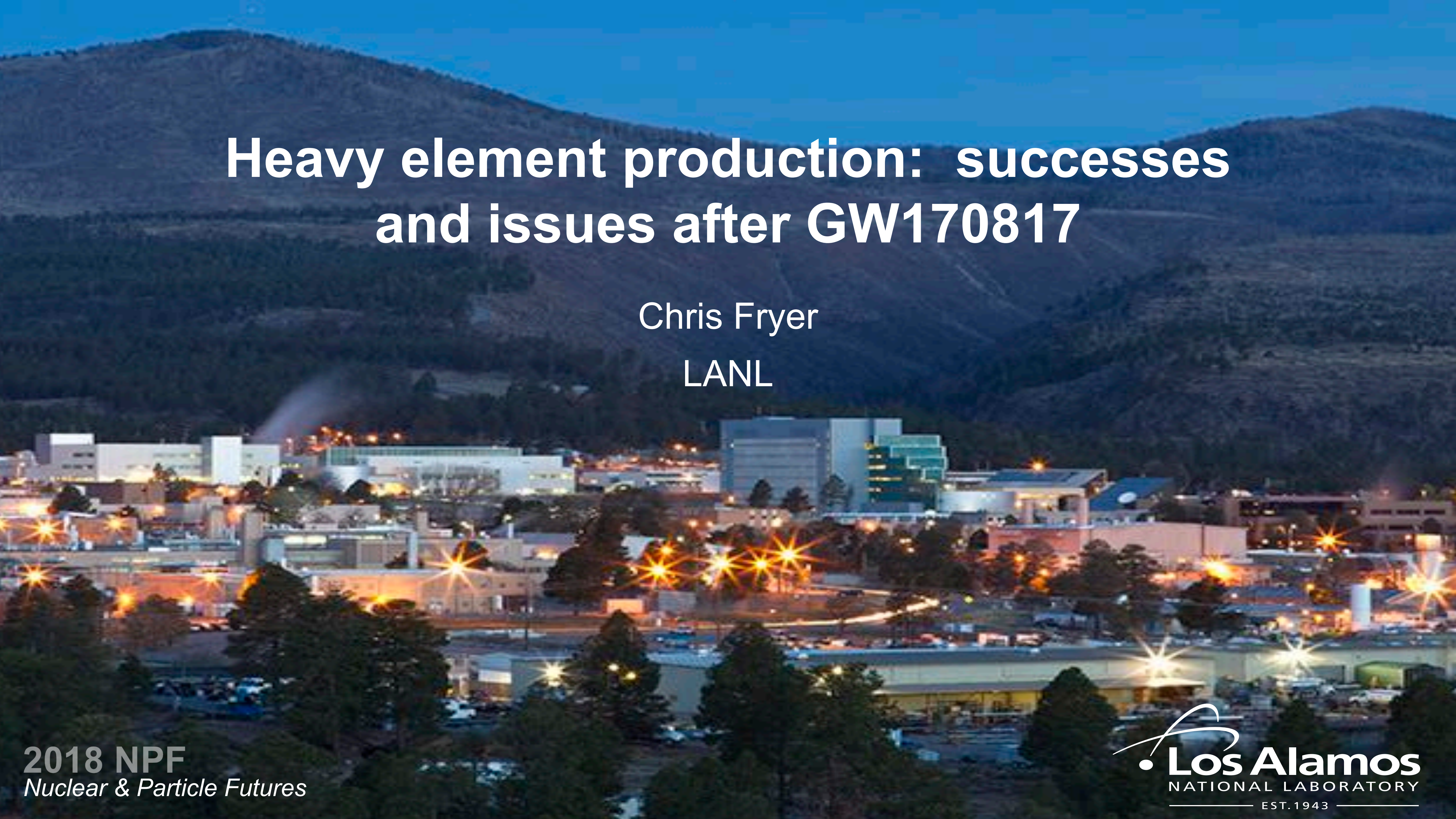


Heavy element production: successes and issues after GW170817

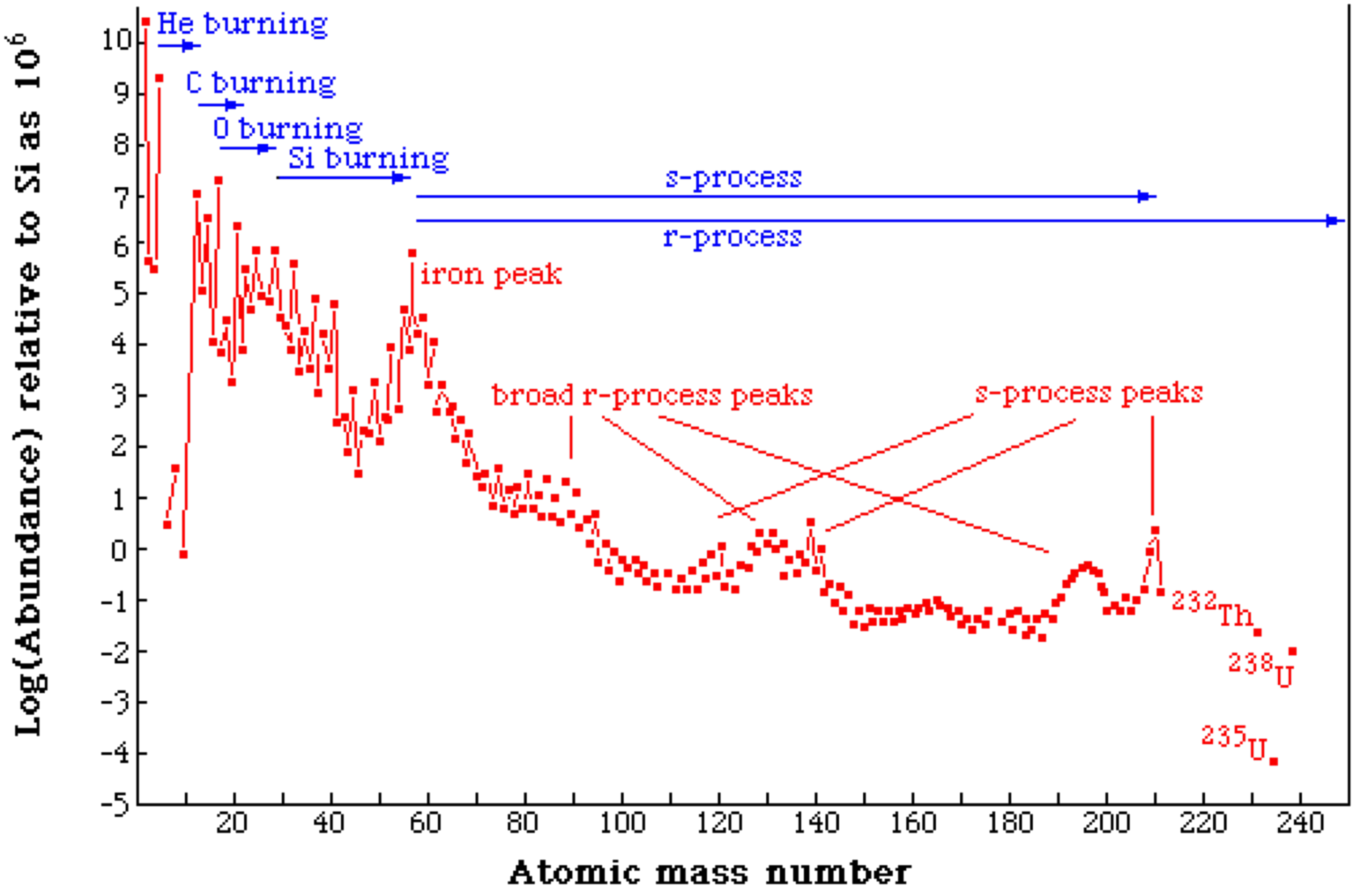
Chris Fryer

LANL

2018 NPF
Nuclear & Particle Futures

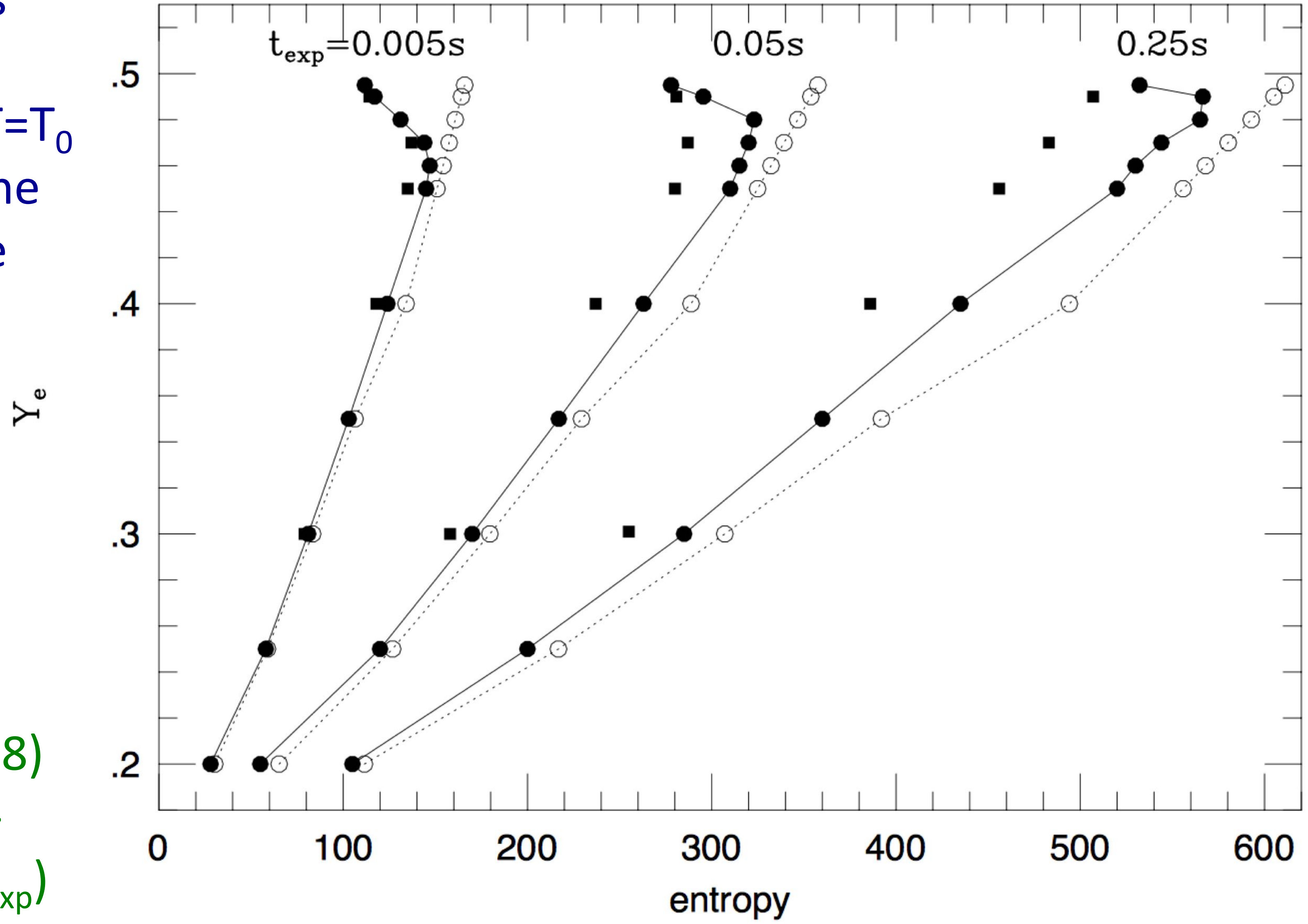
r-Process

Most Elements above the iron peak are believed to be produced through neutron capture. The two extremes are s-process - the neutron capture timescale is much longer (slower) than the decay timescale and r-process - neutron capture rate is much faster (more rapid) than the decay timescale.



