

# SIGNATURES OF HEAVY ELEMENT NUCLEOSYNTHESIS IN TRANSIENTS

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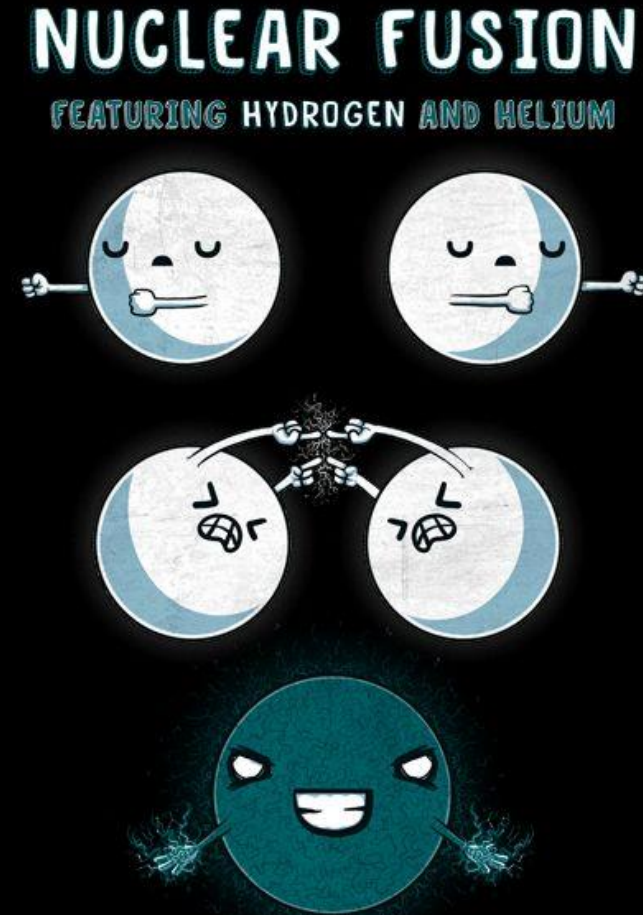


# Outline

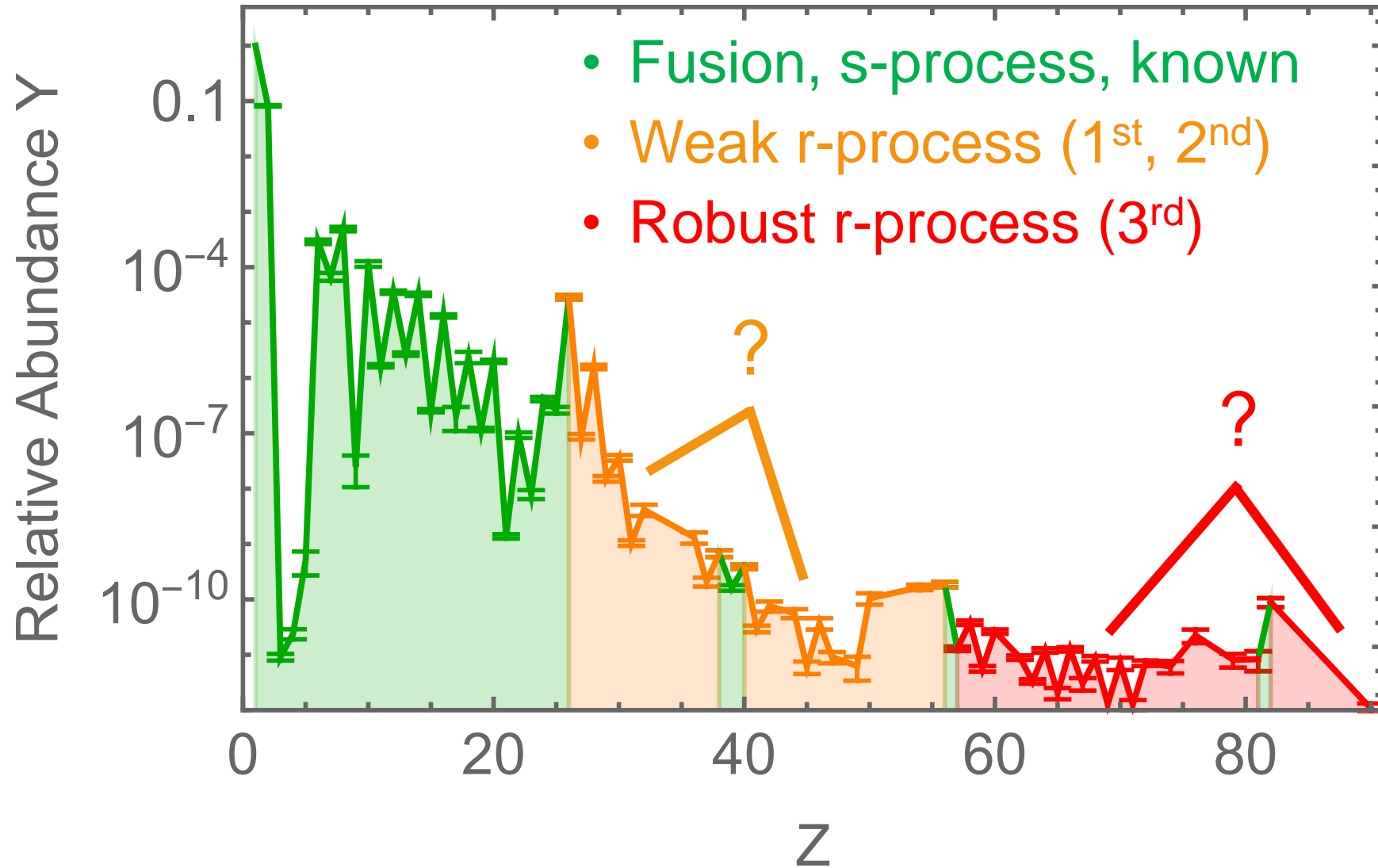
Nucleosynthesis = binding of nucleons into heavier nuclei

