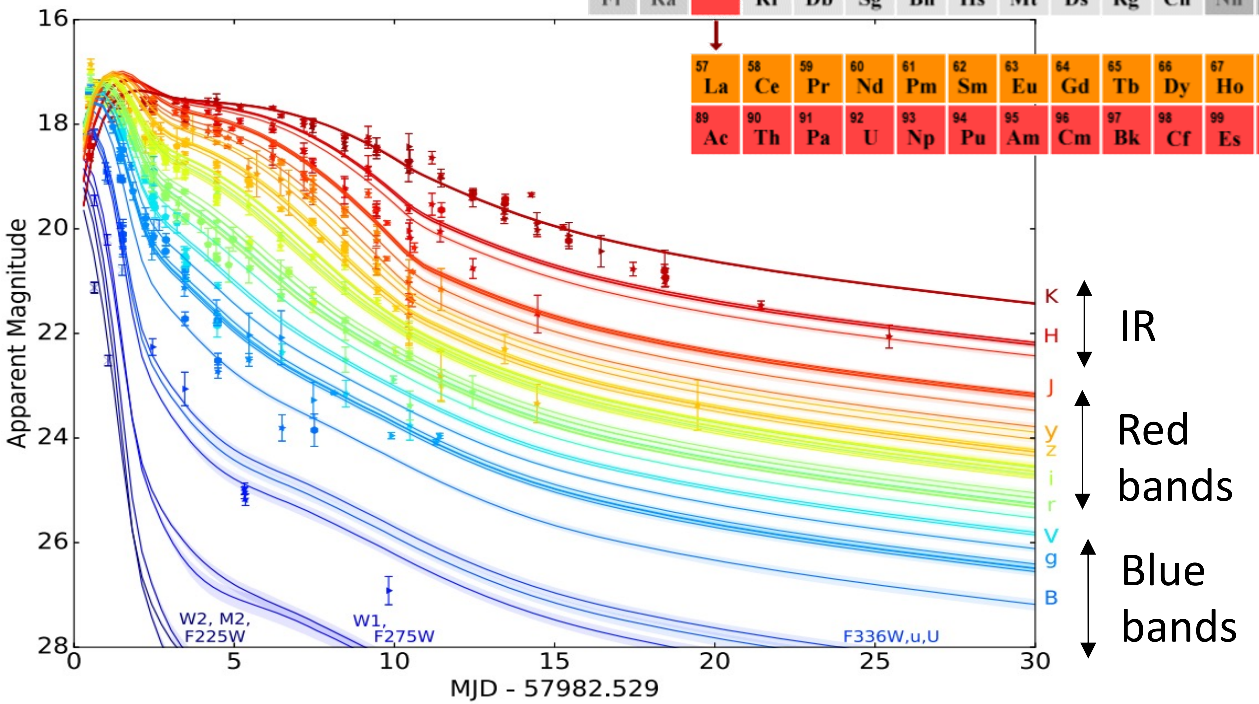
Abbott+17

Over ~70 observing teams (~1/3 of the worldwide astronomical community) followed up on the merger event!

Lanthanide and/or actinide mass fraction ↑, opacity ↑, longer duration kilonova light curve shifted toward infrared



Kilonova light curve



Villar+17

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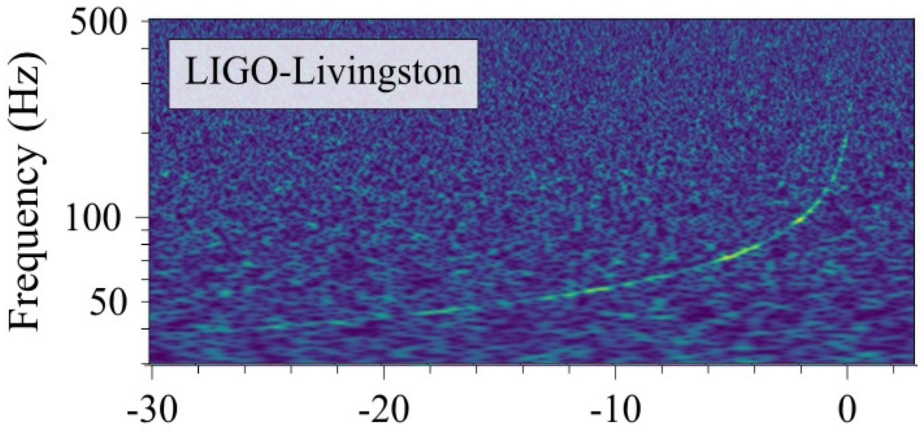
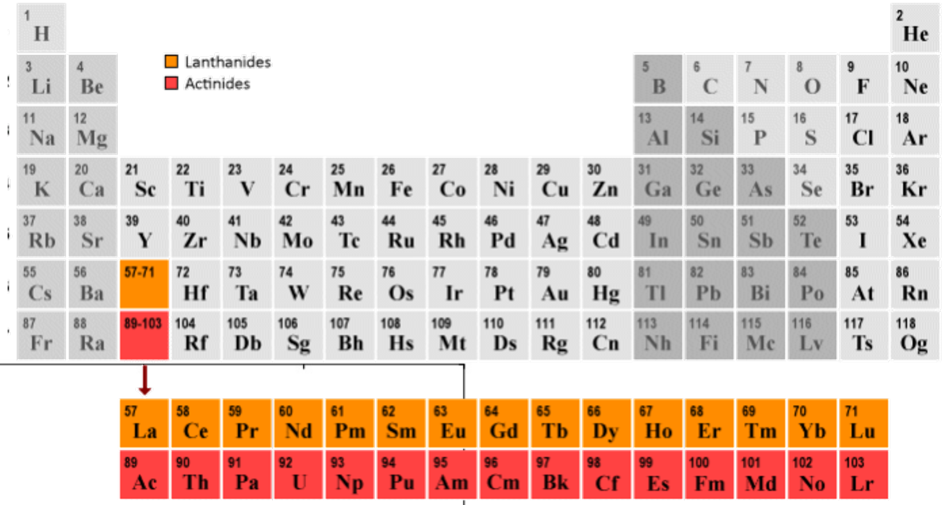


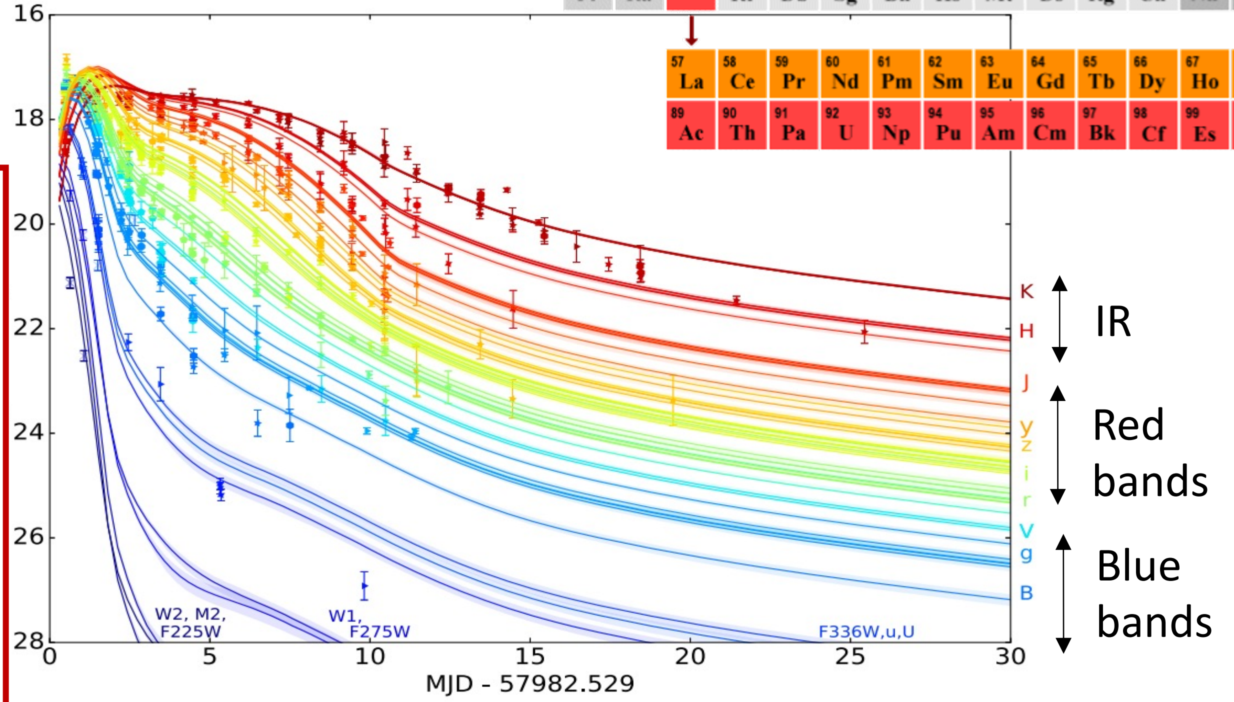
The first ever confirmation that neutron star mergers make at least some heavy elements!

But…

- How representative is this one NSM event?
- Do mergers explain the *r*-process enrichment of the Solar System and the Milky Way?
- Do merger make elements heavier than lanthanides such as gold and uranium?

