R-process nucleosynthesis in GW170817 in the context of metal-poor stars

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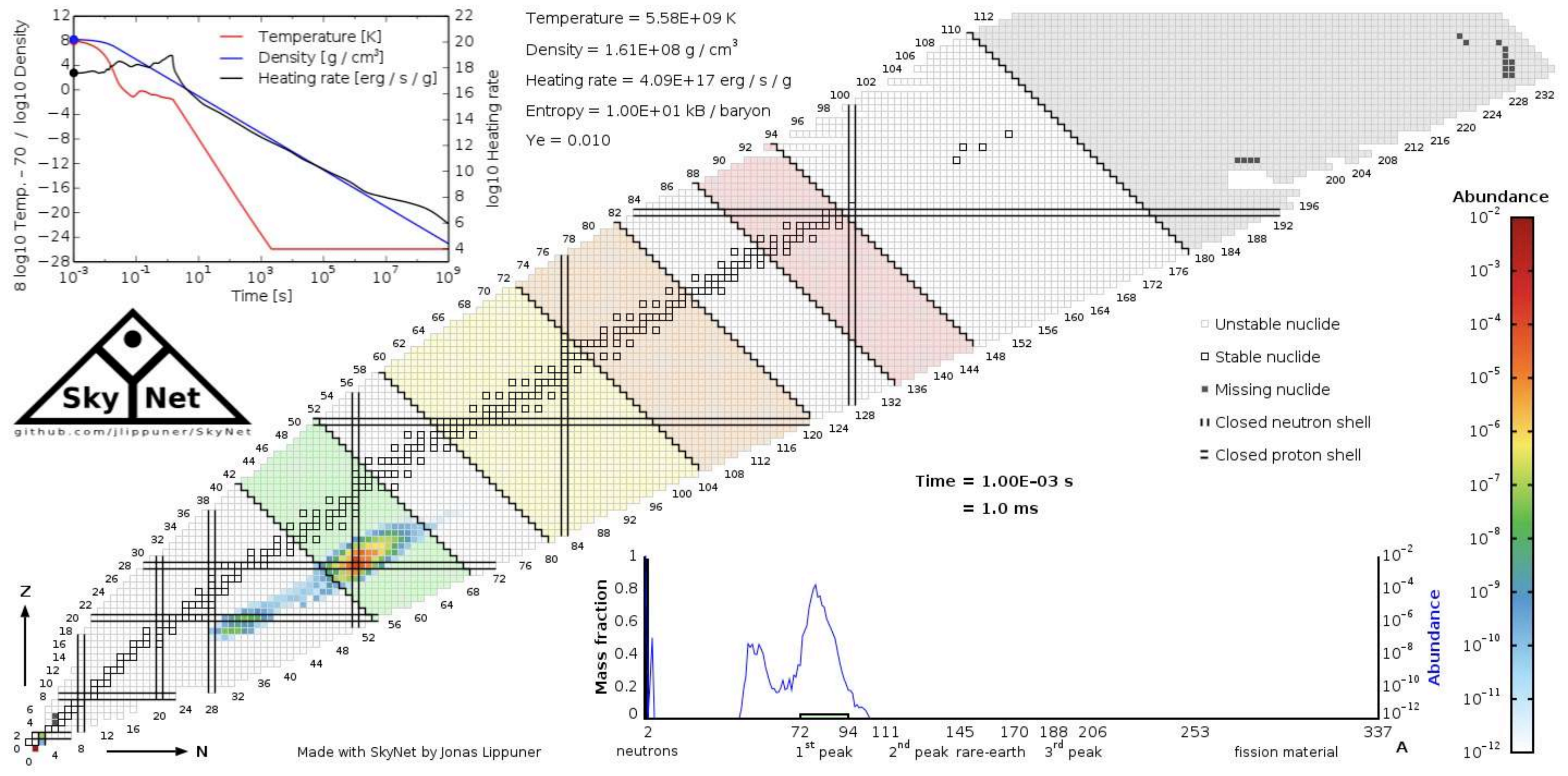
ApJ 882, 40; arXiv:1905.01814

The Rapid Neutron-Capture Process (r-process): What is the source?



Rare core-collapse supernovae or <u>neutron star mergers</u>?