1. Lack of understanding in solar abundances
2. Known astrophysical sites of nucleosynthesis
3. Debated sites and their signatures

*Cosmic rays, neutrinos, kilonovae*



## Distribution of Solar Abundances



[Asplund+ 2021]

# KNOWN SOURCES

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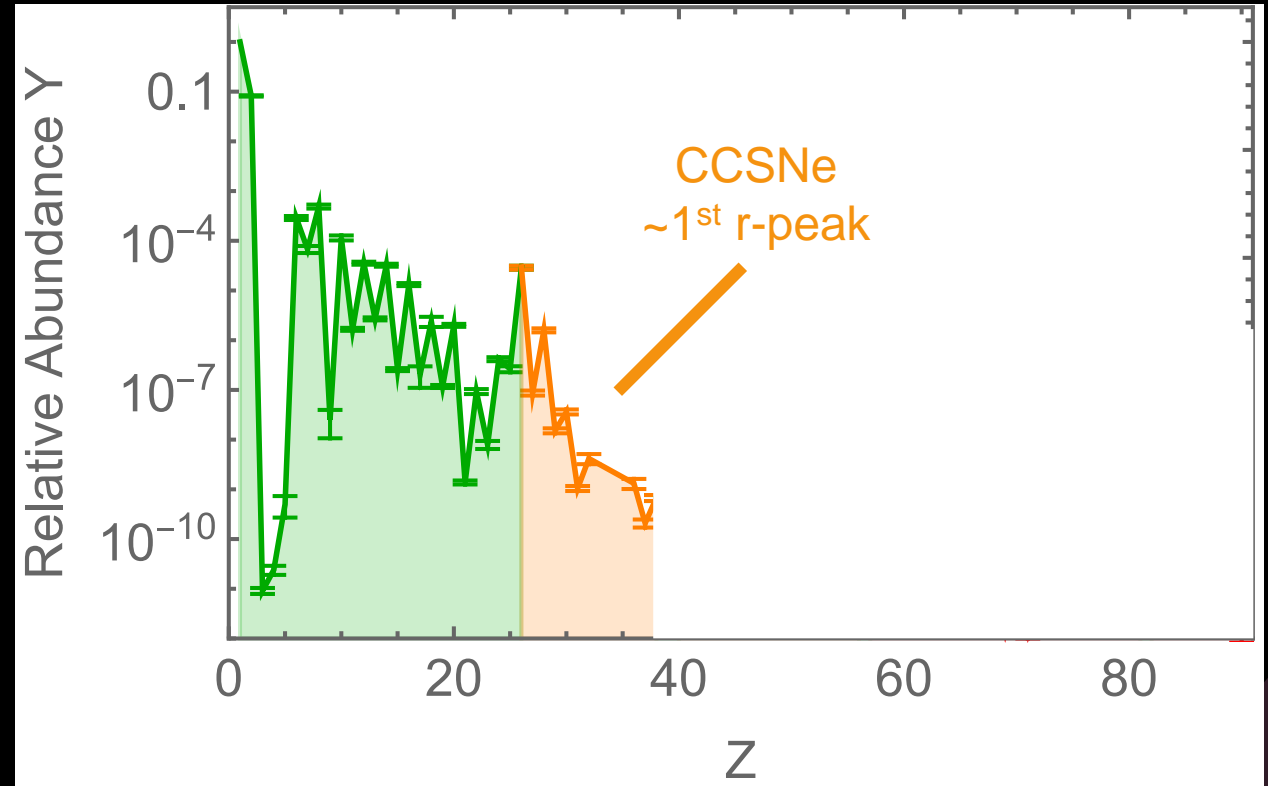
# Core-collapse supernovae (CCSNe)

- CCSNe synthesize up to  $\sim$ Ni in explosive nucleosynthesis  
*Maybe first-peak if slightly neutron rich*

