

# Multi-messenger constraints on heavy elements produced by neutron star mergers

Collaborators: Jocelyn Read, Philippe Landry, Daniel Siegel

Hsin-Yu Chen The University of Texas at Austin

INT 22r-2a Neutron Rich Matter on Heaven and Earth, June 2023

1 H		big	bangi	fusion			cosr	nic ray	r fissio	n •	<b>.</b>						2 He
3 Li	4 Be	mer	ging r	eutro	n stars	? Mina	exploding massive stars 📓					5 B	υO	7 2	8 0	9 F	10 Ne
11 Na	12 Mg	dyin	ng low	mass :	stars	0	exploding white dwarfs 🧖					13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 	54 Xe
55 Cs	56 Ba		72 Hf	73 Та	74 W	75 Re	76 Os	77 lr	78 Pt	79 Au	80 Hg	81 TI	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																



Graphic created by Jennifer Johnson http://www.astronomy.ohio-state.edu/~jaj/nucleo/ Astronomical Image Credits: ESA/NASA/AASNova



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#### <sup>3</sup> Candidate r-process element production site: Binary neutron star or neutron star-black hole mergers

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Credit: Robin Dienel/Carnegie Institution for Science

**Compare to r-process elements observations** 

#### **Compare to r-process elements observations**

Chemical patterns

**Compare to r-process elements observations** 

**Chemical patterns** 

**Evolution history** 

## Milky Way chemical evolution



## Milky Way chemical evolution



## **Milky Way chemical evolution**



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## **Milky Way chemical evolution**



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87 Fr	88 Ra																
			57	58	59	60	61	62	63	64	65	66	67	68	69	70	71

5859606162636465666768697071CePrNdPmSmEuGdTbDyHoErTmYbLu9091929394Very radioactive isotopes; nothing left from starsThPaUNpPuVery radioactive isotopes; nothing left from stars

Graphic created by Jennifer Johnson http://www.astronomy.ohio-state.edu/~jaj/nucleo/

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#### Hsin-Yu Chen / UT Austin

Astronomical Image Credits: ESA/NASA/AASNova

## Milky Way chemical evolution



#### **Milky Way chemical evolution**



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#### **Milky Way chemical evolution**



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#### **Milky Way chemical evolution**



Hotokezaka et al., Int. J. Mod. Phy. (2018) / Siegel et al., Nature (2019)



Iron

Hotokezaka et al., Int. J. Mod. Phy. (2018) / Siegel et al., Nature (2019)



Hotokezaka et al., Int. J. Mod. Phy. (2018) / Siegel et al., Nature (2019)



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Inferred from multi-messenger observations

10

Inferred from multi-messenger observations

Binary neutron star merger rate history

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Inferred from multi-messenger observations

Binary neutron star merger rate history

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Amount of r-process ejecta from each merger

# <sup>11</sup> **A. Binary neutron star merger rate across the history**



# <sup>11</sup> **A. Binary neutron star merger rate across the history**



# Inferred from observations: 12 A. Binary neutron star merger rate across the history



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## A. Binary neutron star merger rate across the history

• Merger rate in the local Universe



LVK Collaboration, PRX (2023)
# A. Binary neutron star merger rate across the history





# A. Binary neutron star merger rate across the history

• Merger delay time distribution





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Adapted from Zevin et al., ApJL (2022)

Adapted from SAGA database, Suda et al. (2008)

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# Inferred from observations: B. Amount of r-process ejecta from each merger



Adapted from SAGA database, Suda et al. (2008)

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# Inferred from observations: B. Amount of r-process ejecta from each merger



• Neutron star equation-of-state



• Neutron star equation-of-state



• Neutron star equation-of-state



• Neutron star equation-of-state



• Neutron star equation-of-state



Stiffer neutron star equation-of state could lead to more ejecta.











• Neutron star mass distribution



LVK Collaboration, PRX (2023)

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**Observations:** 

• Neutron star mass distribution



Neutron star mass distribution



Gravitational-wave and pulsars observations allows for estimation of the amount of r-process ejecta from each merger.

#### **One-zone model**



#### **One-zone model**



Gravitational wave, short gamma-ray burst, pulsar

Adapted from SAGA database, Suda et al. (2008)

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#### **Comparing to Milky Way chemical evolution**















-In the model: observables for SNe, fraction of r-process ejecta that enters ISM, r-process element chemical pattern etc.

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-In the Galactic observations: different stellar observation database.