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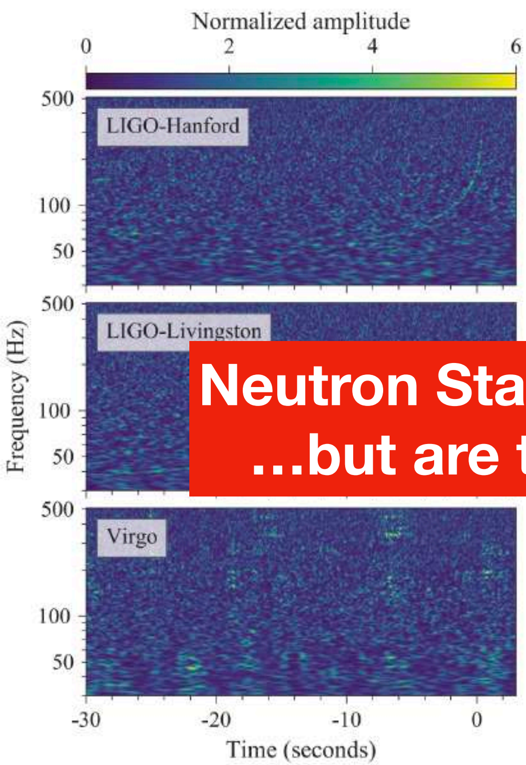
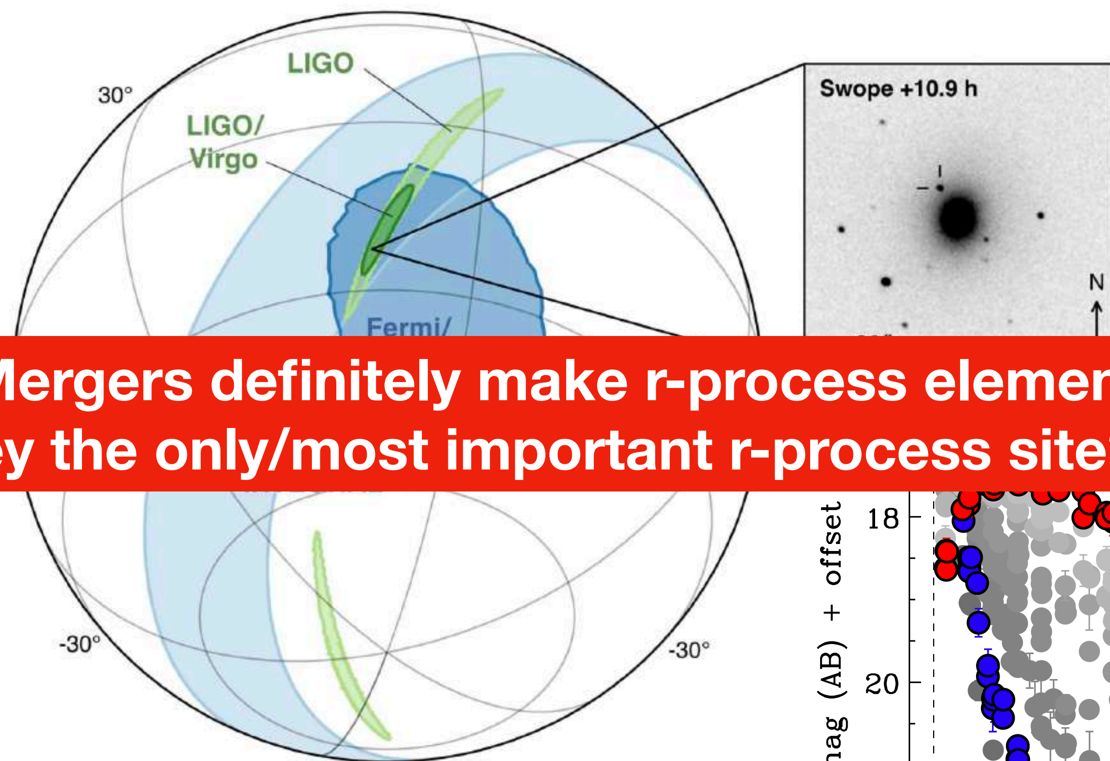
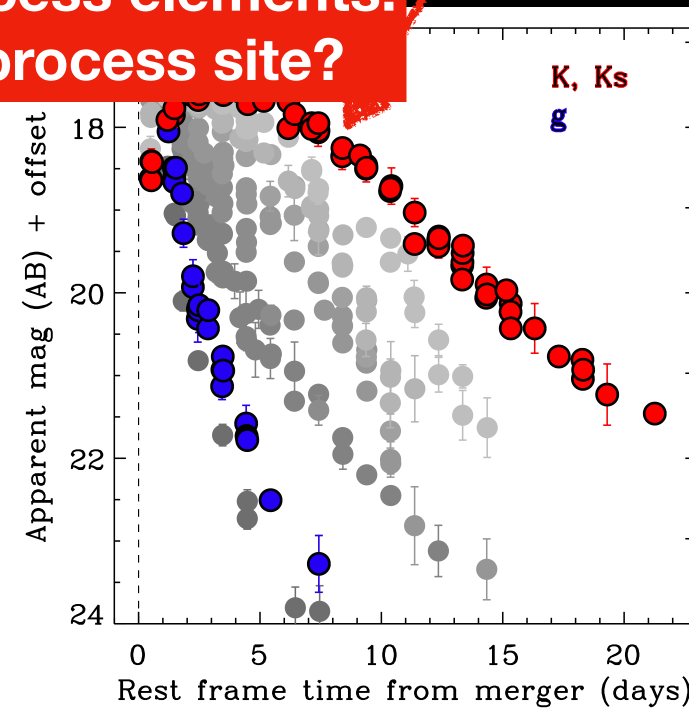
2017: Year of the Neutron Star Merger GW170817





