The University of Texas at Austin

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

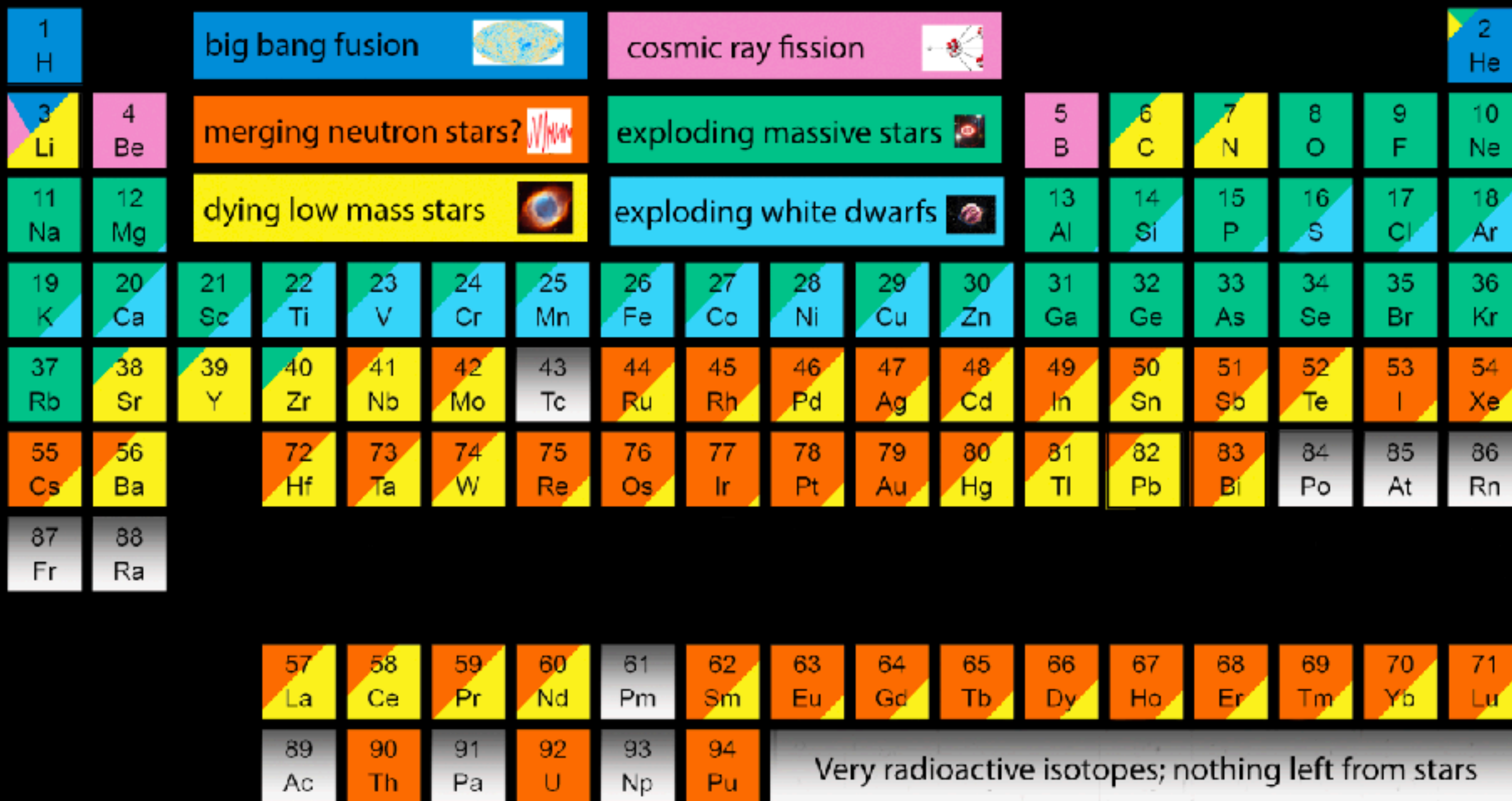
Collaborators: Jocelyn Read, Philippe Landry, Daniel Siegel

Hsin-Yu Chen

The University of Texas at Austin

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

The Origin of the Solar System Elements



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

Astronomical Image Credits:
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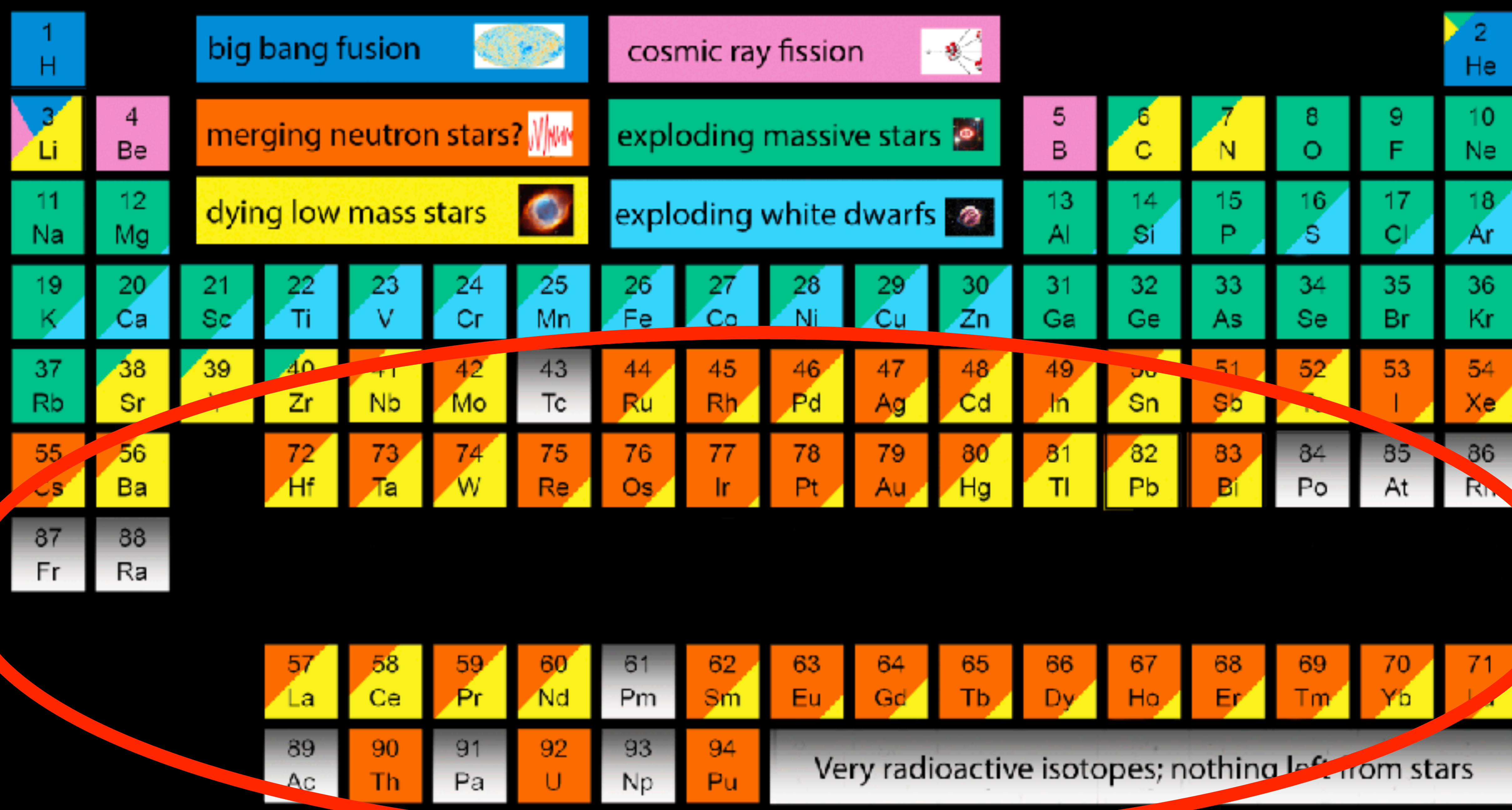

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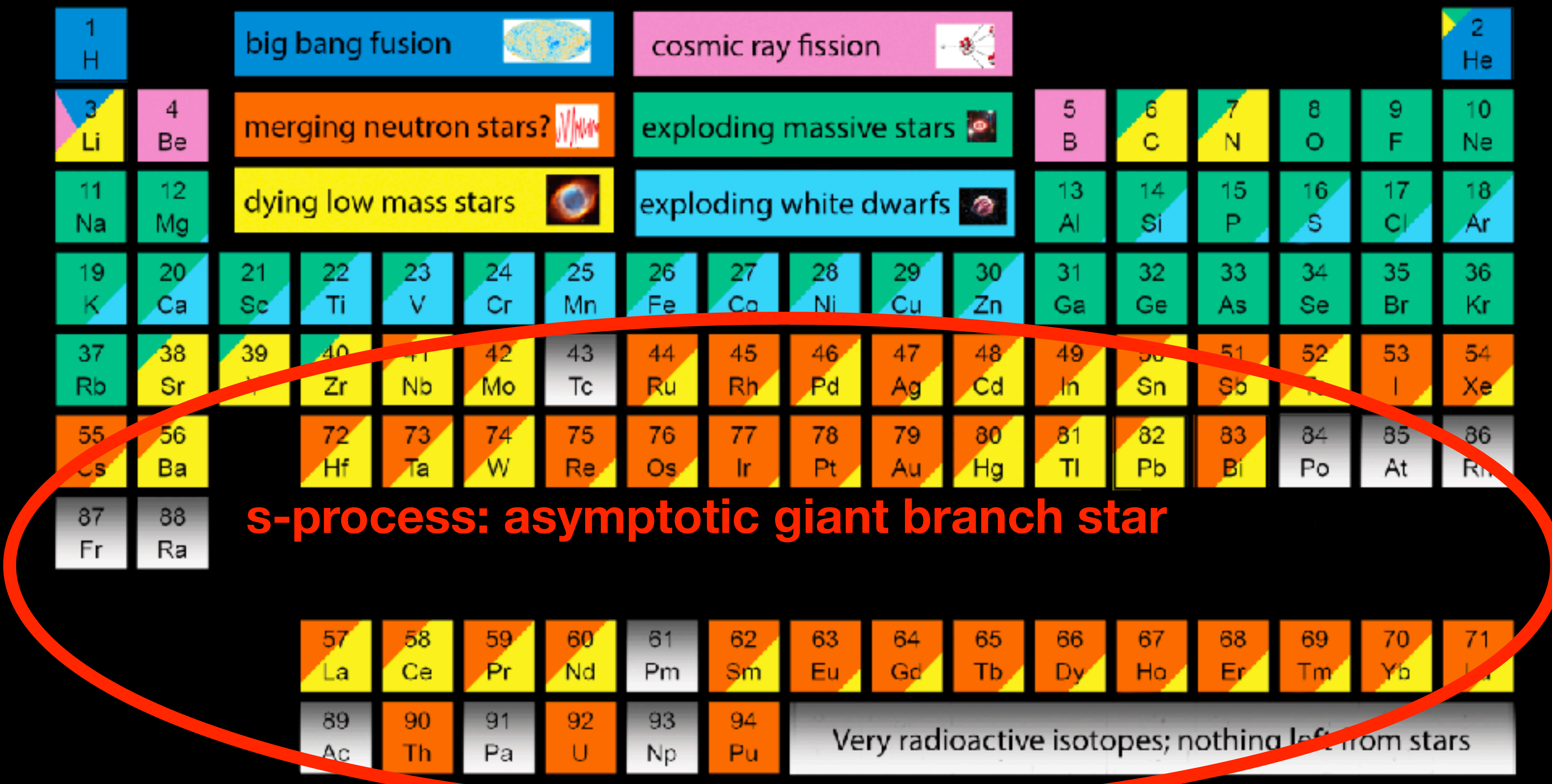

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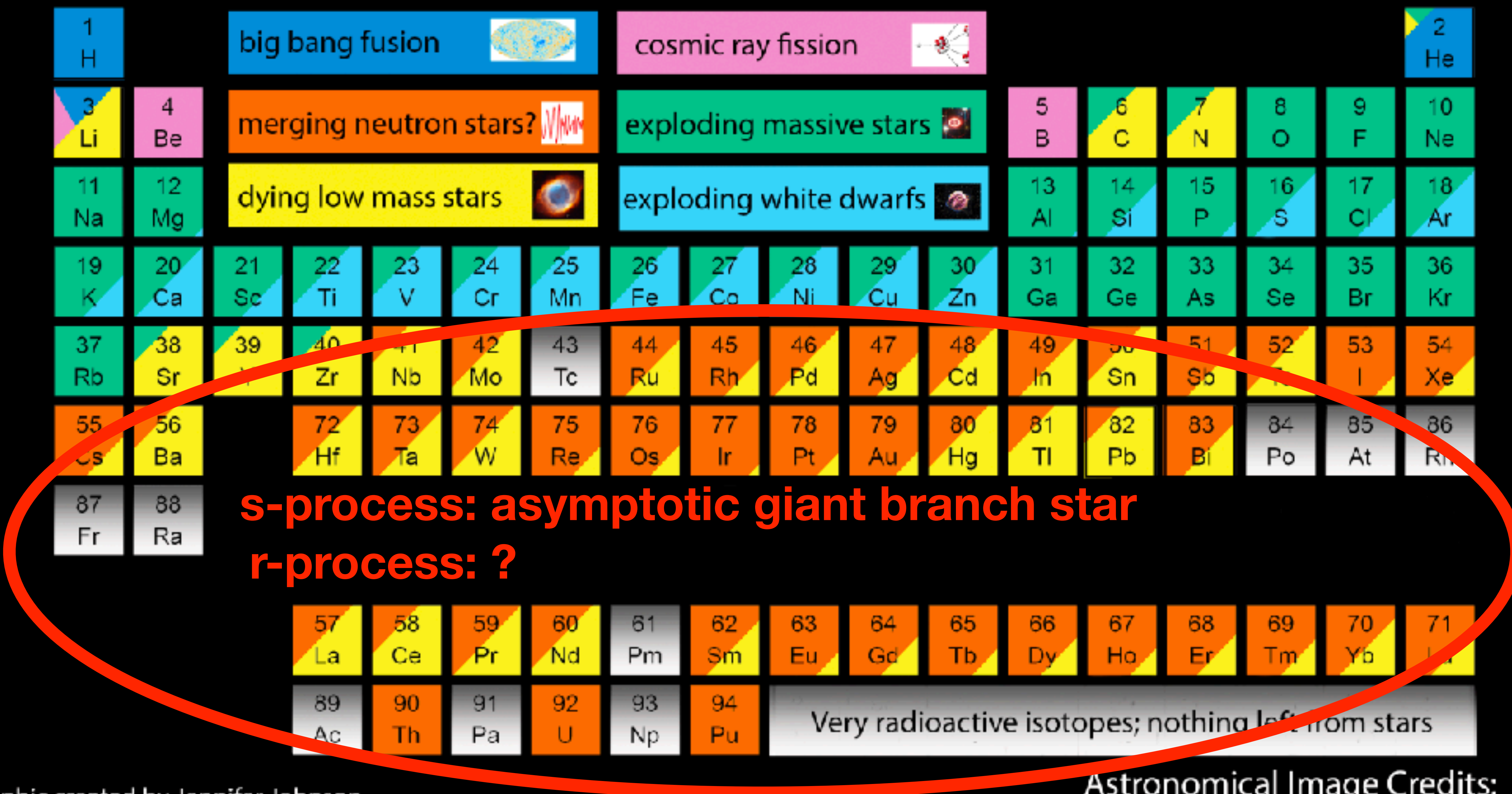

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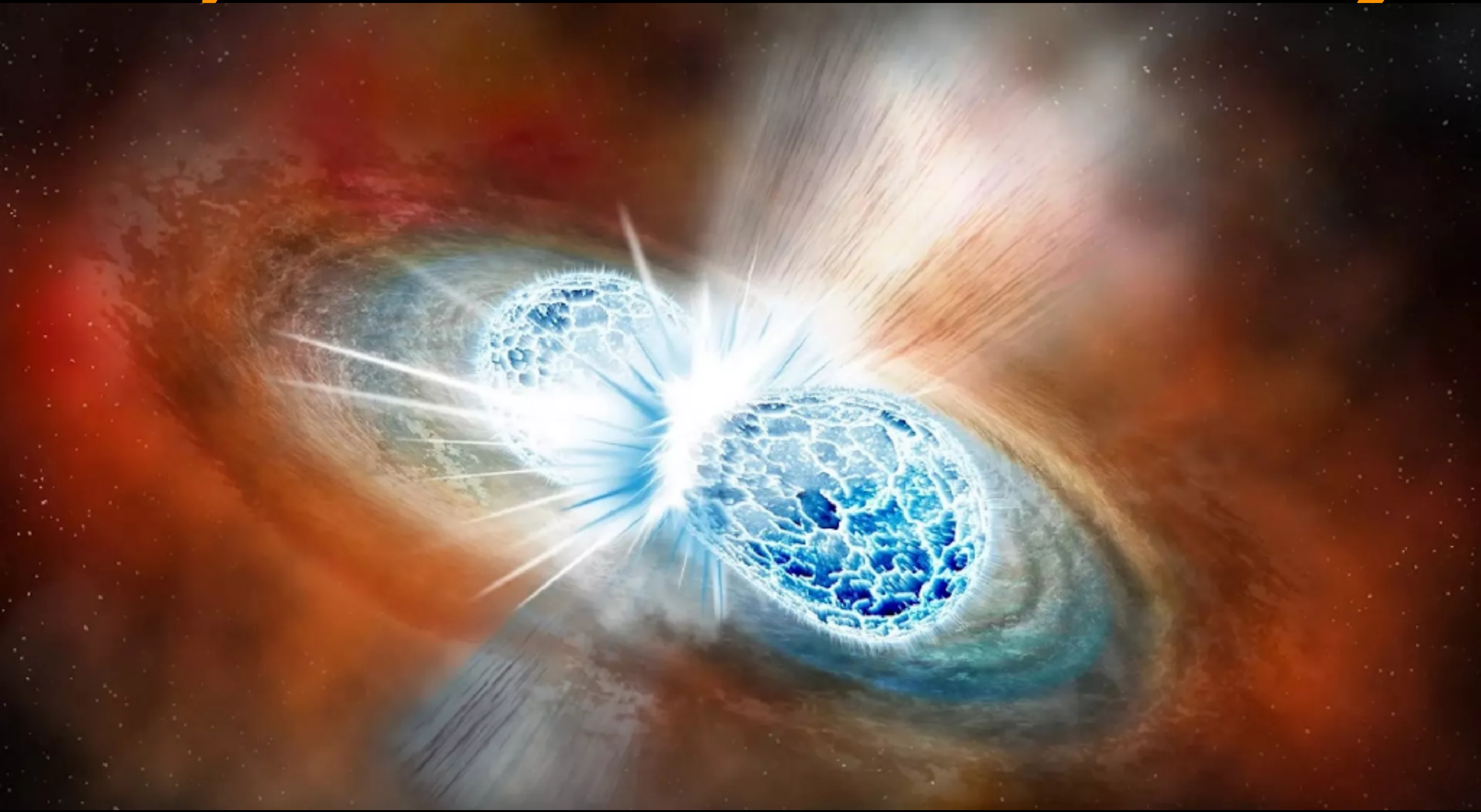
Candidate r-process element production site: Binary neutron star or neutron star-black hole mergers