- **Nucleosynthesis signatures:**

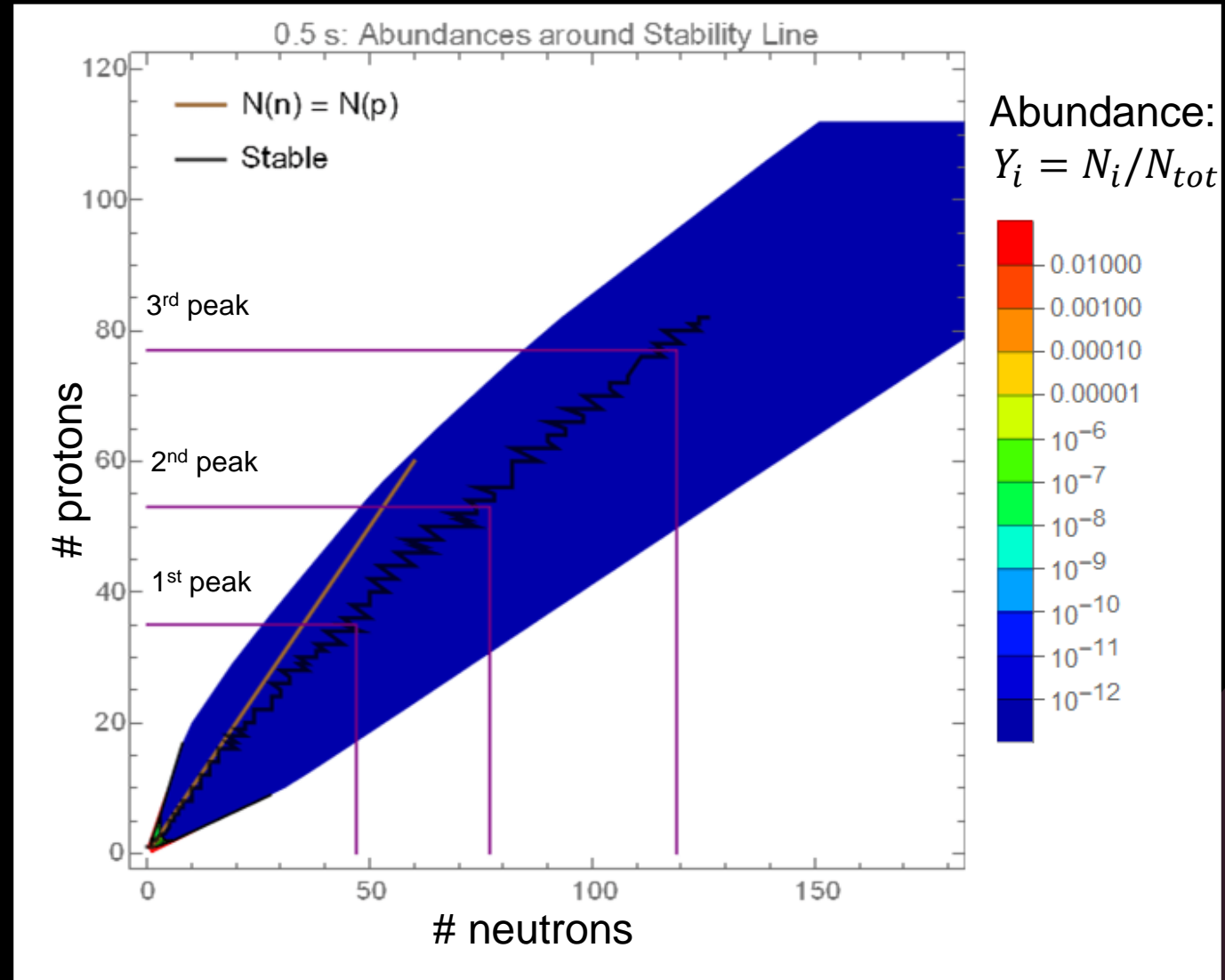
- EM emission as a result of radioactive nickel-56

[Kasen & Woosley 2009]



# Neutron star mergers

- Eject  $\sim 10^{-2}$  solar masses of neutron-rich material
- Robust r-process occurs
- **Nucleosynthesis signatures:**
  - Kilonovae – decay of massive, unstable nuclei powers EM emission
  - Multimessenger confirmation of the r-process (GW170817, AT2017gfo)