Lanthanides: high opacity red kilonova, smoking gun for r-process



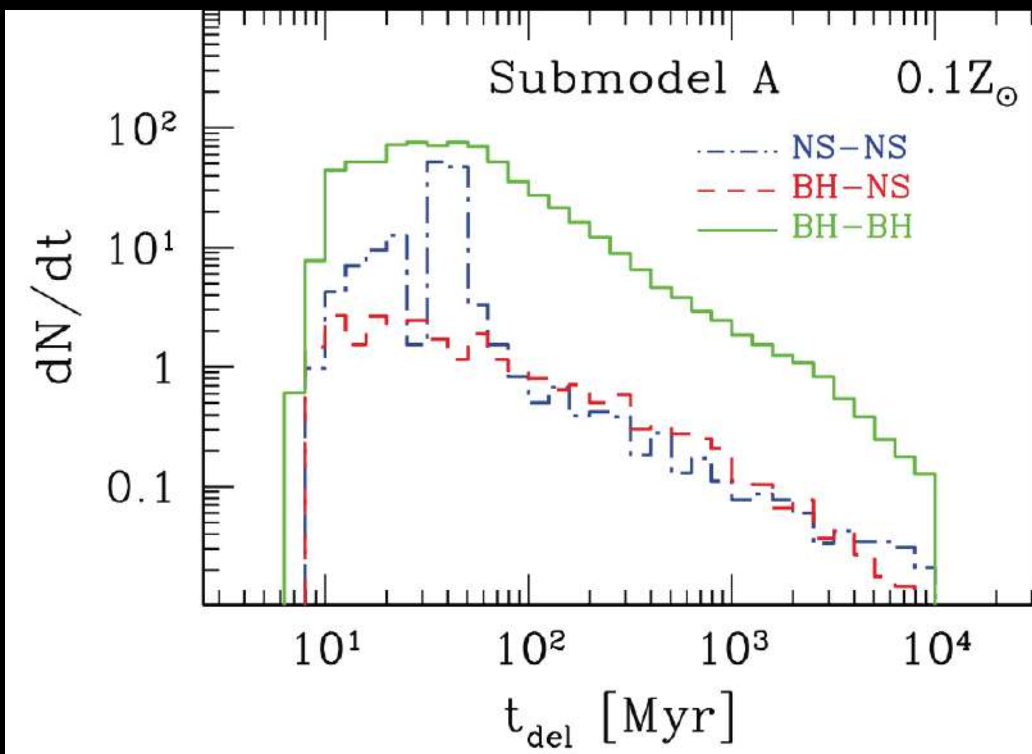
Neutron Star Mergers definitely make r-process elements!
...but are they the only/most important r-process site?

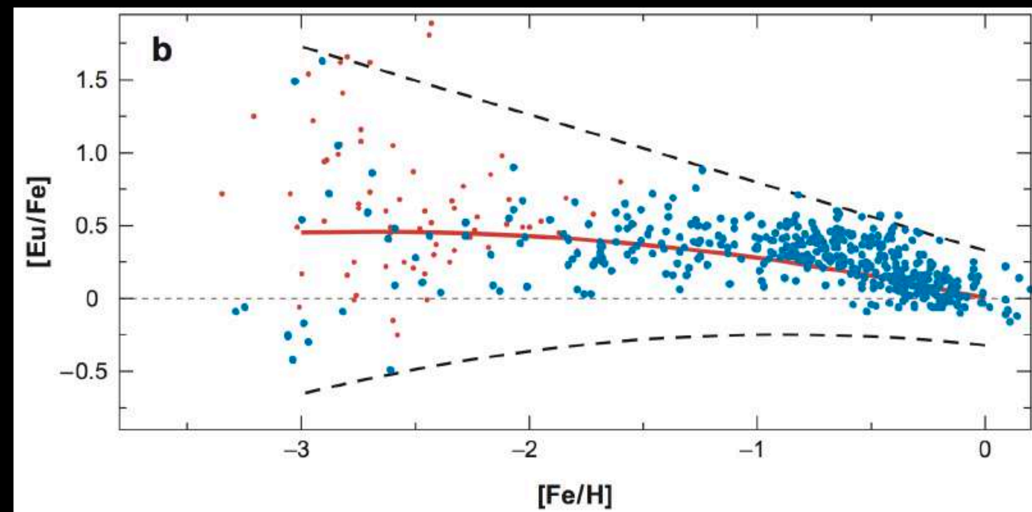
Triple coincidence of gravitational waves, short gamma ray burst, **kilonova** afterglow

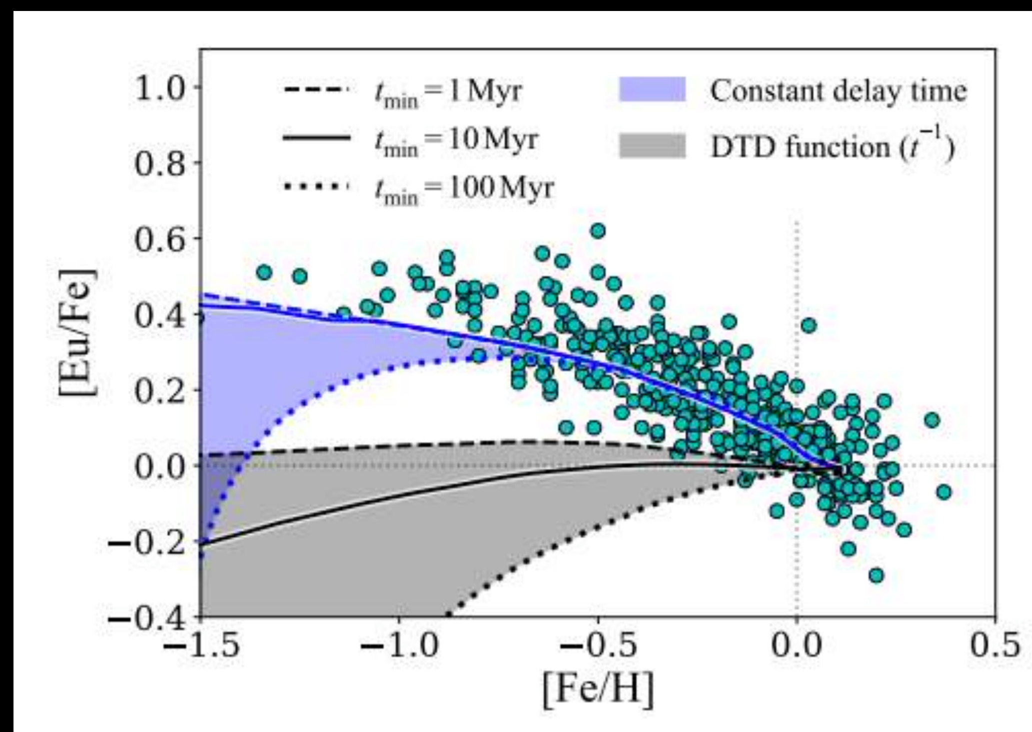
LIGO/VIRGO Collaboration 2017; Drout et al. 2017