Credit: Robin Dienel/Carnegie Institution for Science

Compare to r-process elements observations

Compare to r-process elements observations

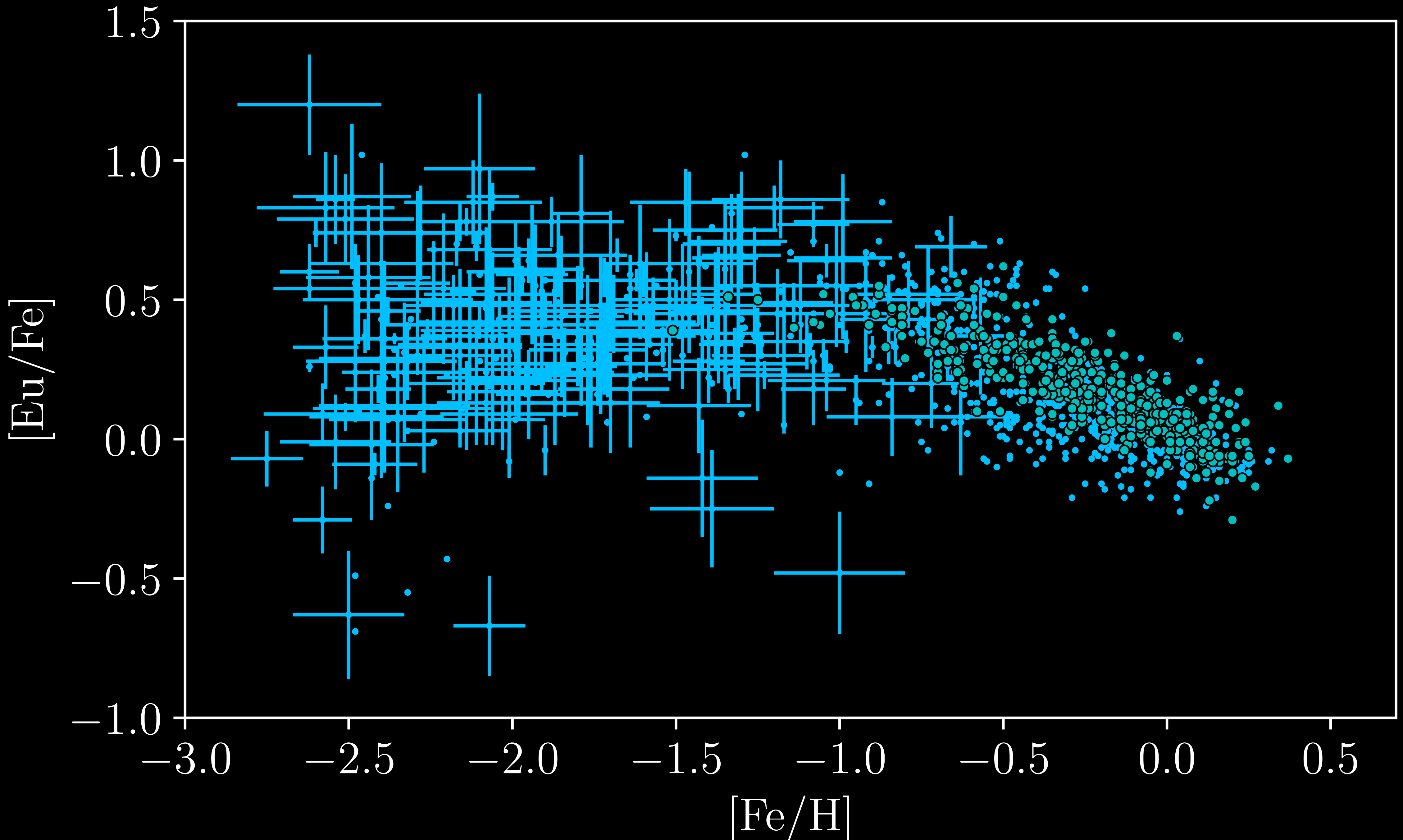
Chemical patterns

Compare to r-process elements observations

Chemical patterns

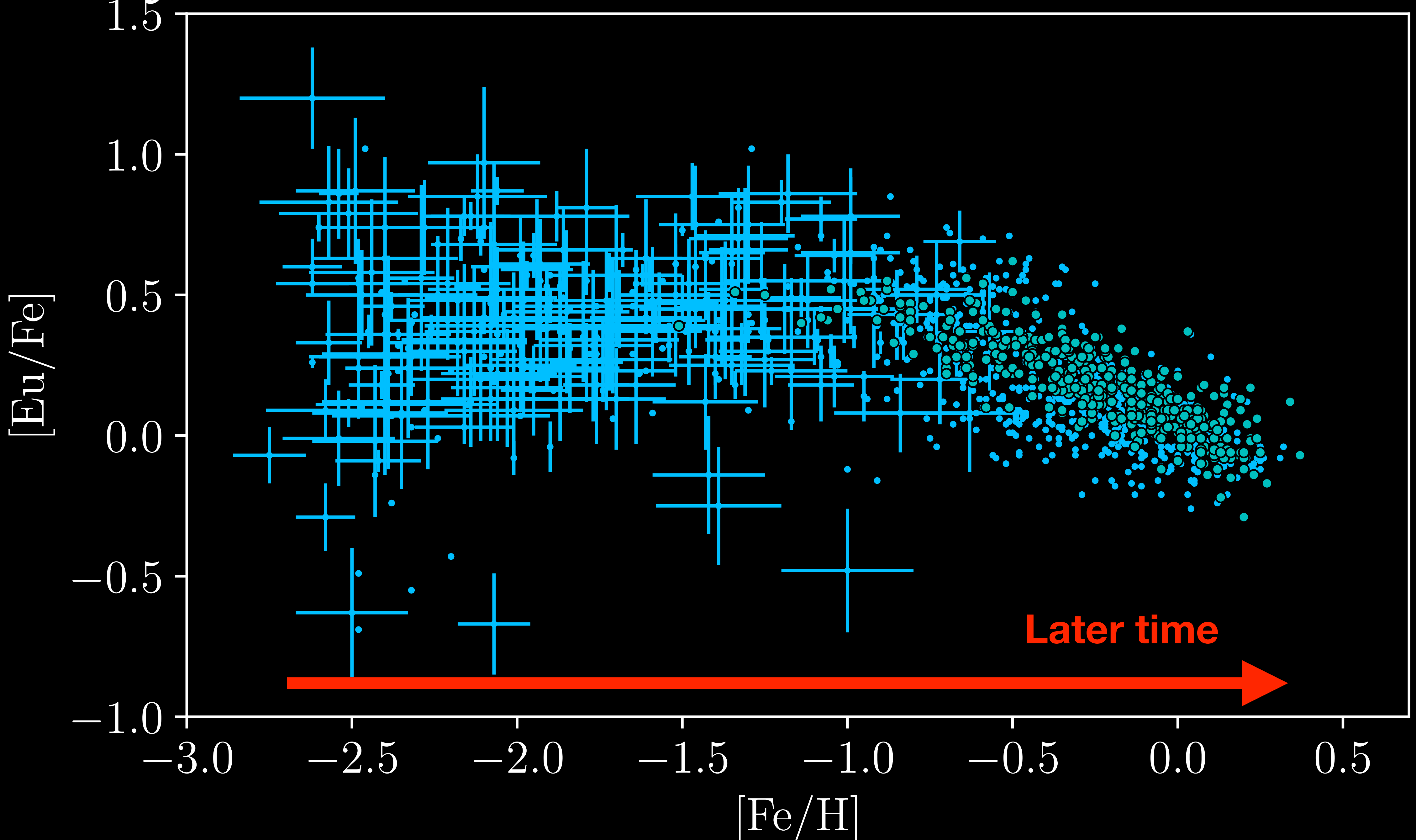
Evolution history

Milky Way chemical evolution



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

Milky Way chemical evolution



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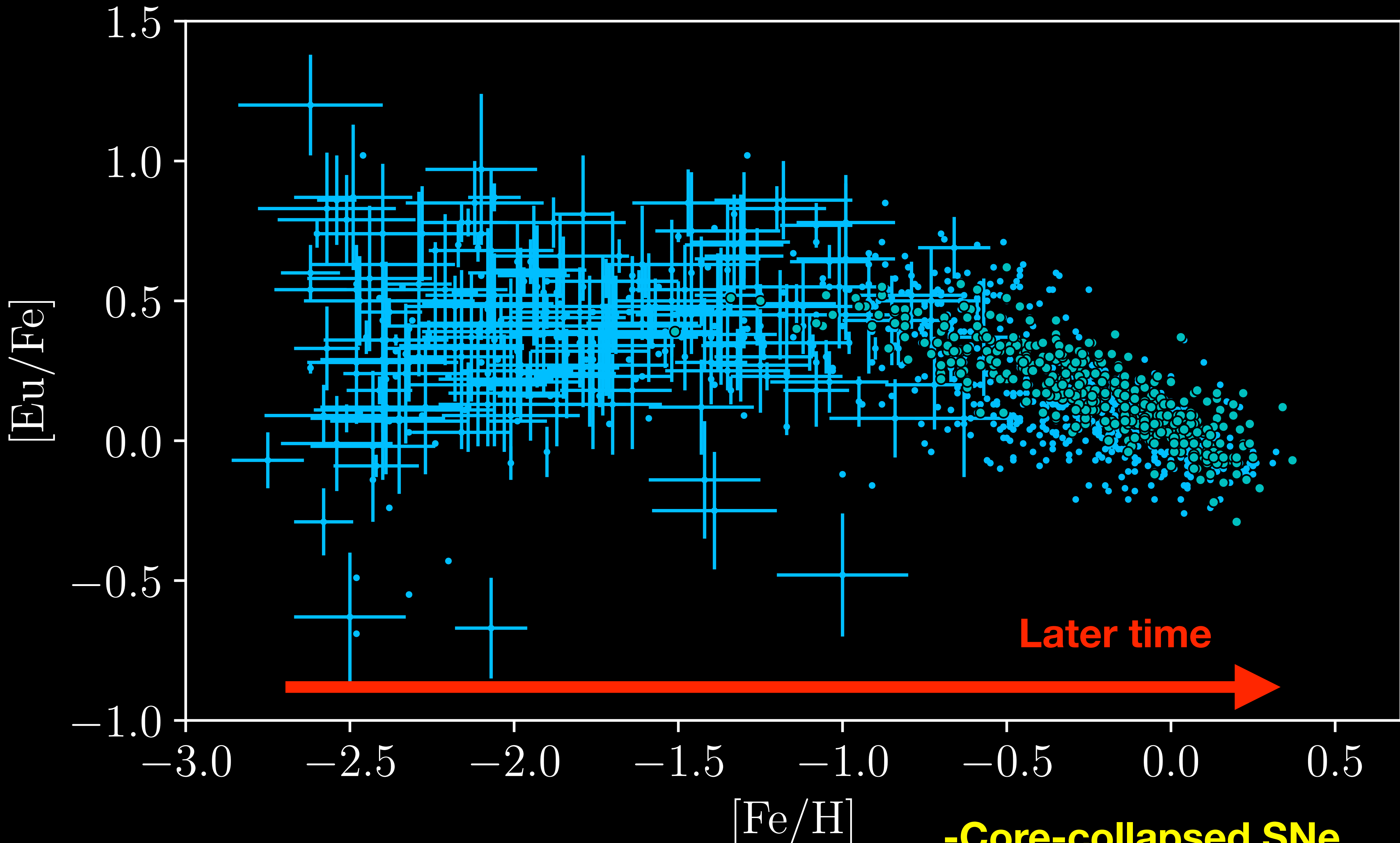
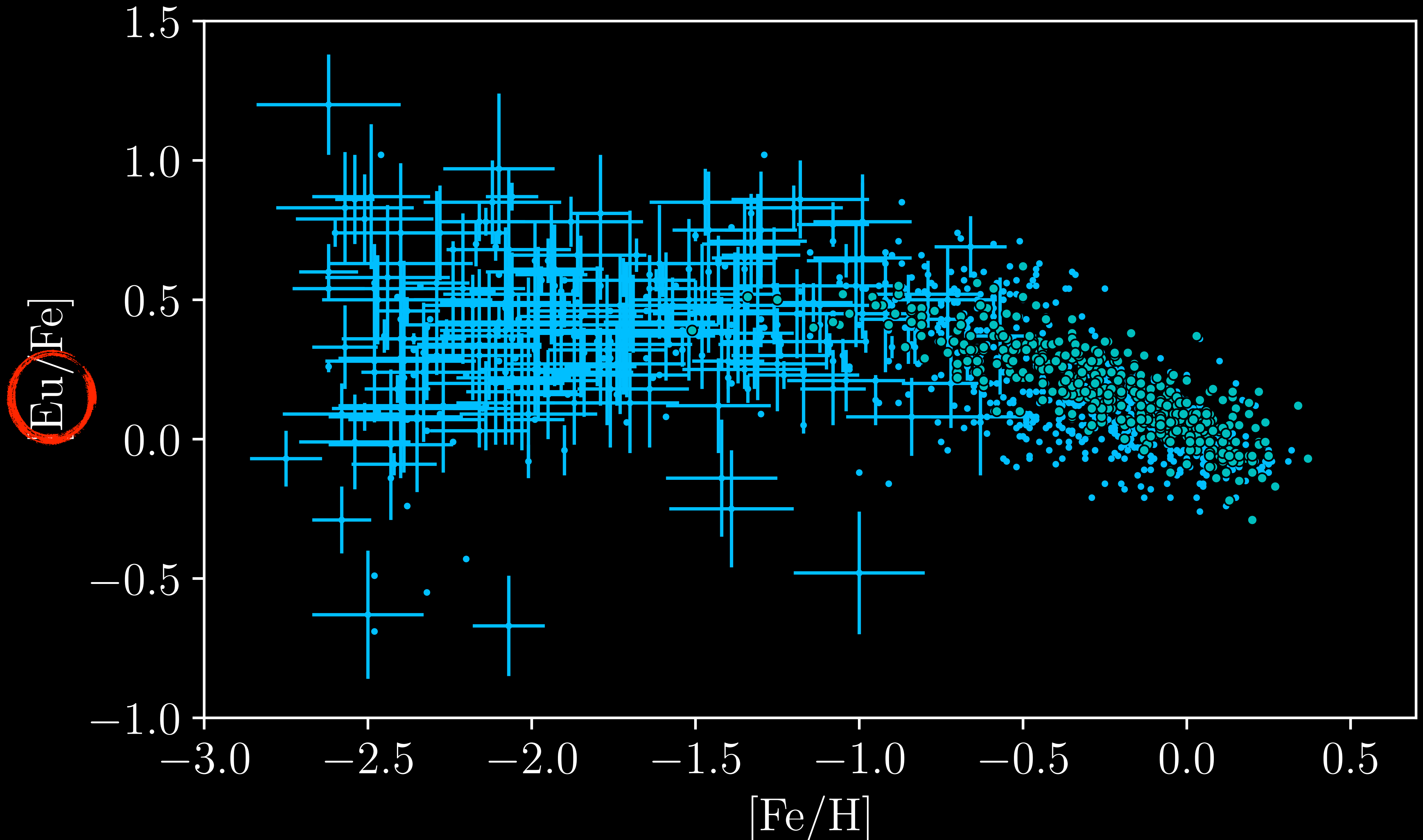


-Core-collapsed SNe

-Type Ia SNe

Milky Way chemical evolution



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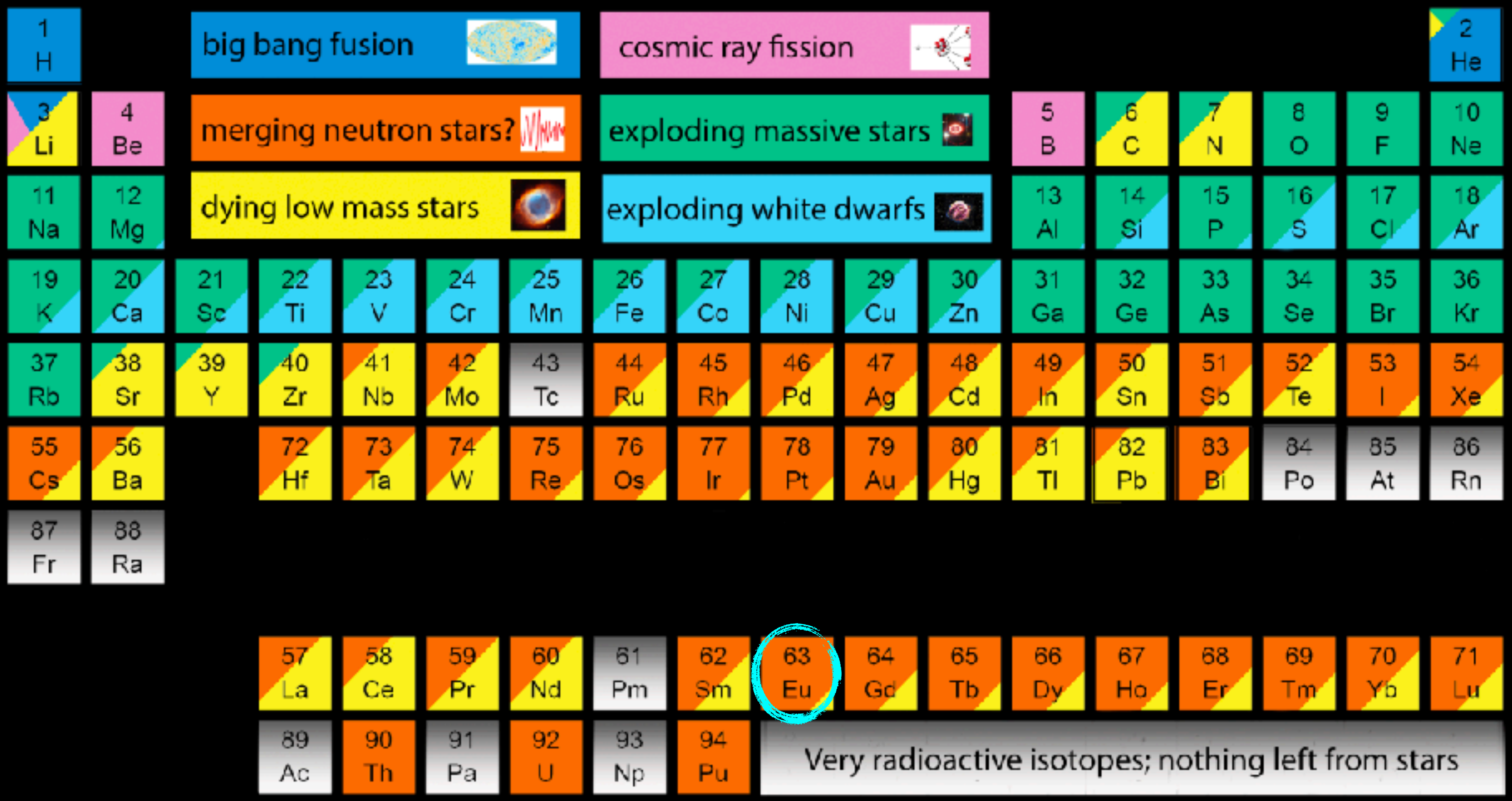

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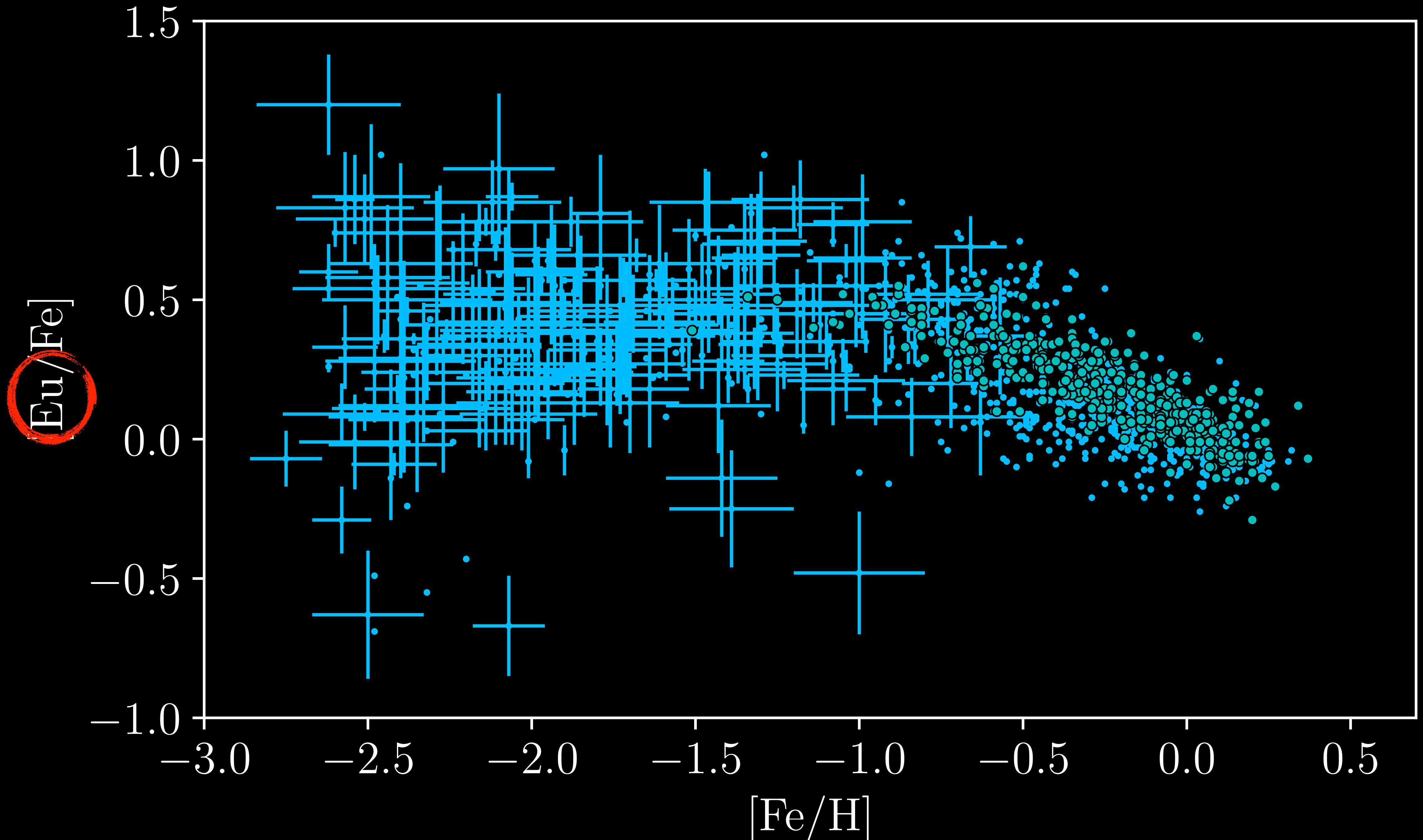

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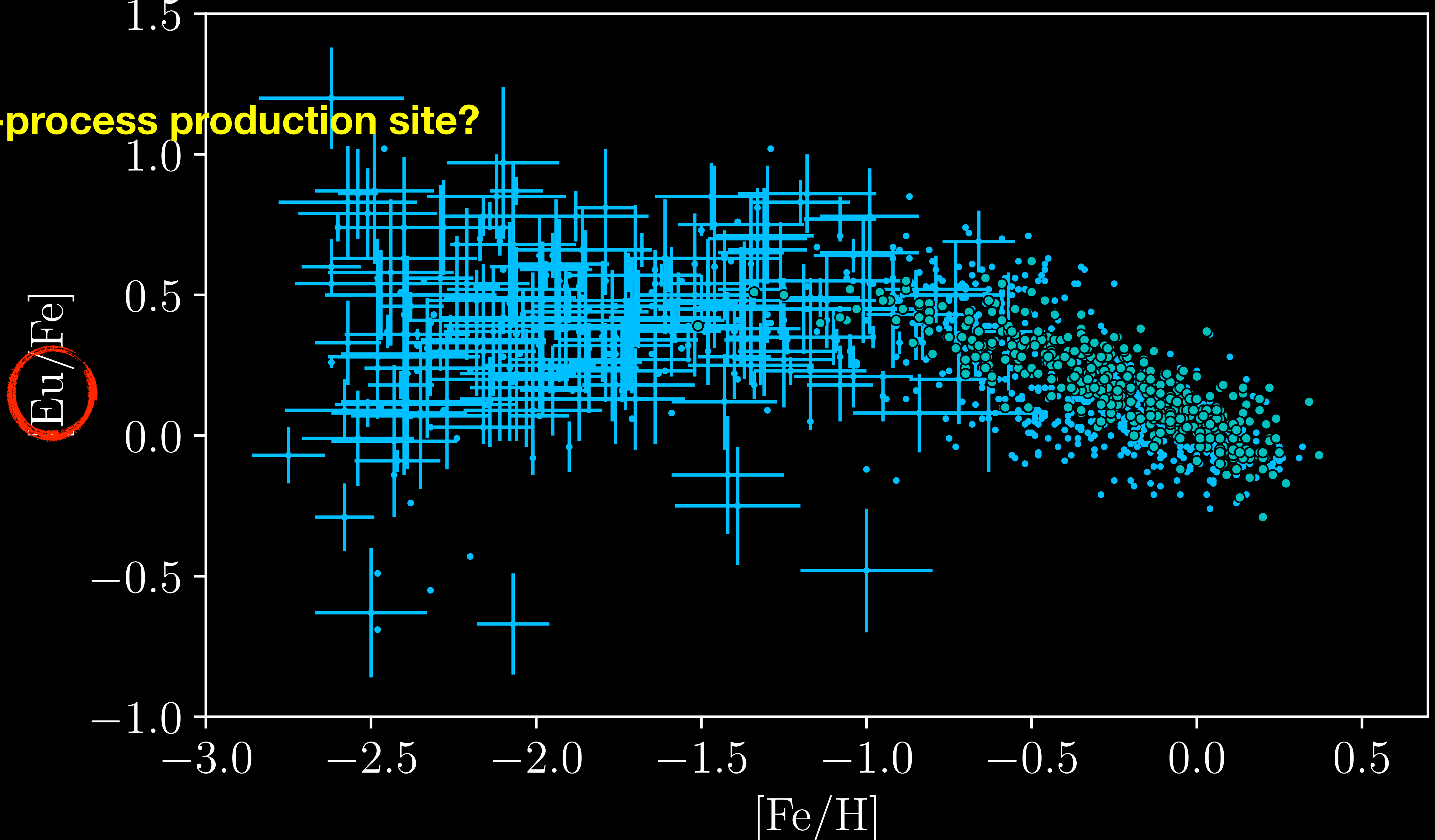
Milky Way chemical evolution

-r-process production site?



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Milky Way chemical evolution

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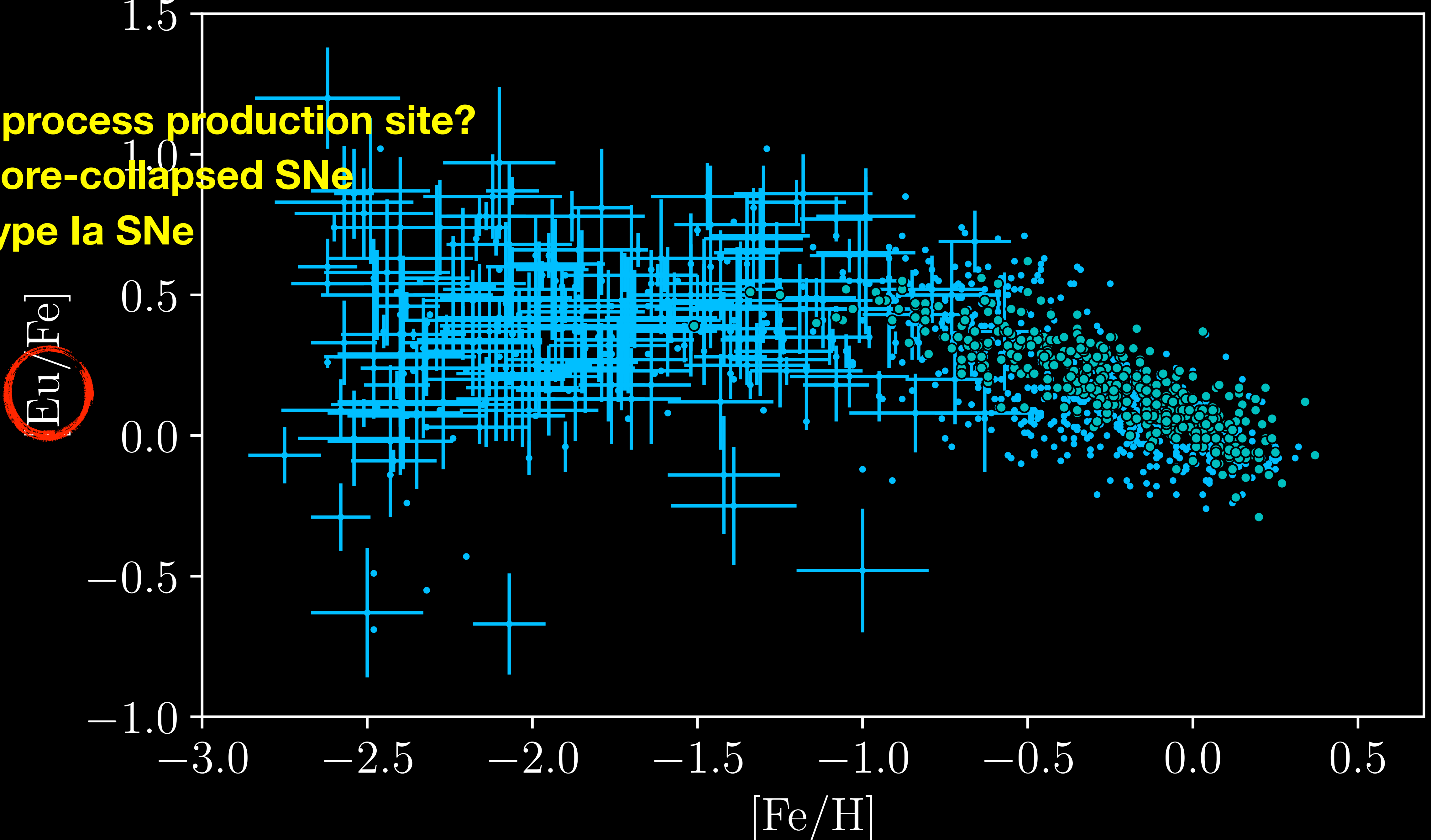

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Milky Way chemical evolution

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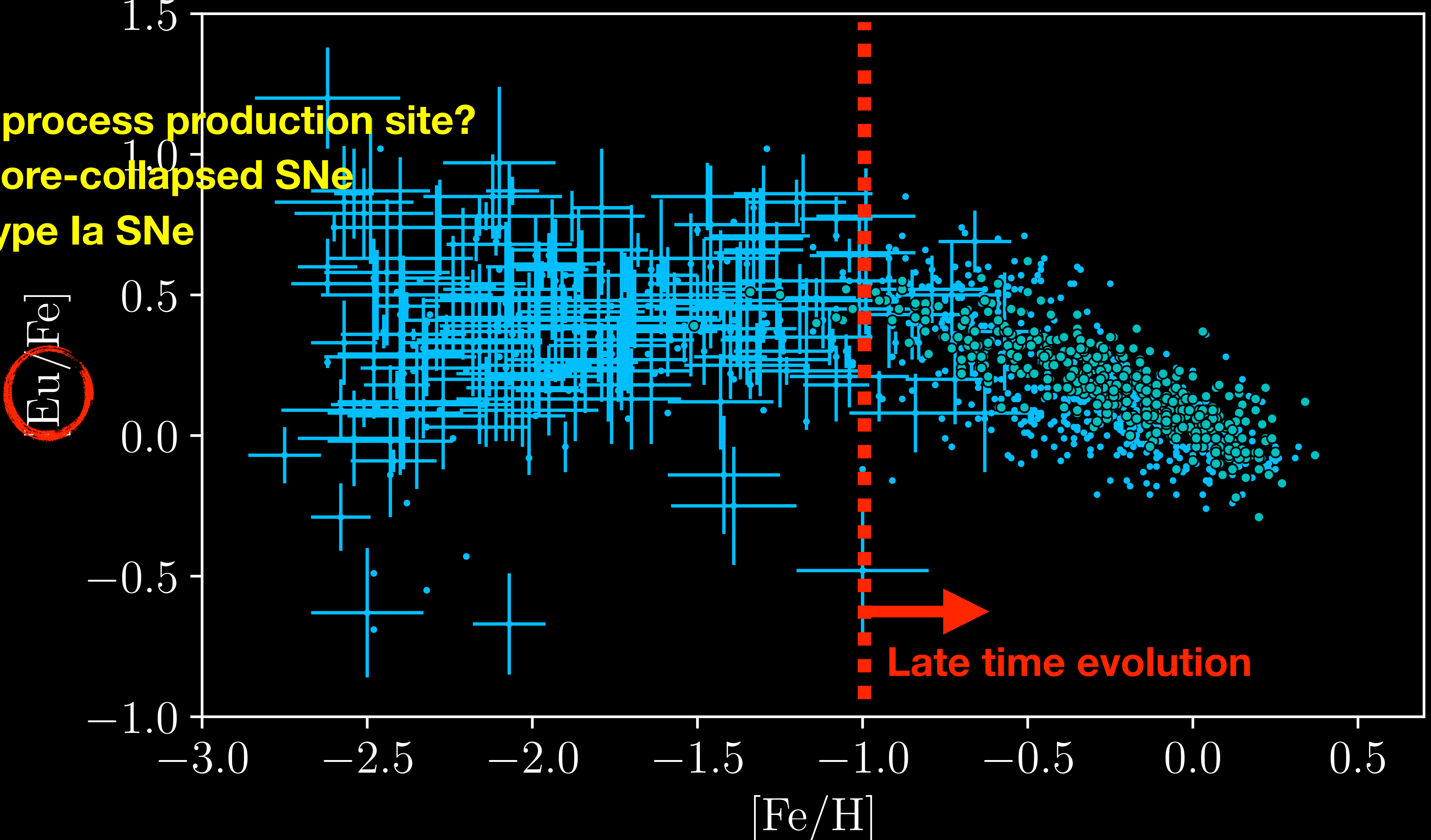