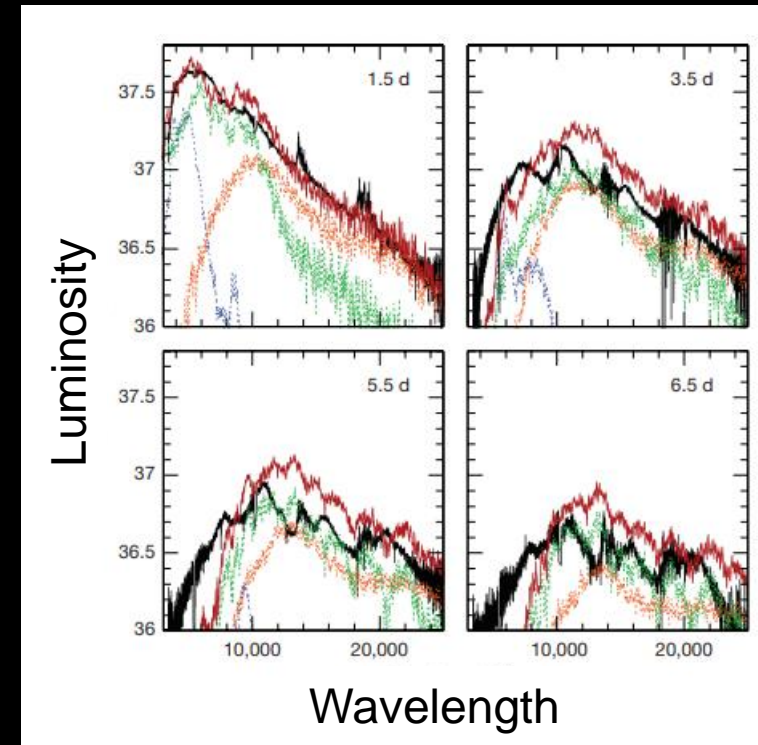
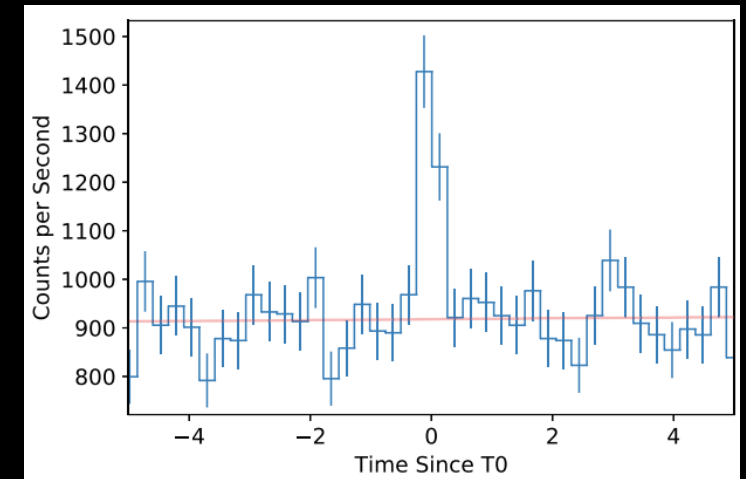
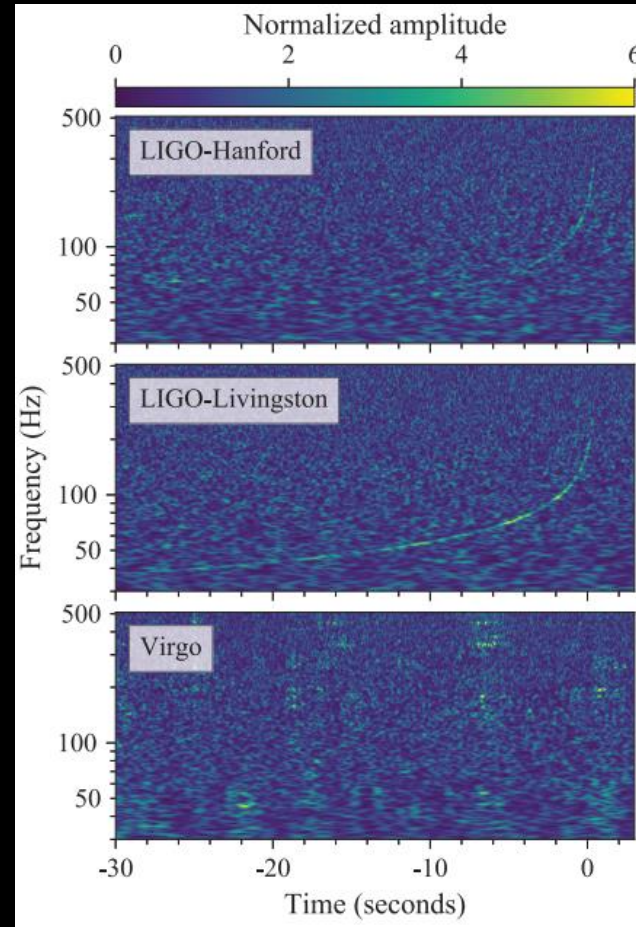