NSM delay times cause difficulties for chemical evolution

NS binaries take some time before they merge







Figures:
Dominik et al. 2012;
Sneden et al. 2008;
Cote et al. 2019

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NSM delay times cause difficulties for chemical evolution

Fundamental concerns the same as pre-GW170817

These difficulties can be addressed!

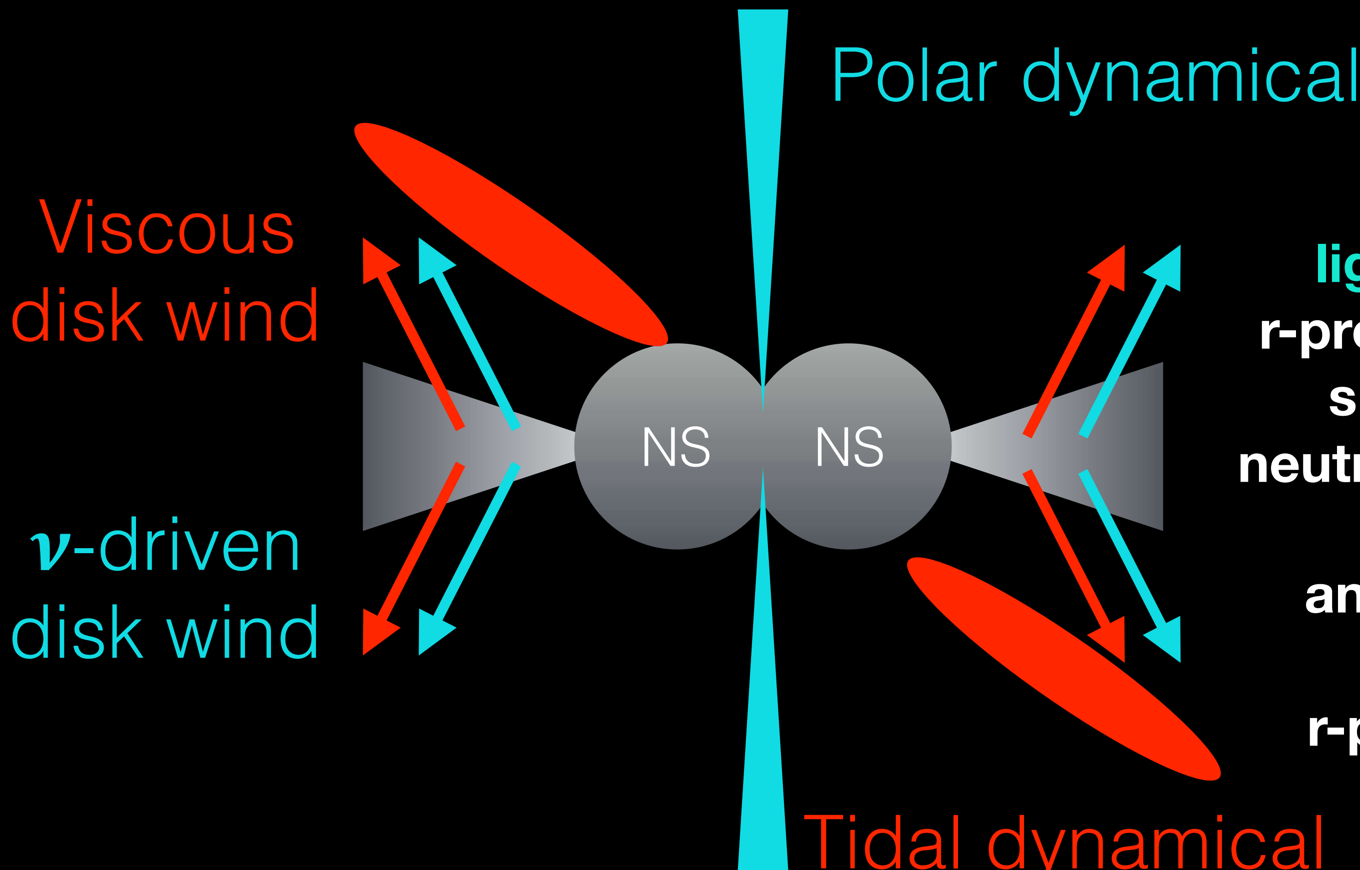
(e.g., Tsujimoto+Shigeyama 14, Shen+15, van de Voort+15, Ishimaru+2015, Hirai+15, Ji+2016, Beniamini+16ab/19, Duggan+18, Ojima+18, Safarzadeh+19, Schonrich+Weinberg 19, Andrews+19, …)

Possible aspects include:

hierarchical galaxy formation,
fast merging neutron stars,
adding early rare supernovae to NSM

What can we do that is new with GW/KN?

NSMs should not make identical r-process yields



The ratio of light and heavy r-process elements should vary in neutron star mergers

and thus also in metal-poor r-process stars!