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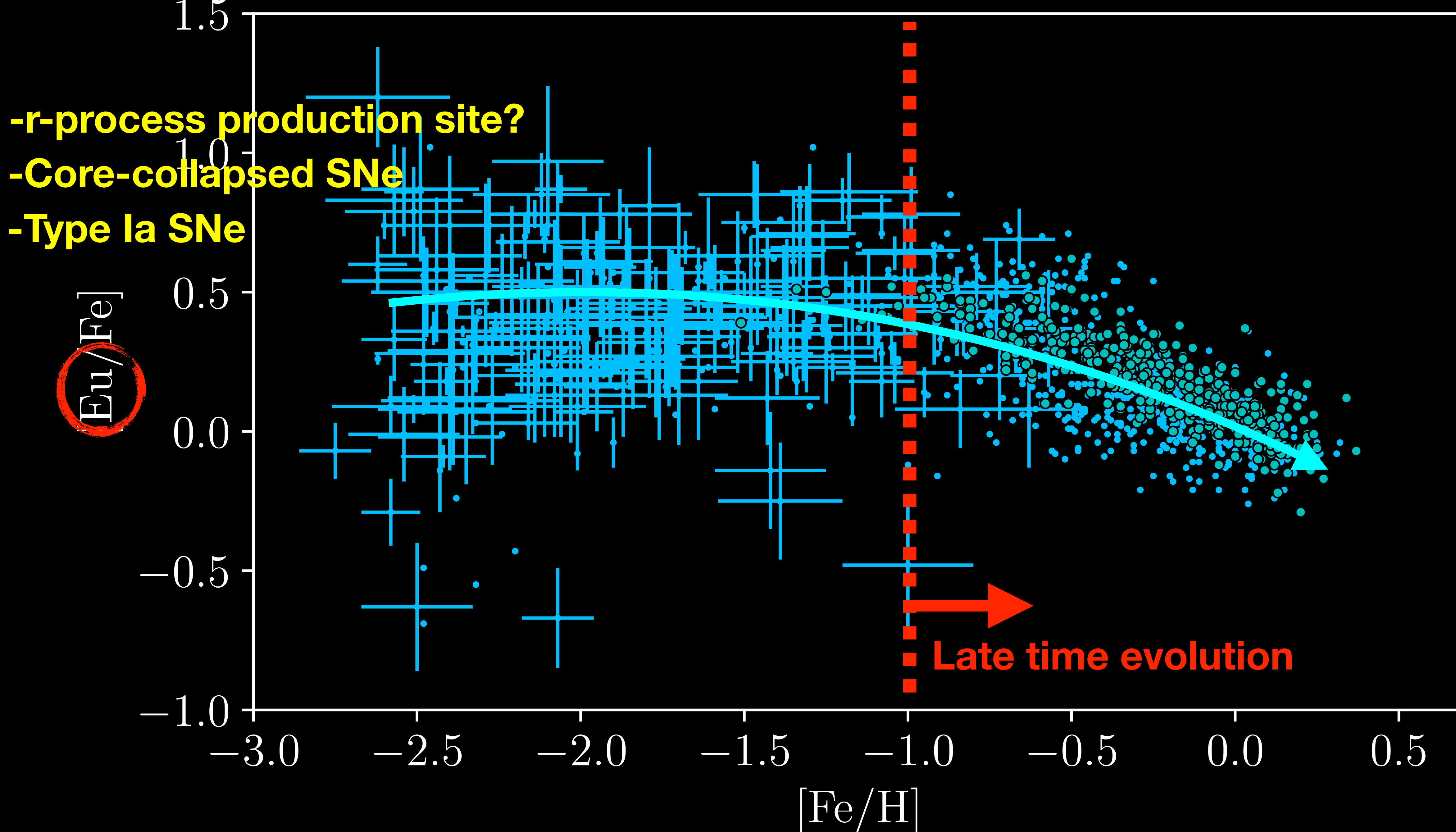
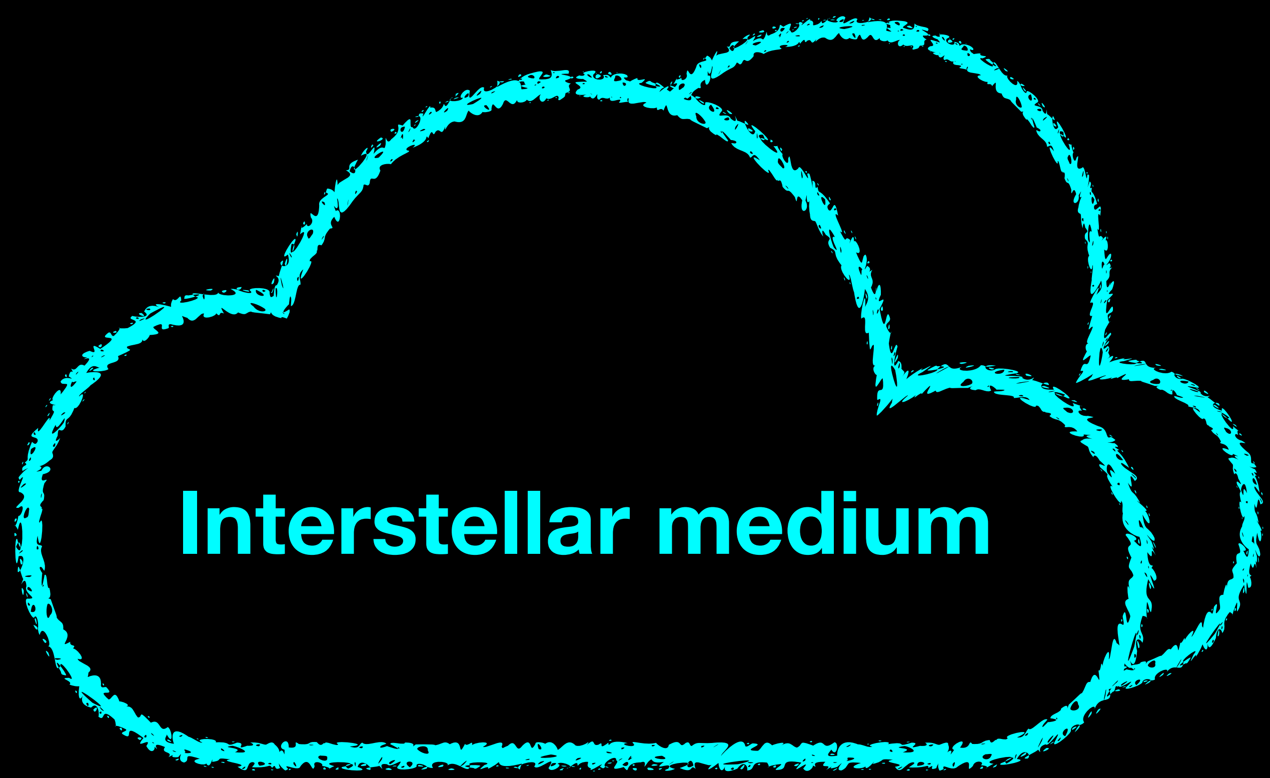


One-zone model

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



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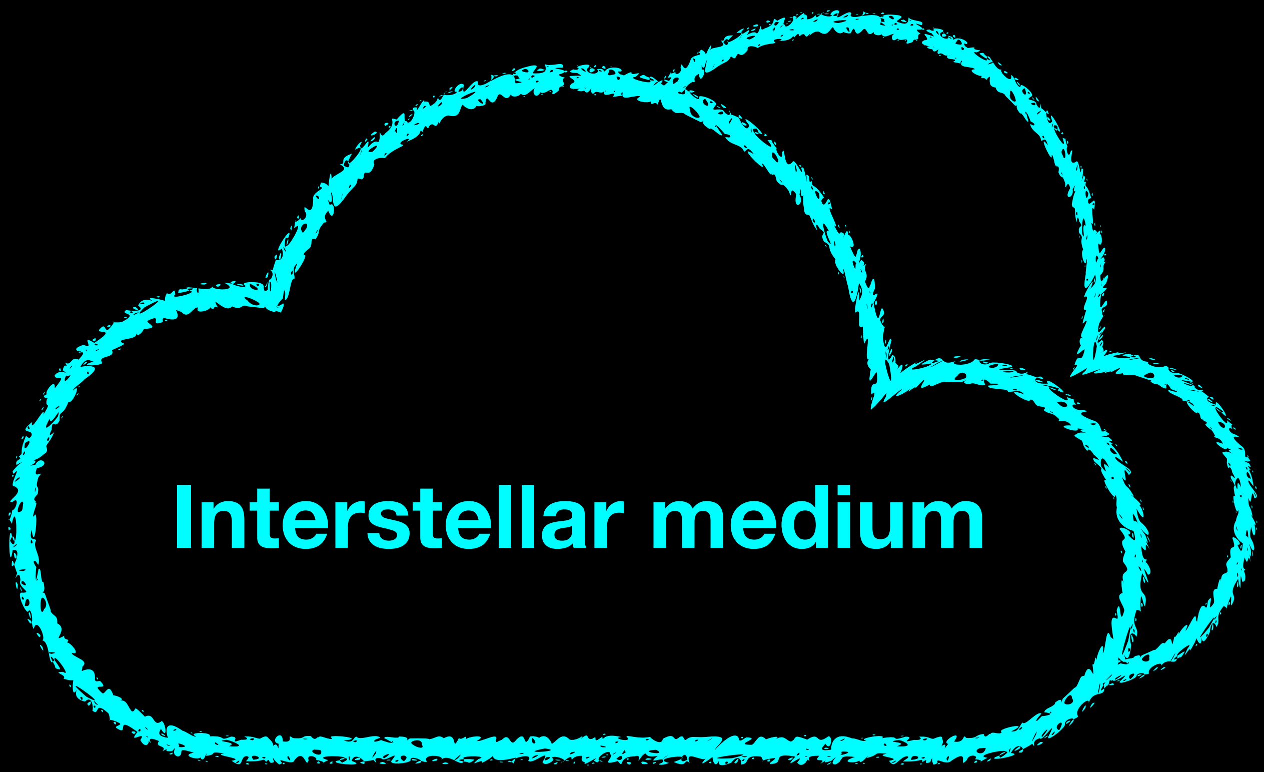
Iron



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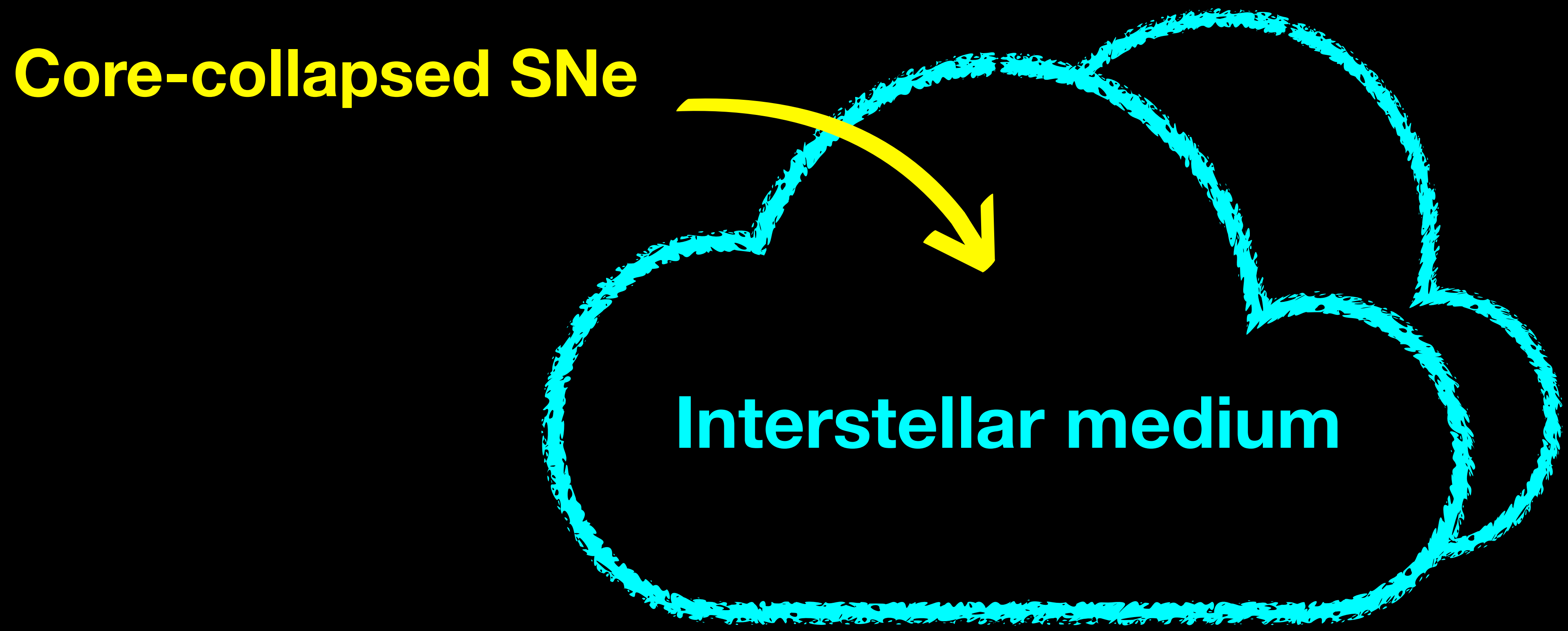

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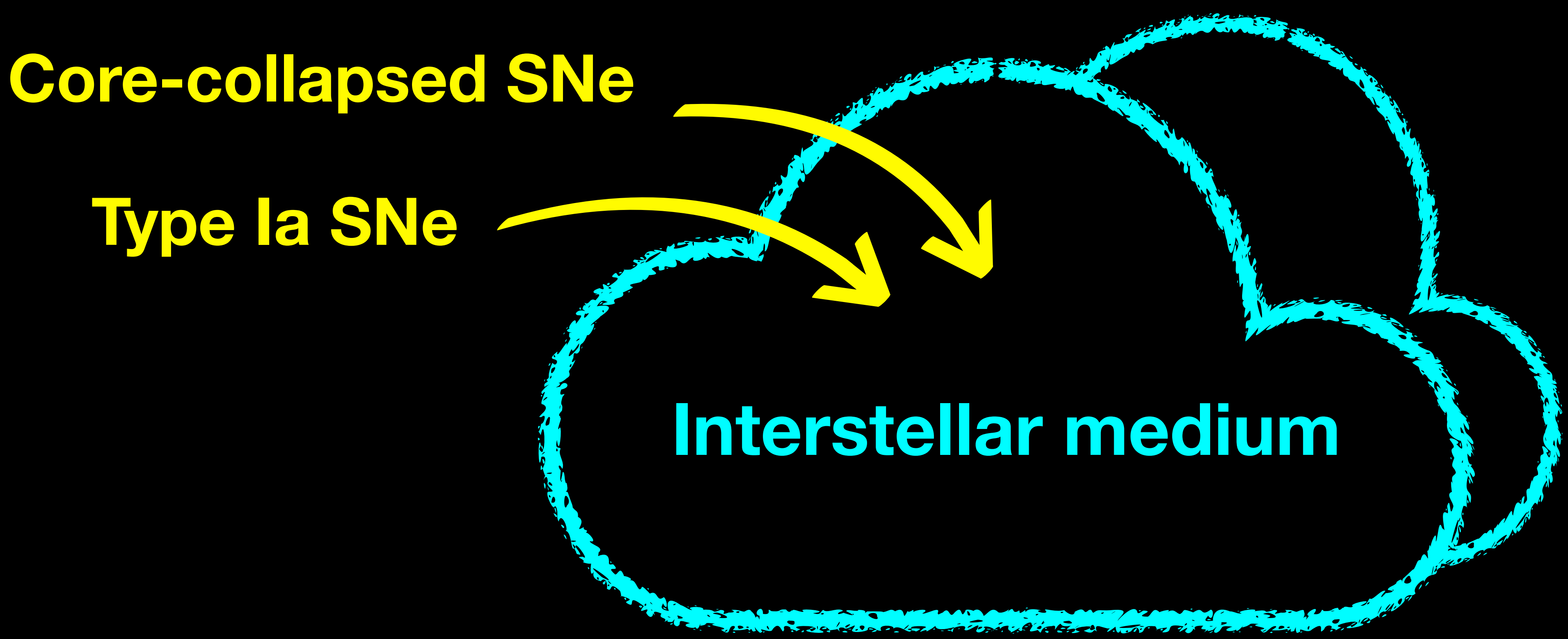

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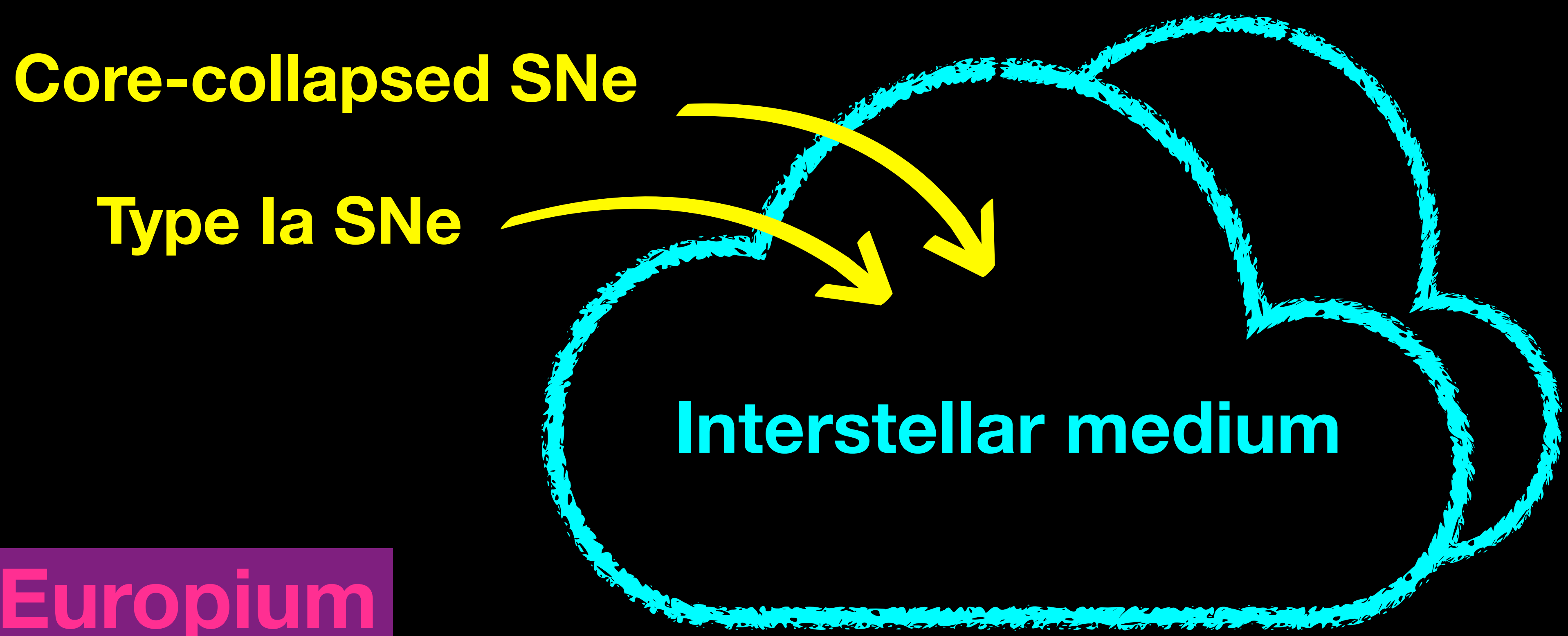


Europium

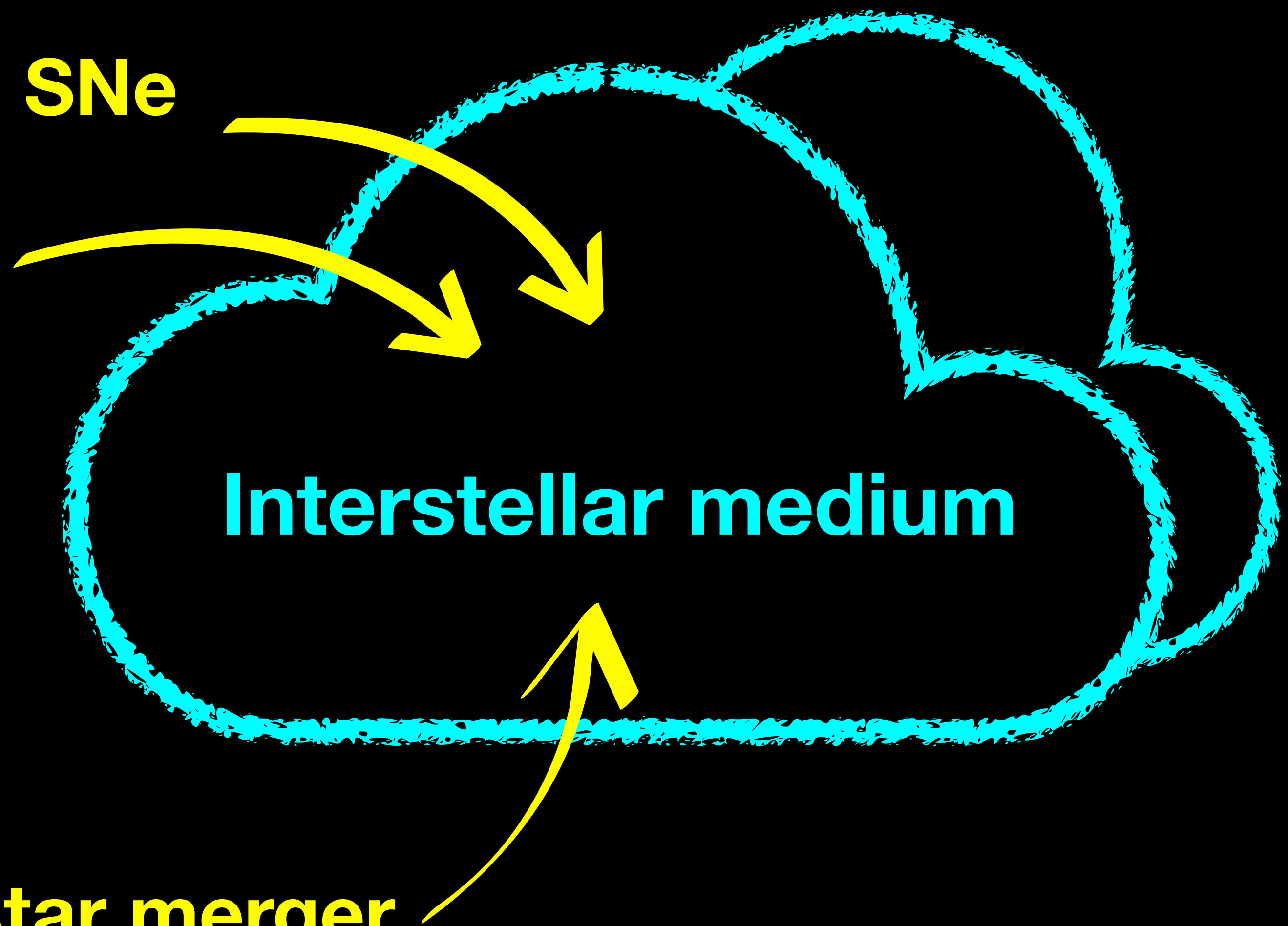
One-zone model

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

Iron

Core-collapsed SNe

Type Ia SNe



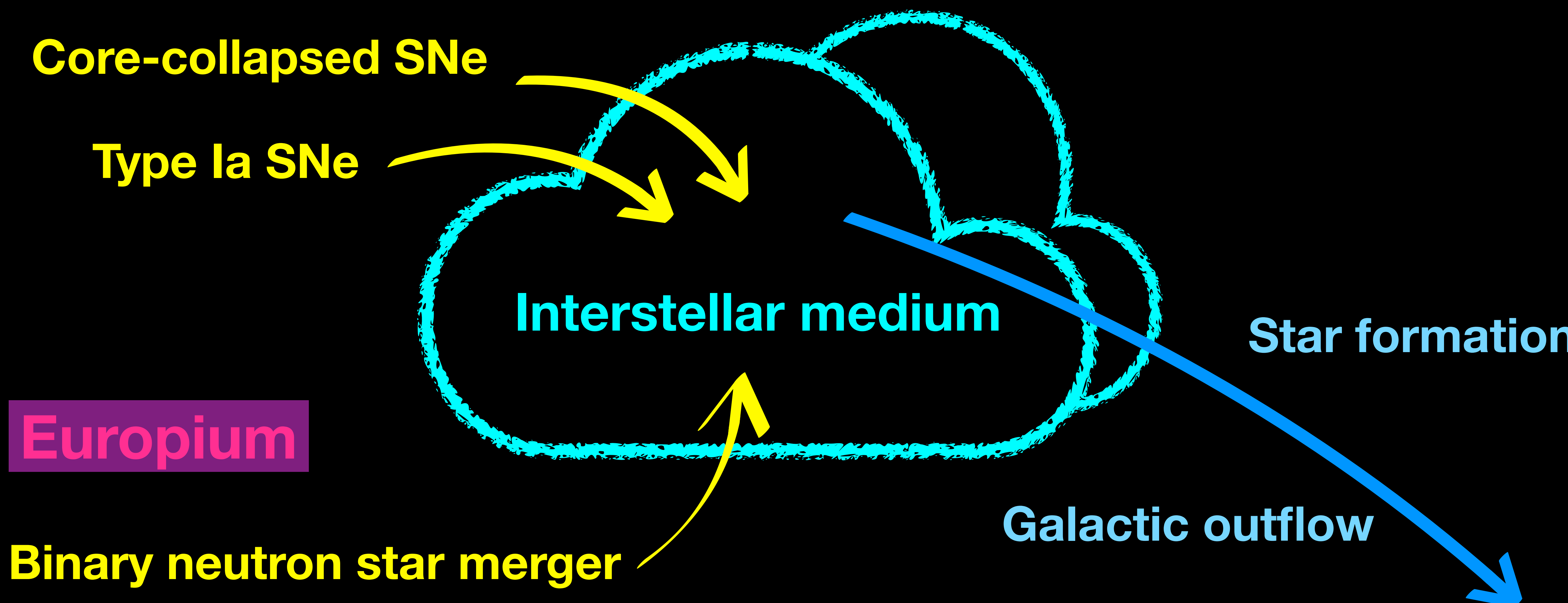
Europium

Binary neutron star merger

One-zone model

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

Iron



Inferred from multi-messenger observations

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Binary neutron star merger rate history