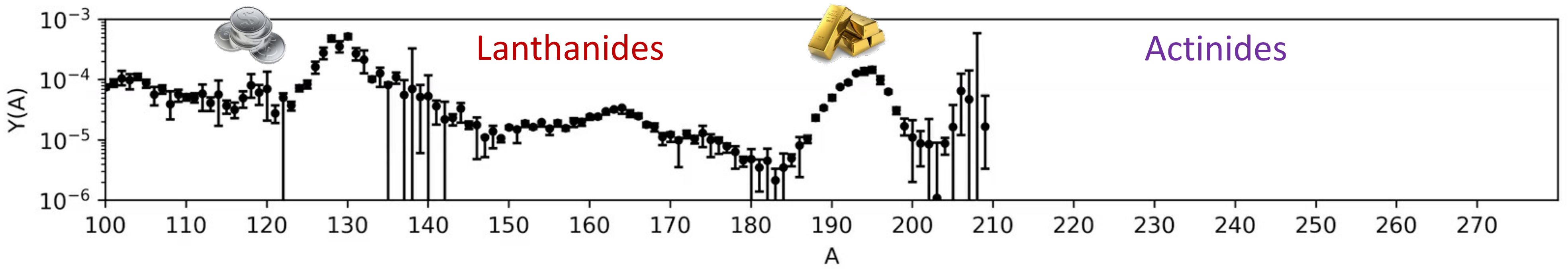


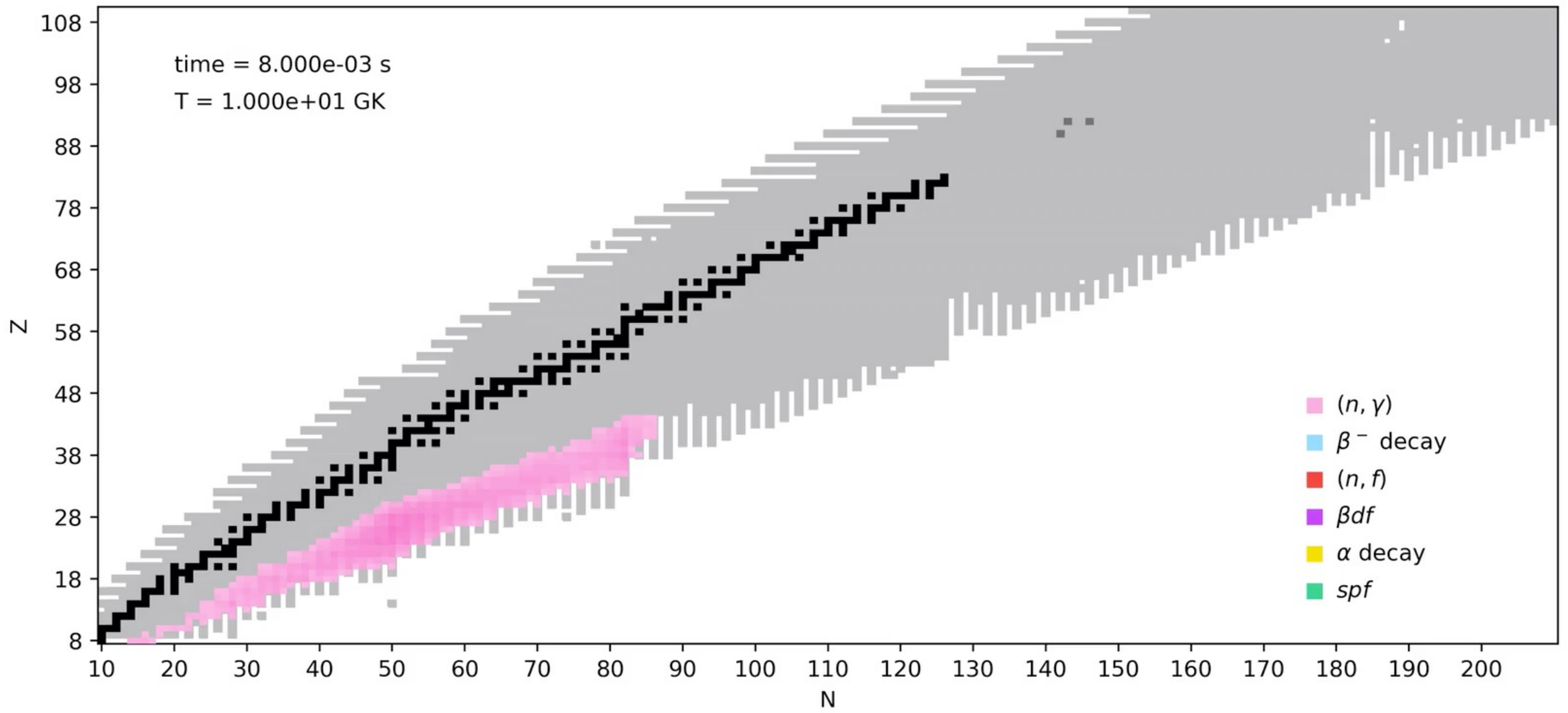
Kilonova light curve



Villar+17

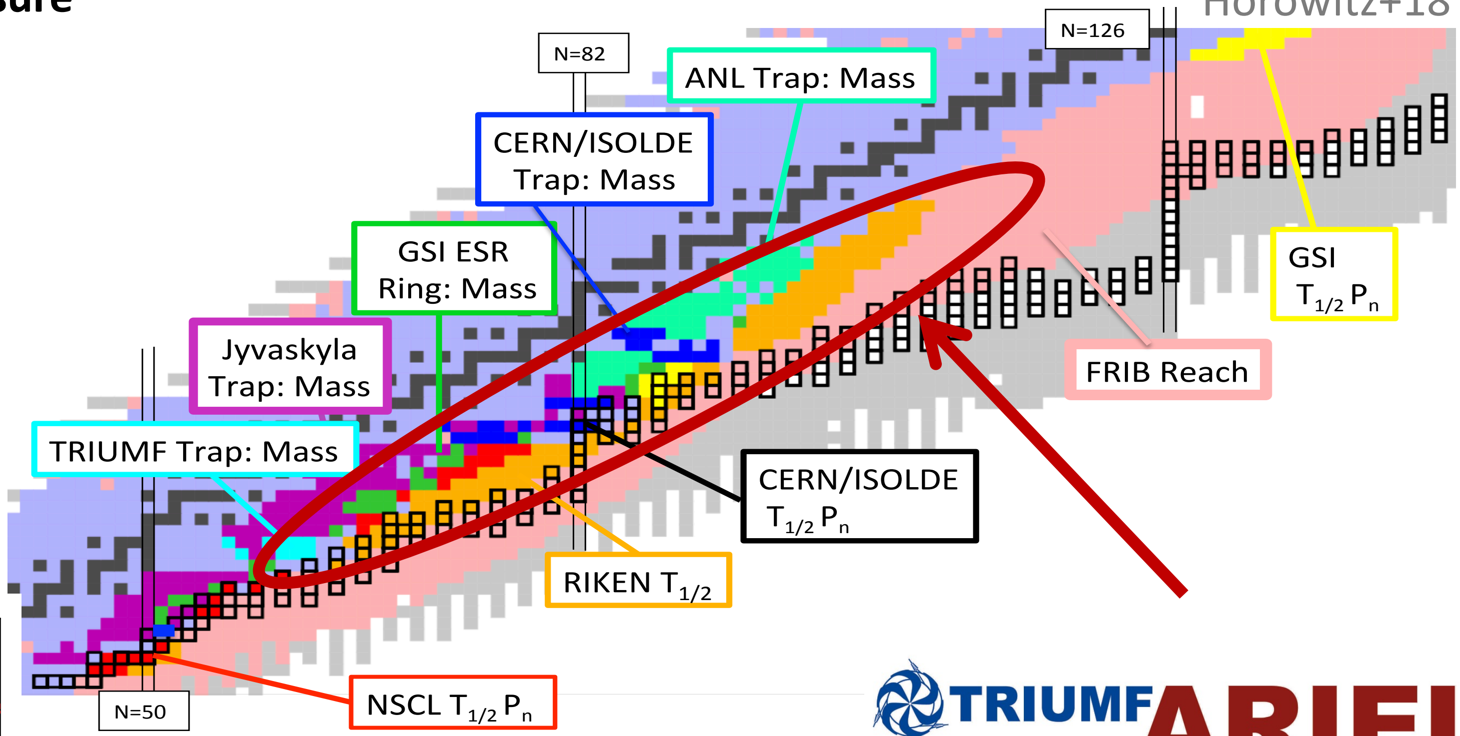
r-process outcomes depend on nuclear physics



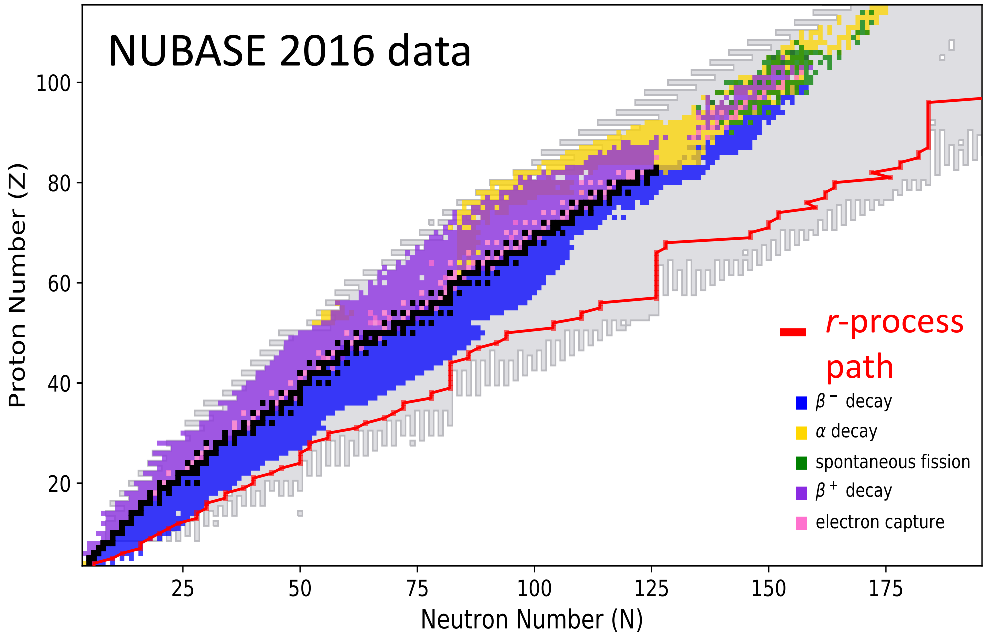


Movie by Vassh

Worldwide experimental campaigns to measure the properties of neutron-rich nuclei: masses, half-lives, reaction rates, neutron emission probabilities…

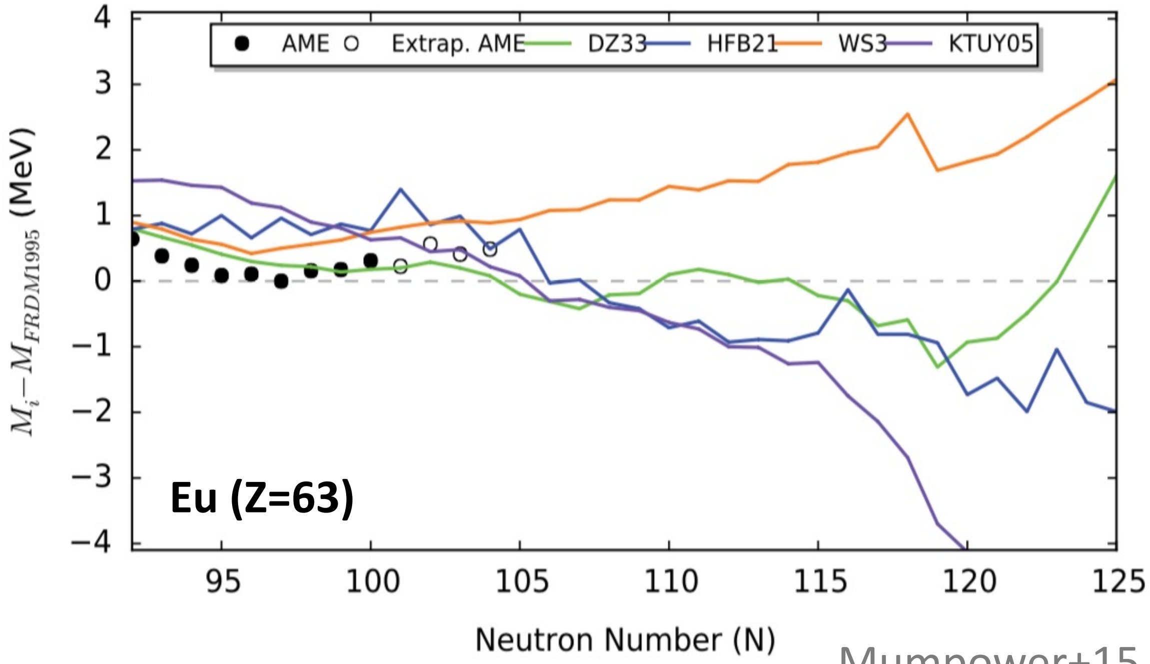


TRIUMF ARIEL
ADVANCED RARE ISOTOPE LABORATORY



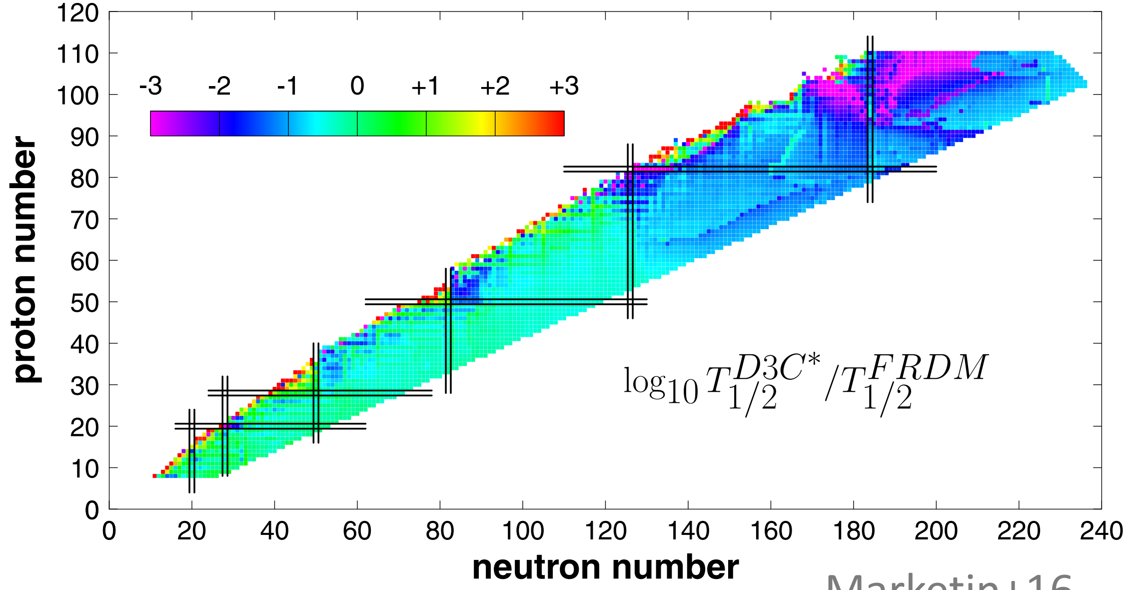
Theory developments:
Structure theory (masses, deformation, level densities…), reaction theory (capture cross sections…), fission yields and rates, and β-decay rates….