-In the model: observables for SNe, fraction of r-process ejecta that enters ISM, r-process element chemical pattern etc.

-In the Galactic observations: different stellar observation database.

-More realistic models.

### **Other r-process element production candidates:**

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#### Collapsar



Siegel et al, Nature (2019)

Accretion disk

# Other r-process element production candidates: Collapsar Magnetorotational core-collapse supernova



Siegel et al, Nature (2019)

#### Accretion disk

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Magnetic jet drives neutronrich materials away from the proto-neutron star Mösta et al., ApJ (2018)



# Summary

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-Multi-messenger observations allow for inference of r-process elements progenitor.

# Summary

-Multi-messenger observations allow for inference of r-process elements progenitor.

-Binary neutron star mergers may not be able to account for Galactic r-process element observations.
Thank you!

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## A. Binary neutron star merger rate across the history

### • Merger delay time distribution



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# A. Binary neutron star merger rate across the history

### • Merger delay time distribution



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# **Observational and numerical uncertainties are still very large**

-Considering very large numerical uncertainties



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# **Observational and numerical uncertainties are still very large**

-Considering very large numerical uncertainties



#### -Varying neutron star EoS



# **Observational and numerical uncertainties are still very large**

### -Considering very large numerical uncertainties



#### -Varying neutron star EoS



### -Varying merger rates

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## **Comparing the total amount of ejecta**

Black hole mass

Black hole spin

Label	$m_1$	$ \chi_1 $	$\operatorname{Tilt}$	$M_{ m ej,NSBH}/M_{ m ej,Total}$
Gap+aligned spin	Uniform in log, $[5, 40]M_{\odot}$	Uniform in [0,0.95]	Aligned	30%
Gap+BBH-like spin	Uniform in log, $[5, 40]M_{\odot}$	BBH-like	BBH-like	1%
No gap+aligned spin	Uniform in log, $[m_{\rm TOV}, 40] M_{\odot}$	Uniform in [0,0.95]	Aligned	49%
No gap+aligned spin	Uniform in log, $[m_{\rm TOV}, 40] M_{\odot}$	BBH-like	BBH-like	1 <b>1%</b>
EBH-like mass+aligned spin	BBH-like	Uniform in [0,0.95]	Aligned	77%
BBH-like mass+spin	BBH-like	BBH-like	BBH-like	35%

### **Comparing the total amount of ejecta**

Black hole mass

Black hole spin

Label	$m_1$	$ \chi_1 $	Tilt	$M_{ m ej,NSBH}/M_{ m cj,Total}$
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dap. arrenta opin			migned	0070
Gap+BBH-like spin	Uniform in log. $[5, 40]M_{\odot}$	BBH-like	BBH-like	1%
				100
No RahiarrEnea shin	$0 \mod 1000 \mod 1000, [mm] 000, 40] m_{\odot}$	Omorni in [0,0.30]	Angneu	4370
No gap+aligned spin	Uniform in log, $[m_{\rm TOV}, 40] M_{\odot}$	BBH-like	BBH-like	11%
BBH-like magateligned onin	DDU III.	$II_{1}:f_{2}$ in [0.0.05]	A 1: manual	770%
DDIT		[0,000]		
BBH-like mass+spin	BBH-like	BBH-like	BBH-like	35%
		-		

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## **Comparing the total amount of ejecta**

Black hole mass

Black hole spin

Label	$m_1$	$ \chi_1 $	Tilt	$M_{ m ej,NSBH}/M_{ m cj,Total}$
(low to 1 i much on in	Uniform in low [F 40] M	Listens in [0.0.05]	A 1:	2007
adb. arrEnca obru	01110111 11 108, [0, 10]11.0		migned	0070
Gap+BBH-like spin	Uniform in log, $[5, 40]M_{\odot}$	BBH-like	BBH-like	1%
		TT 10 1 [0.0.0F]		1007
No gaptarighed spin	$0 \mod 1000, [m_{\rm TOV}, 40] m_{\odot}$	[0,0.35]	Angheu	4370
No gap+aligned spin	Uniform in log, $[m_{\rm TOV}, 40] M_{\odot}$	BBH-like	BBH-like	1 <b>1%</b>
BBH-like magateligned onin	DDU lileo	Uniform in [0.0.05]	Alimond	770%
DDII		0		
BBH-like mass+spin	BBH-like	BBH-like	BBH-like	35%
		-		

Despite the uncertainties, binary neutron star mergers likely produce more heavy elements than neutron star-black hole mergers in the past 2.5 billion years.