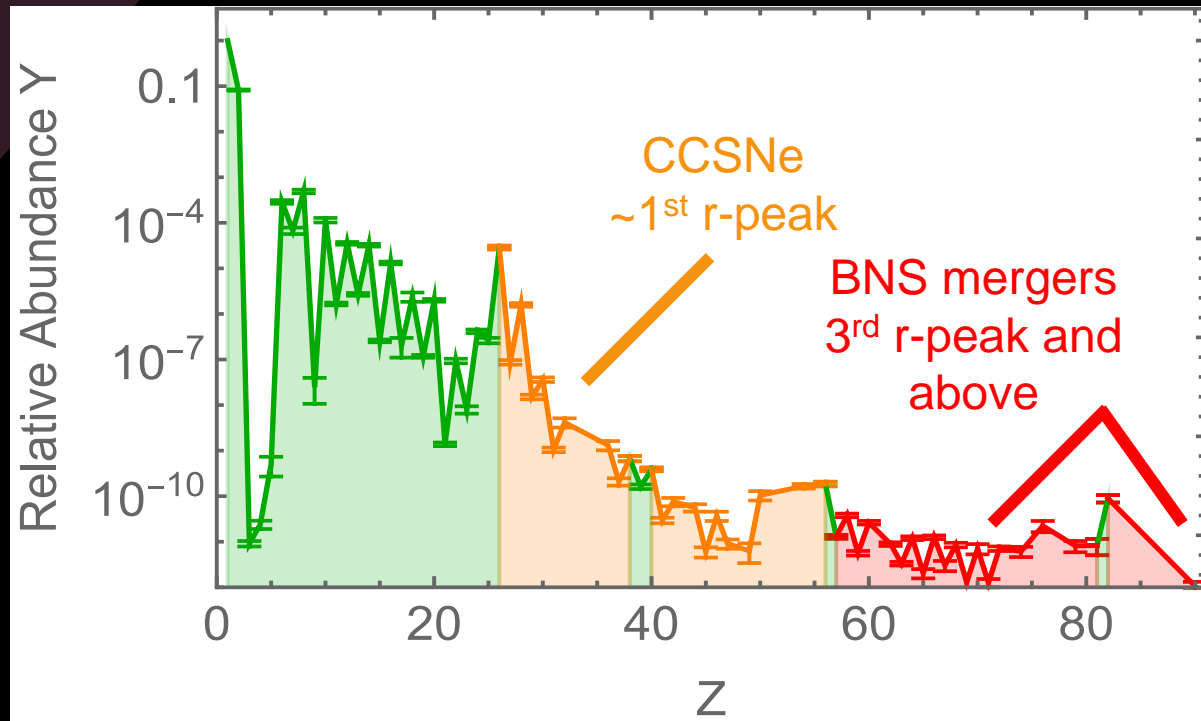
# Neutron star mergers

[Abbott+ 2017a]  
[Goldstein+ 2017]  
[Abbot+ 2017b]

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# Known sources



- Nucleosynthesis known to occur in CCSNe and BNS mergers
- Is BNS the sole site of robust r-process?
- Other sites with faster timescales may be necessary

[Côté+ 2019]  
[Kobayashi+ 2020]  
[Simon+ 2023]