Modeling masses all the way to the dripline



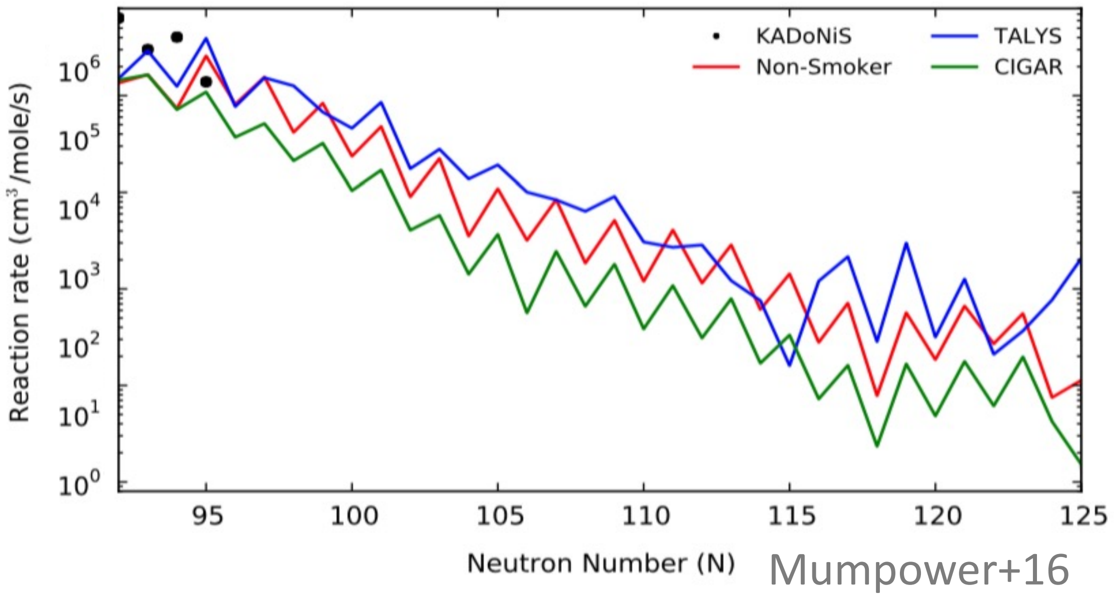
Mumpower+15

β-decay calculations



Marketin+16

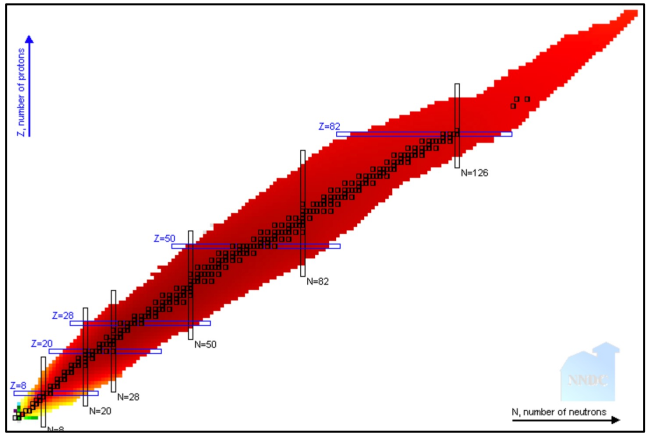
Neutron capture models



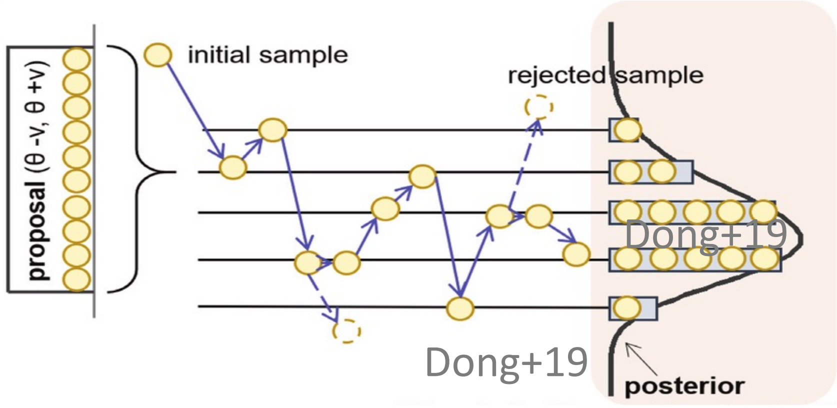
Mumpower+16

Spotlight on the impact of nuclear masses and statistical methods

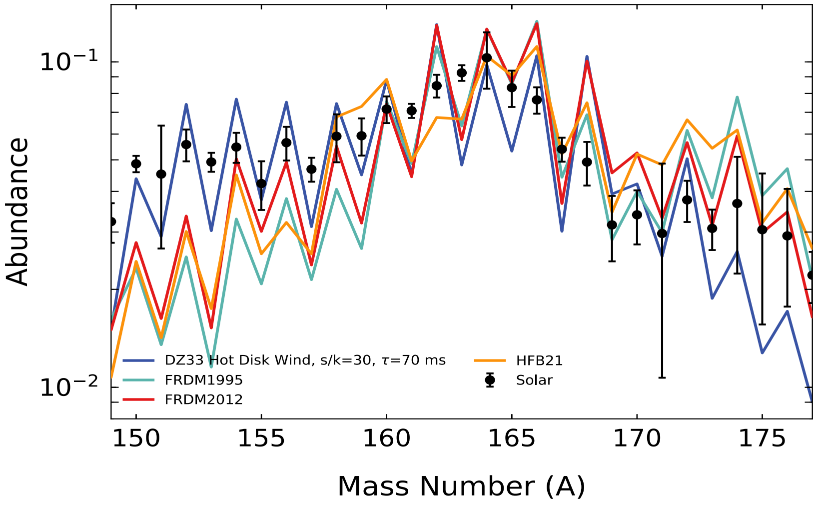
Nuclear masses



MCMC



r-process abundances



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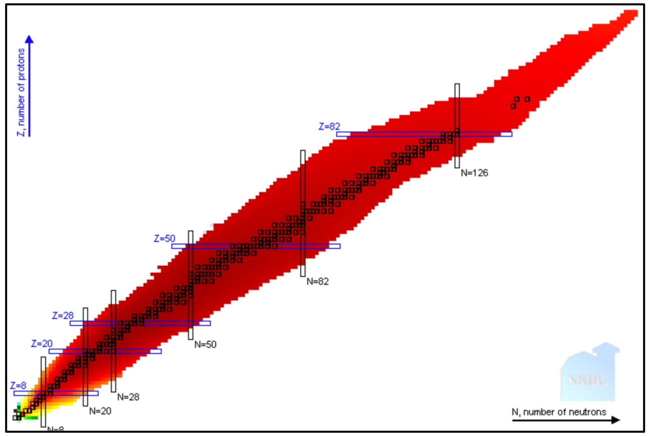

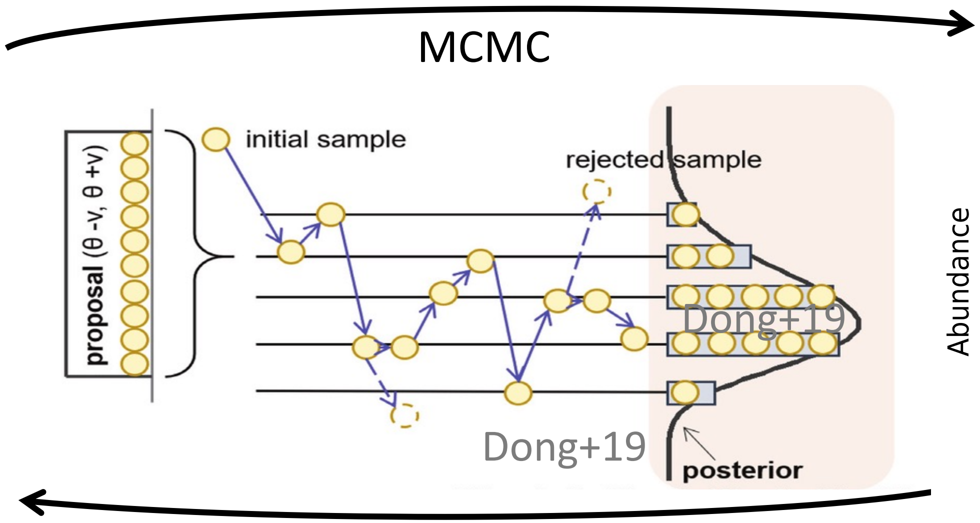

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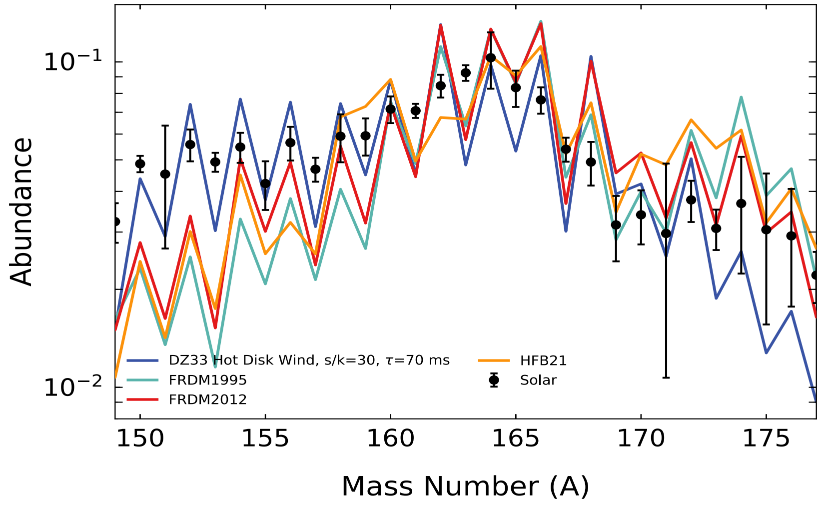
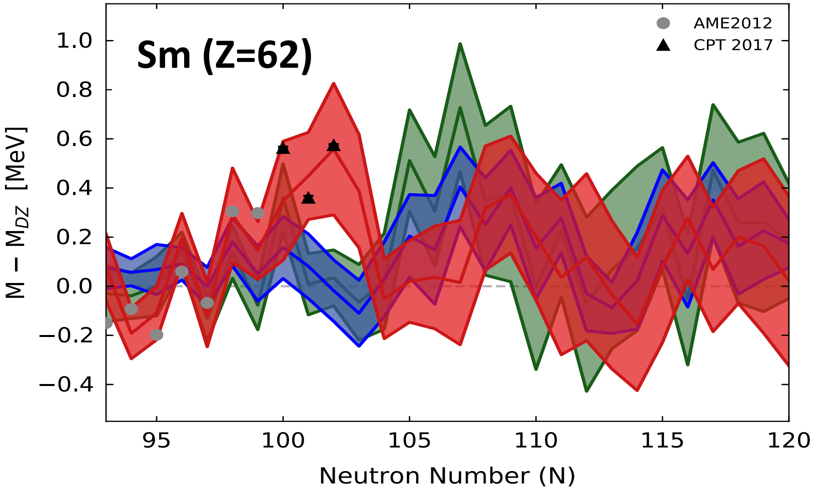
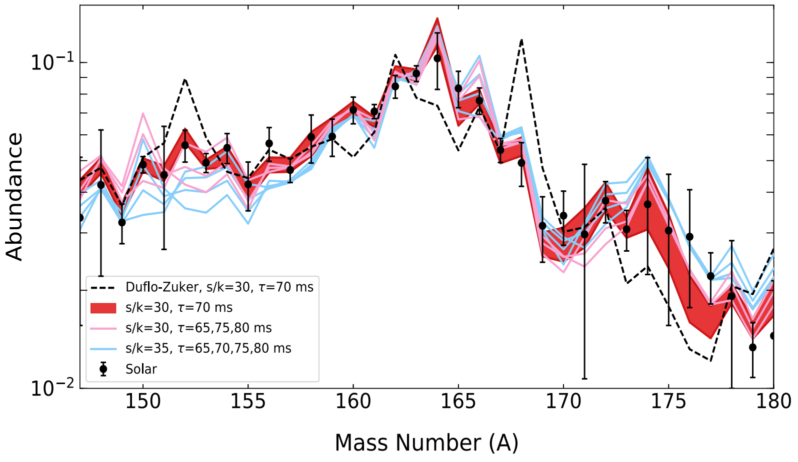






Neutron star merger accretion disk winds (no fission):

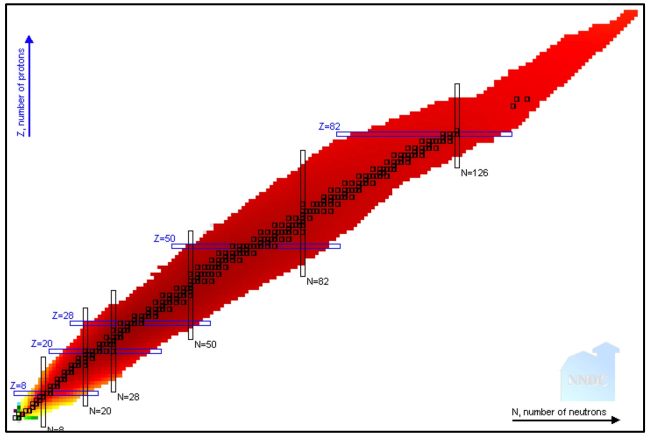
Hot = extended (n,γ)⇆(γ,n) equilibrium

Cold = photodissociation falls out early

Vassh+21 (ApJ); see also Orford,Vassh+18 (PRL)

Spotlight on the impact of nuclear masses and statistical methods

Nuclear masses



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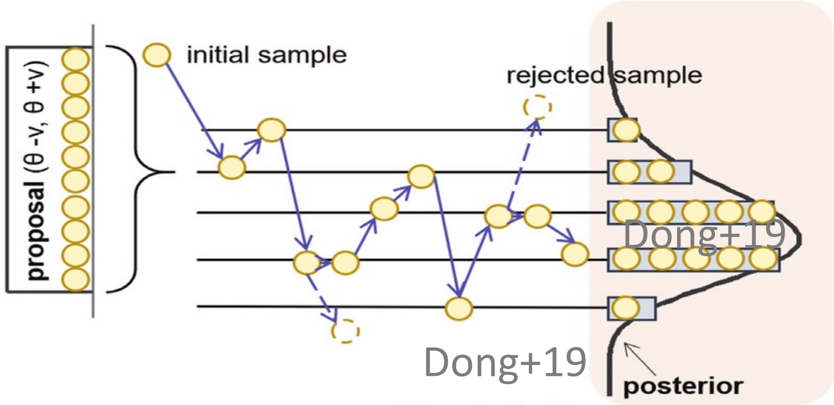