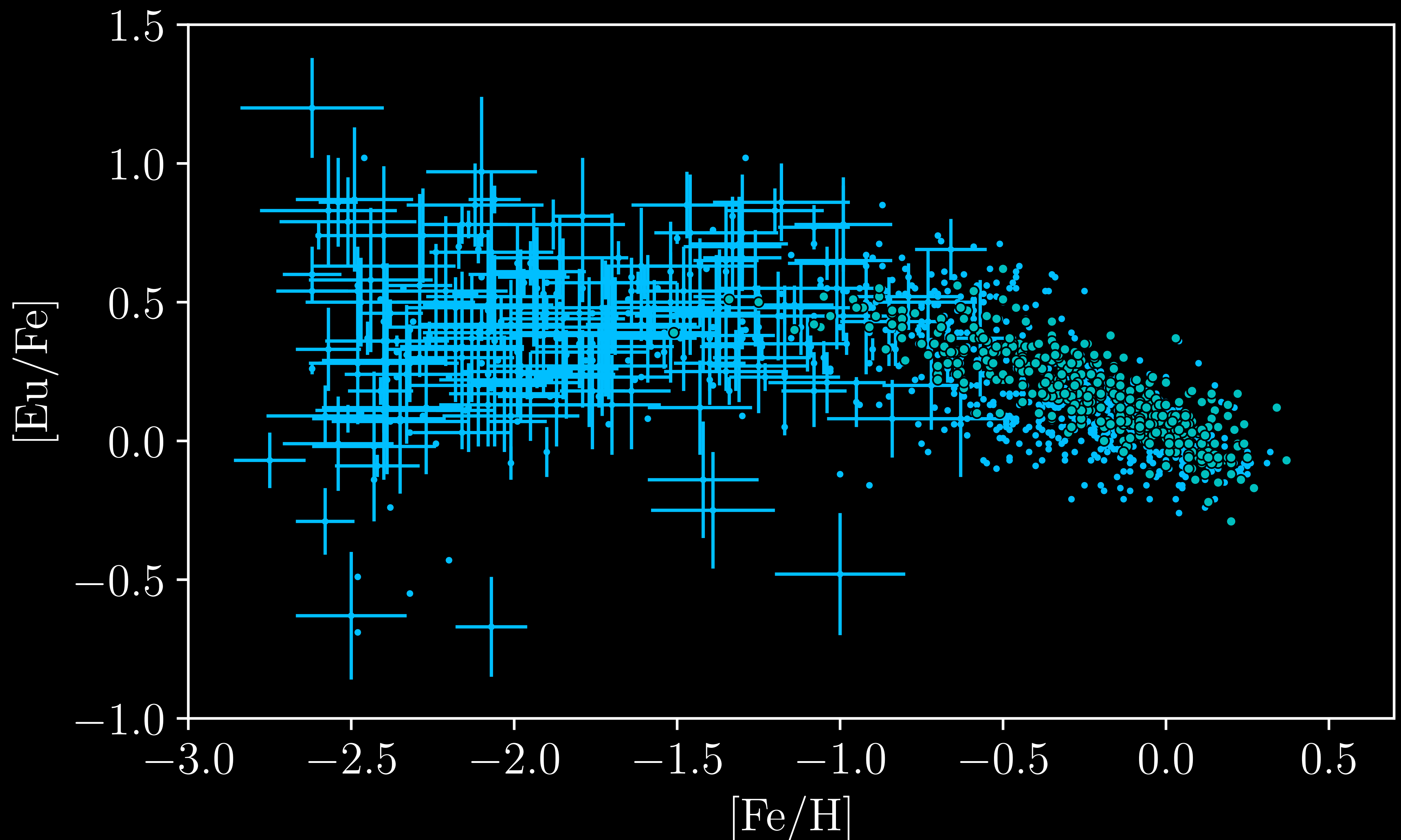
Inferred from multi-messenger observations

Binary neutron star merger rate history

Amount of r-process ejecta from each merger

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

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



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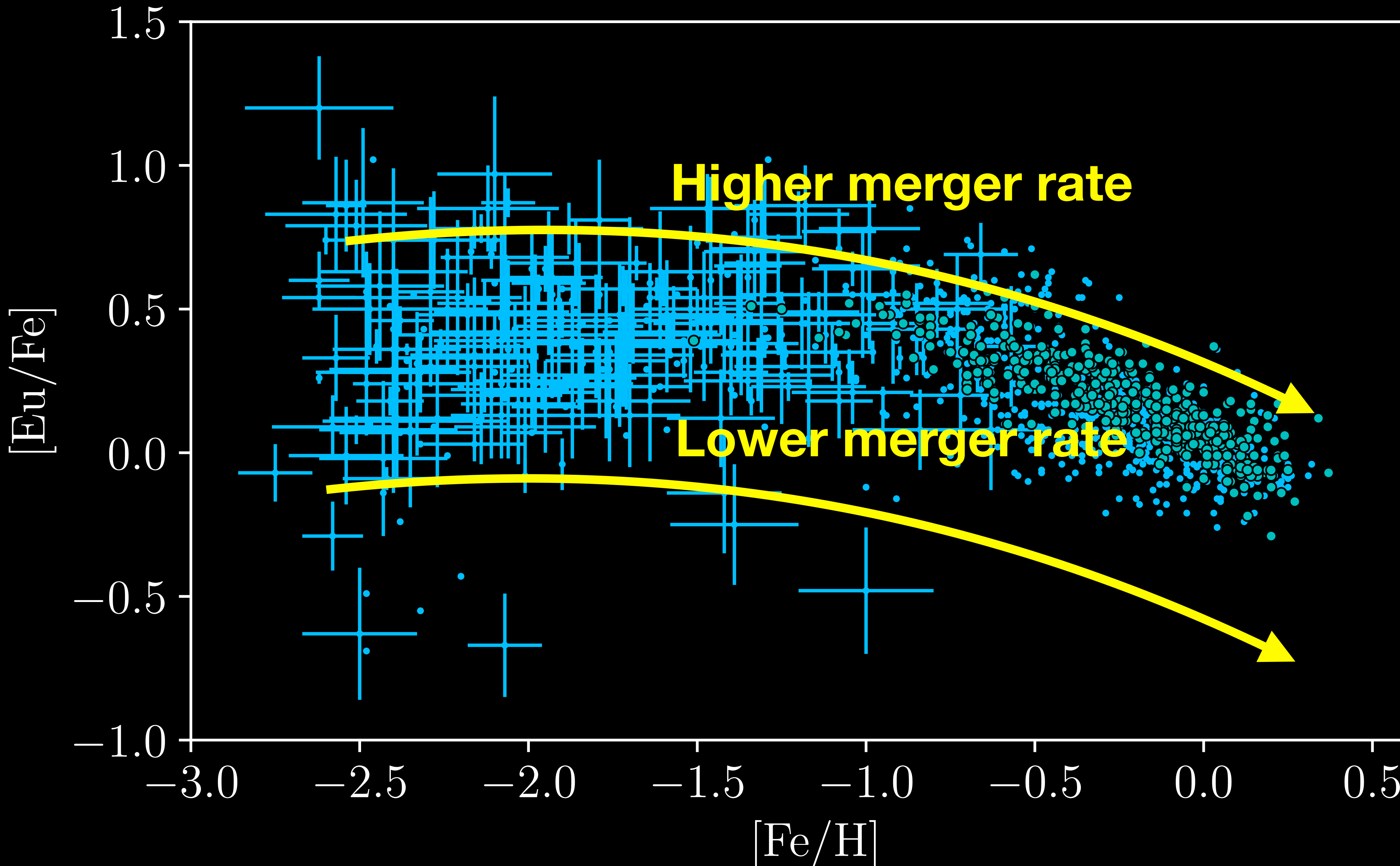

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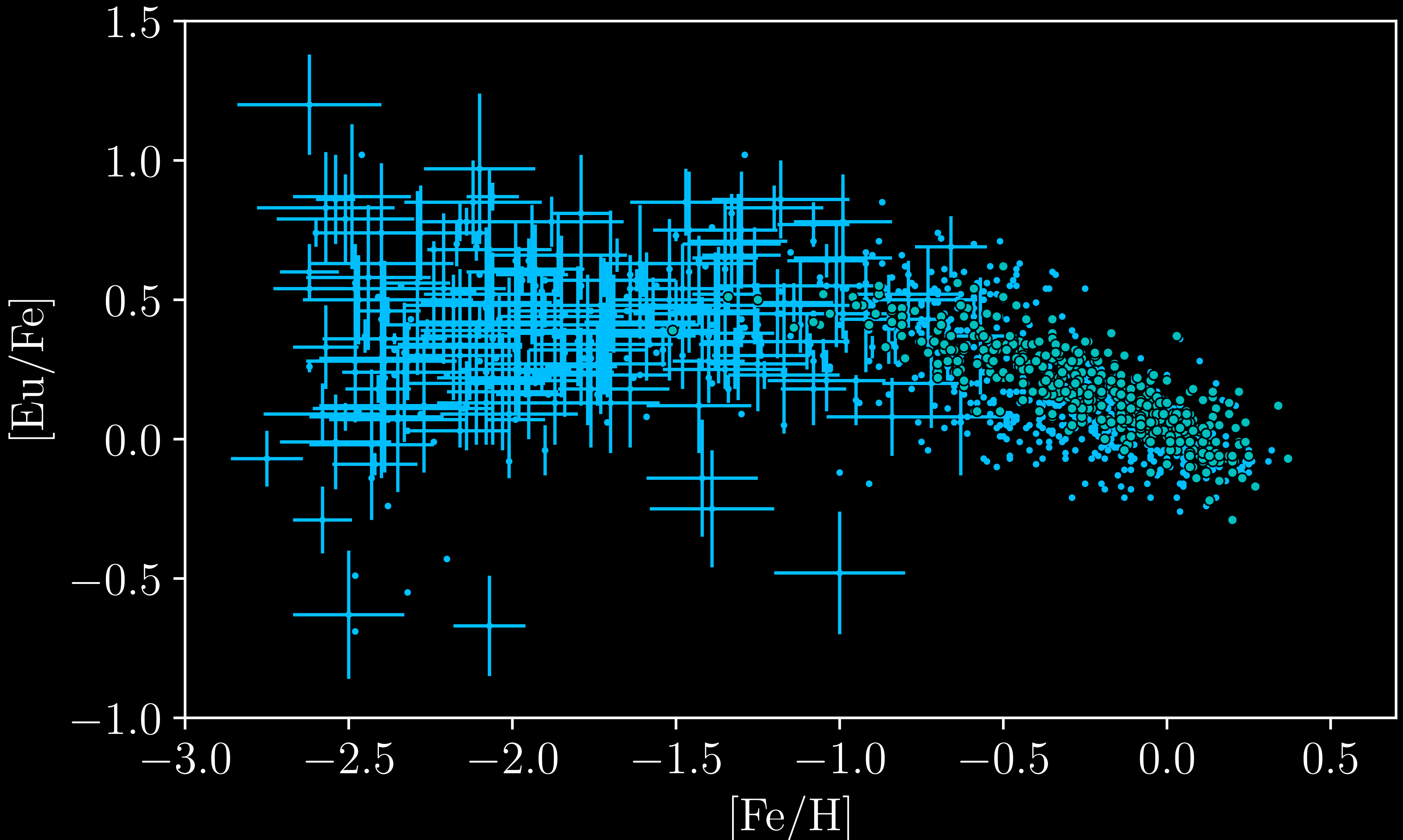

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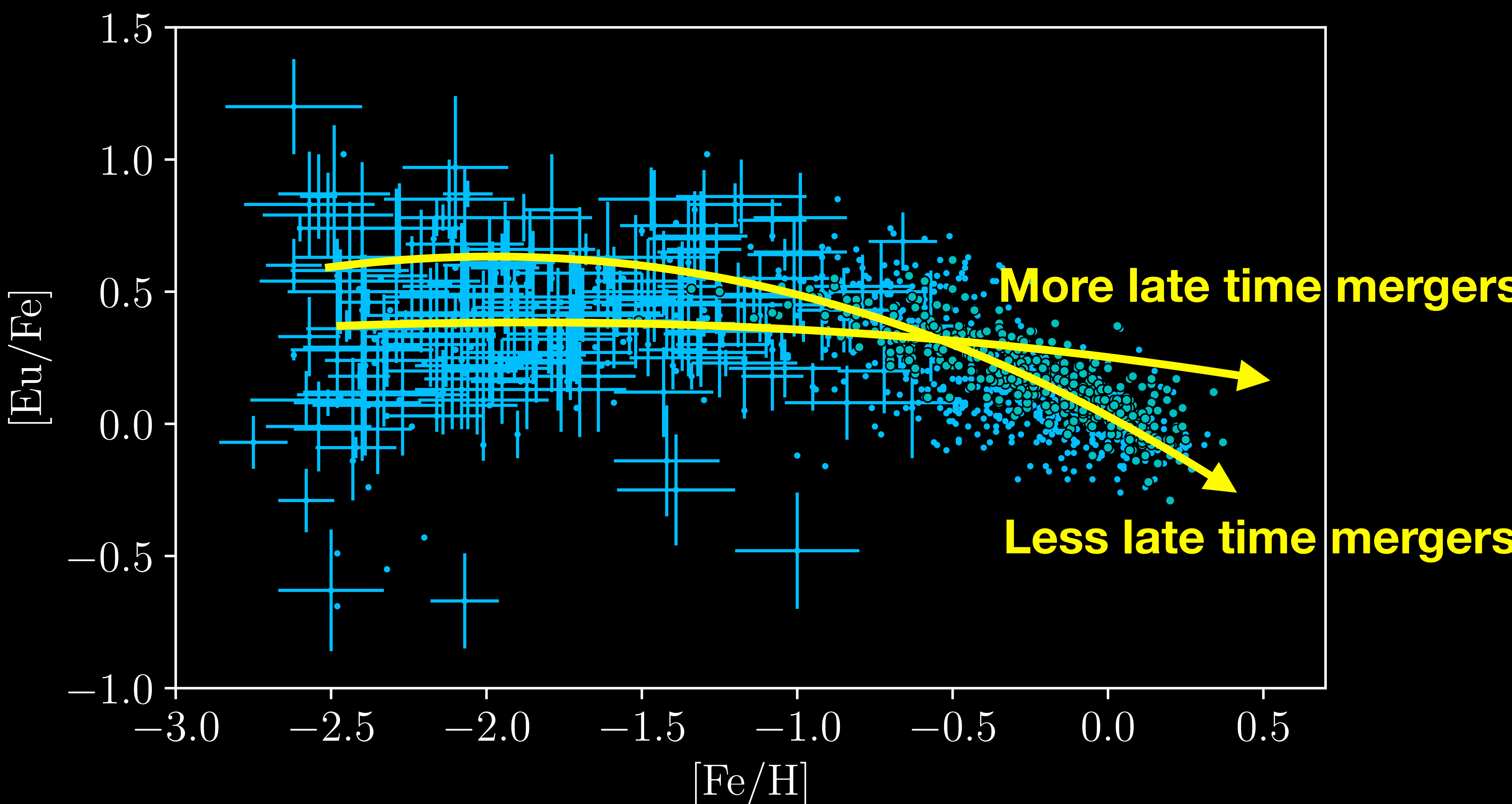
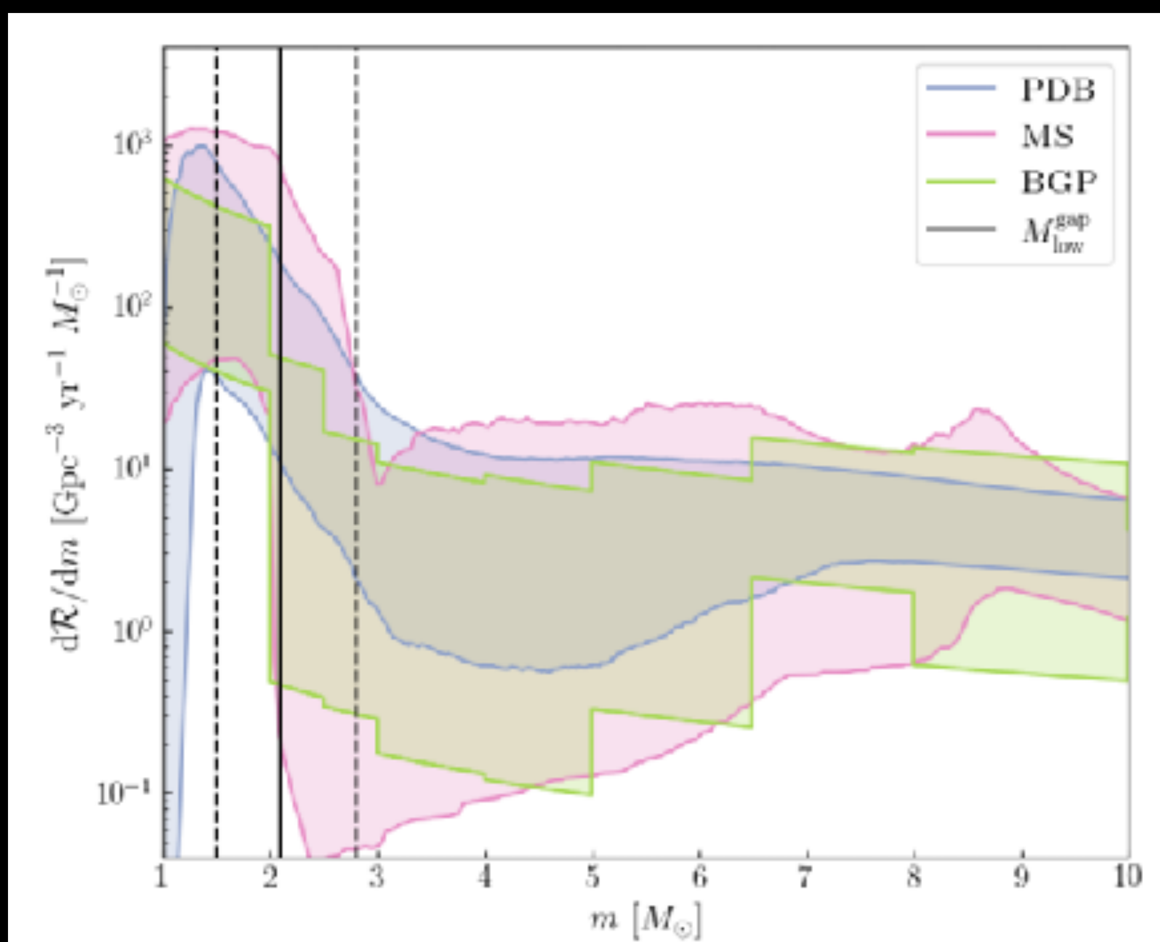
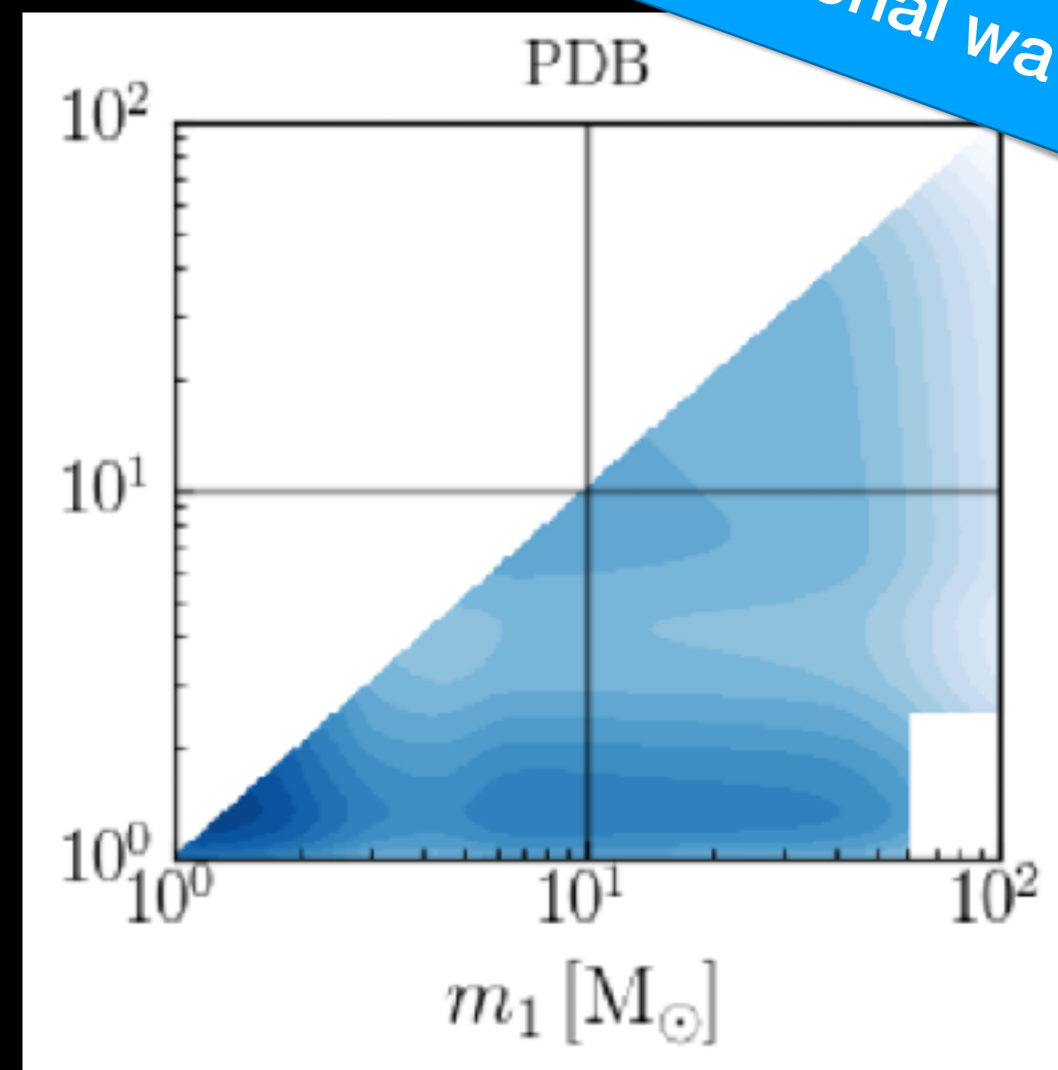


A. Binary neutron star merger rate across the history

- Merger rate in the local Universe

Observations: Gravitational waves

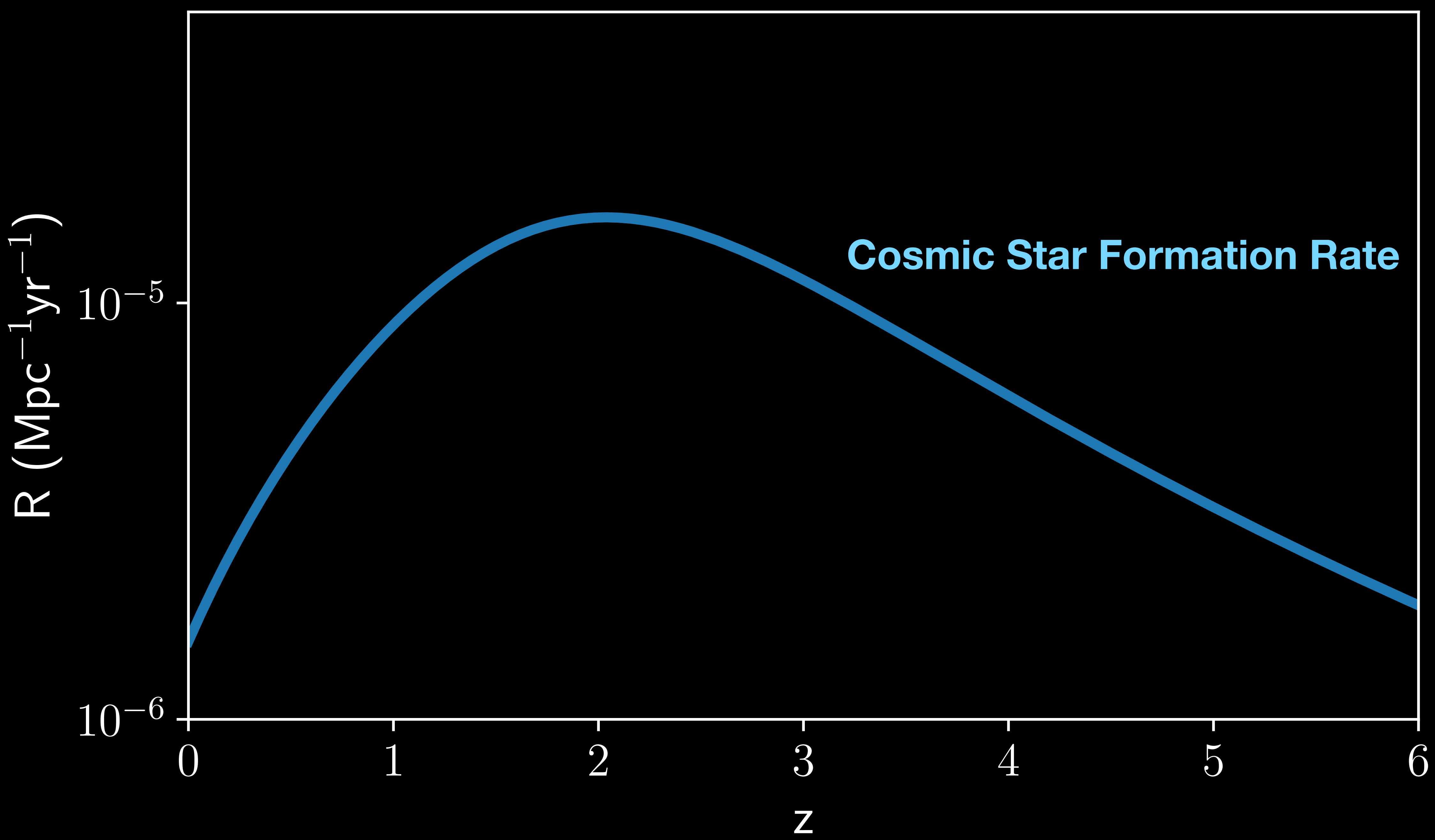




LVK Collaboration, PRX (2023)