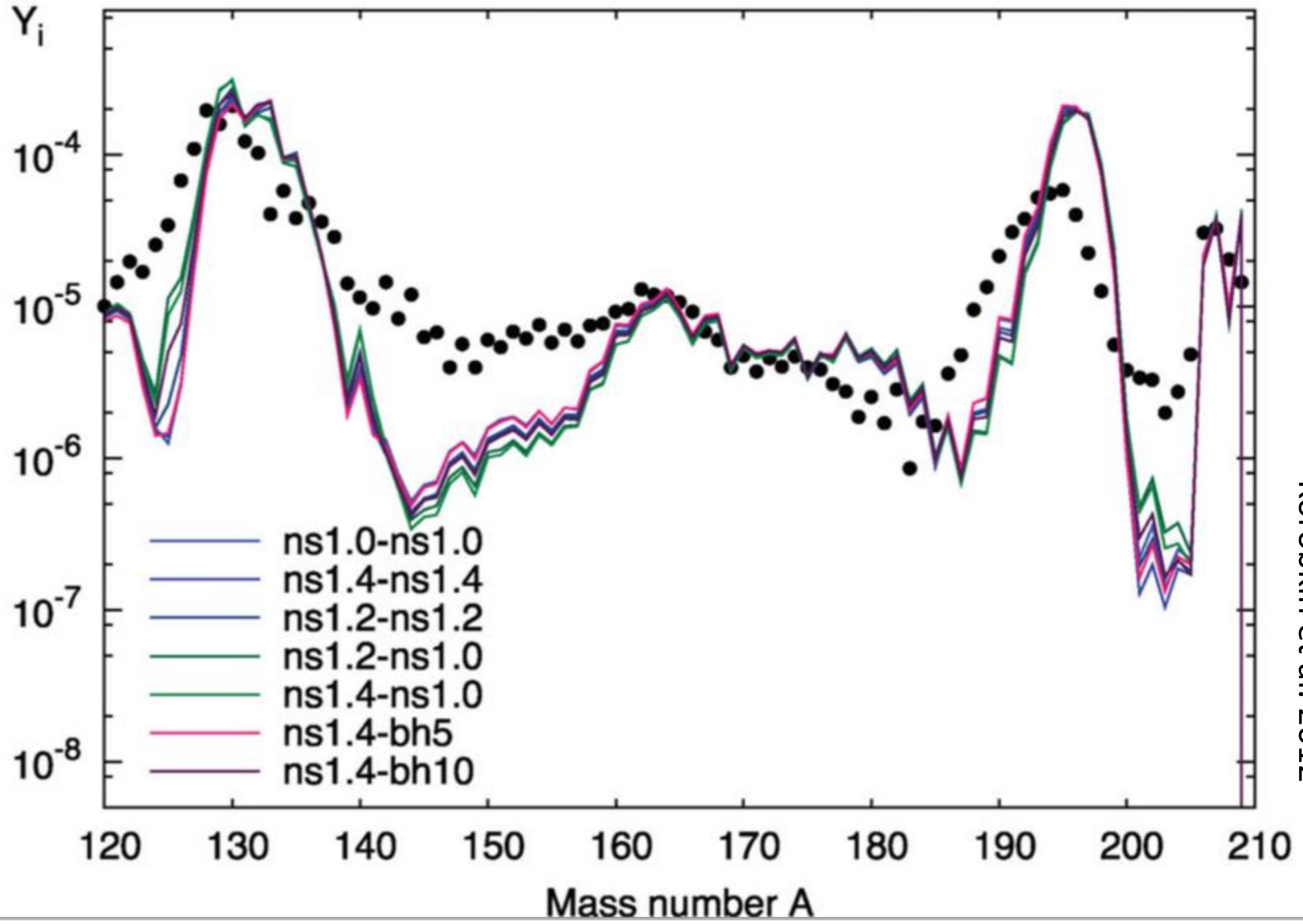
Sites of r-Process: NS Winds, Jets, & Neutron Star Mergers

Qian, Woosley and collaborators studied neutrino driven winds from neutron stars. With a simple trajectory evolution , $T=T_0 e^{(-1.28t/t_{exp})}$, they determined the conditions needed to produce the 3rd r-process peak. Hoffman et al. (1997) determined that either high entropy, low Y_e, or fast expansion timescales were needed to produce the r-process. Based on this, Thompson and ud-Doula (2018) derived a figure of merit for r-process production: $S^3/(Y_e^3\ t_{exp})$



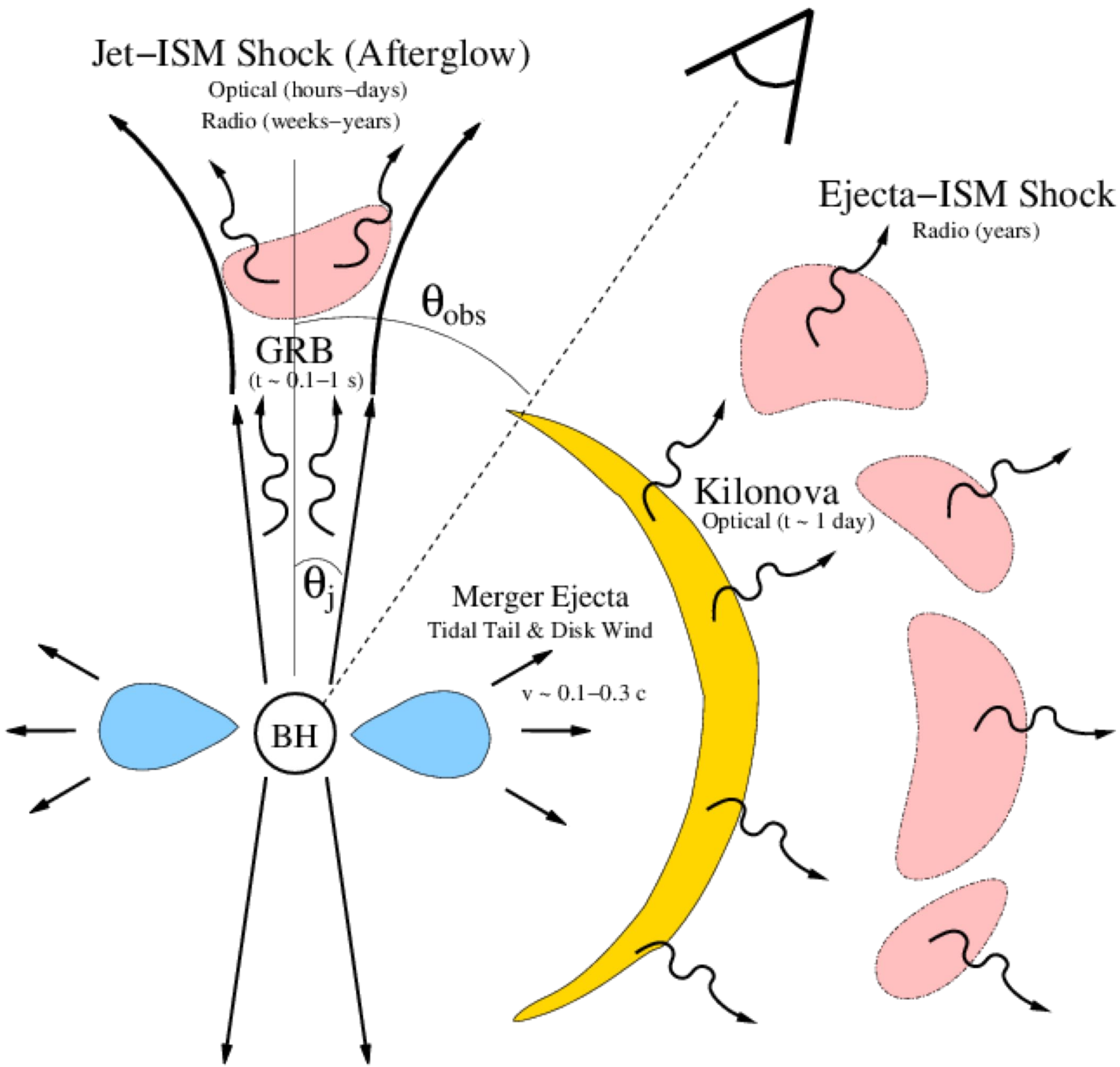
r-Process in Neutron Star Mergers

Dynamical Ejecta: Y_e is low, much easier to make a relatively clean r-process abundance profile