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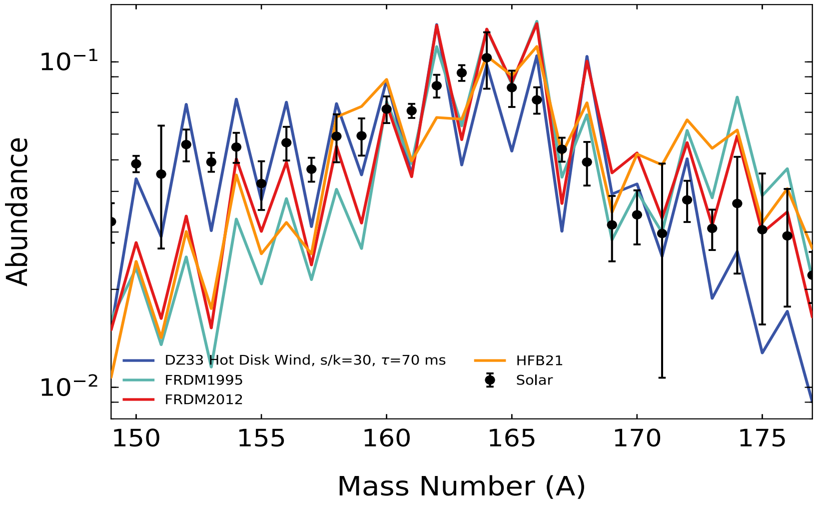
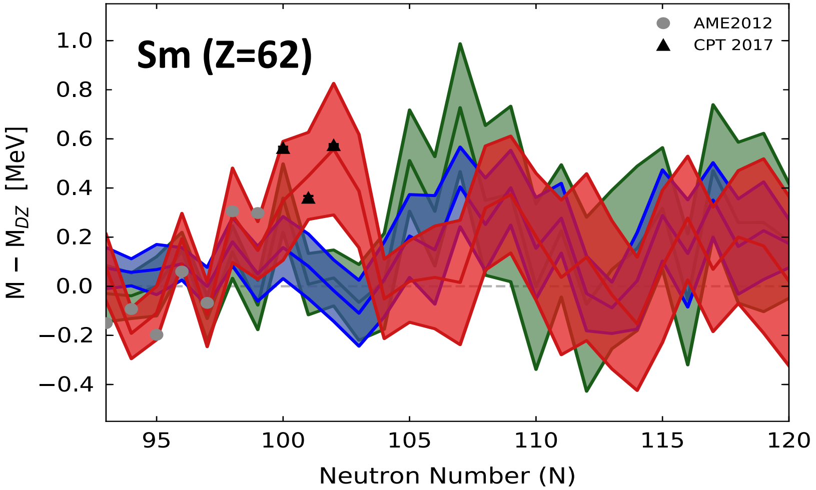
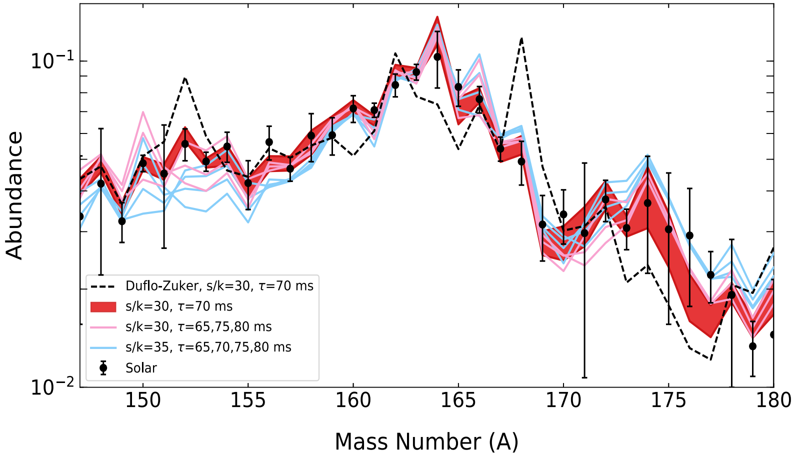




*We have now applied our method to astrophysical conditions which synthesize fissioning nuclei!
Vassh+22 (to be submitted soon)



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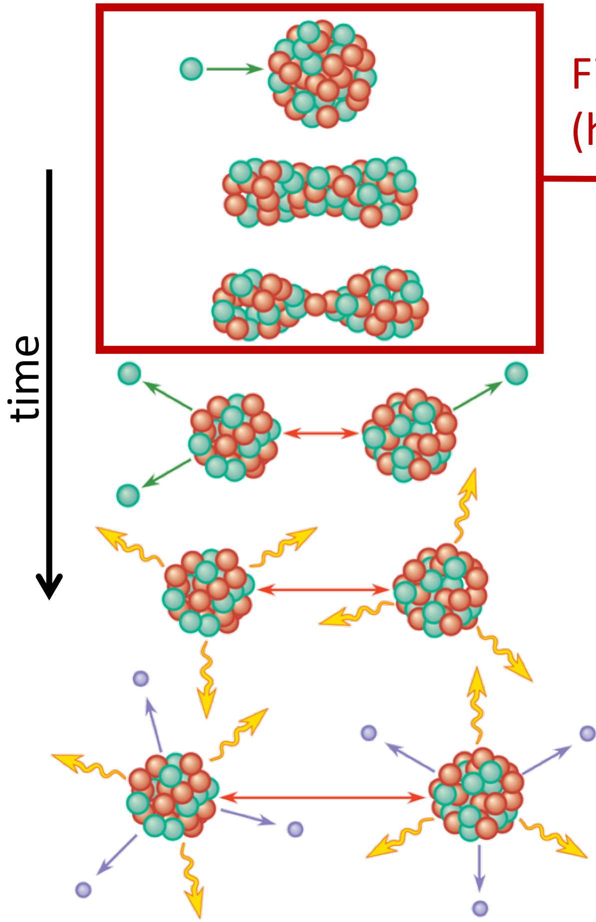
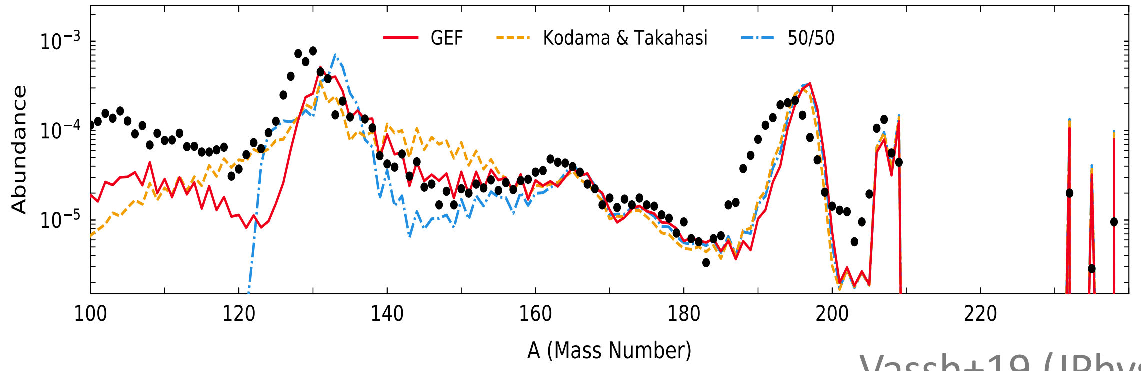
Actinides in mergers? Spotlight on nuclear fission in astrophysics

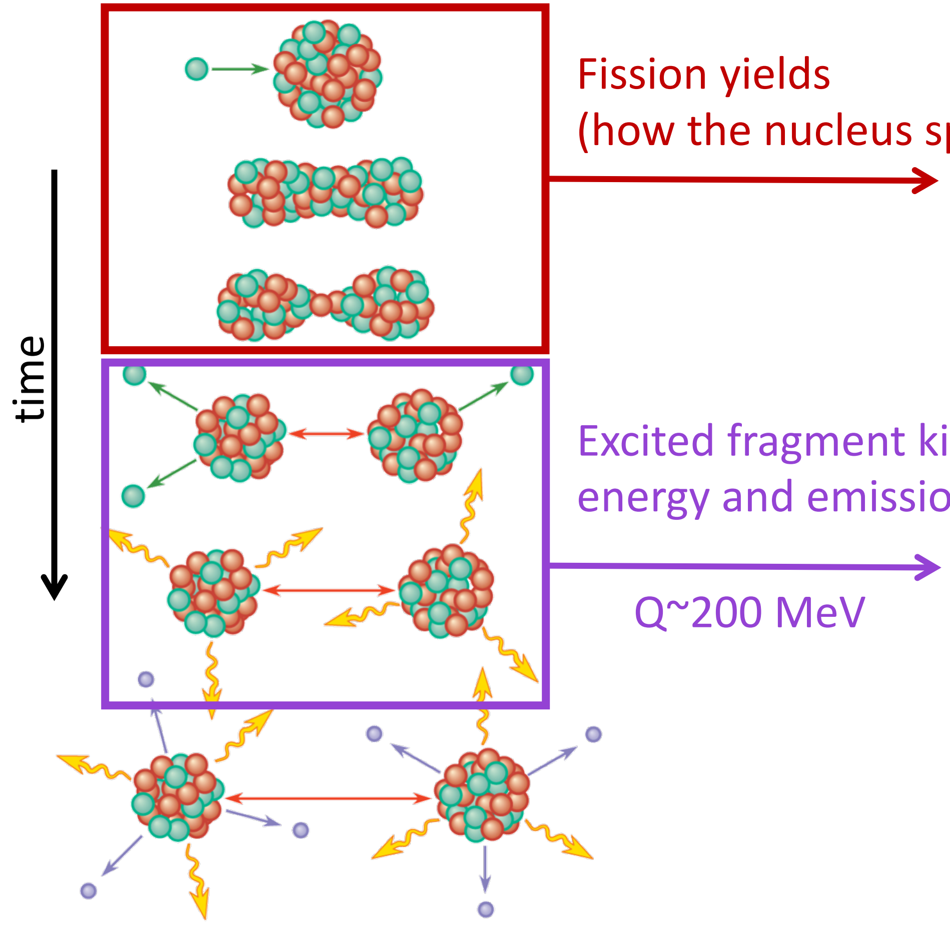


Fission yields
(how the nucleus splits)



Vassh+19 (JPhysG)

Actinides in mergers? Spotlight on nuclear fission in astrophysics



Fission yields
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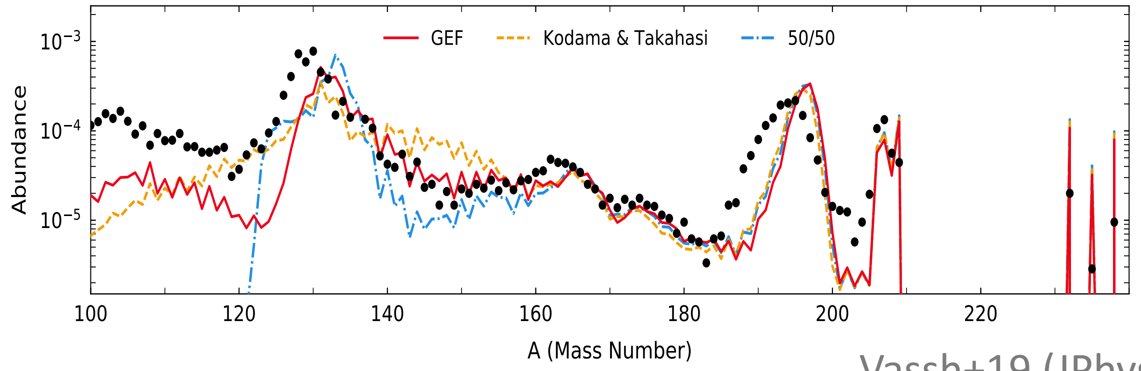
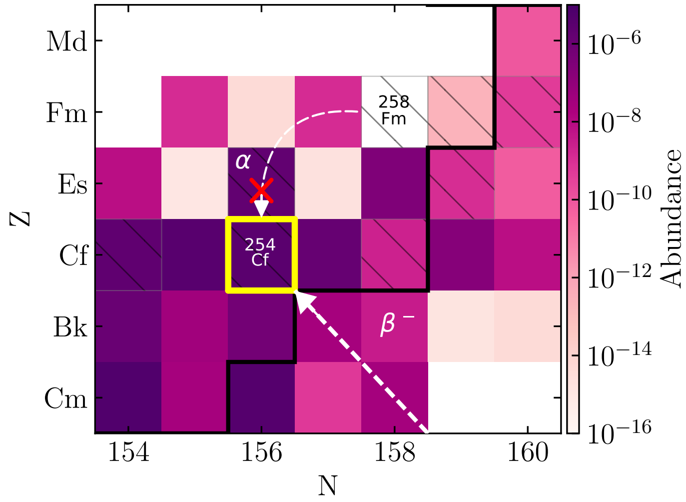
Excited fragment kinetic energy and emission

Q~200 MeV

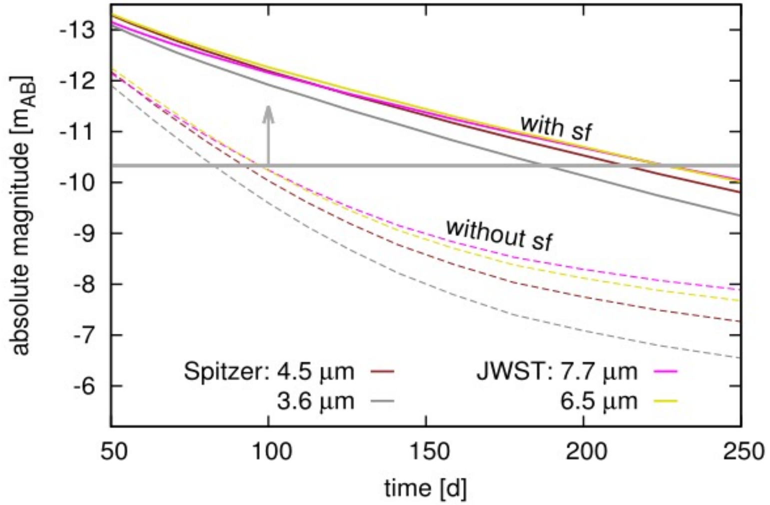


Vassh+19 (JPhysG)