A. Binary neutron star merger rate across the history

- Merger delay time distribution



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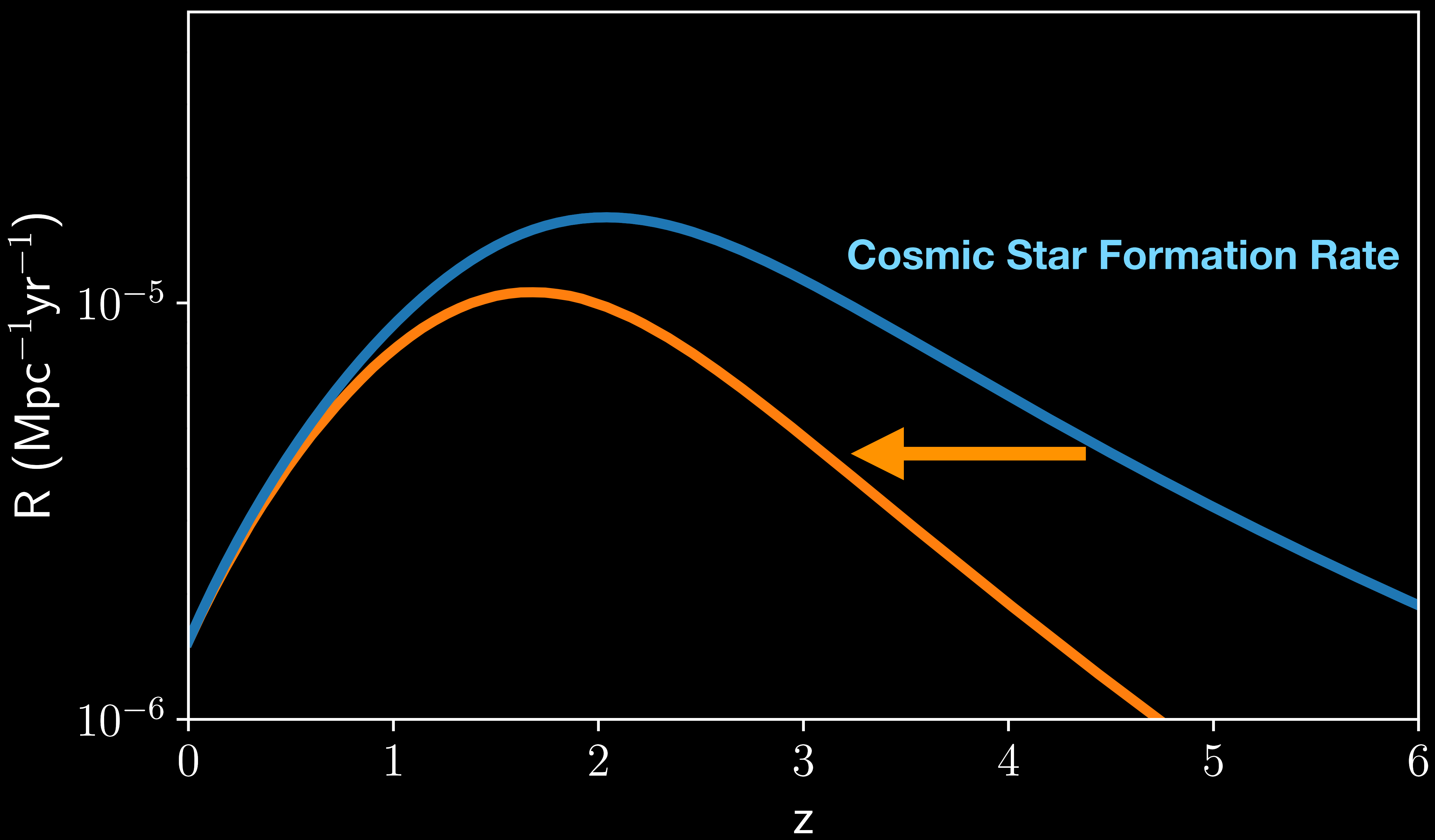

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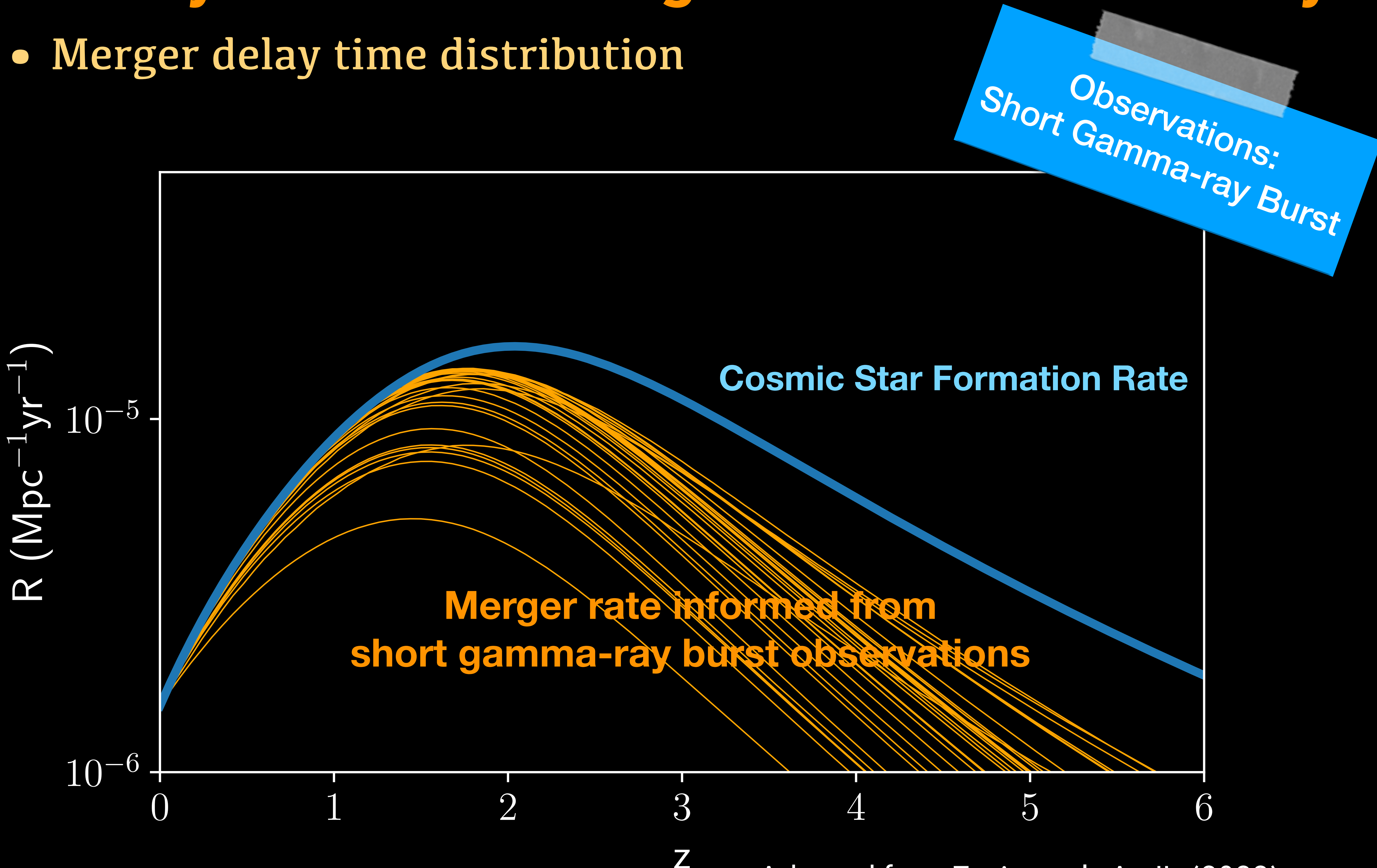

Adapted from Zevin et al., ApJL (2022)

A. Binary neutron star merger rate across the history

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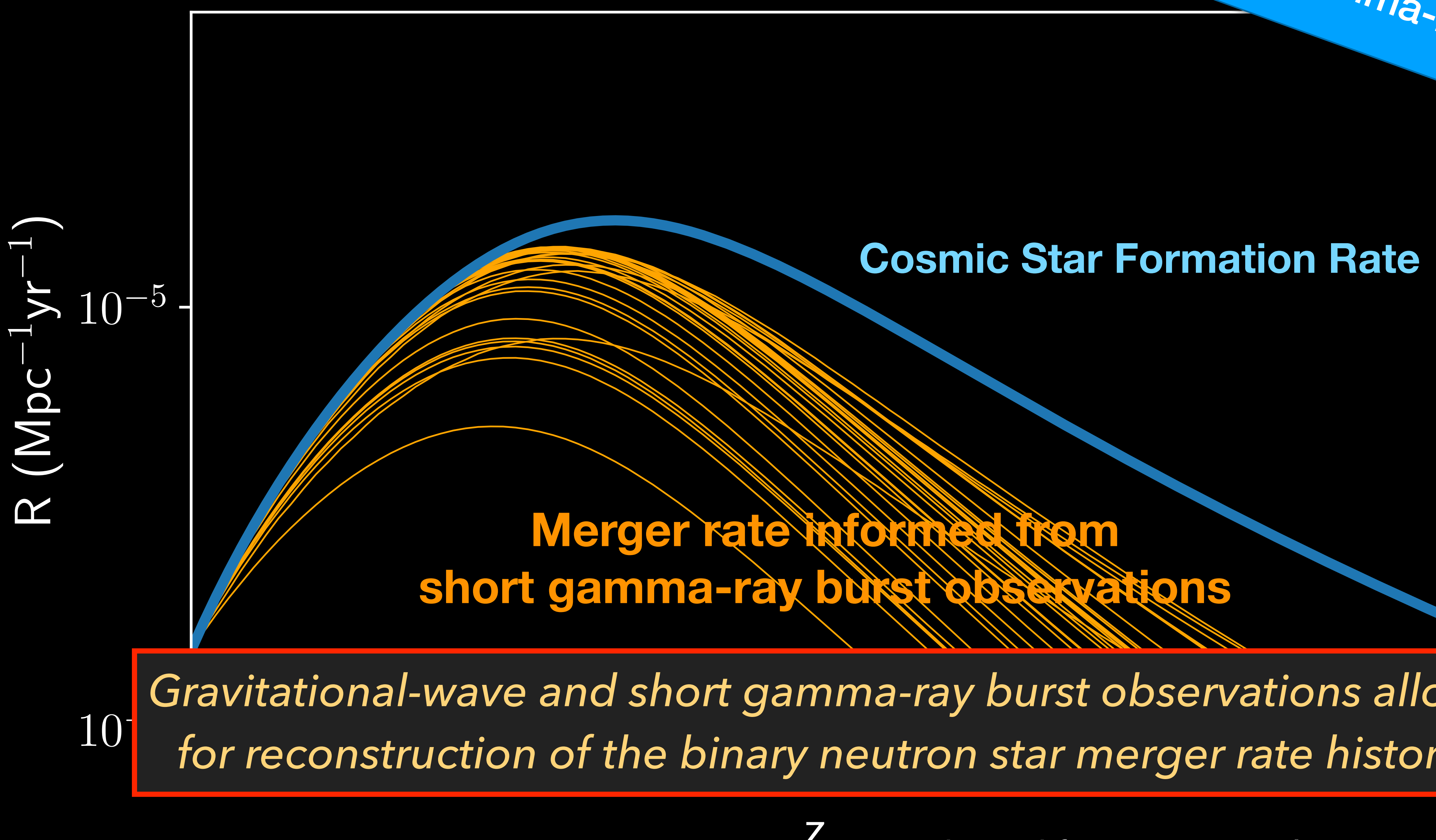
Observations:
Short Gamma-ray Burst

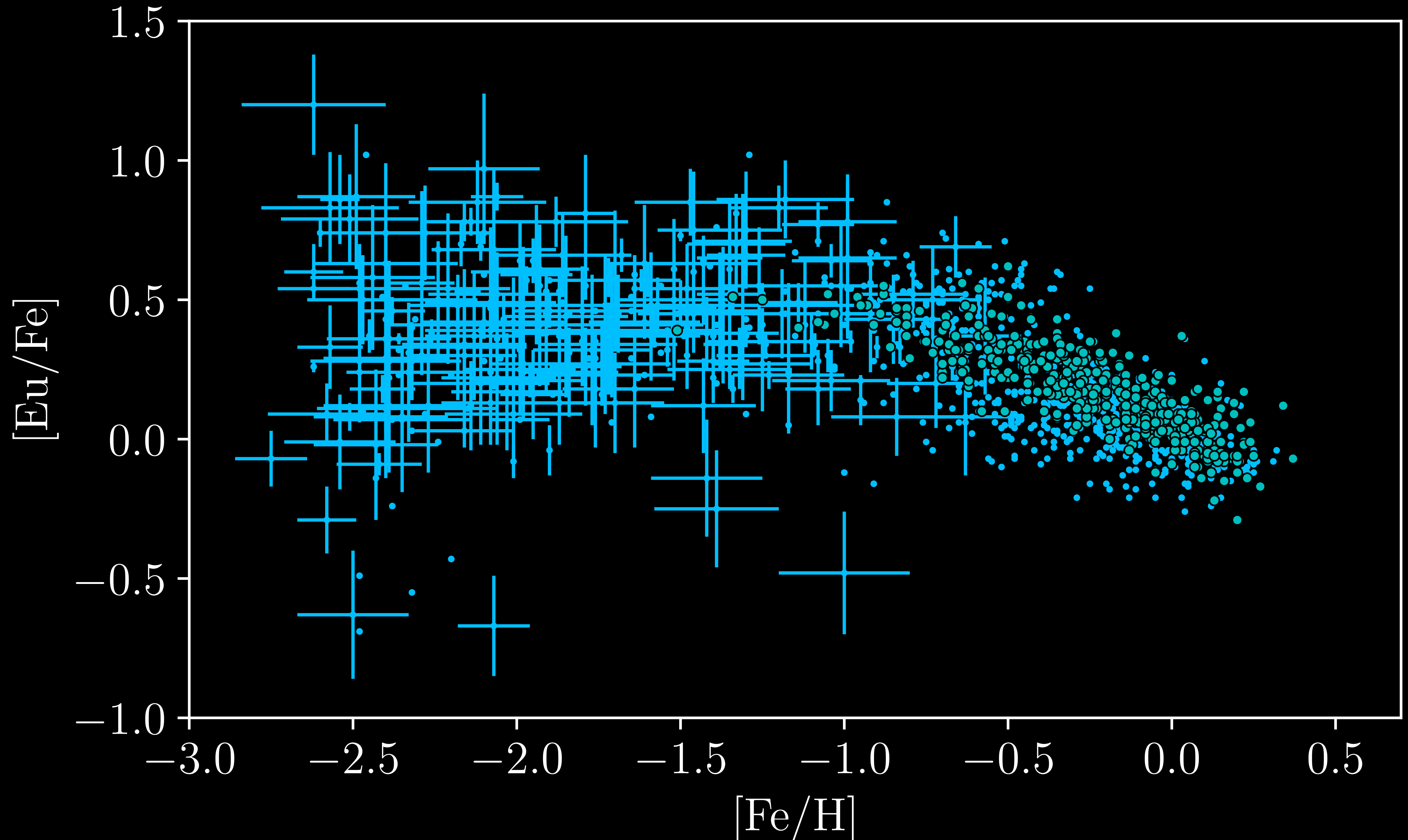


Gravitational-wave and short gamma-ray burst observations allows for reconstruction of the binary neutron star merger rate history.

Adapted from Zevin et al., ApJL (2022)

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

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



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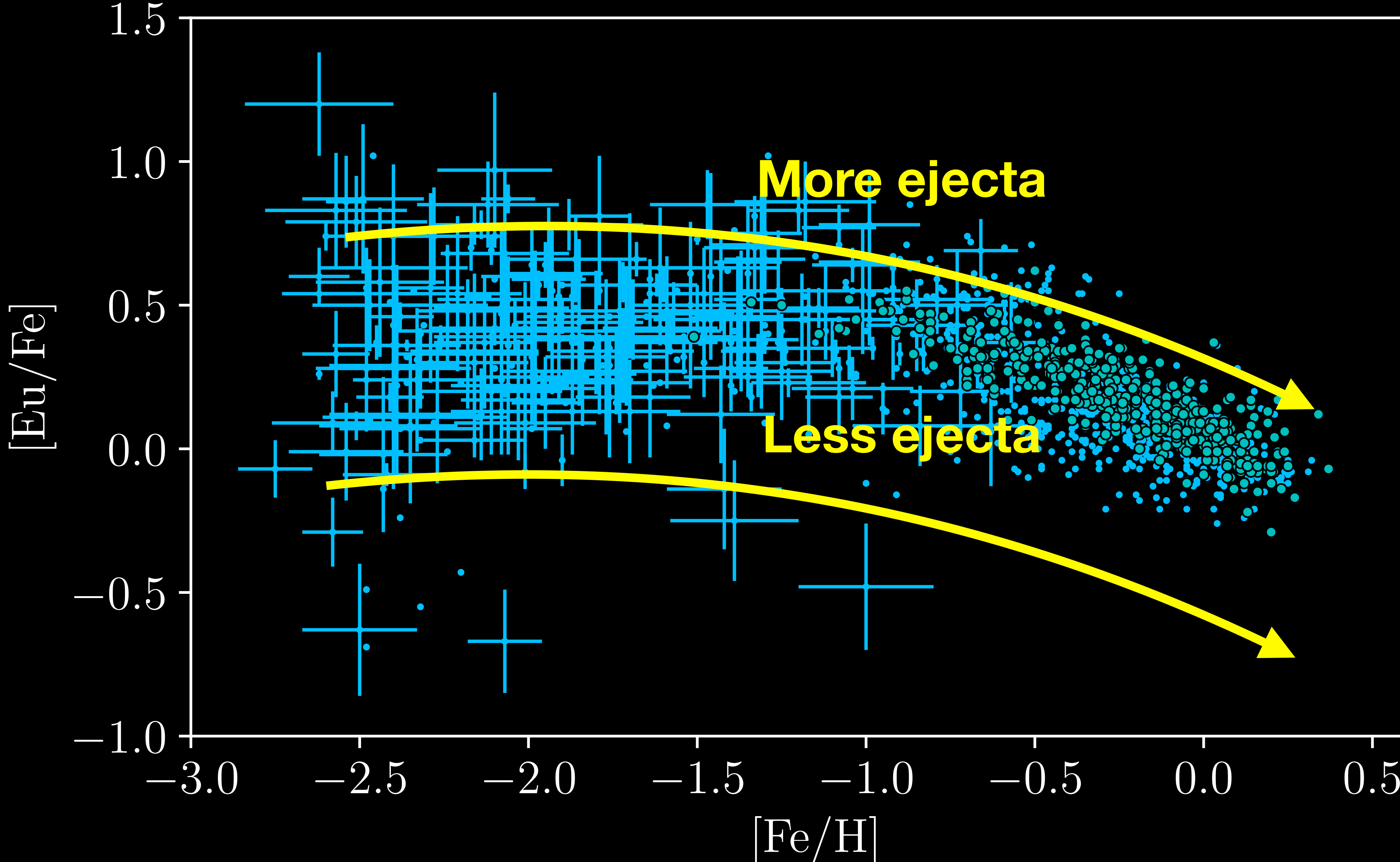
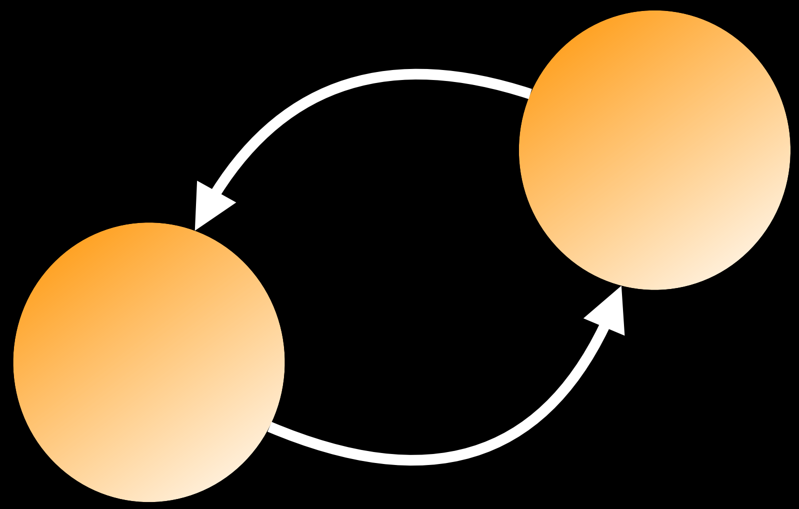


B. Amount of r-process ejecta from each merger

- Neutron star equation-of-state



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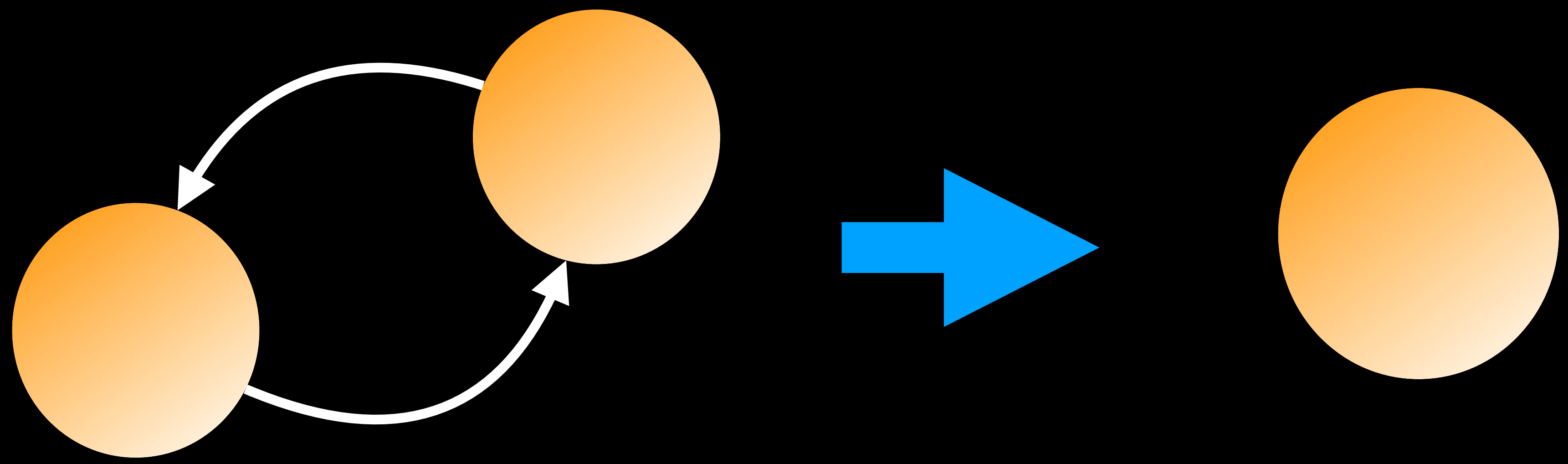

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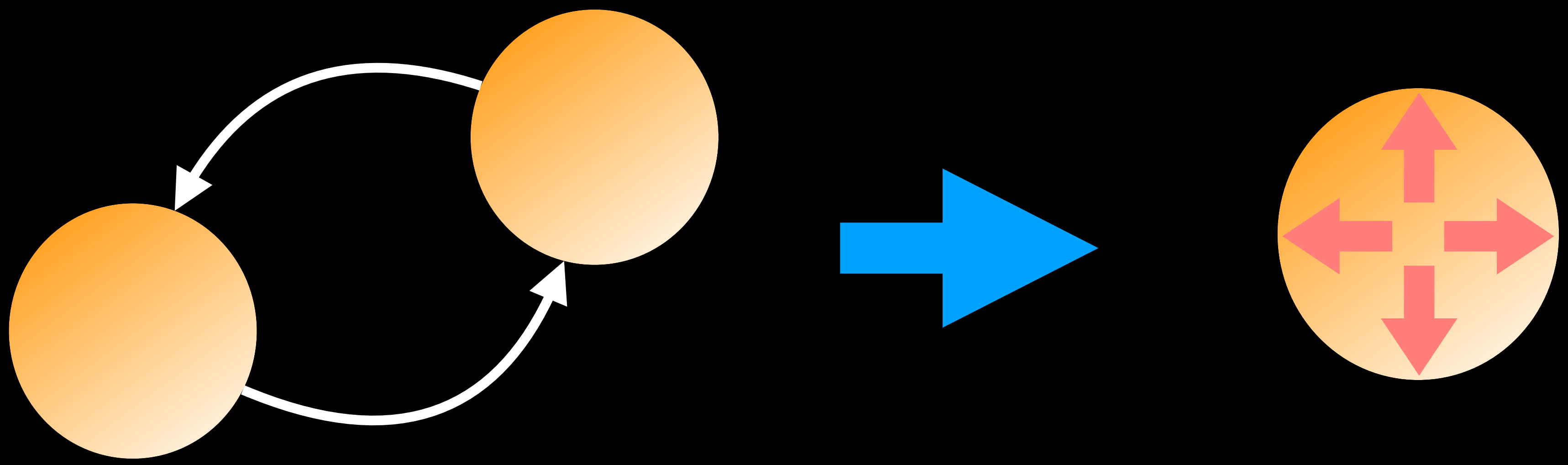

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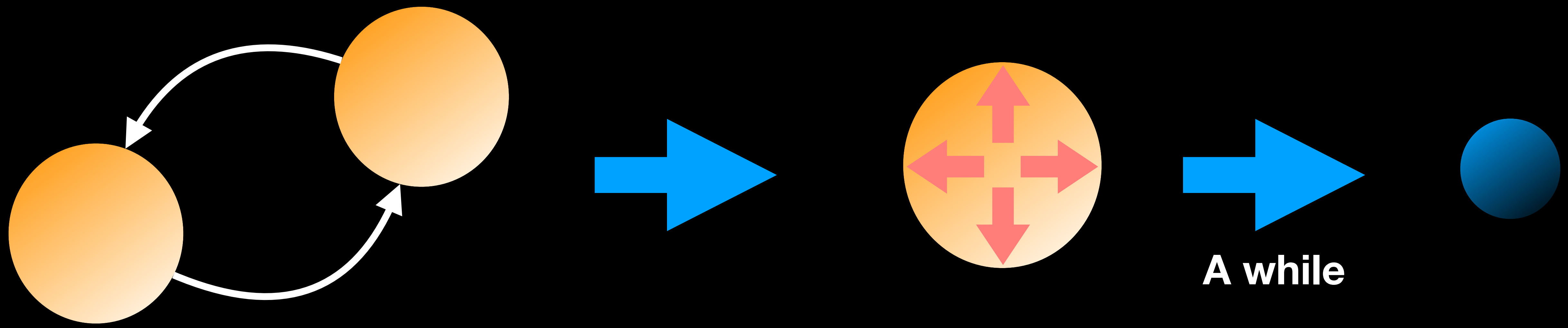