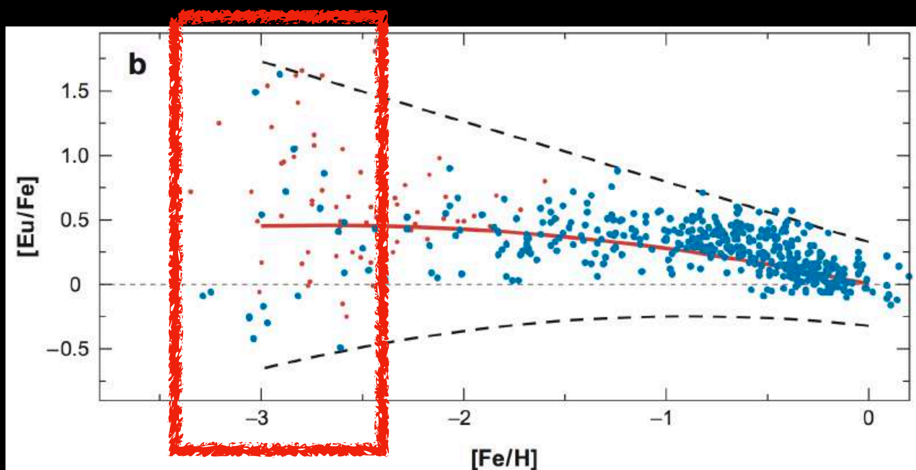
Blue: high Y_e, neutron-poor, **light** 1st-peak r-process

Red: low Y_e, neutron-rich, **heavy** 2nd+3rd peak r-process

see e.g. Metzger 2017, poster by T. Tsujimoto

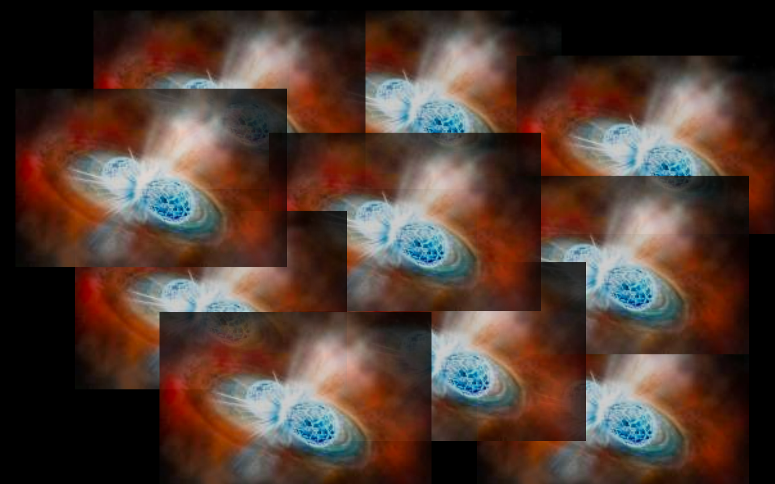
Varying R-Process Abundances in Stars Implies Different Kilonova Compositions

The ***lanthanide fraction*** X_{La} ~ 0.1 heavy/(heavy+light) is measurable in both stars and kilonovae



Measure X_{La} in existing metal-poor Milky Way stars (assume each star = 1 neutron star merger)

Figure: Sneden et al. 2008



Predict X_{La} for future kilonovae

Determining X_{La} in metal-poor stars (1): Which Stars?

- Metal-poor, r-dominated: [Fe/H] < -2.5, [Ba/Eu] < -0.4
- **Pure sample**: [Eu/Fe] > 0.7
  Roederer et al. 2018: 46 metal-poor stars
- **Complete sample**: any [Eu/Fe]
  JINAbase (Abohalima & Frebel 2018):
  146 metal-poor and r-dominated stars

  Results verified with R-Process Alliance data
  (Hansen et al. 2017, Sakari et al. 2018)