Cf-254 has measured half-life ~60 days



Predicted kilonova light curve with and without late time Cf heating

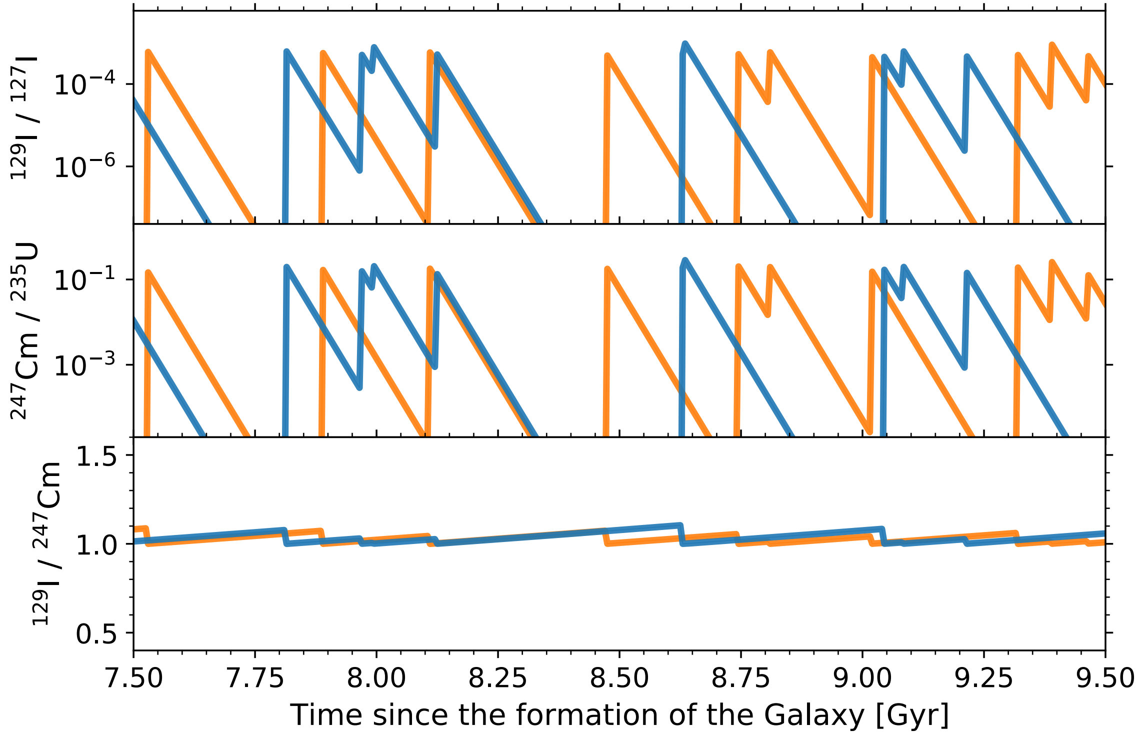


Zhu+18 (including Vassh)(ApJ Letters)

The last *r*-process event in our solar system

Only 4 radioactive isotopes in meteorites linked to *r* process with $T_{1/2} < 1$ Gyr:

^{129}I	$T_{1/2}$ = 15.7 Myr	^{244}Pu	$T_{1/2}$ = 80 Myr
^{247}Cm	$T_{1/2}$ = 15.6 Myr	^{235}U	$T_{1/2}$ = 700 Myr



Côté+21 (including Vassh) (Science)

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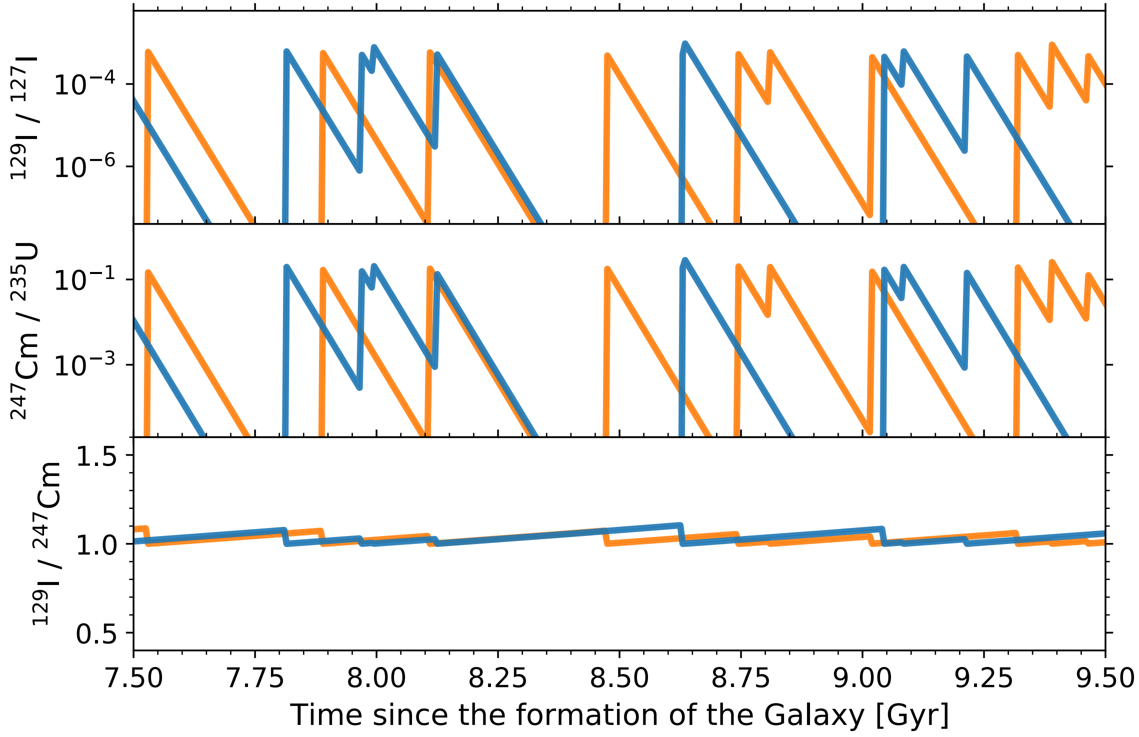
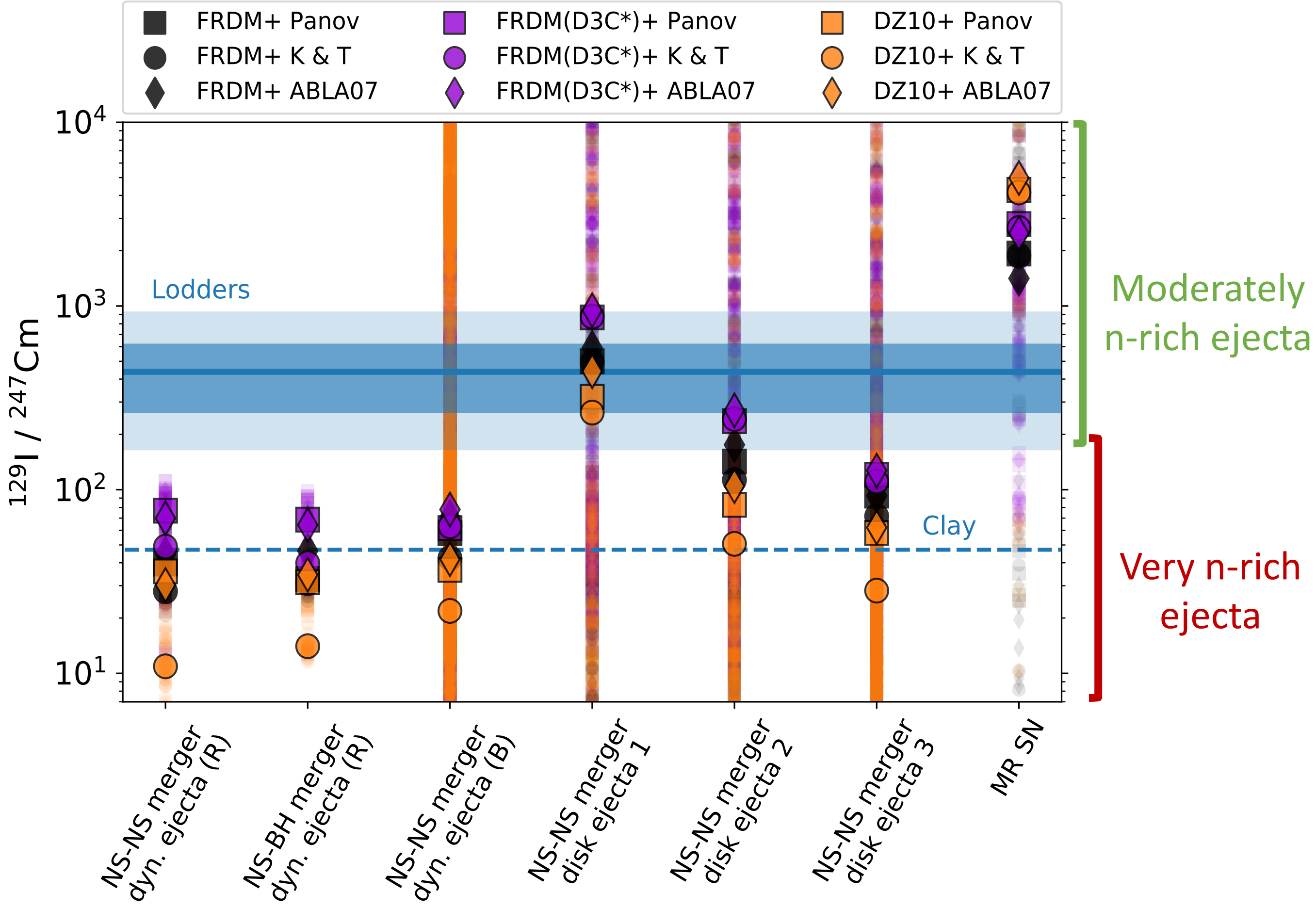
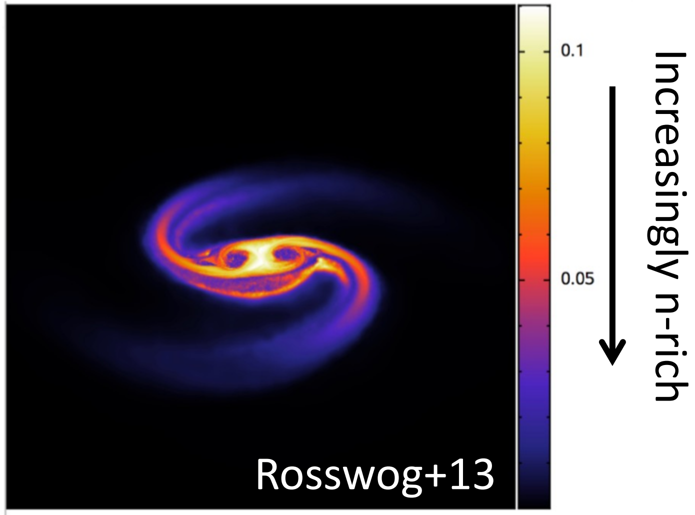




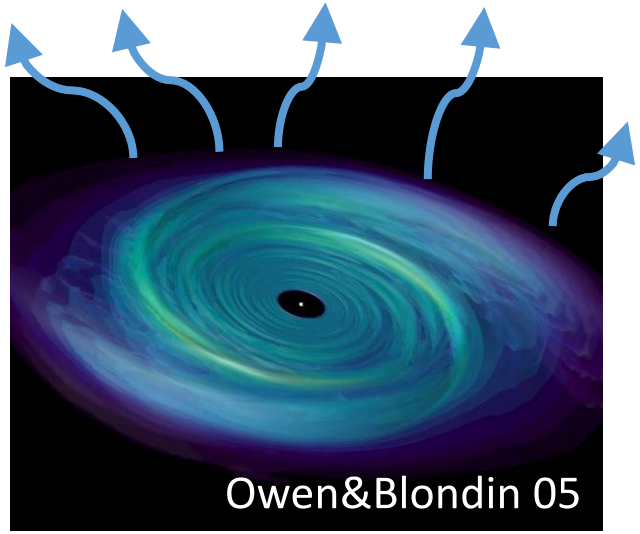
Côté+21 (including Vassh) (Science)