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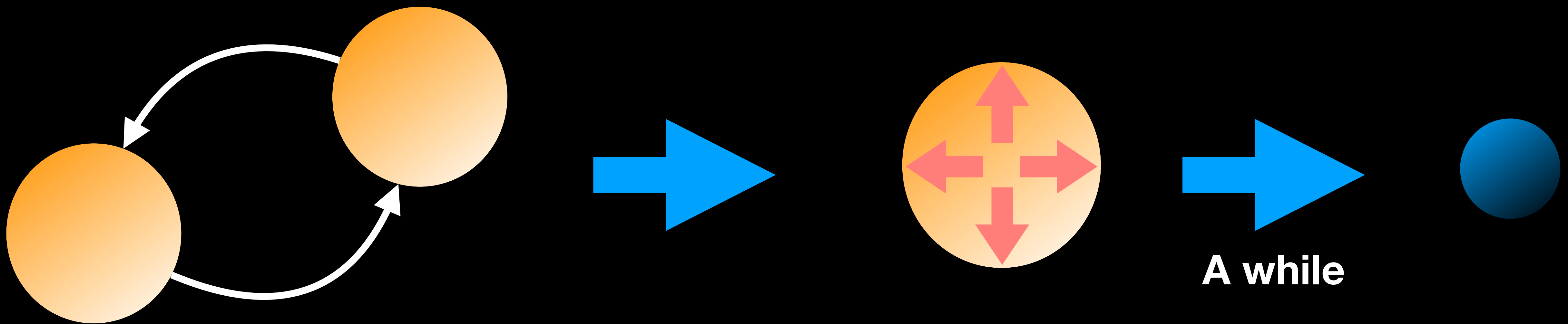
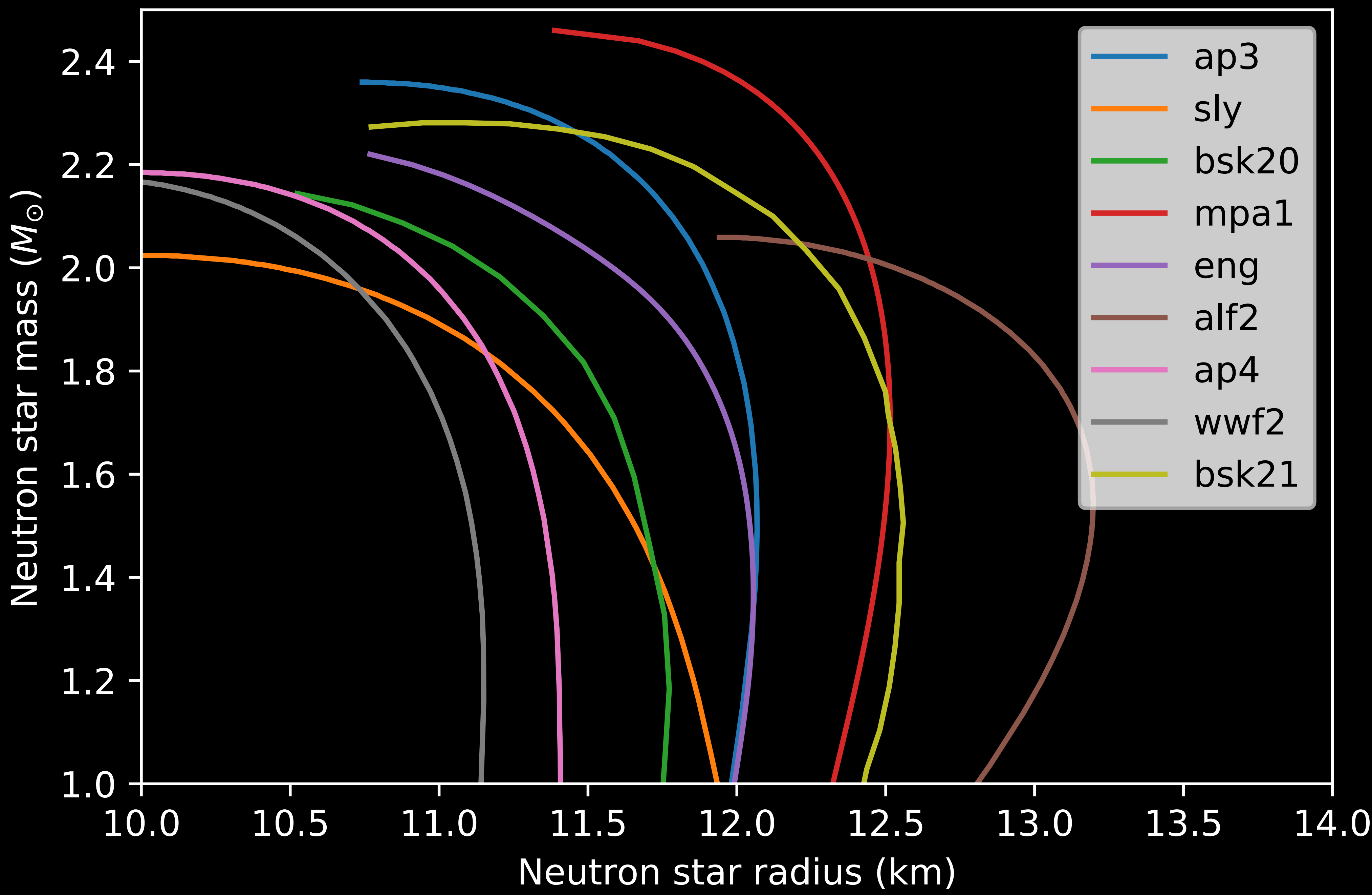


Stiffer neutron star equation-of state could lead to more ejecta.

B. Amount of r-process ejecta from each merger

- Neutron star equation-of-state



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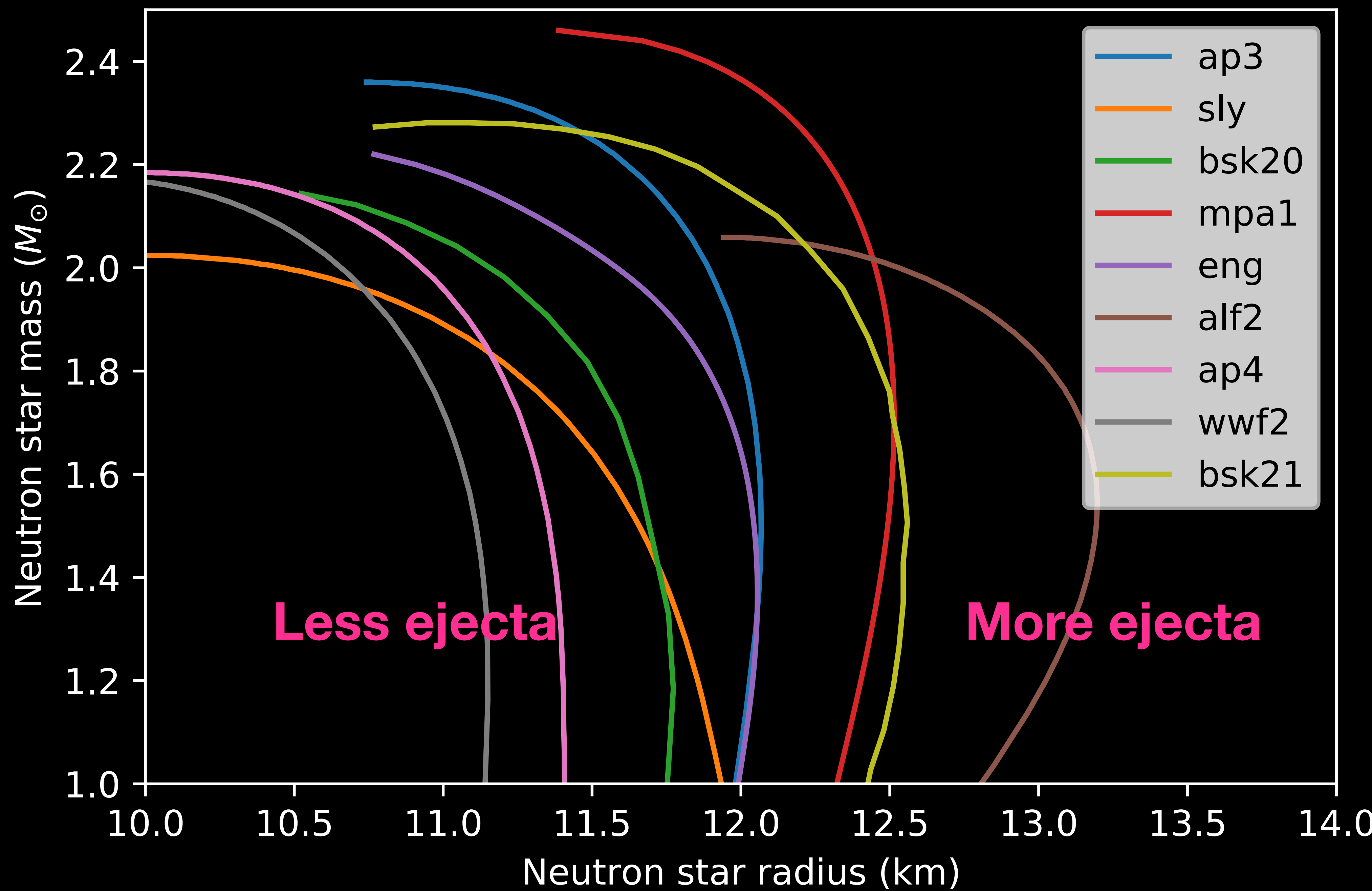

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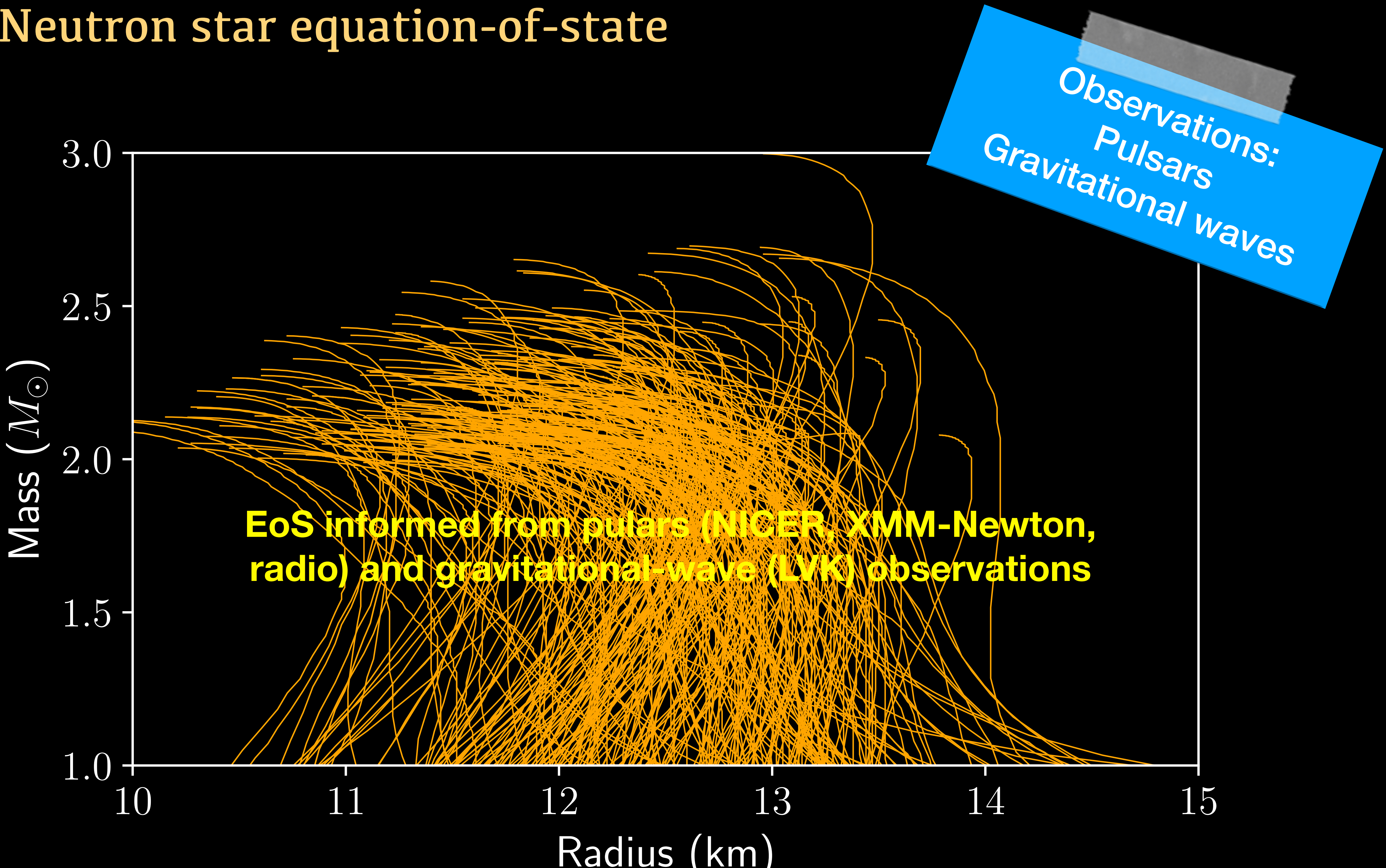
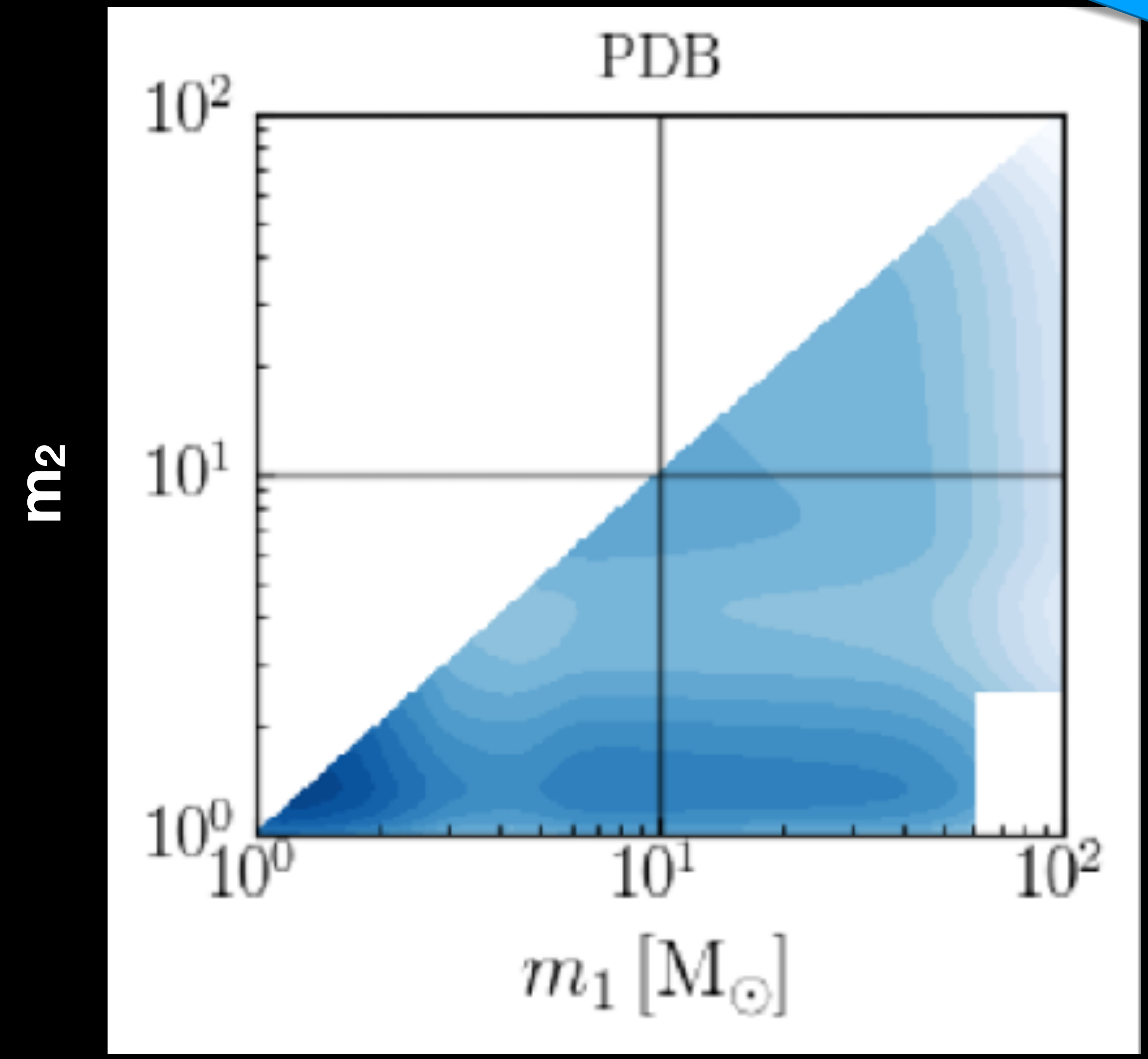


Adapted from Legred et al., PRD (2021)

B. Amount of r-process ejecta from each merger

- Neutron star mass distribution

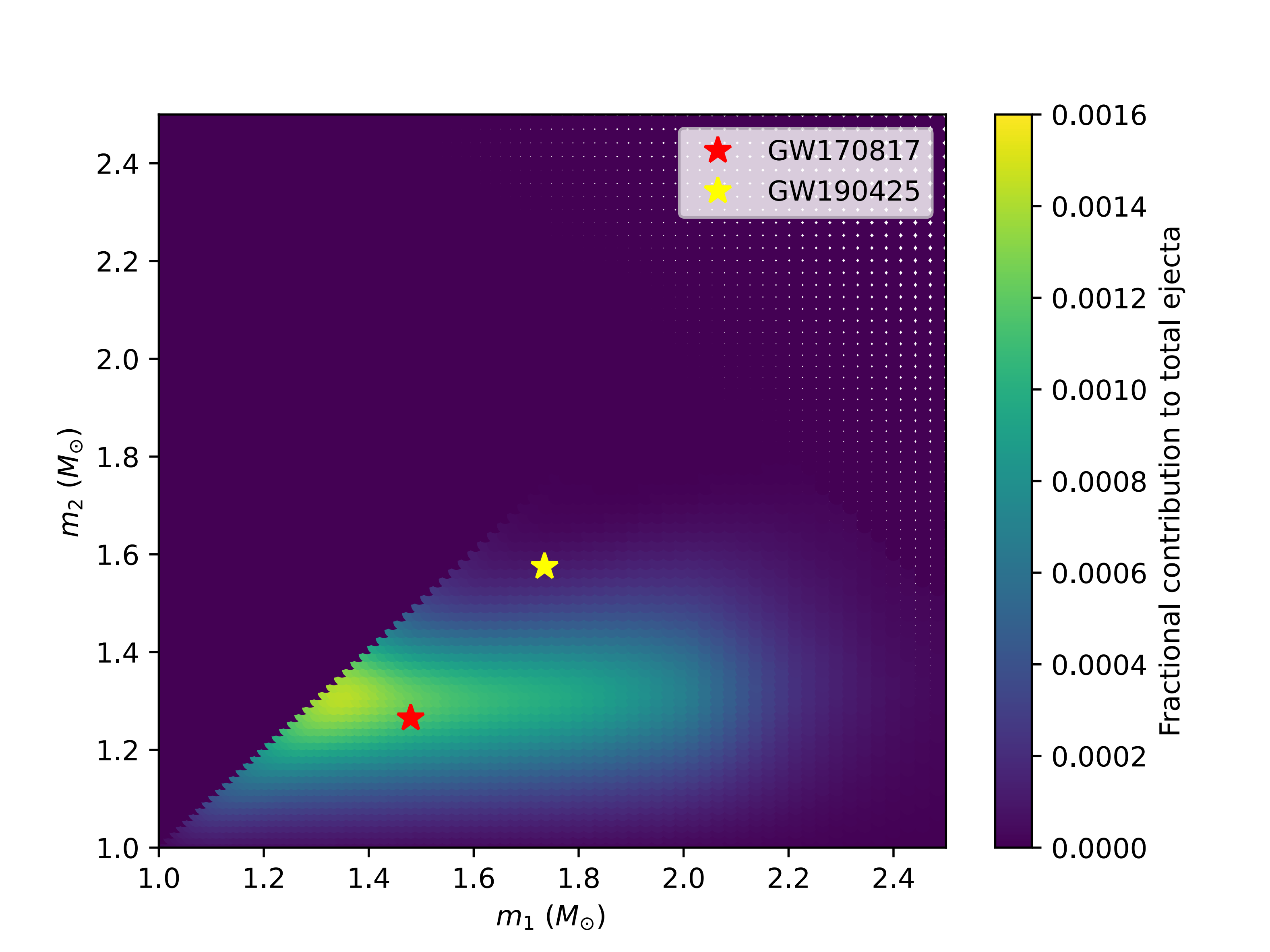
Observations: Gravitational waves



LVK Collaboration, PRX (2023)

B. Amount of r-process ejecta from each merger

- Neutron star mass distribution



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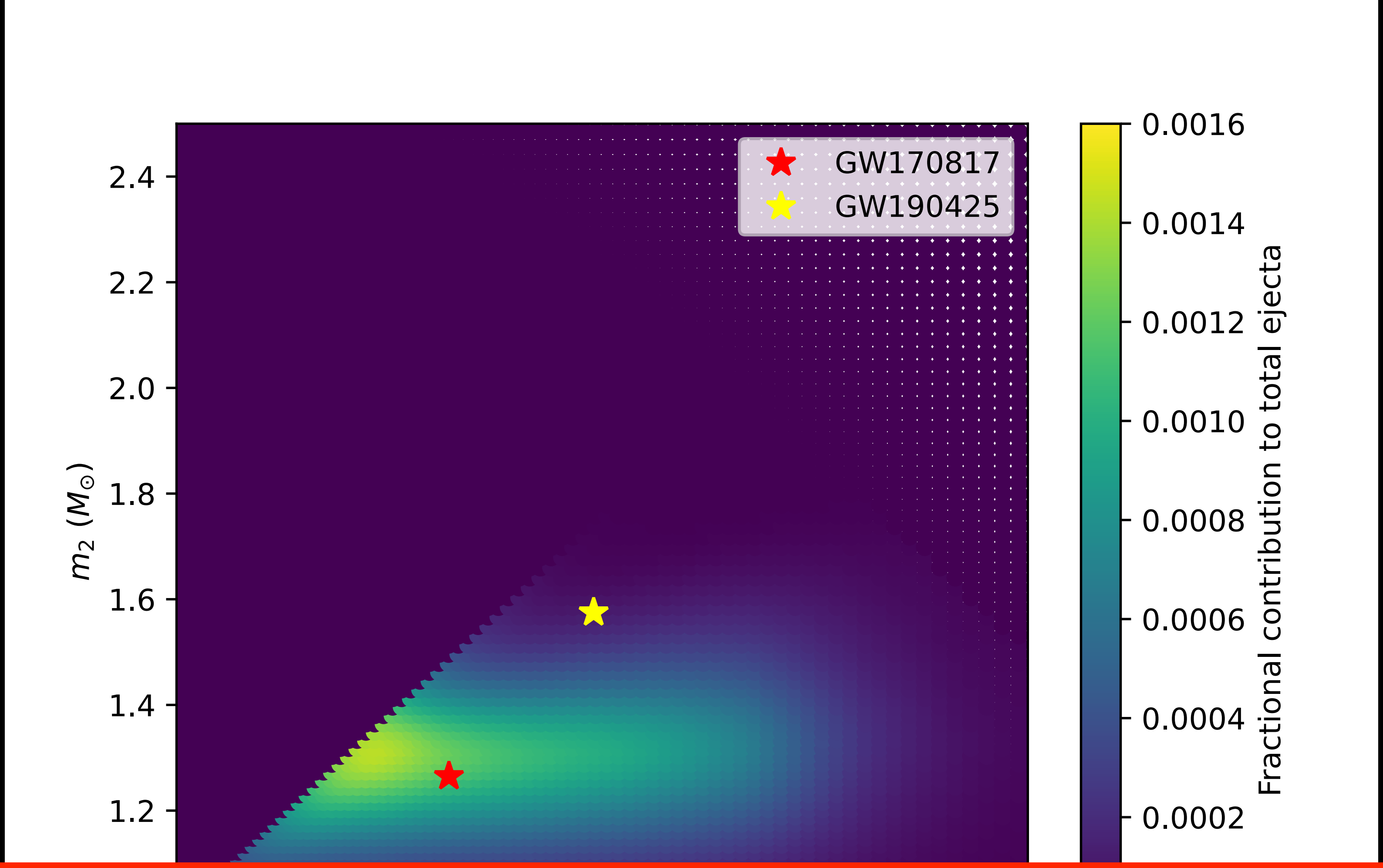
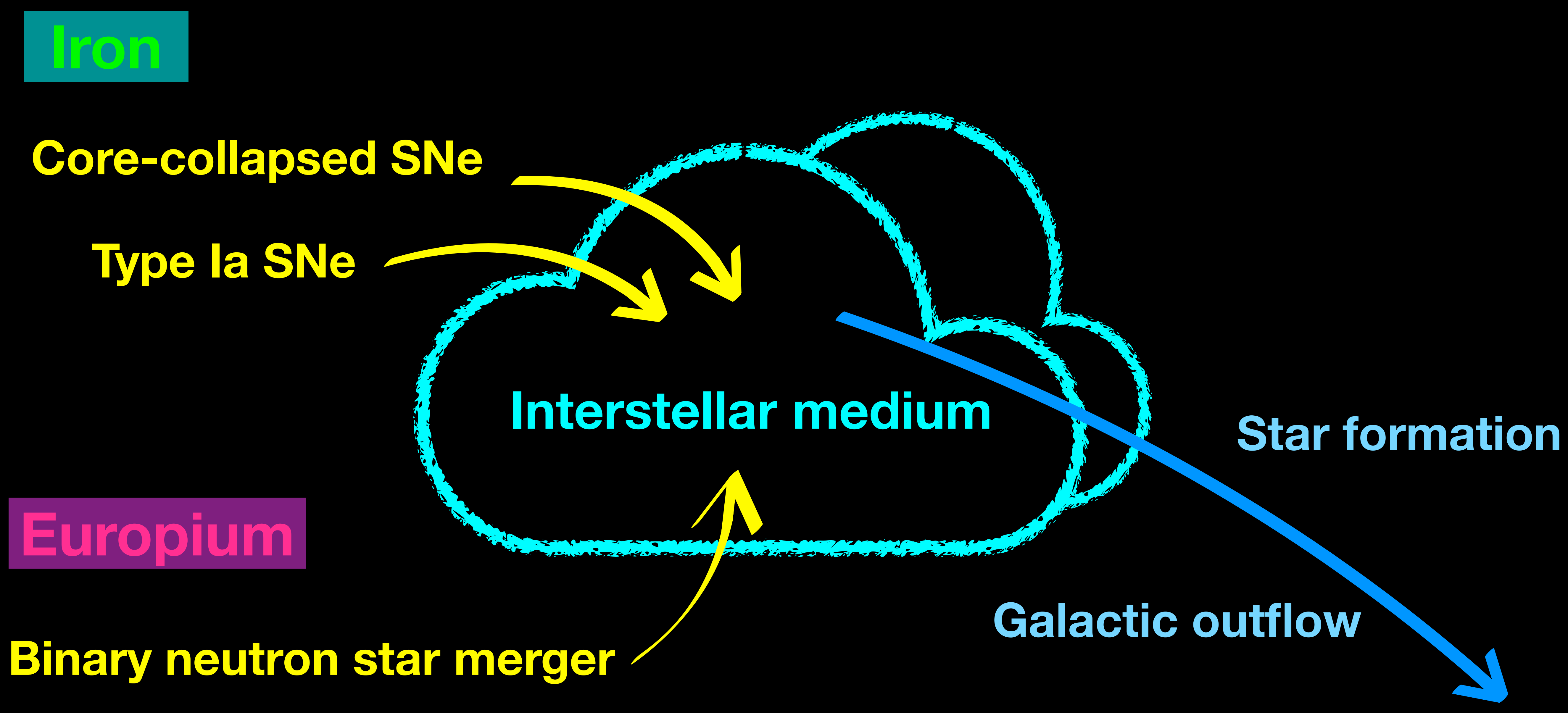


Gravitational-wave and pulsars observations allows for estimation of the amount of r-process ejecta from each merger.