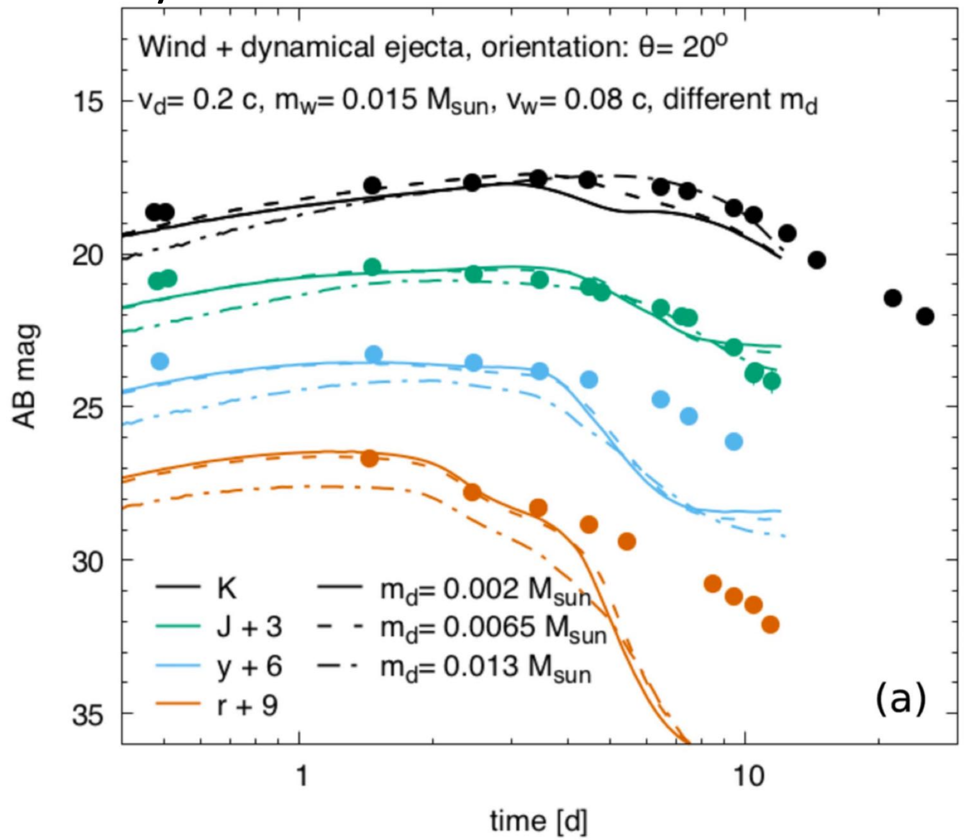
Korobkin et al. 2012

GW170817

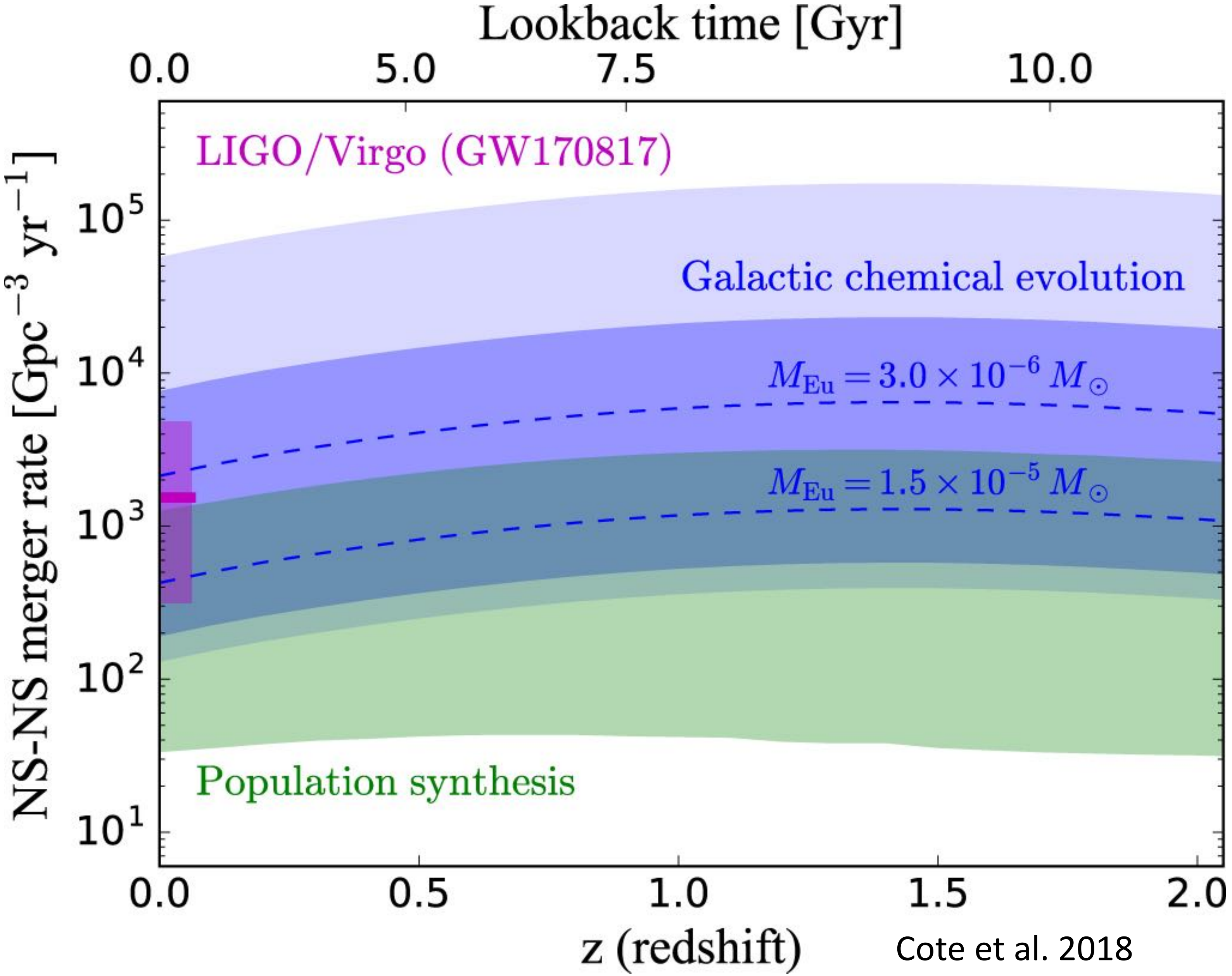


August 17, 2017: First detection of a GW event in EM spectrum: over 200 papers since November!!!