Impact of neutrino physics treatment in *r*-process sites

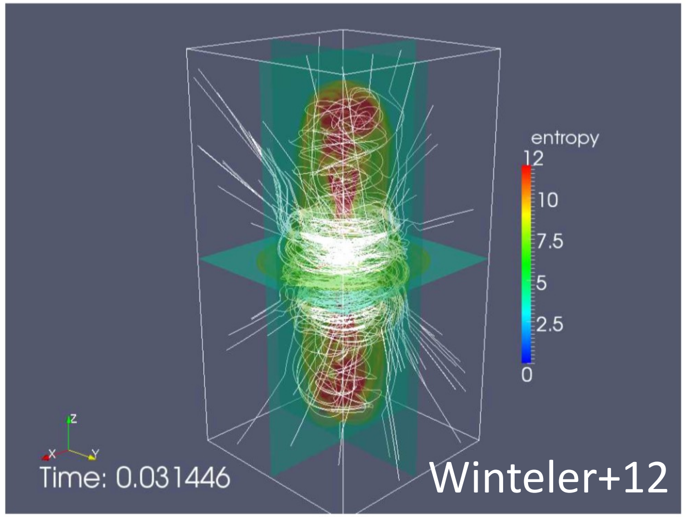
NSM Dynamical Ejecta

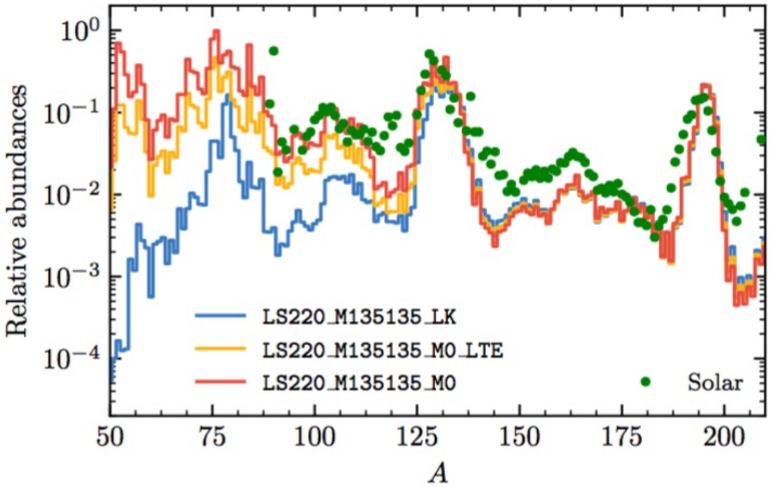


Accretion Disk Winds

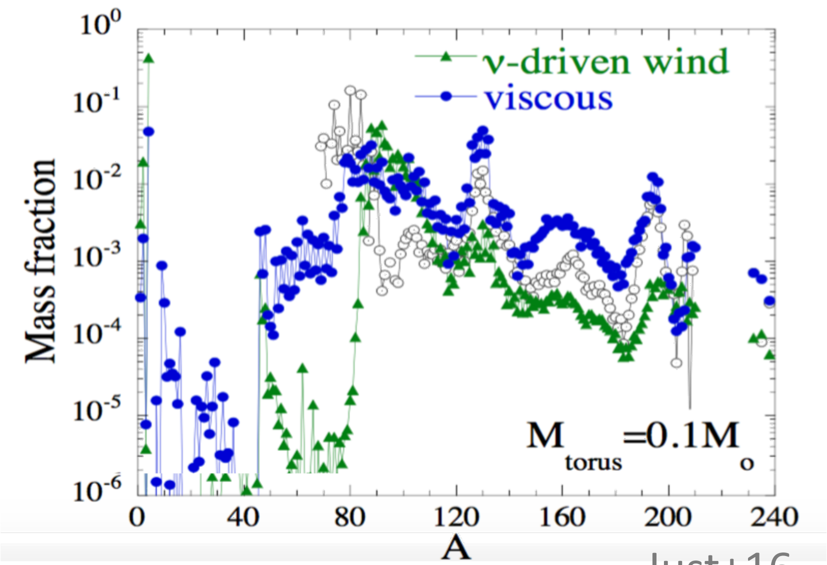


MHD Supernovae

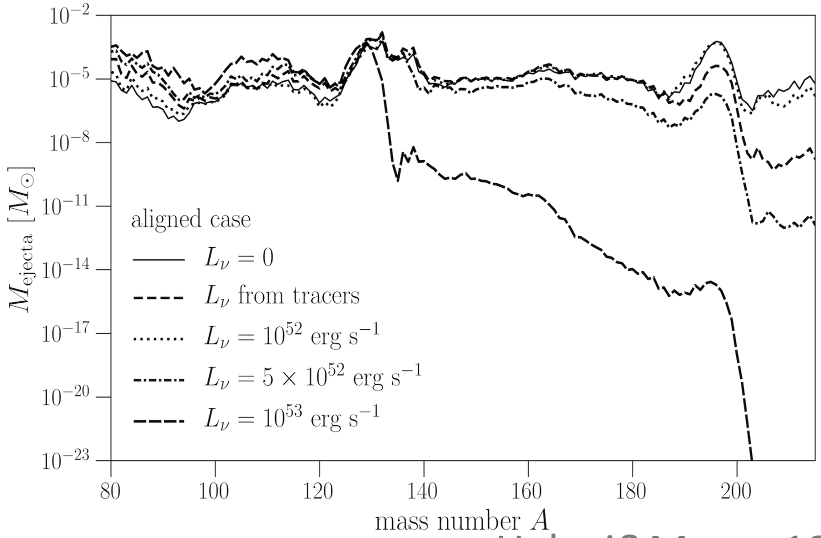




Radice+19; also Perego+19



Just+16



Halevi&Mosta 18

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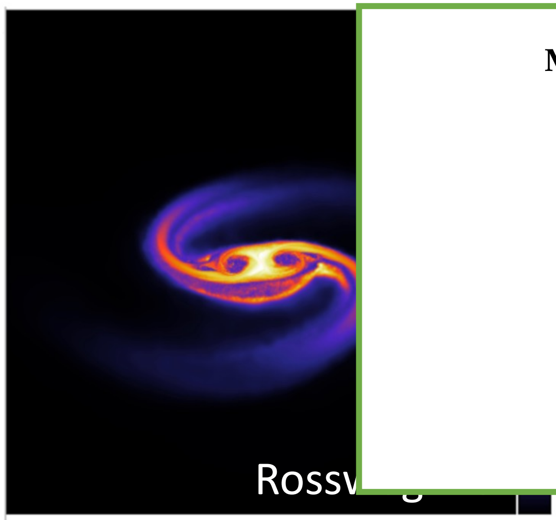
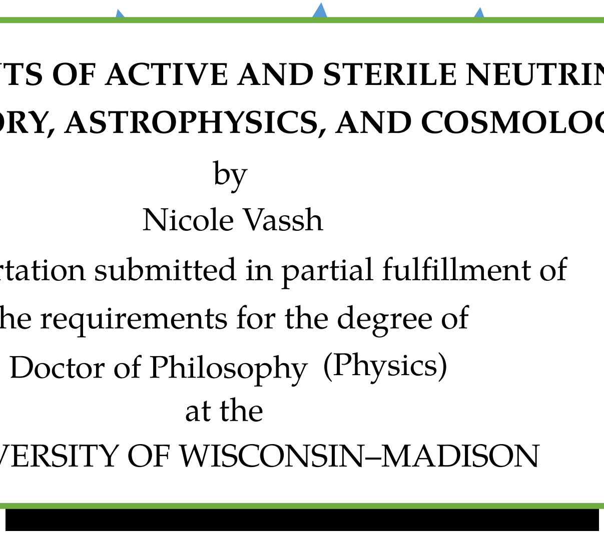
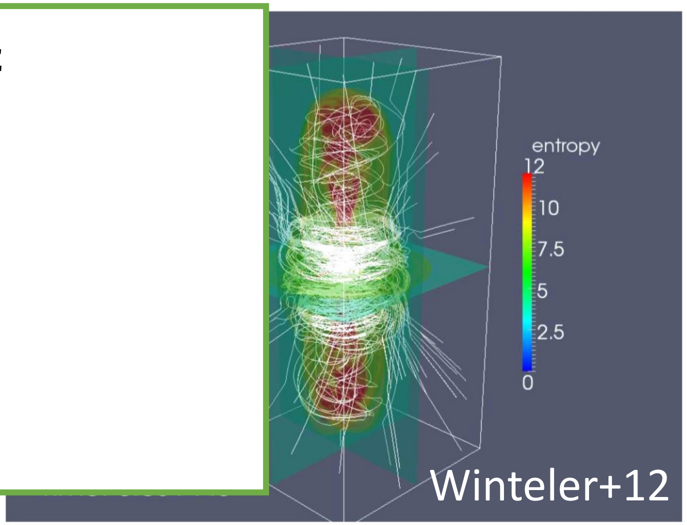
MHD Supernovae

MAGNETIC MOMENTS OF ACTIVE AND STERILE NEUTRINOS IN THE LABORATORY, ASTROPHYSICS, AND COSMOLOGY

by

Nicole Vassh

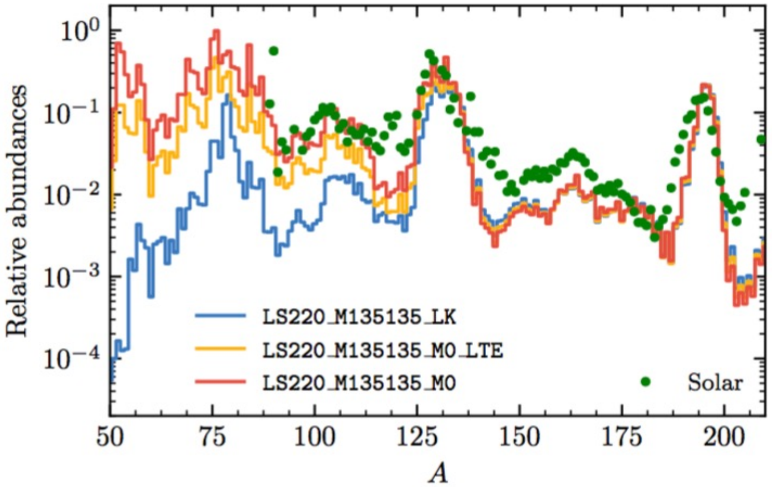
A dissertation submitted in partial fulfillment of

the requirements for the degree of

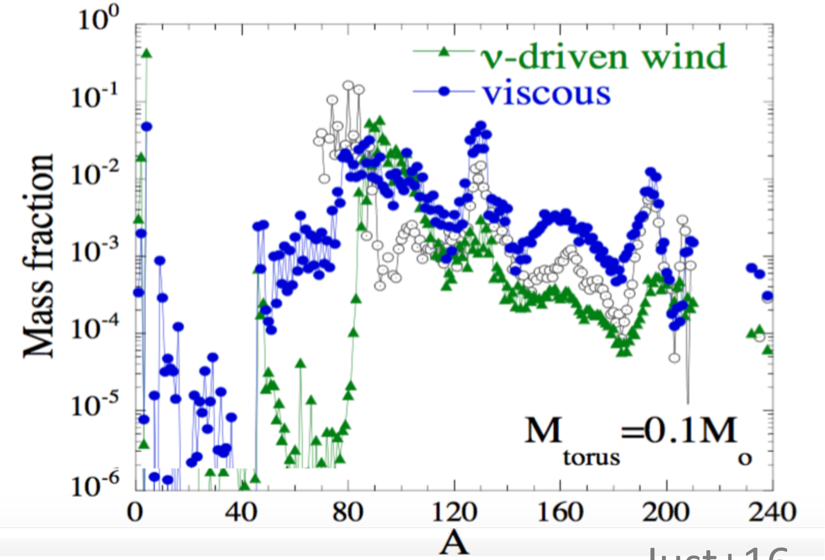
Doctor of Philosophy (Physics)

at the

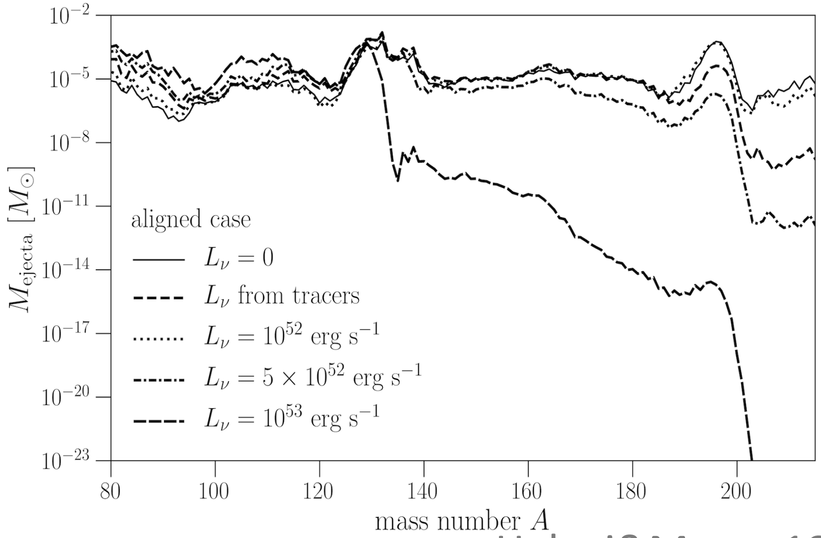
UNIVERSITY OF WISCONSIN–MADISON



Radice+19; also Perego+19



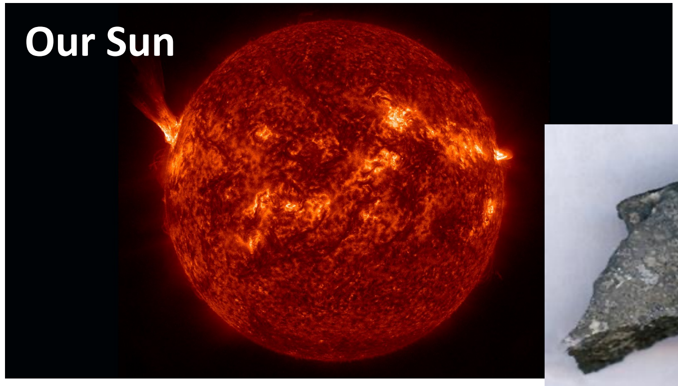
Just+16

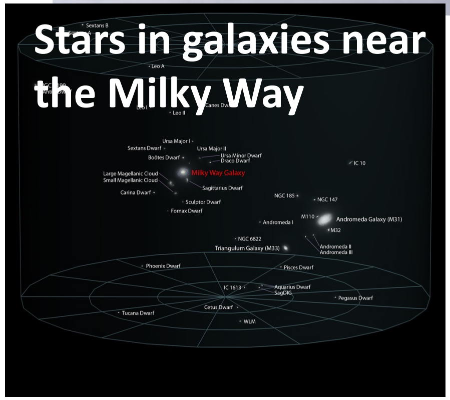


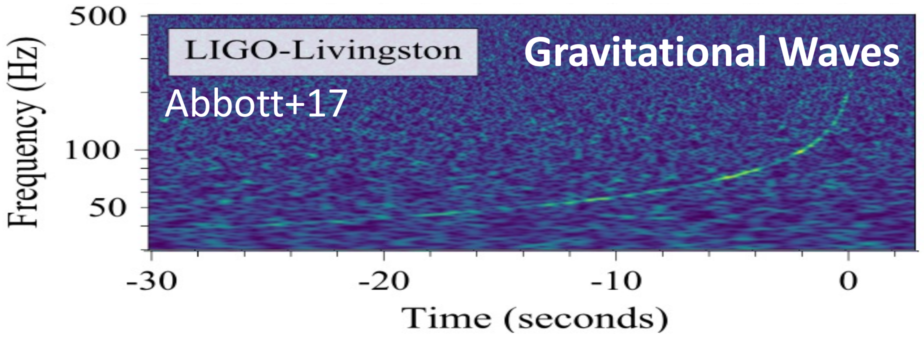
Halevi&Mosta 18

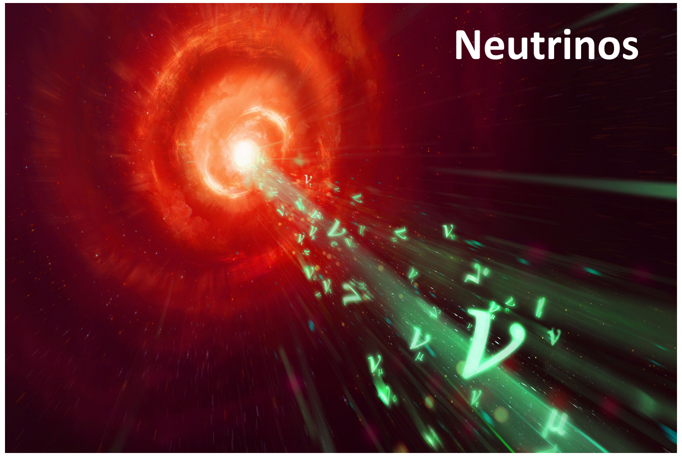
Era of diverse observables and multi-messenger observations