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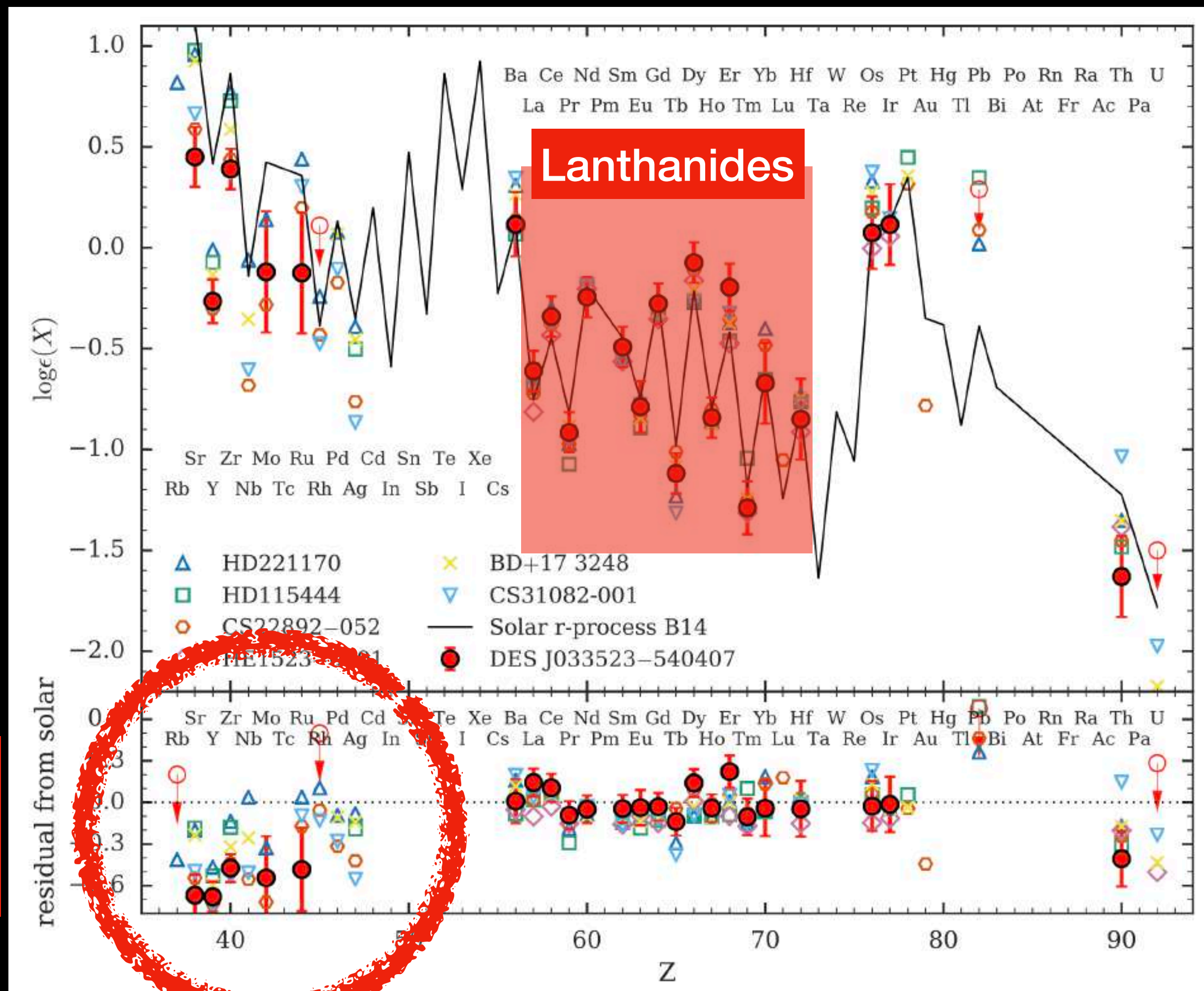
Determining X_{La} in metal-poor stars

(2): How to Measure X_{La}?



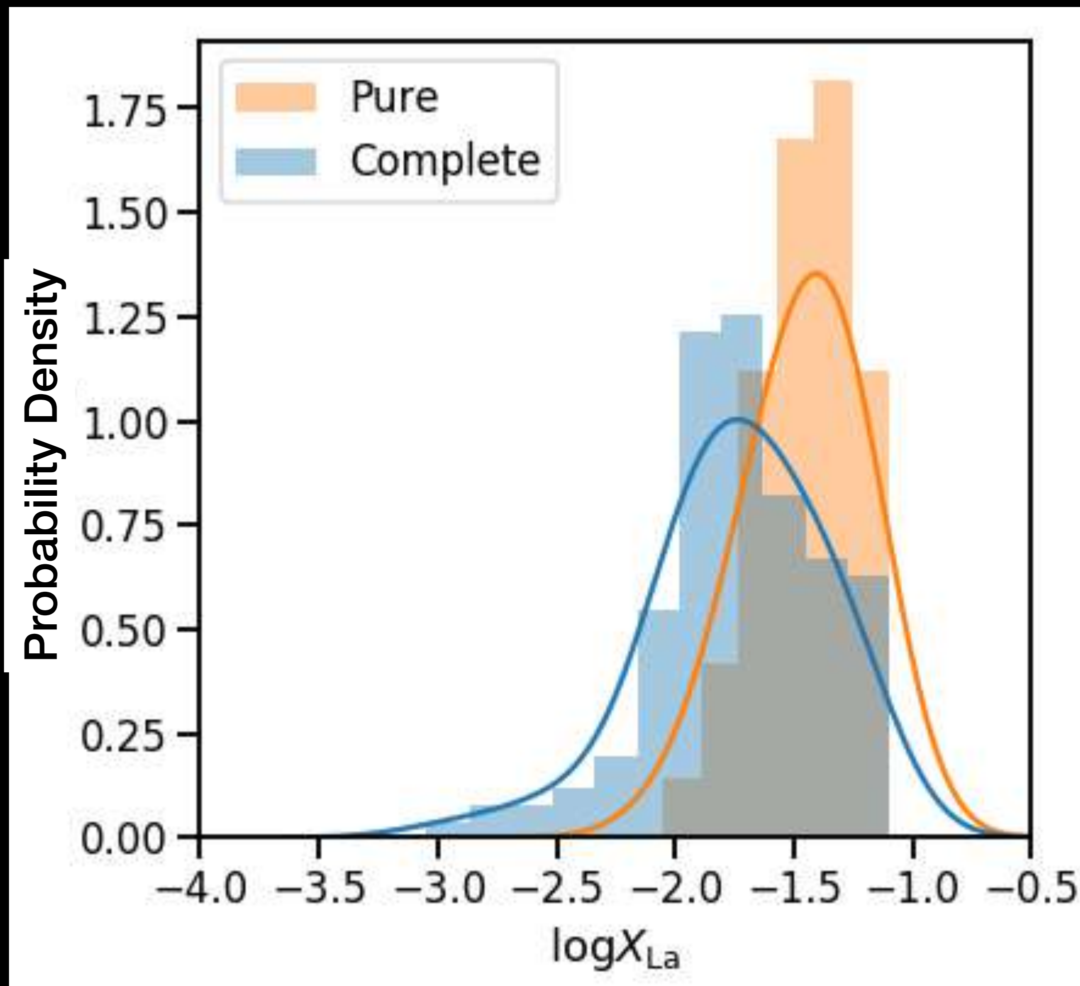
This scatter -> different X_{La}

We do not measure all elements: extrapolate with the solar r-process pattern

X_{La} ~ 0.1 heavy/(heavy+light)

Ji & Frebel 2018

Metal-poor star lanthanide fraction distribution



Pure sample has higher X_{La}: it is a biased sample!