- Can probe ejecta composition! Dominant r-process site?
- Changing our understanding of jet structures.
- Rate is high! With LIGO improvements (running in the fall), we expect 10s of events per year.
- Can we understand these mergers well enough to pinpoint the yields?

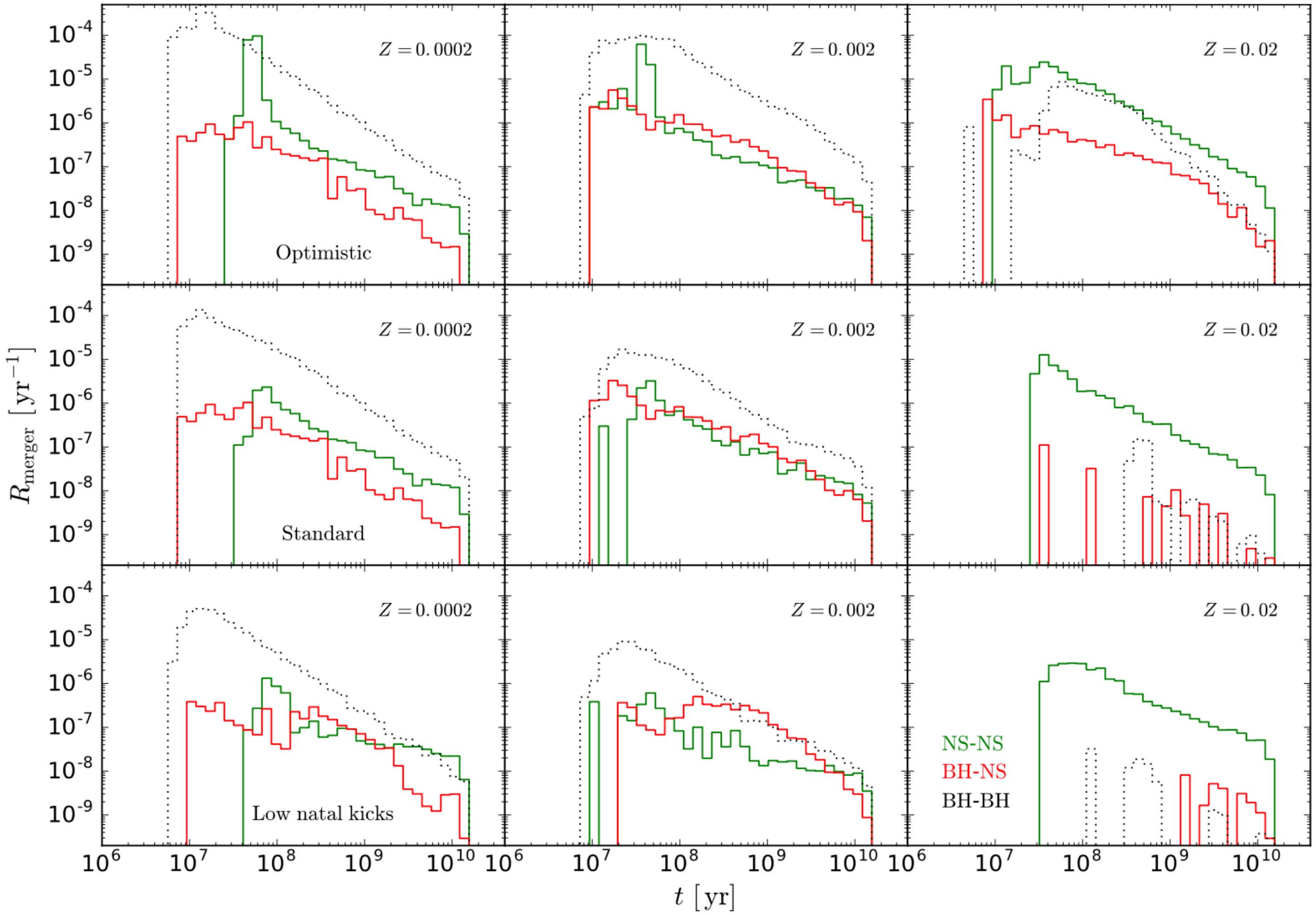


Inferred Rate from GW170817 matches what is needed



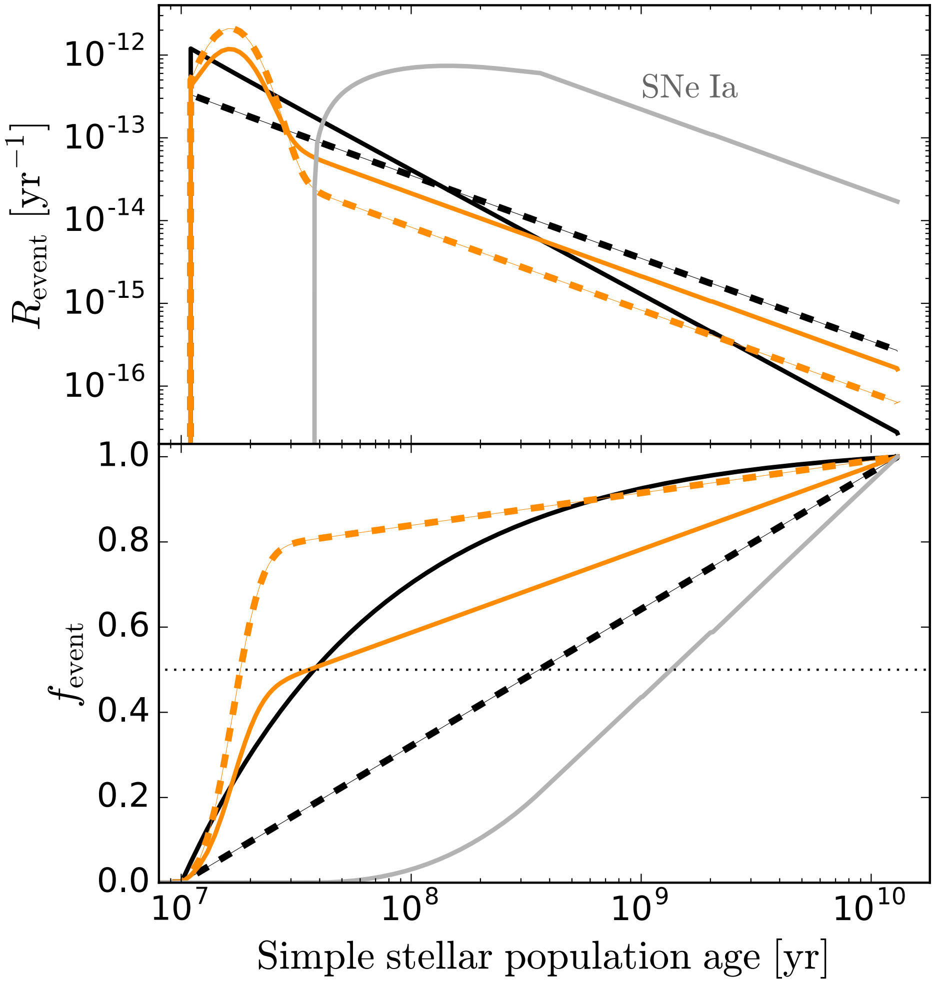
Cote et al. 2018

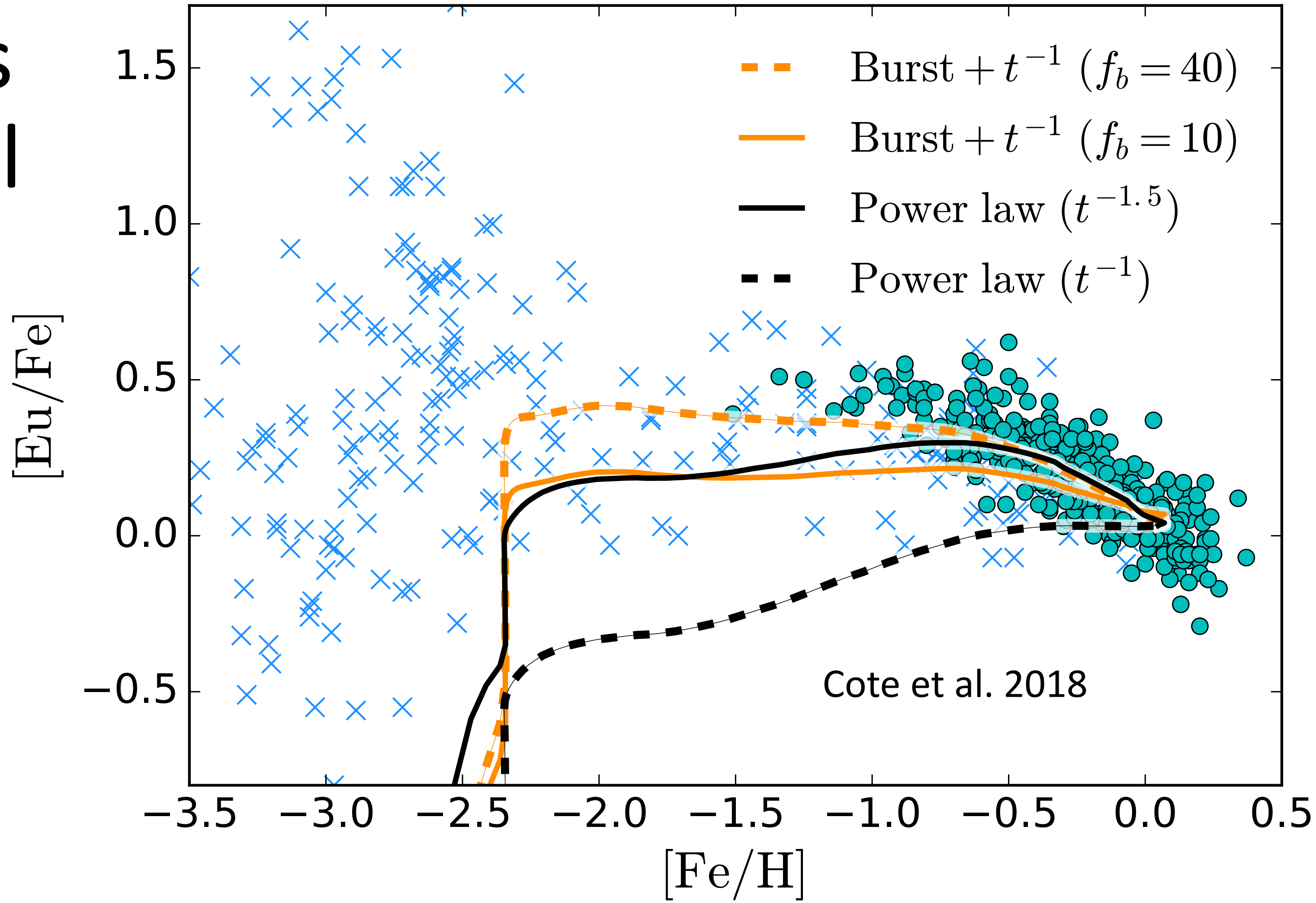
Current population synthesis models argue for a $t^{\sim 1}$ profile. Are we missing something?