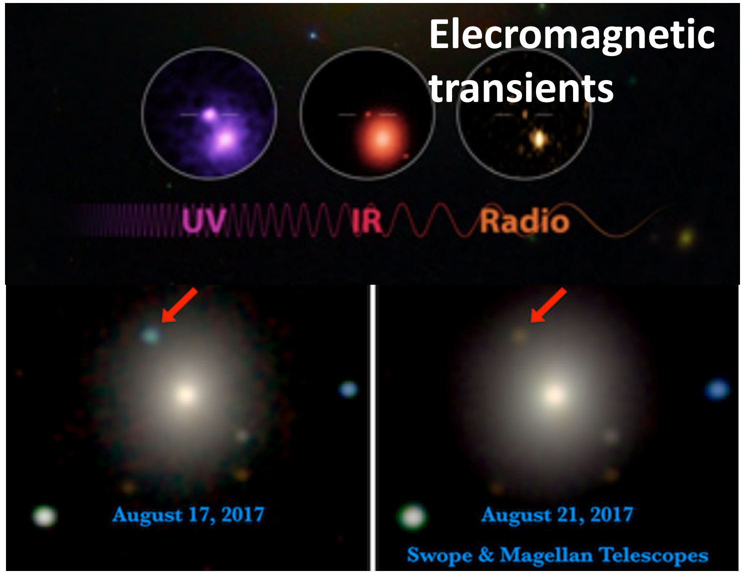
- Our Sun and meteorites are key informants on Solar System element origins
- Stellar abundances of stars in our Milky Way and beyond address the robustness of nucleosynthesis processes
- GW170817 the first observed multi-messenger binary neutron star merger: LIGO begins to provide NSM rates
- Electromagnetic follow-up: AT2017gfo kilonova light curve implied at least lanthanide elements produced
- Neutrinos and light curve seen for multi-messenger event SN1987A and we have bigger and better detectors now!







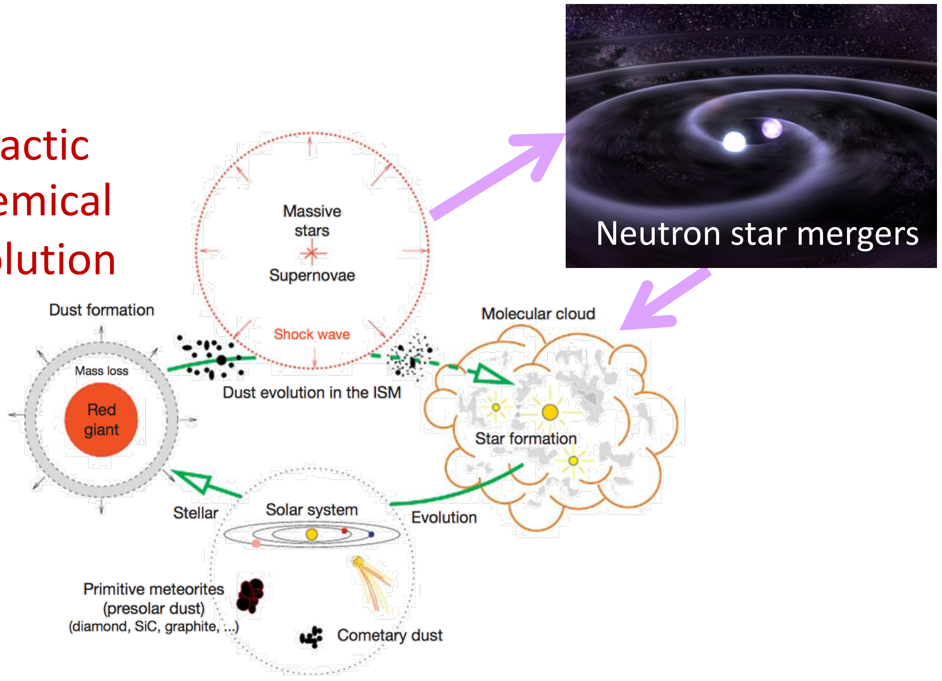




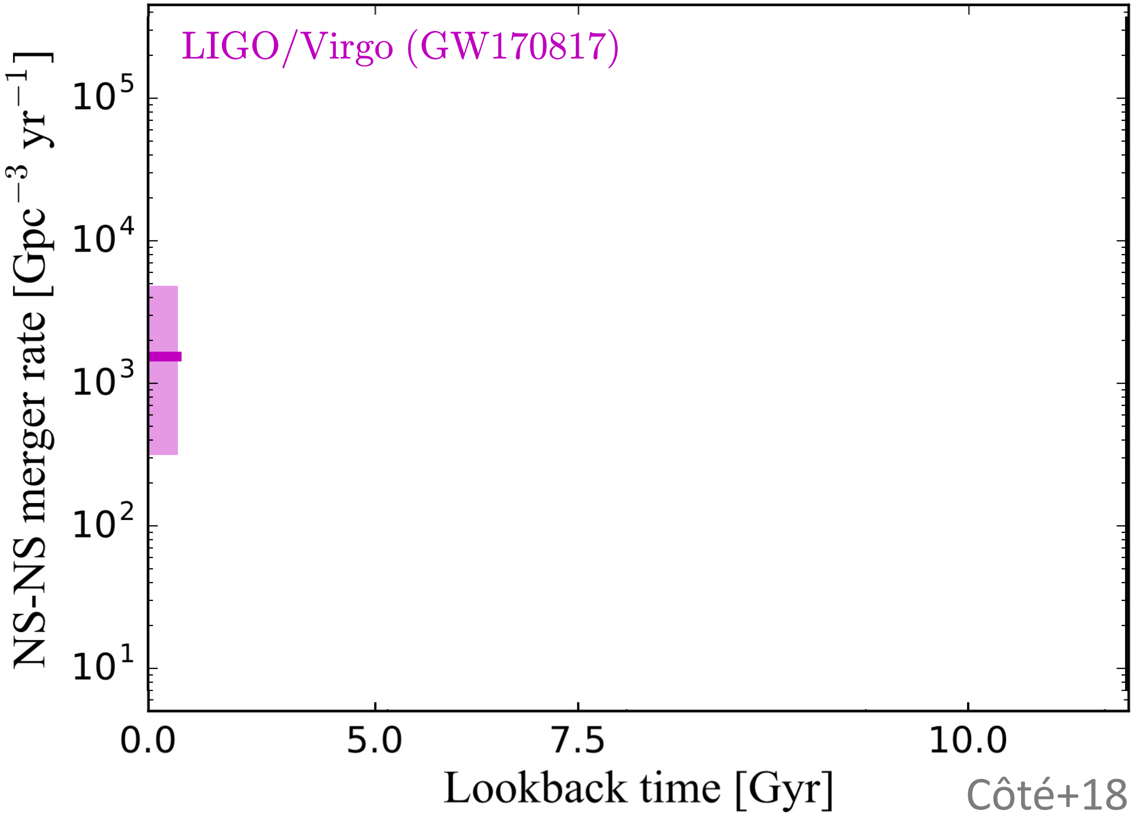
1M2H/UC Santa Cruz and Carnegie Observatories/Ryan Foley

Do binary NS mergers make enough heavy elements?

Galactic Chemical Evolution



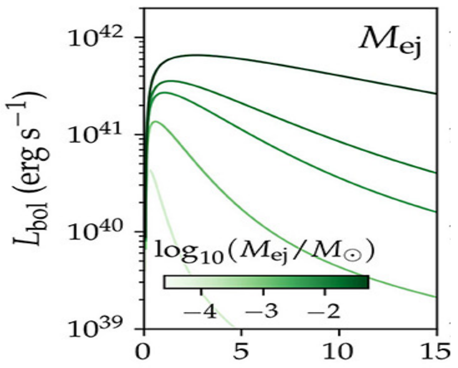
Palm+14



Côté+18 (including Vassh) (ApJ)

Do binary NS mergers make enough heavy elements?

Barnes 20

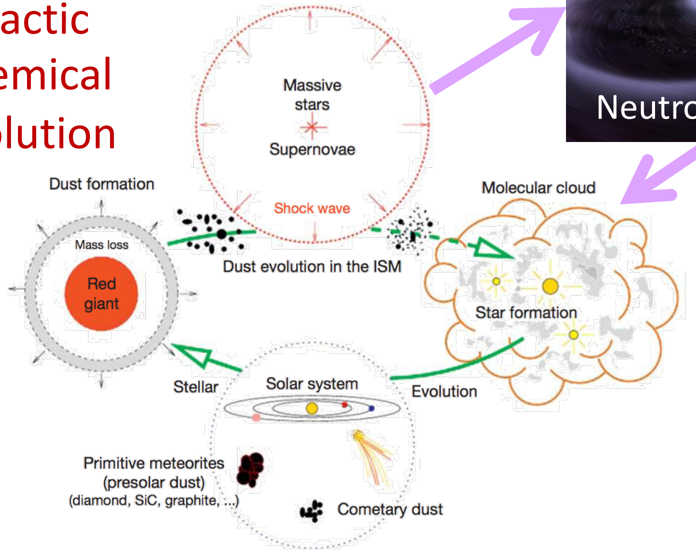


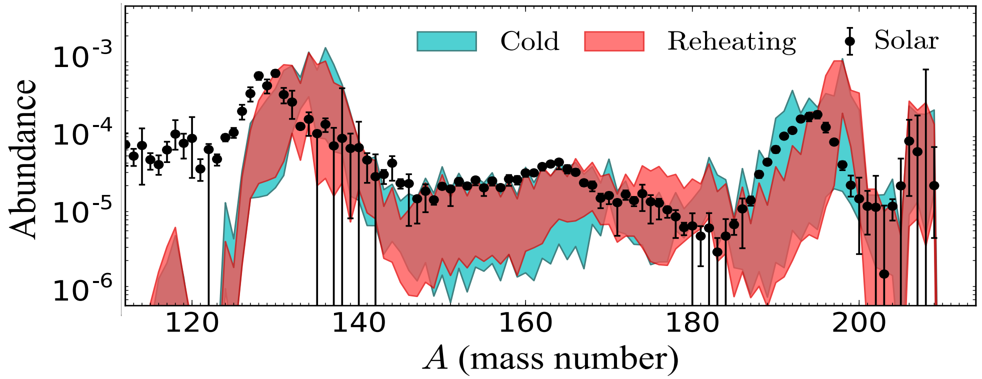
Light Curves

Take estimates for GW170817 mass ejection range from literature

Galactic Chemical Evolution

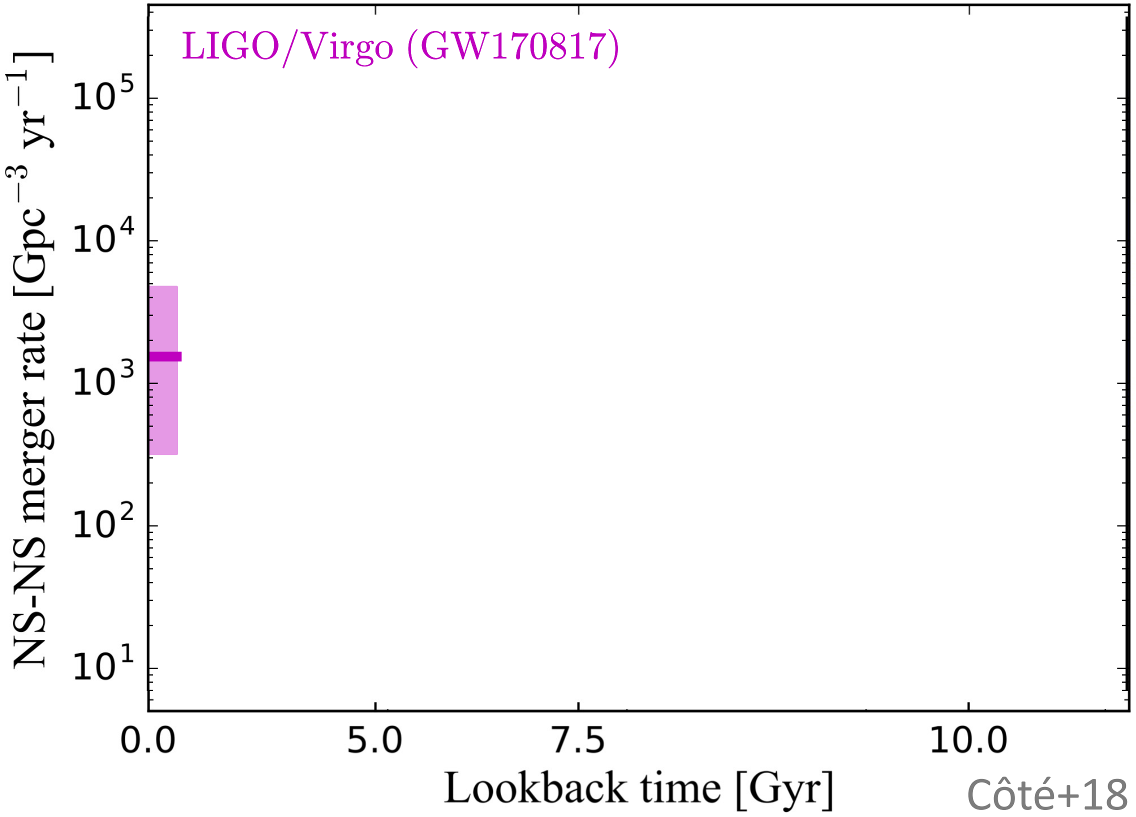
Palm+14





Nucleosynthesis Predictions

Abundance range of dynamical ejecta from 10 mass models



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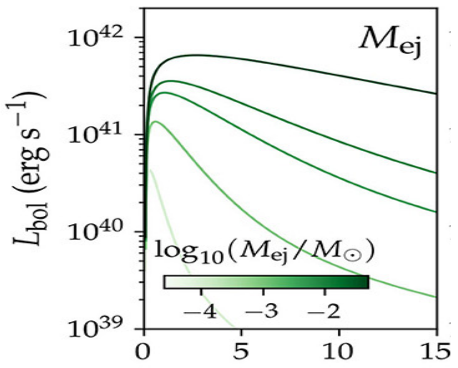