Also see poster by T. Tsujimoto

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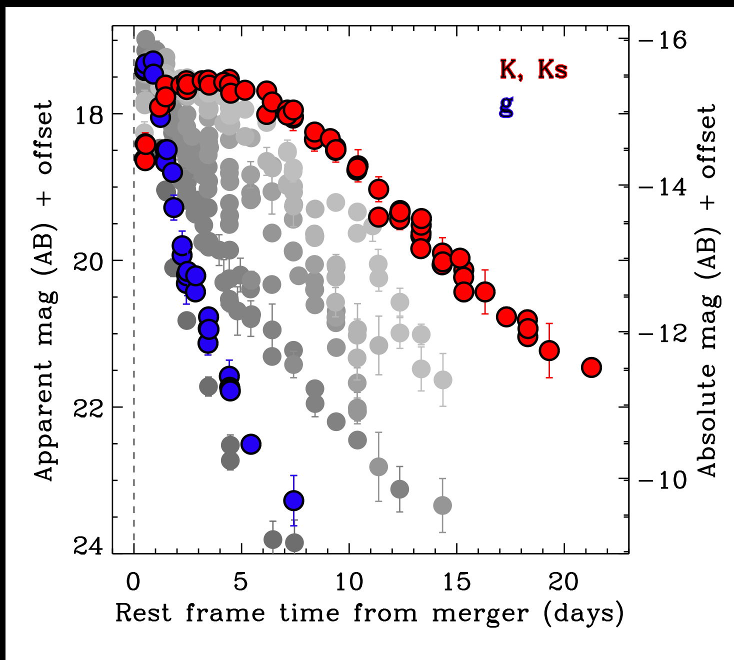
Determining X_{La} in Kilonovae

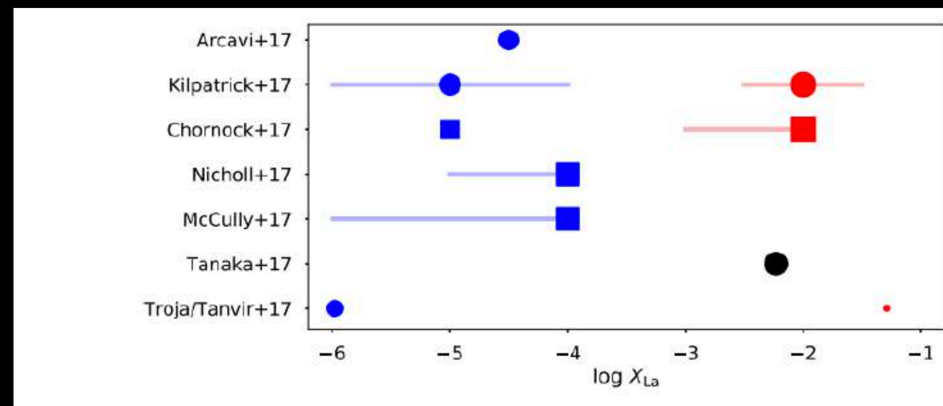
Kilonovae have *red* and *blue* components



At least two different mass components:
blue = La-poor (low opacity)
red = La-rich (high opacity)

Stars probe the *sum* of all components (Including any hidden ones)