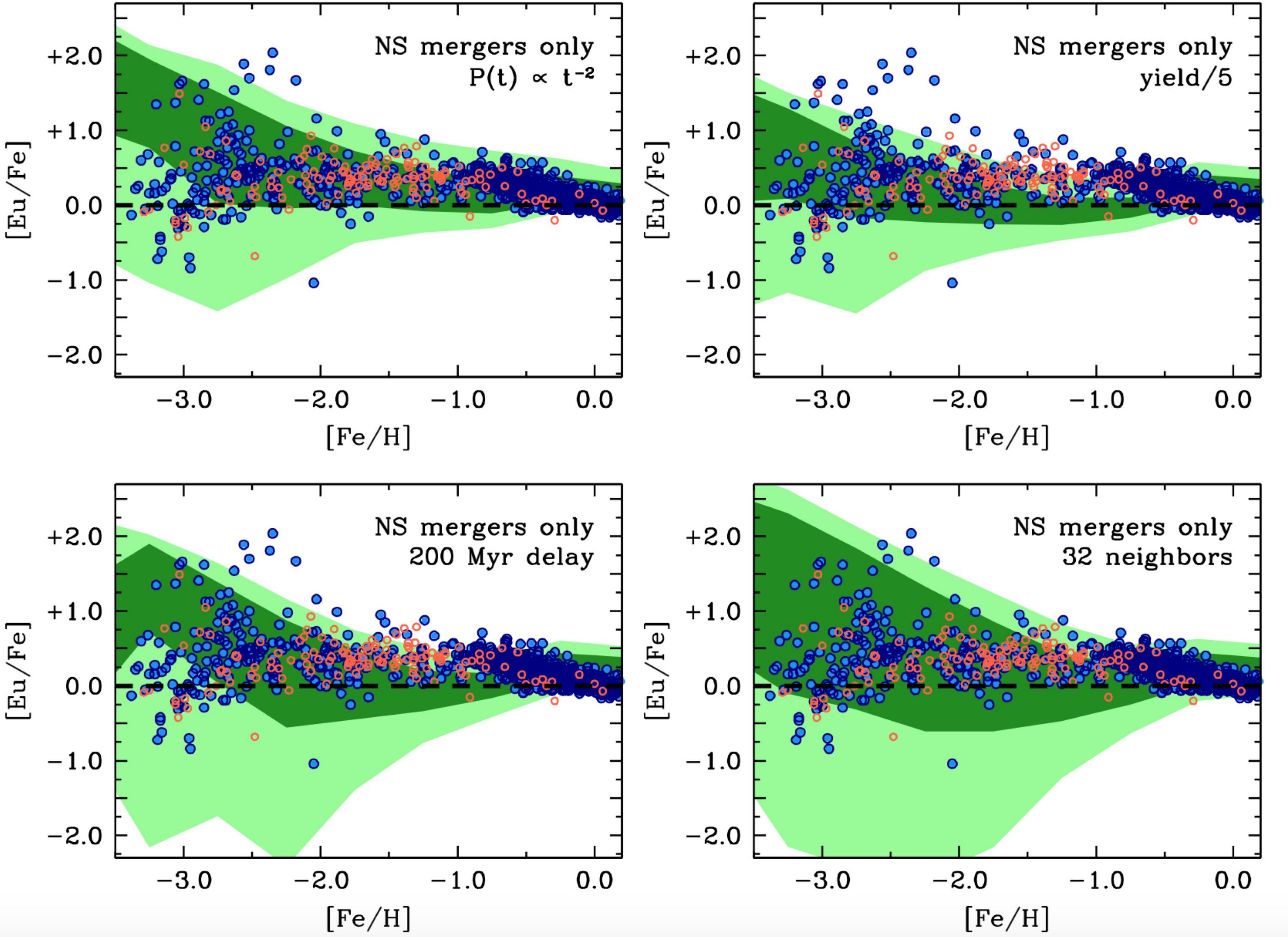
Cote et al. 2018

Neutron Star Mergers and Galactic Chemical Evolution





Modifications to the predicted time-dependent merger rate may be needed to match the data.



Other Solutions exist, but not without going beyond what the population synthesis models predict.

Shen et al. 2015

- Depending upon the light-curve and spectral models, the amount of wind vs. dynamical ejecta varies considerably.
- The dynamical ejecta is neutron rich and produces the right distribution of 2nd and 3rd r-process peaks.
- But if there is a lot of wind ejecta that produces predominantly 1st and 2nd peaks, can we explain the r-process yields?

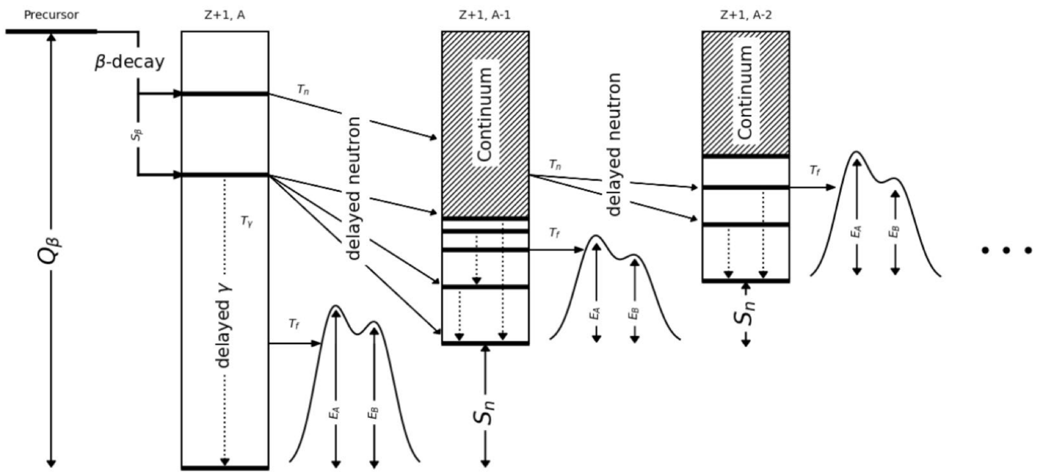
Table 1. Estimates of Ejected Masses for High-opacity Lanthanide-rich Material (m_{dyn}) and Medium-opacity "Winds" (m_w), Sourced from the Recent Literature for GW170817

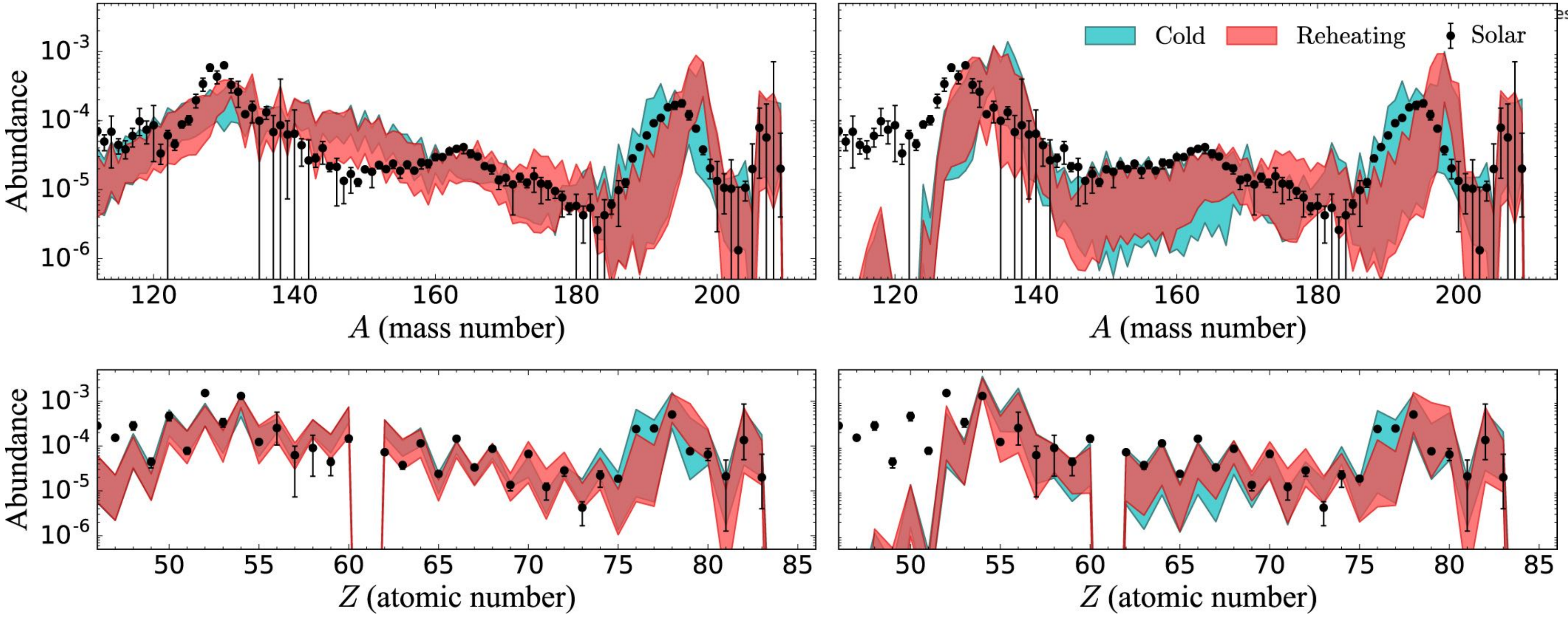
Reference	m_{dyn} $[M_\odot]$	m_w $[M_\odot]$
Abbott et al. (2017a)	0.001–0.01	⋯
Arcavi et al. (2017)	⋯	0.02–0.025
Cowperthwaite et al. (2017)	0.04	0.01
Chornock et al. (2017)	0.035	0.02
Evans et al. (2017)	0.002–0.03	0.03–0.1
Kasen et al. (2017)	0.04	0.025
Kasliwal et al. (2017b)	>0.02	>0.03
Nicholl et al. (2017)	0.03	⋯
Perego et al. (2017)	0.005–0.01	10^{-5} – 0.024
Rosswog et al. (2017)	0.01	0.03
Smartt et al. (2017)	0.03–0.05	0.018
Tanaka et al. (2017)	0.01	0.03
Tanvir et al. (2017)	0.002–0.01	0.015
Troja et al. (2017)	0.001–0.01	0.015–0.03