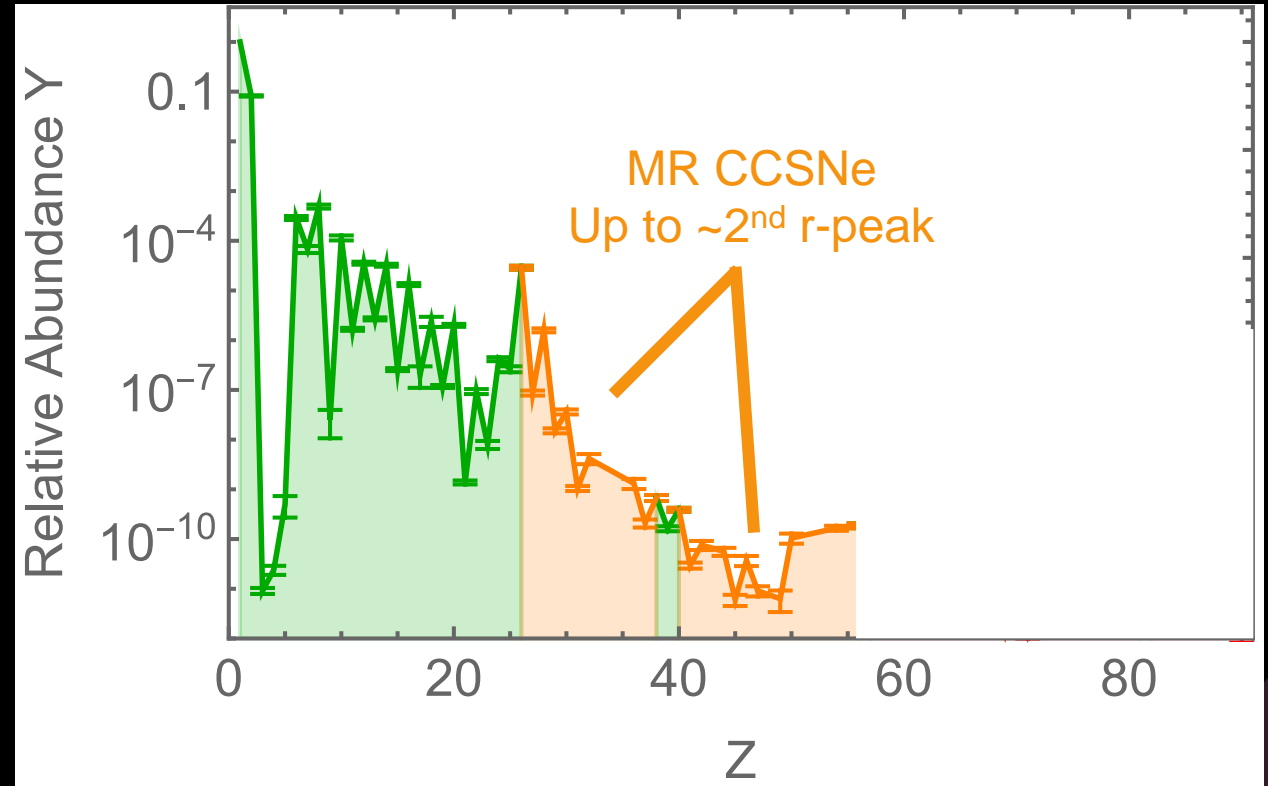


# DEBATED SOURCES

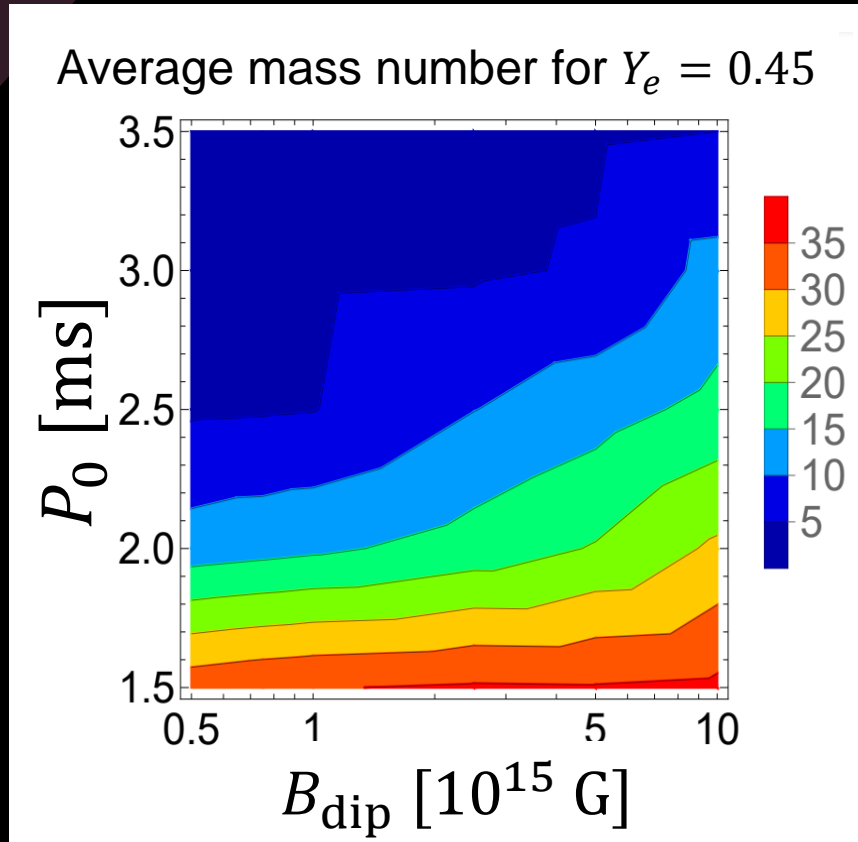
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# Magnetorotational (MR) CCSNe

- Rare CCSNe powered by magnetized, rapidly rotating progenitors
  - More neutron rich, lower entropy*
  - Better for nucleosynthesis*
- Heavier nuclei ( $\sim 2^{\text{nd}}$  peak)
  - Robust  $r$ -process ( $> 3^{\text{rd}}$  peak) unlikely*
- **Nucleosynthesis signatures:**
  - Heavy UHECRs
  - Neutrinos from nuclei interactions



# Signatures of MR CCSNe



[Ekanger+ 2022, arXiv: 2201.03576]

- Moderately neutron rich outflows  
*Weak r-process*
- Average mass number  $A$  influenced by spin and magnetization
- Protomagnetars may give rise to long GRBs

[Metzger+ 2010]