One-zone model



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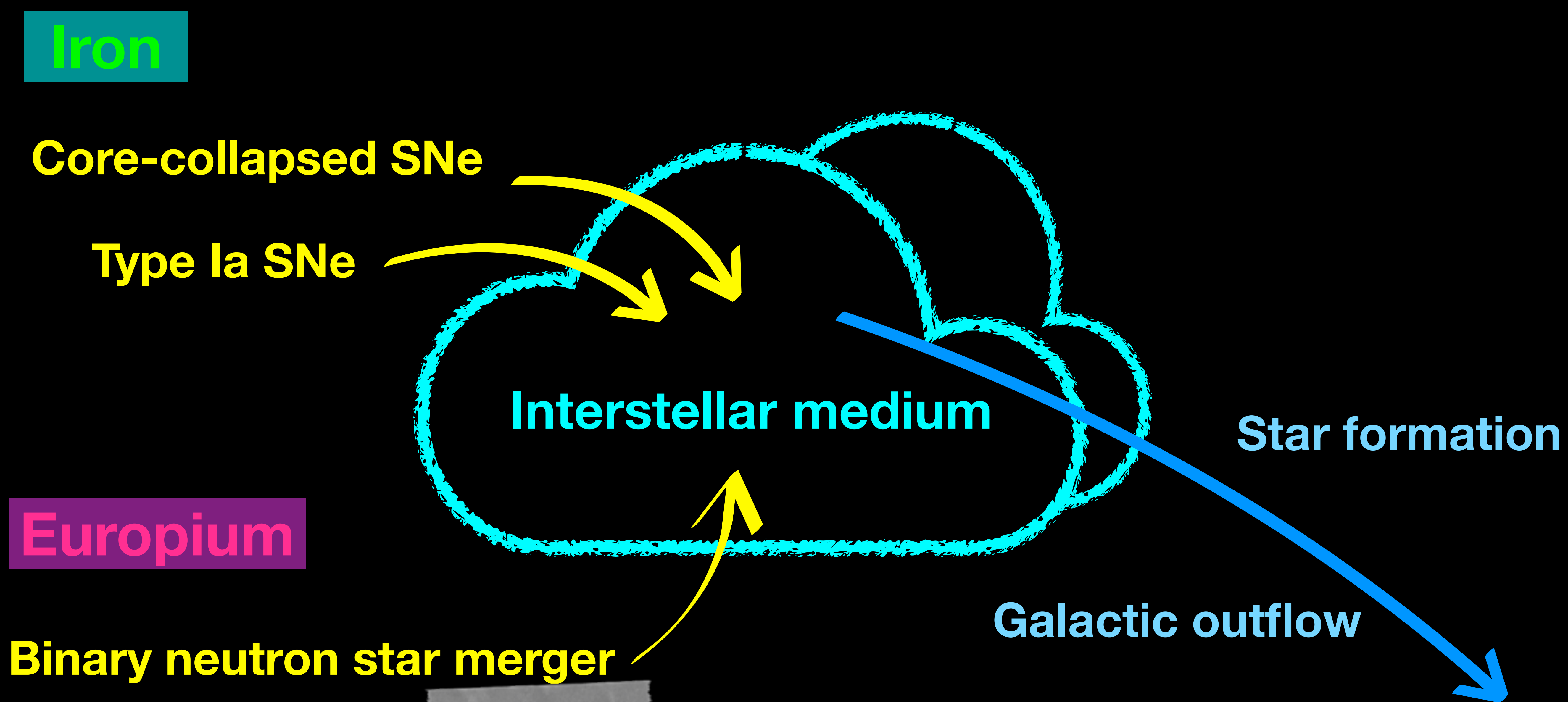
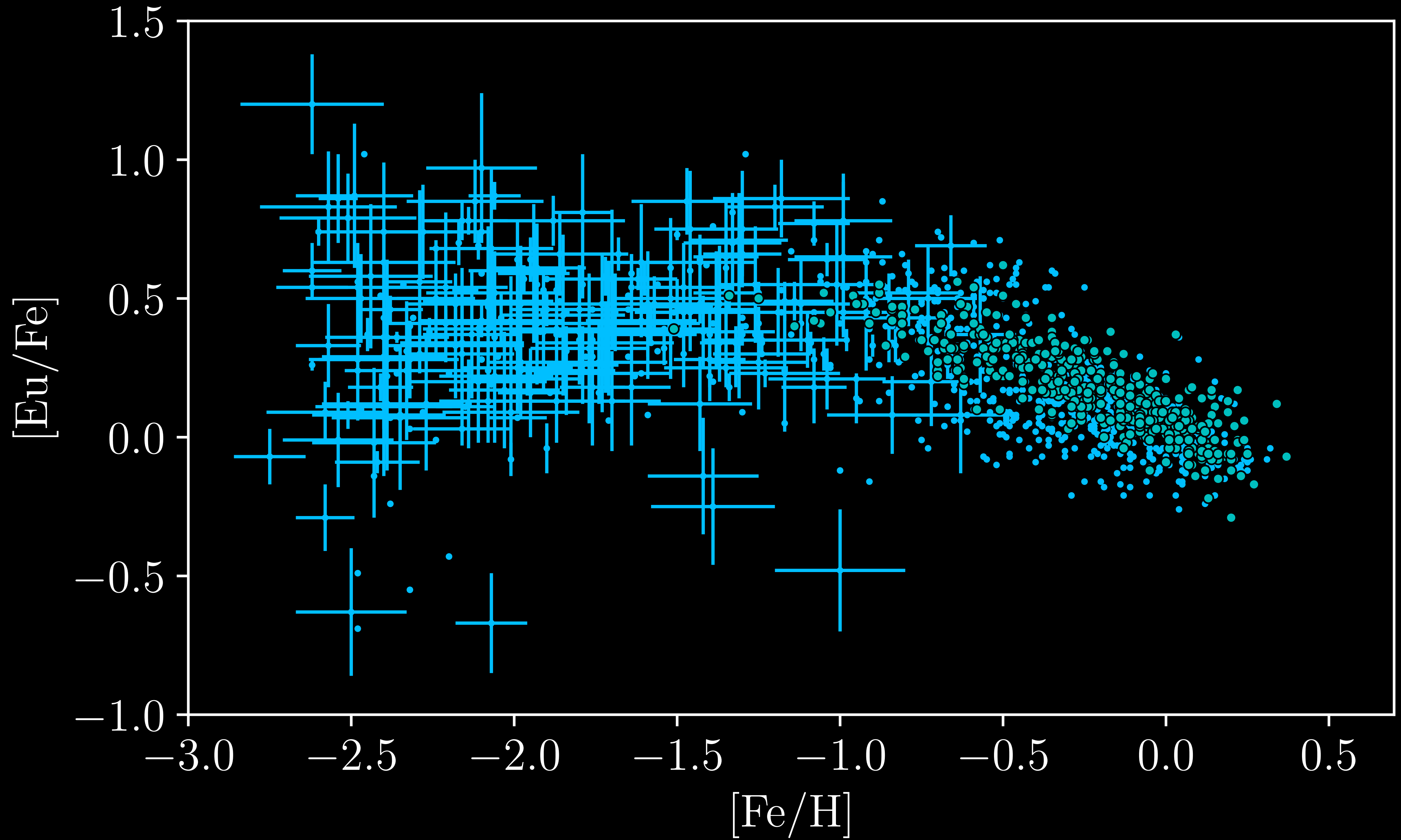


Observations:
Gravitational wave, short gamma-ray burst, pulsar

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

Comparing to Milky Way chemical evolution



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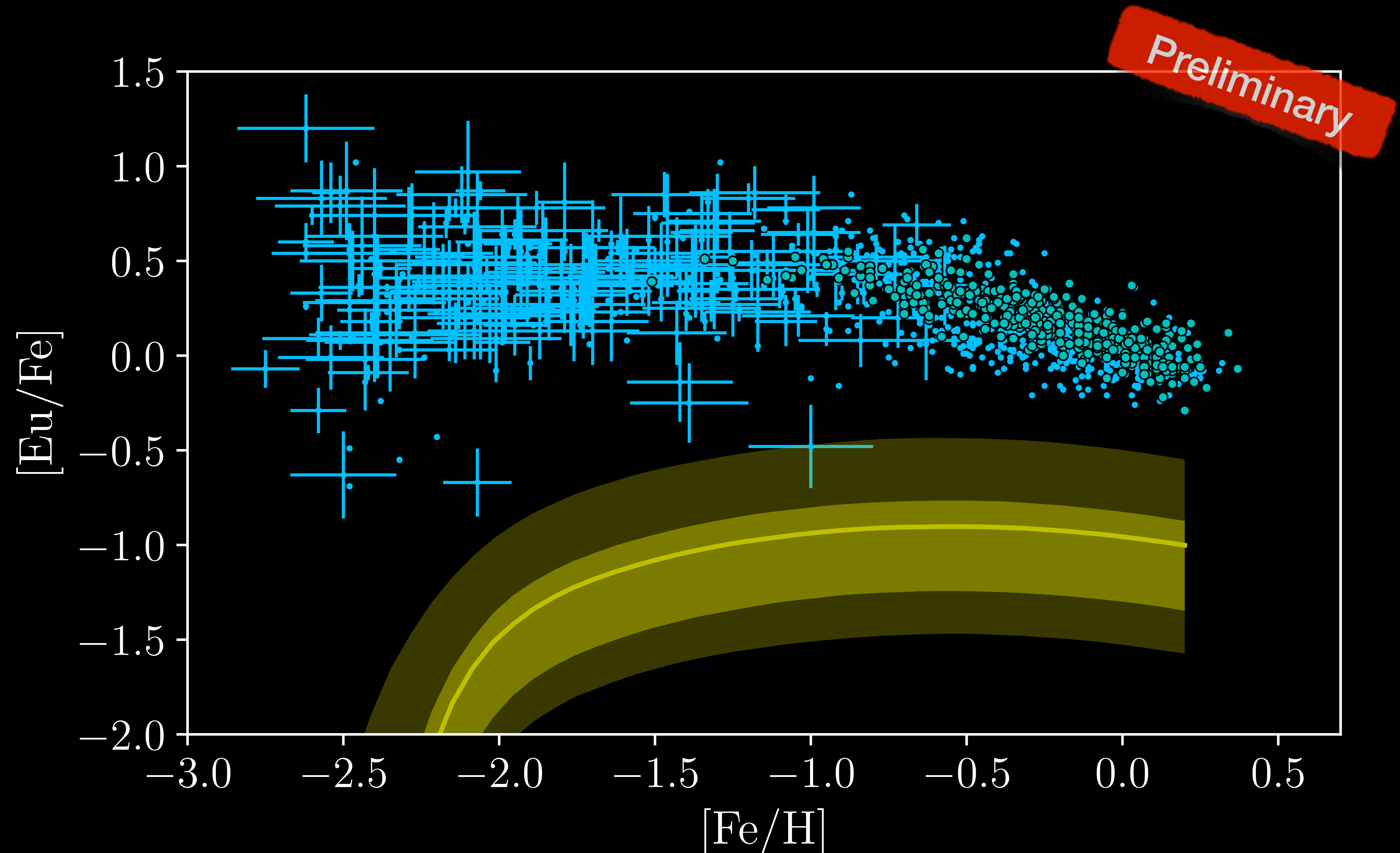

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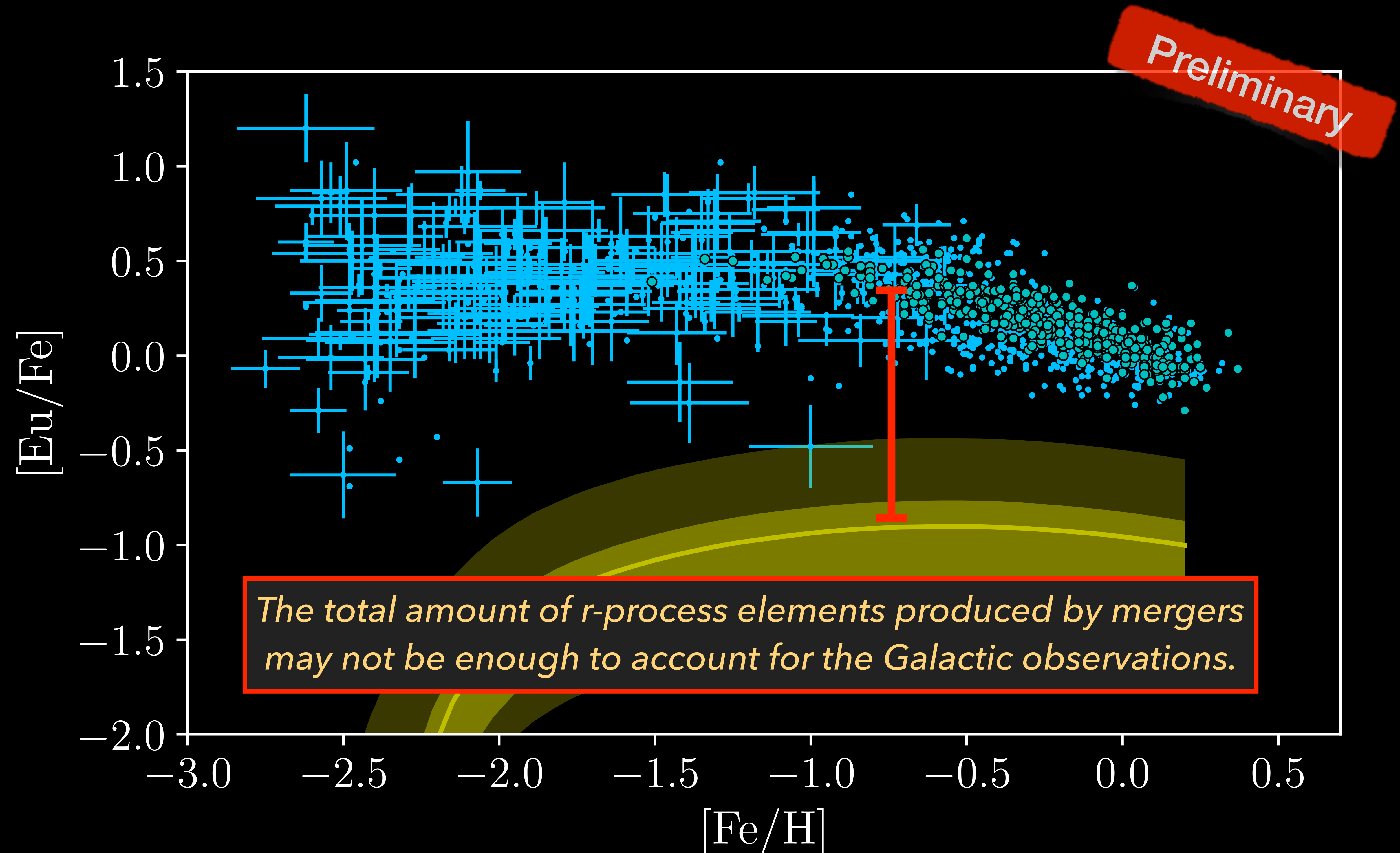

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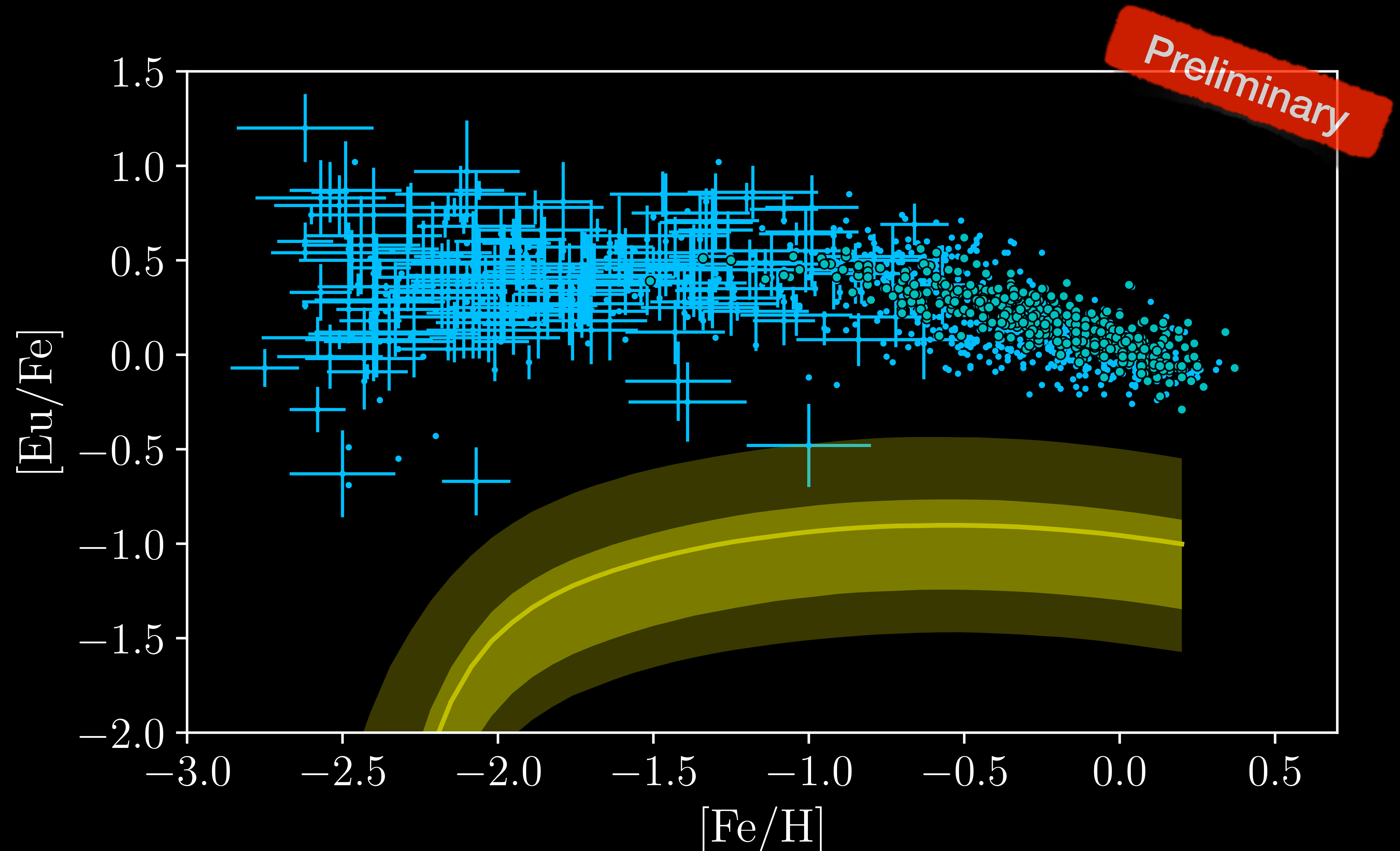

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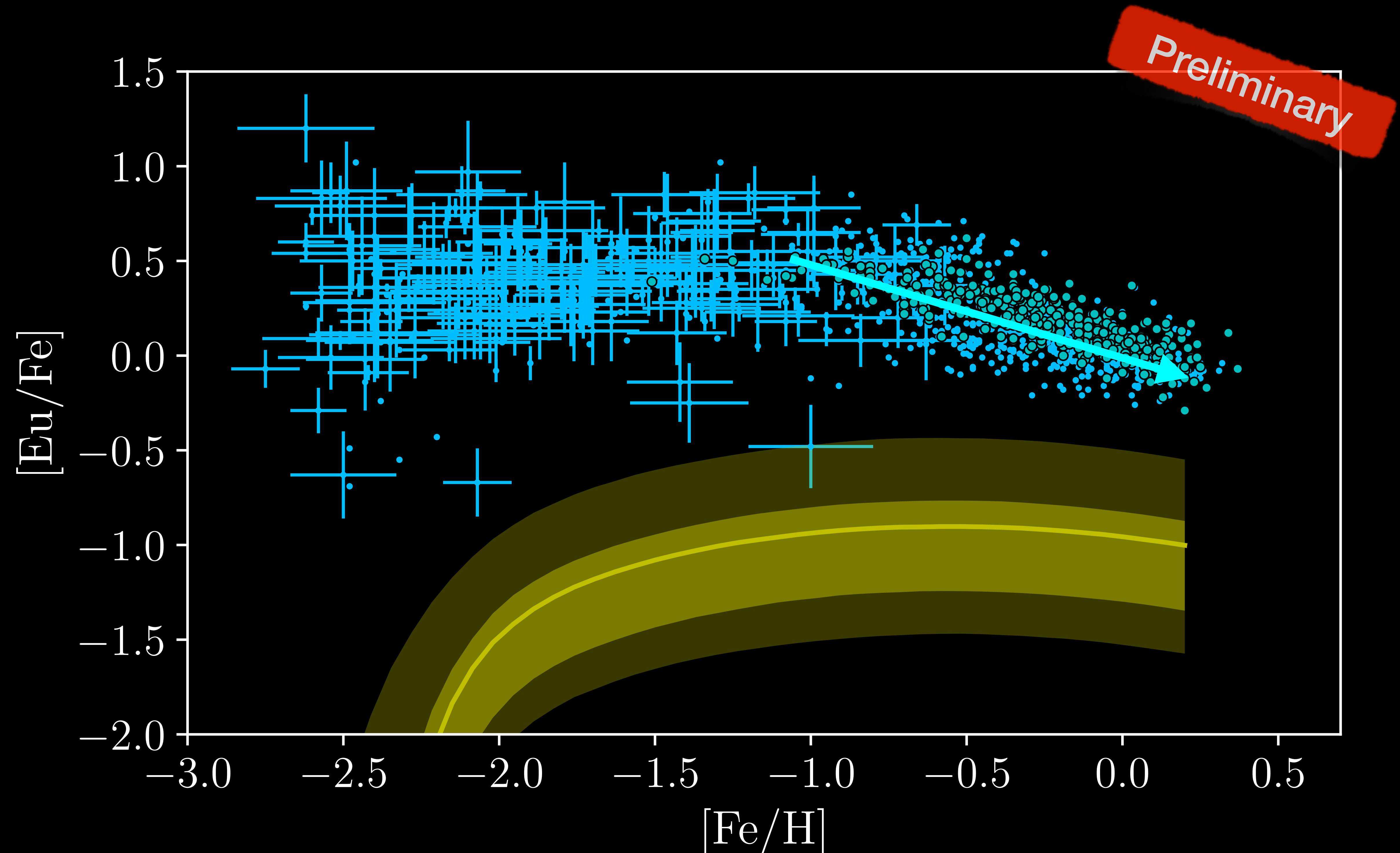

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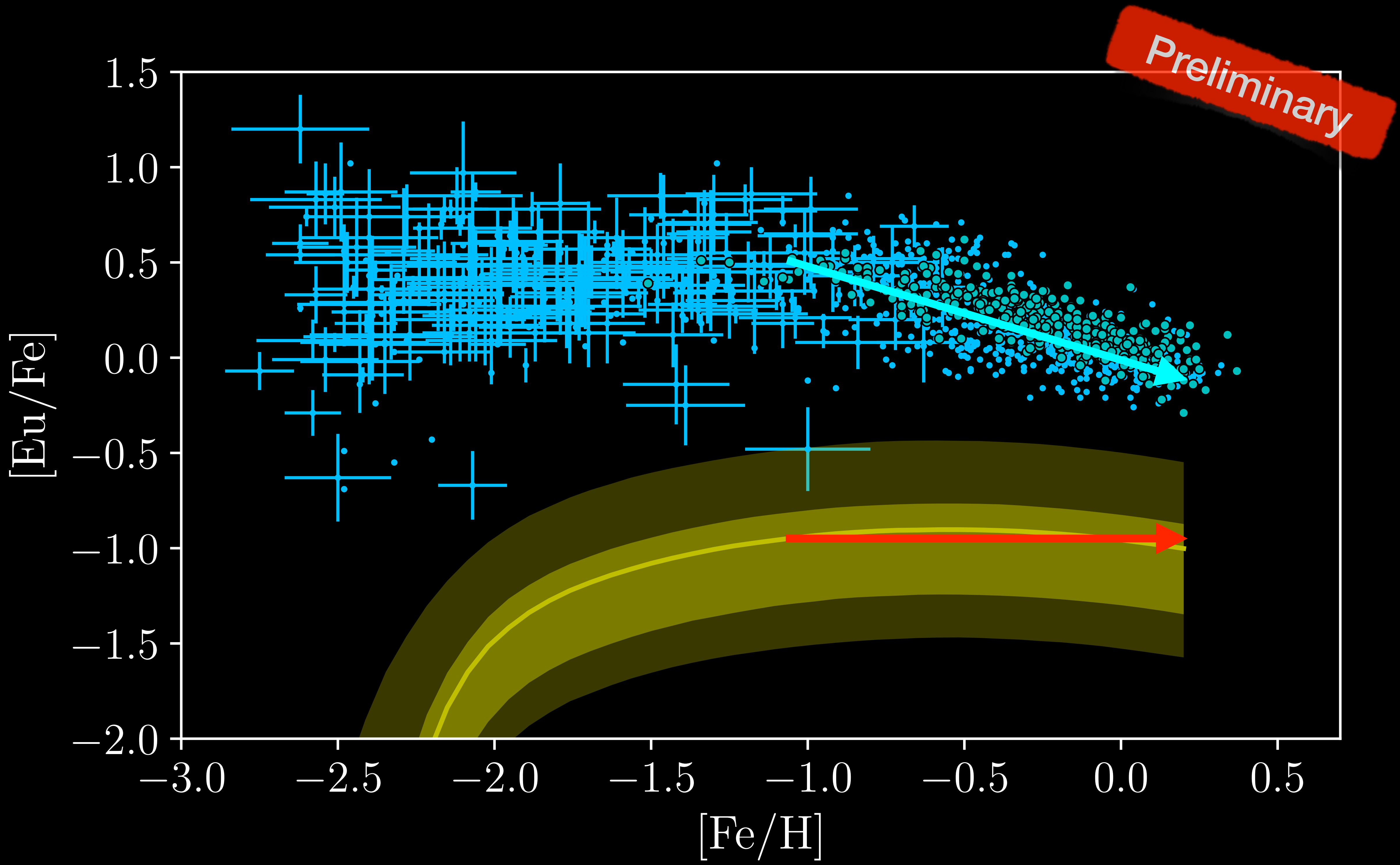

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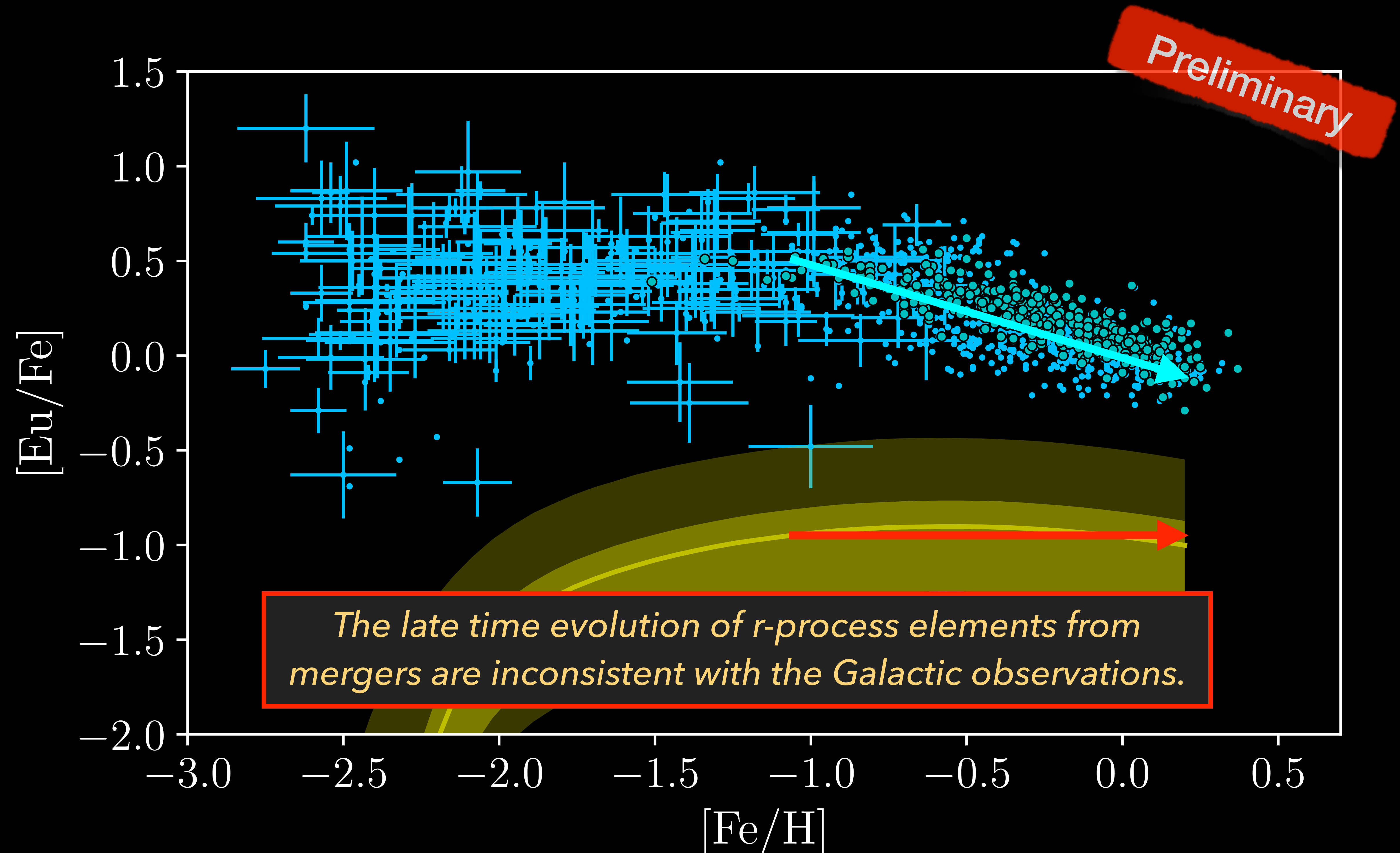

Possible explanations

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-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.