Nuclear Physics problem

MULTI-CHANCE βDF

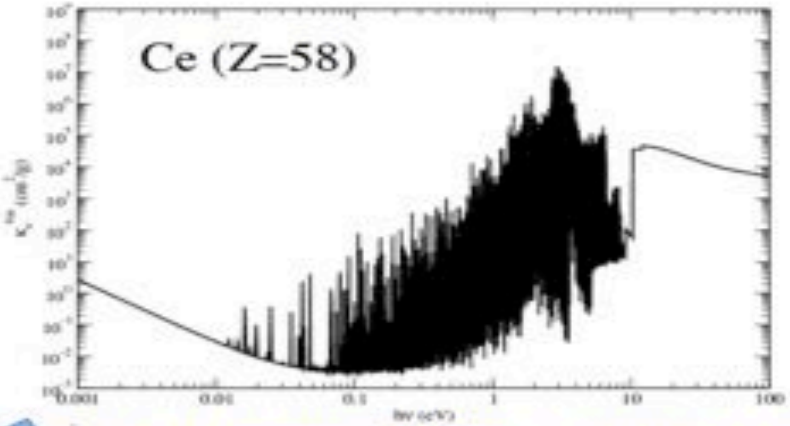
- Understanding the relative production of r-process depends on the nature of the ejecta (wind versus dynamical ejecta) and the clean signal from neutron star mergers may not be so clean.
- Uncertainties in the nuclear physics can also drastically alter the yields.





Fission rates (multi-chance beta-delayed fusion and reaction rates) are active areas of research.

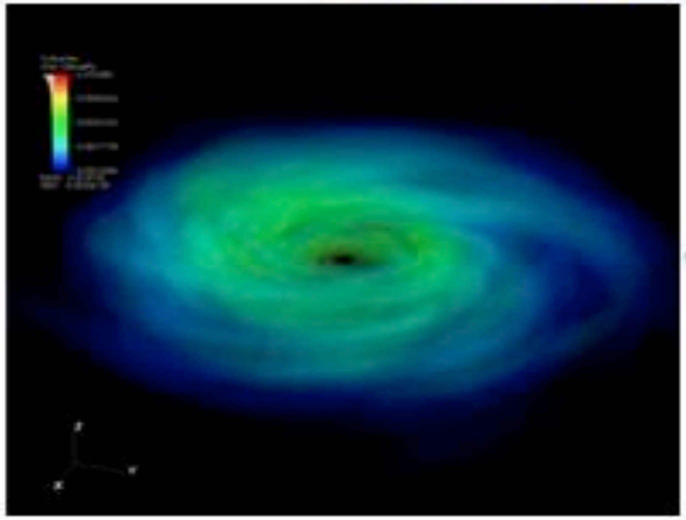
LANL plan: full system models



Atomic Physics Calculations of Lanthanide Opacities (Fontes et al. 2017)

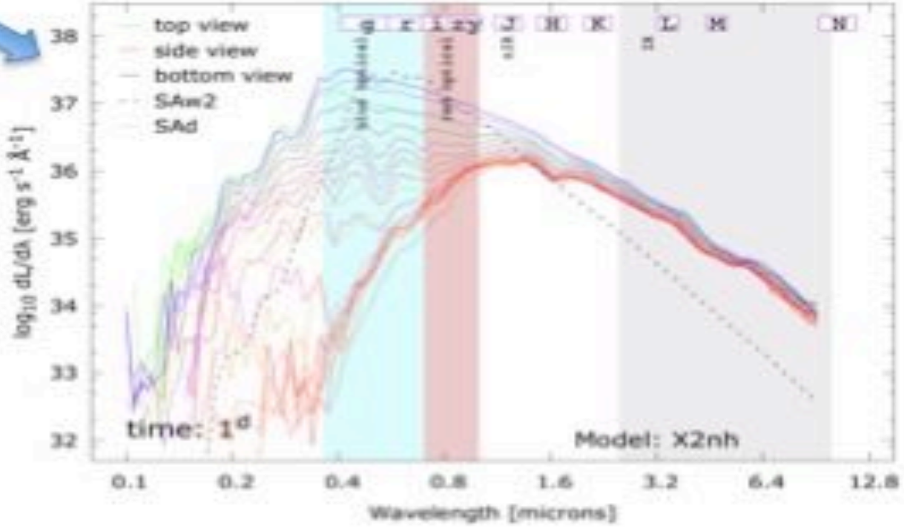
Nuclear matter, neutrino, nuclear reaction and atomic physics all feed into simulation program (engines and emission models).

The RAPTOR-P telescope has a 500 sq-degree field-of-view and can simultaneously cover the full LIGO and Fermi boxes for early optical emission starting about 6 seconds after the receipt of event trigger.



Preliminary study of a turbulent magnetically driven accretion flow of an accretion disk formed of neutron star material after the in-spiral and coalescence of two neutron stars.

Engines provide characteristics (velocities, densities, compositions) for emission models



Spectra for one of our multi-dimensional transport models at 1 day over a range of viewing angles (Wollaeger et al. 2018)

Simulations guide filters and observing strategies.

Observations validate theory.