# Black hole-neutron star mergers

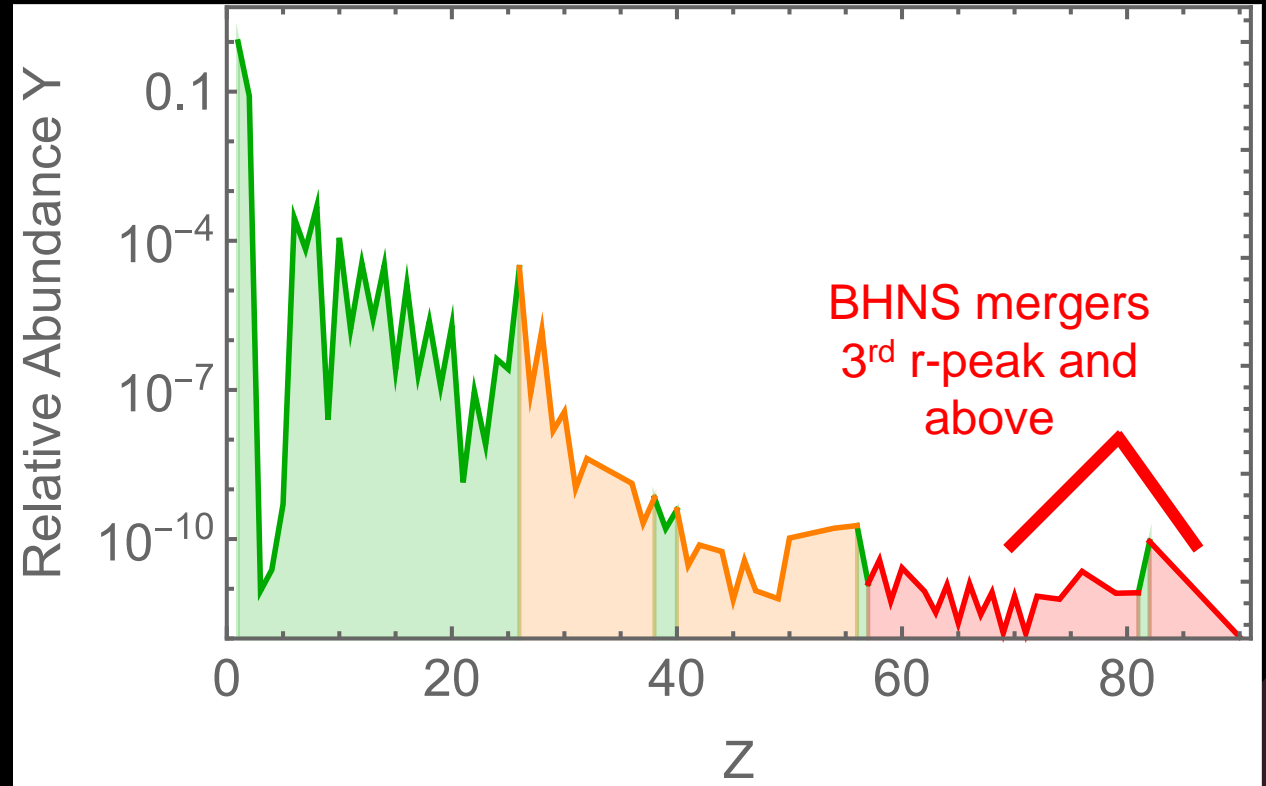
- Typical BHNSs merge and eject  $\sim 10^{-1}$  solar masses of very neutron-rich material