Lanthanide fractions in GW170817



Vary by ~5x in ejected mass but all agree

log X_{La} ~ -2.2 ± 0.5

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Drout et al. 2017

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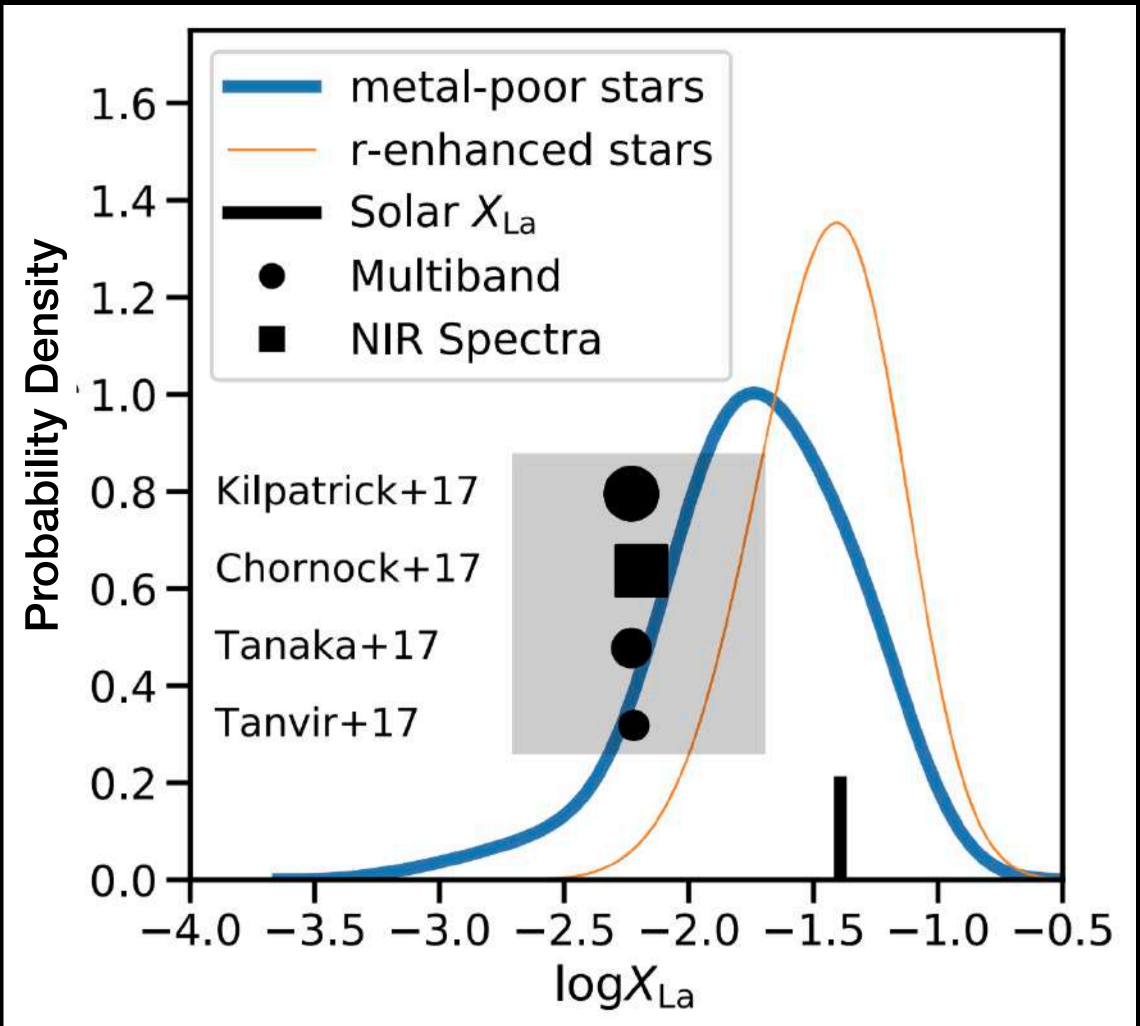
GW170817 is consistent with (but at the low end of) metal-poor star lanthanide fractions



- GW170817 has $\log X_{La} \sim -2.2 \pm 0.5$ → Unusually large amount of Sr, Y, Zr!
- **Future KN should have higher X_{La}!** R-enhanced stars have ~10x higher X_{La}
- **If not**: NSM cannot be the source of early r-process

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How to get higher X_{La} Kilonovae in NS mergers?

- **Enhance tidal dynamical contributions**
  - Larger mass ratio; higher eccentricity
  - NS equation of state/tidal deformability, spin
- **Suppress blue kilonova component**
  - Prompt collapse to BH
  - NS-BH mergers
  - Blue kilonova is not r-process (not likely: Watson+2019 detected Sr)
- **Increase X_{La} of disk winds and/or suppress disk wind mass**
  - Faster disk mass ejection (less neutrinos)

High-X_{La} KN are redder and probably eject less mass (shorter and fainter)

Systematic Concerns

Metal-poor Stars

- Solar pattern not sufficient to describe metal-poor stars
  - First peak too massive
  - Variation in H (2nd peak)
- Hard cutoffs in atomic mass
- Contamination from other sources in 1st peak
- *Actinides* not included

Need UV spectra

Kilonovae

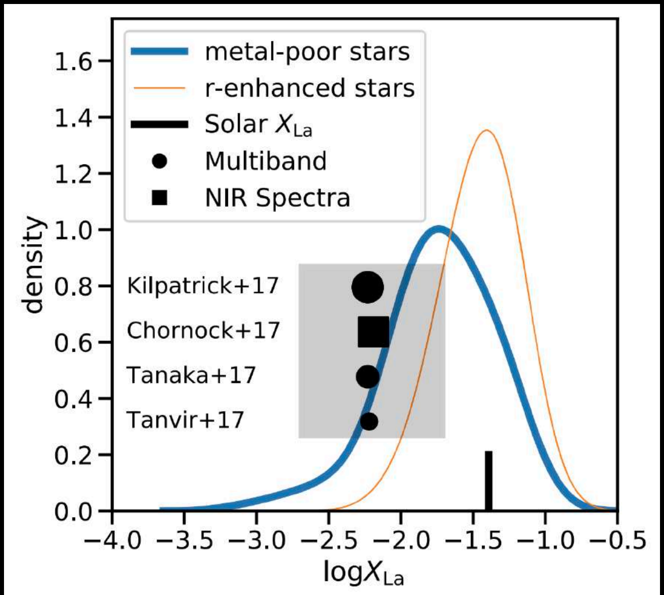
- Viewing angle effects or other hidden mass components
- Early blue component is not r-process elements
- Translation from opacity to lanthanide fractions
- Uncertain nuclear physics (heating, thermalization rates)
- *Actinides*?

See talk by E. Holmbeck

Need more kilonovae

Summary

- **Metal-poor stars predict future kilonovae should be lanthanide rich**
  ~10% of kilonovae should have $X_{La} > 10^{-1.2}$
  -> fainter, shorter, and redder



- If not, then need at least one other significant early r-process site

- Require both early optical and mid-infrared followup observations of kilonovae

- R-enhanced stars are a strongly biased sample of r-process composition