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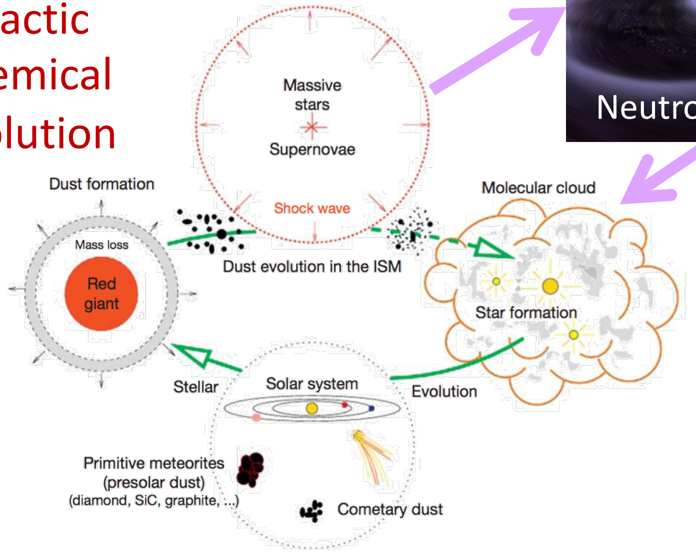

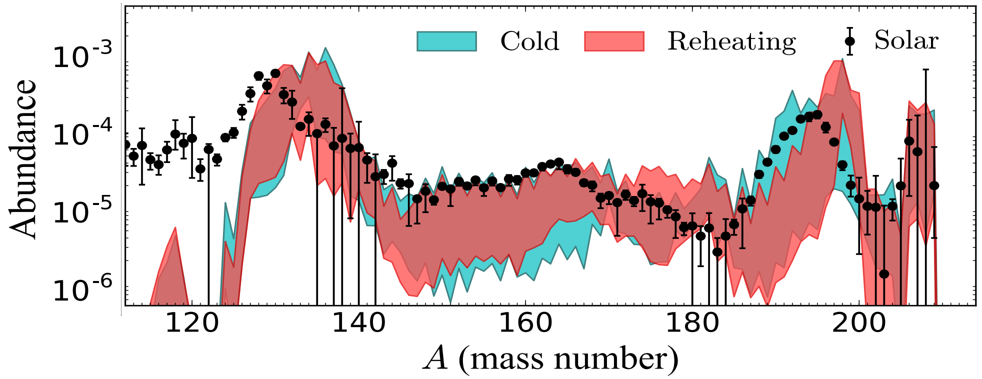

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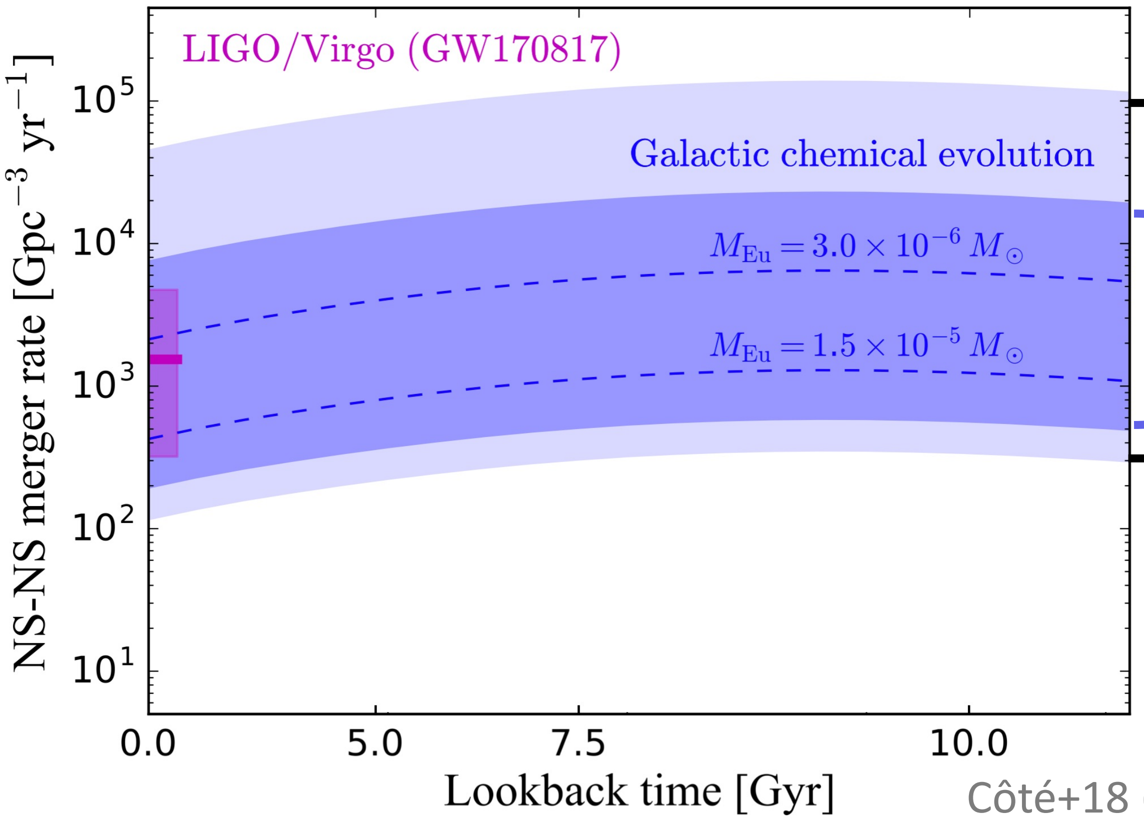


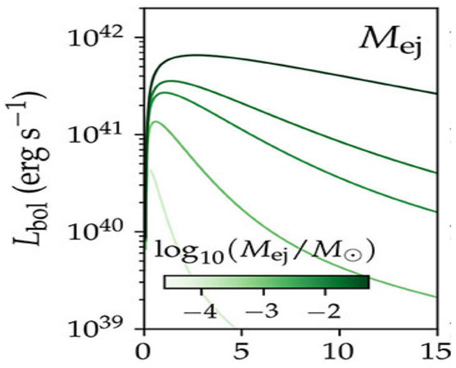
GCE with Solar Abund.

nuclear physics uncertainties

Côté+18 (including Vassh) (ApJ)

Do binary NS mergers make enough heavy elements?

Barnes 20



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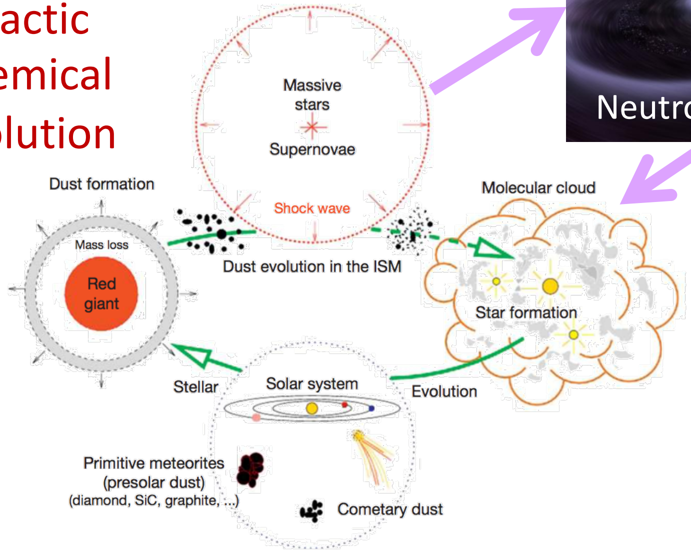

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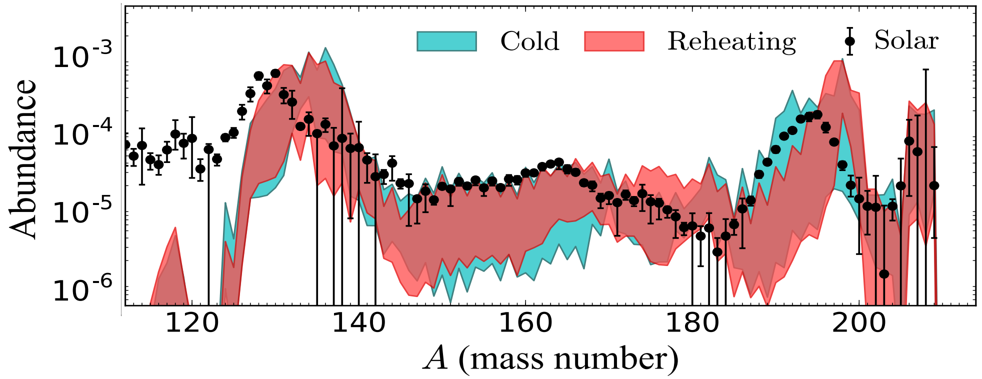

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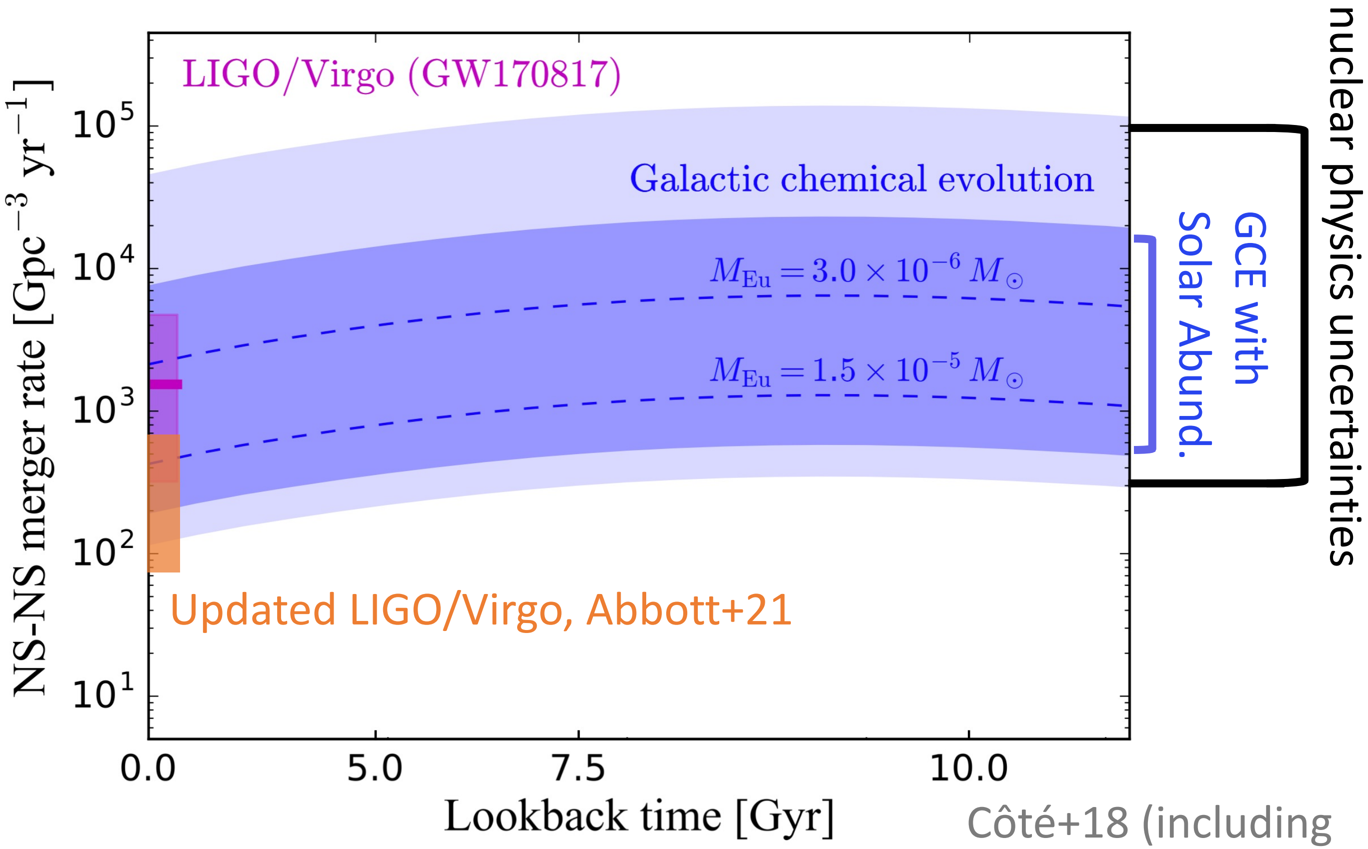

Côté+18 (including Vassh) (ApJ)

*Now another confirmed NSNS merger GW190425 as well as a June 2021 confirmation of two NSBH mergers GW200105 and GW200115!

Science goals

- Investigate the origins of the heaviest elements
- Probe the properties of exotic, unstable nuclei
- Motivate and support local and international nuclear physics campaigns at ARIEL and FRIB
- Capitalize on statistical methods and machine learning techniques for nuclear astrophysics problems
- Study the nature of the neutrino and its role in shaping element production at explosive sites

Interested? nvassh@triumf.ca