*Less frequent*

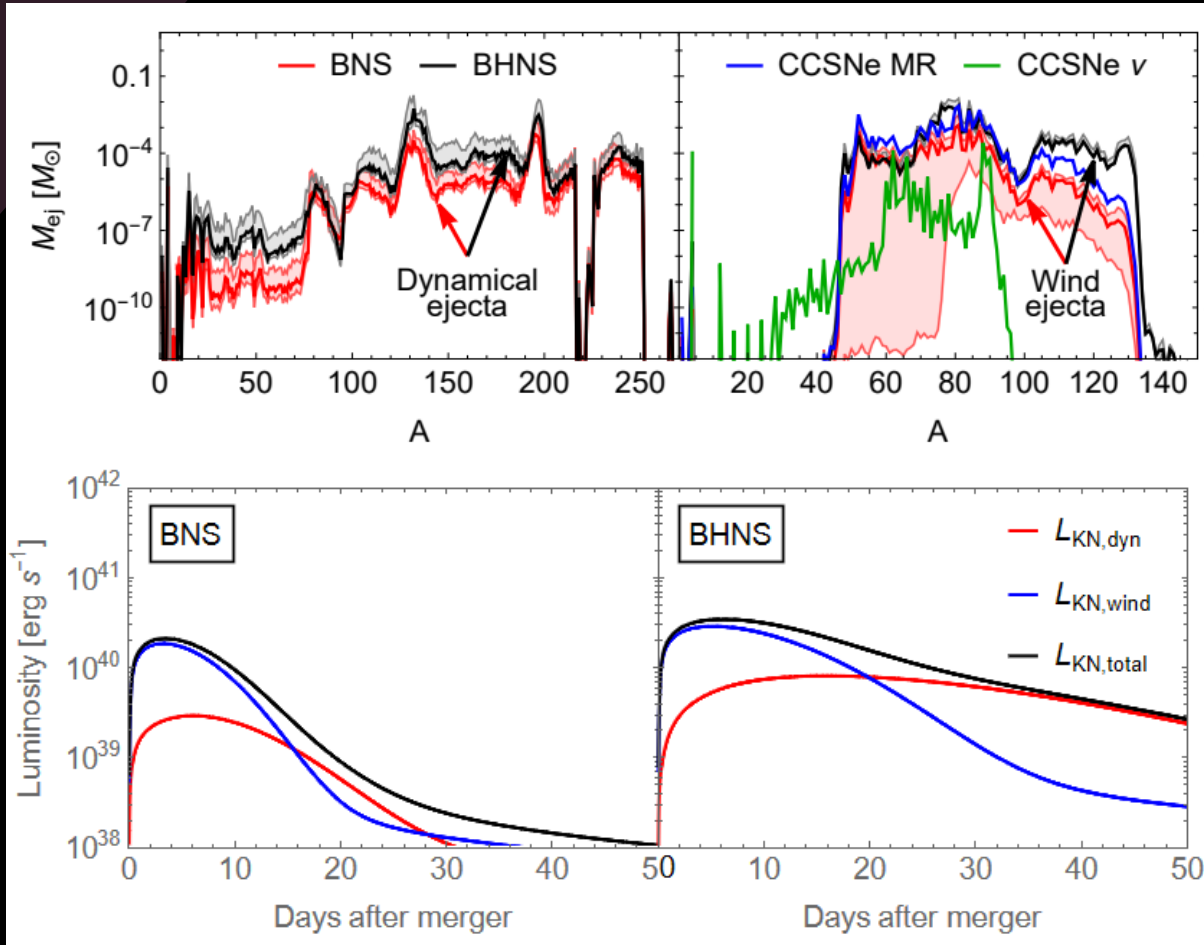
*Some don't eject mass*

- **Nucleosynthesis signatures:**

- Should also have kilonovae, but not yet detected



# Signatures of BNS, BHNS mergers



[Ekanger+ 2023, arXiv: 2303.00765]

- BNS and BHNS mergers likely sites of r-process  
*Synthesis of very heavy elements*  
*\*Showing mass number A*
- Gives rise to UVOIR emission  
*BHNS characteristically brighter and longer-lasting compared to BNS*



# Predicted KN event rates w/ LSST



Vera C. Rubin Observatory

- Large optical survey can detect KNe
  - *first BHNS KN?*
- Based on LIGO rates:

~7 BNS events/year  
~2 BHNS events/year



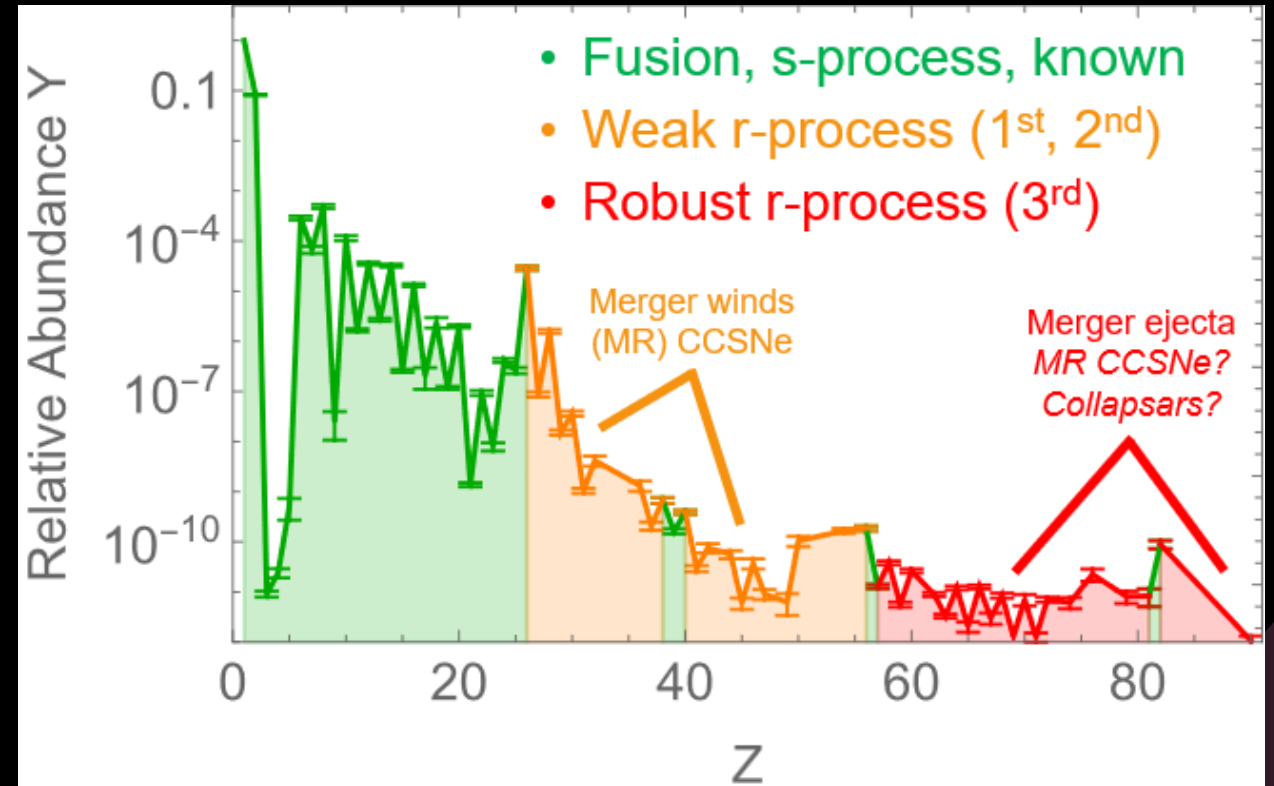
# WRAPPING UP



# Conclusions

- Nucleosynthesis is prevalent in many systems
- **Signatures** connect heavy elements to astrophysical transients  
*UHECRs, neutrinos, kilonovae, etc.*
- LSST can detect

~7 BNS events/year  
~2 BHNS events/year



# THANK YOU!