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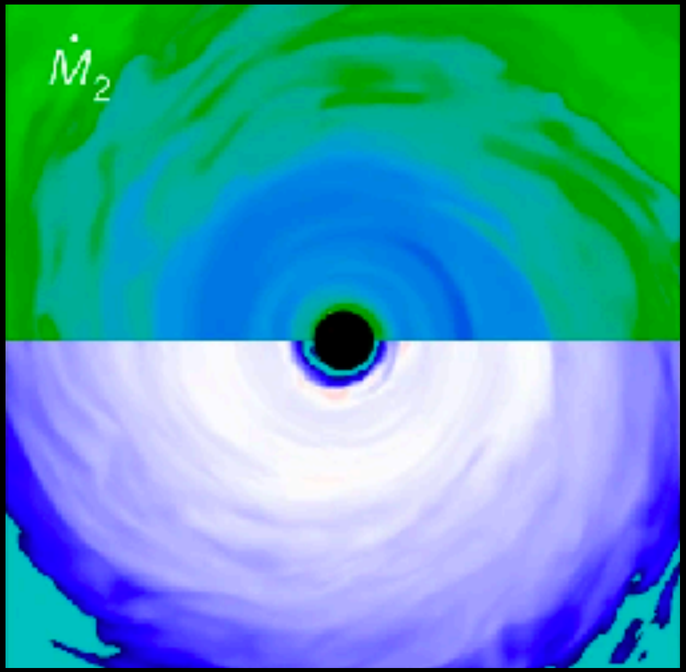
-In the Galactic observations: different stellar observation database.

-More realistic models.

Other r-process element production candidates:

Collapsar

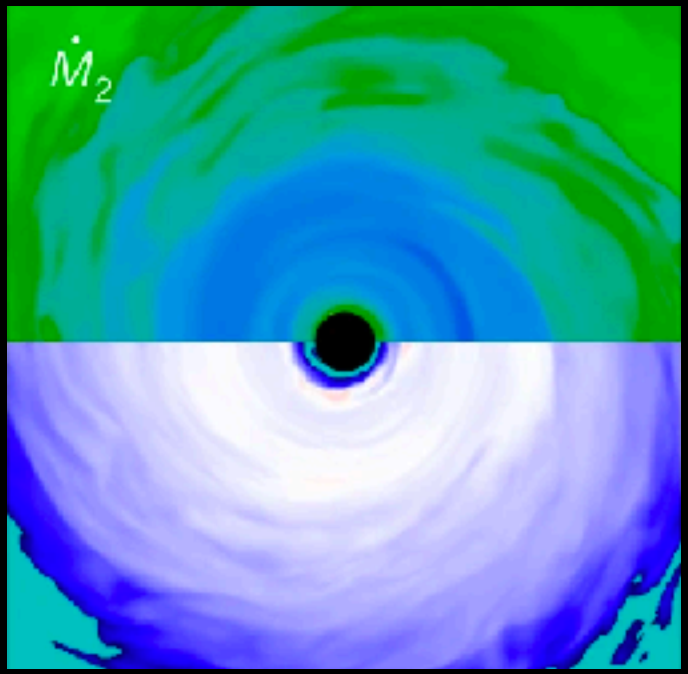


Siegel et al, Nature (2019)

Accretion disk

Other r-process element production candidates:

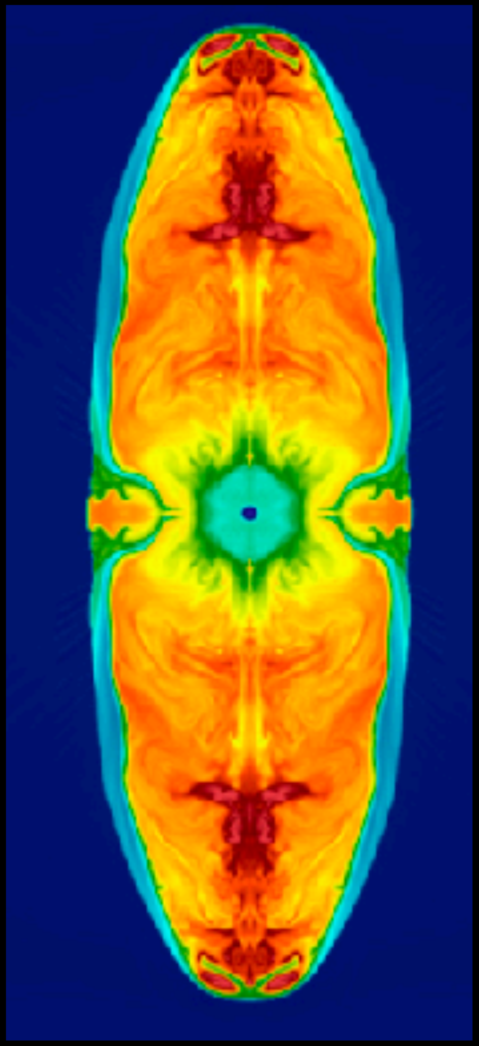
Collapsar



Siegel et al, Nature (2019)

Accretion disk

Magnetorotational core-collapse supernova



Magnetic jet drives neutron-rich materials away from the proto-neutron star

Mösta et al., ApJ (2018)

Summary

Summary

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

Summary

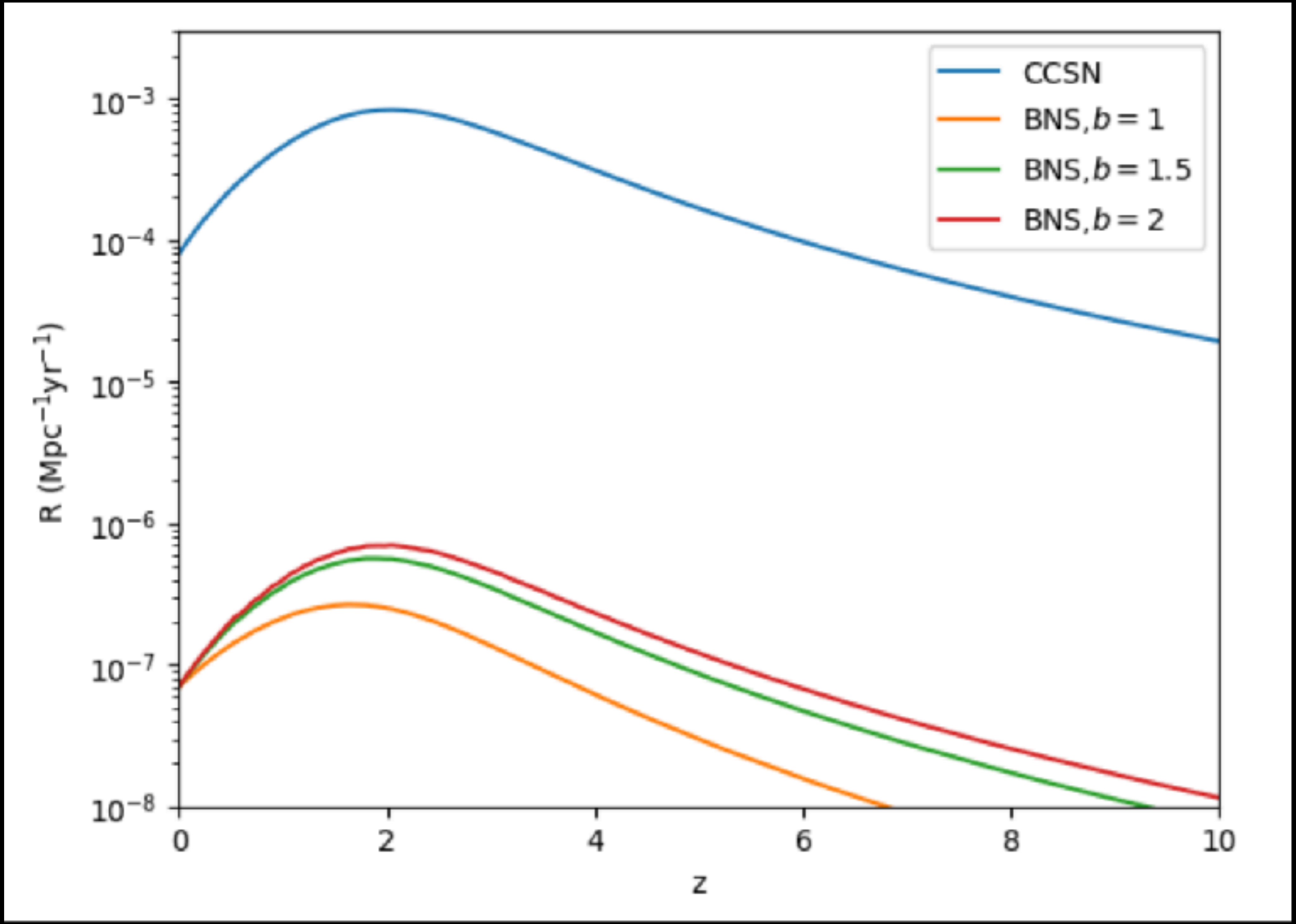
-Multi-messenger observations allow for inference of r-process elements progenitor.

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

Thank you!

A. Binary neutron star merger rate across the history

- Merger delay time distribution



Hsin-Yu Chen / UT Austin

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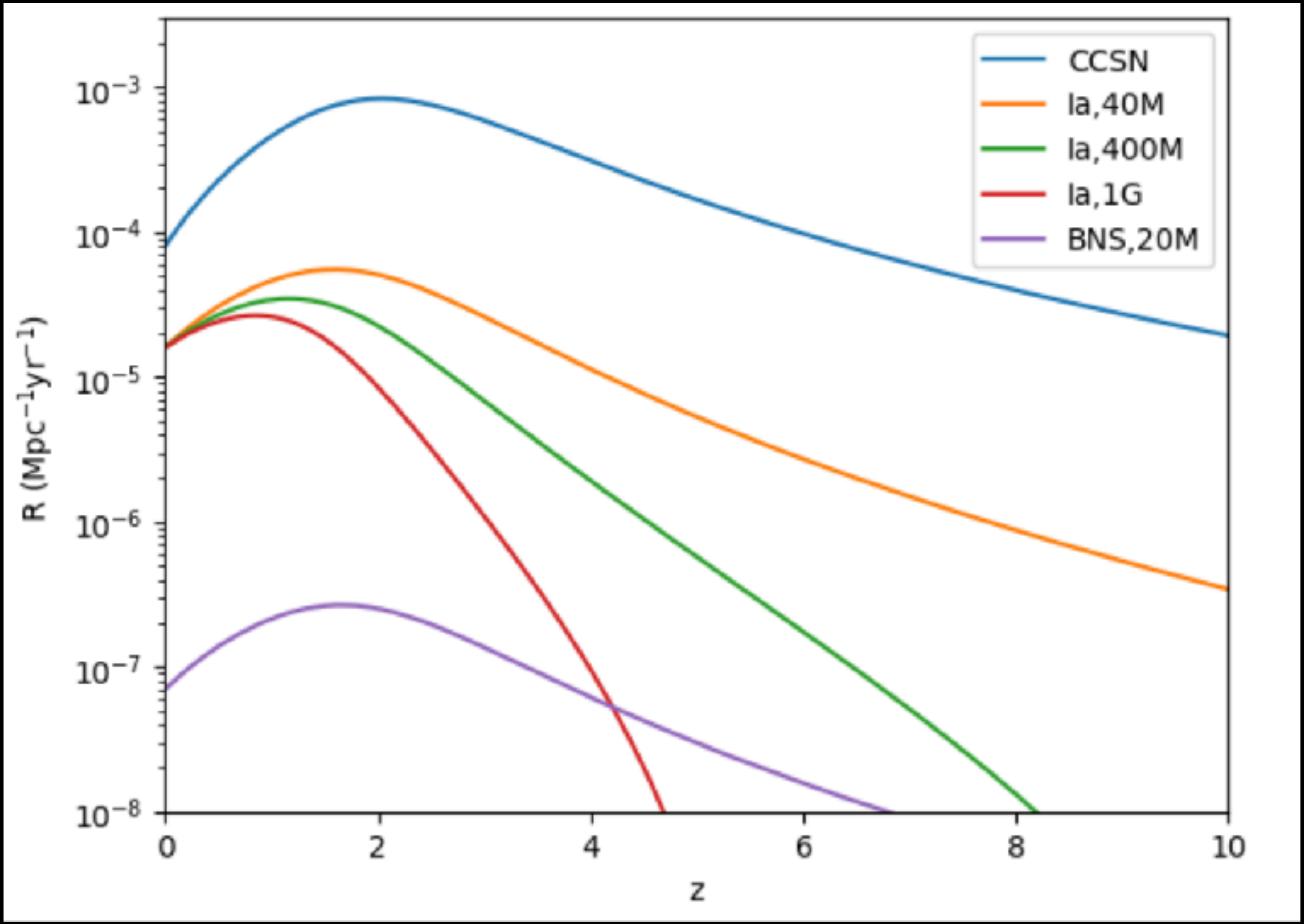
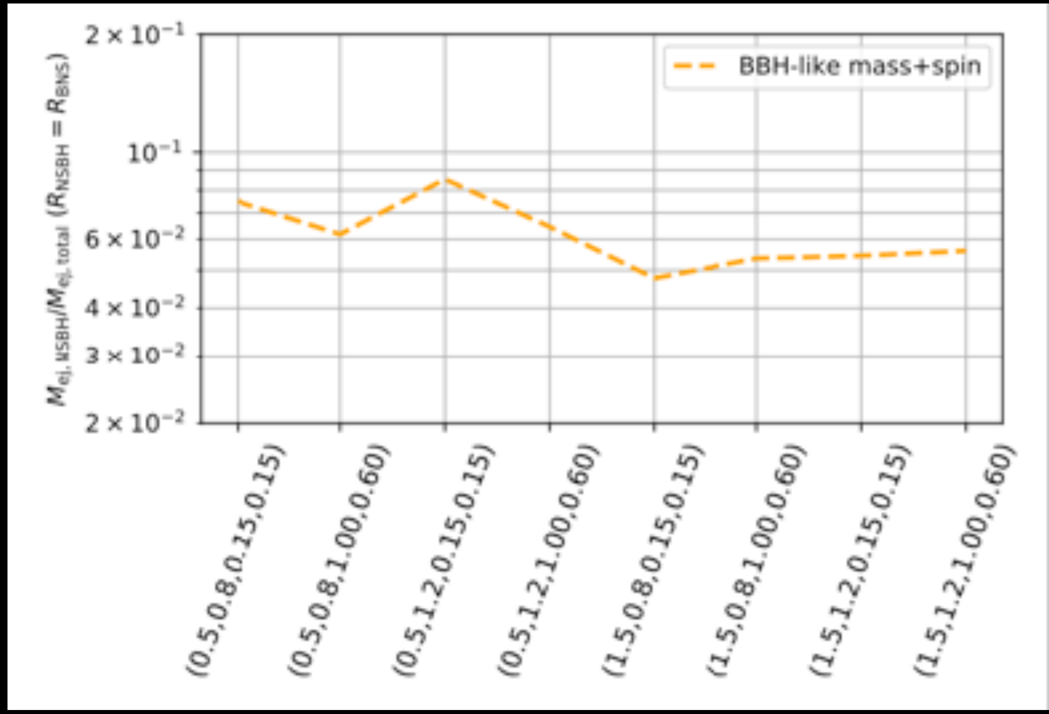


Observational and numerical uncertainties are still very large

-Considering very large numerical uncertainties



Chen, Vitale & Foucart, 2107.02714, ApJL (2021)

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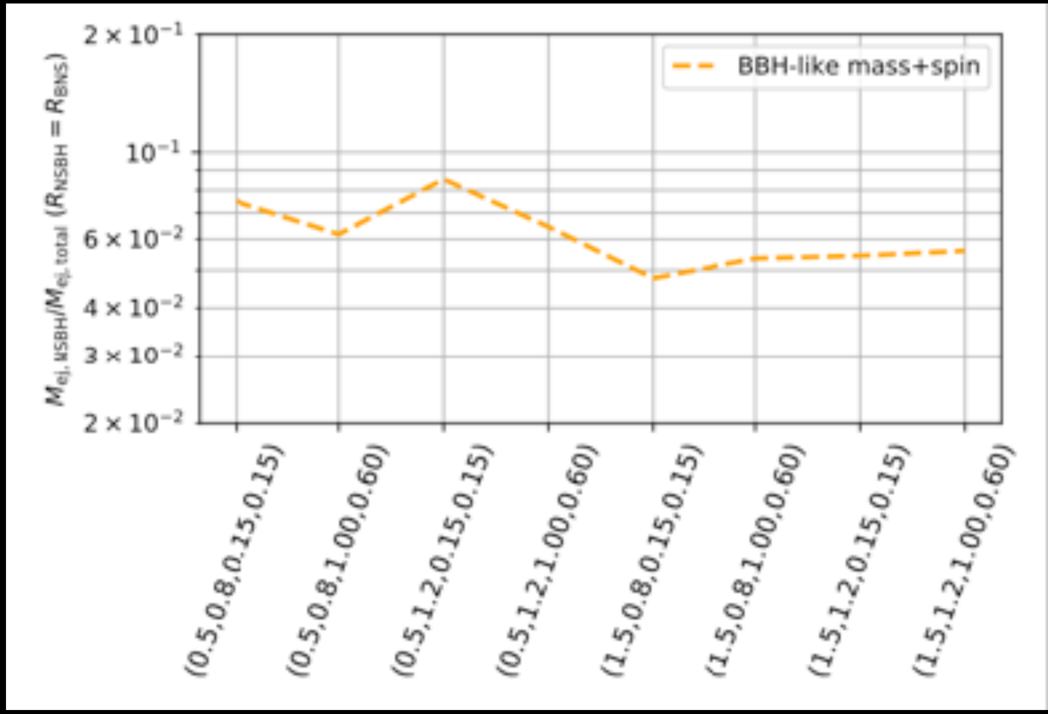
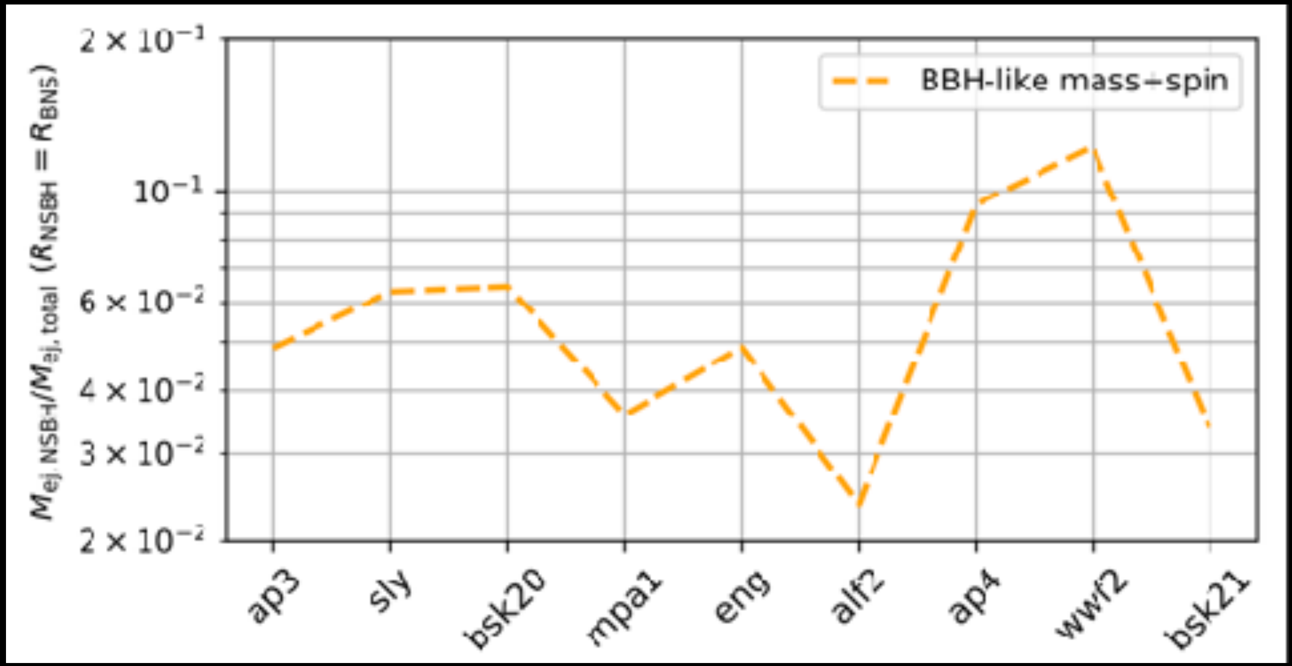


-Varying neutron star EoS



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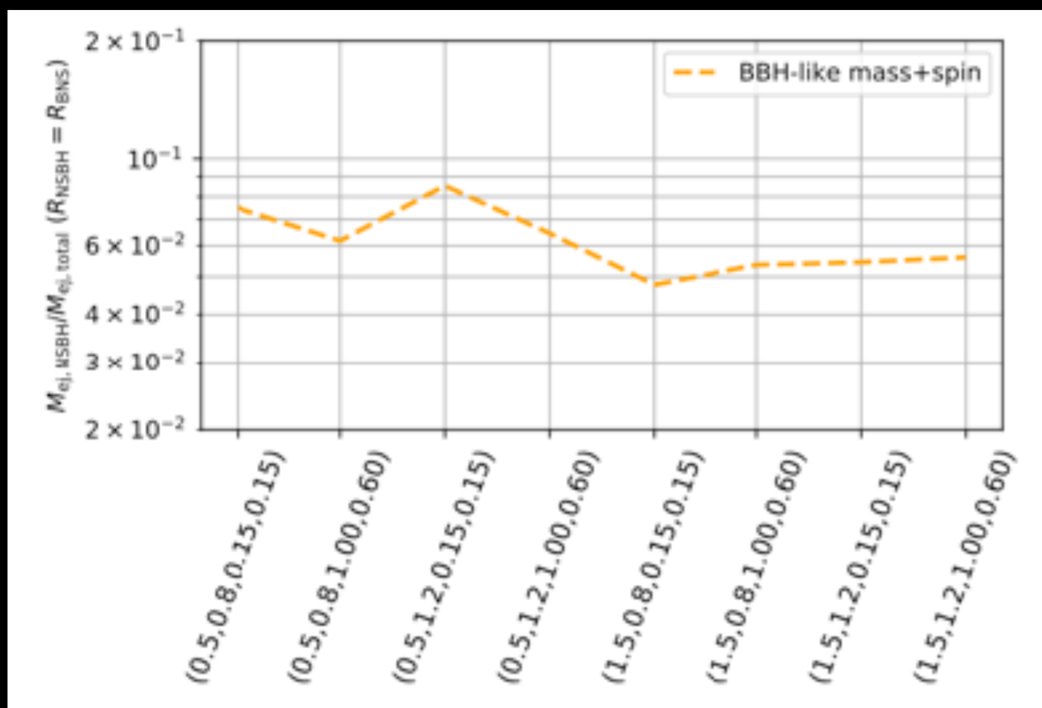
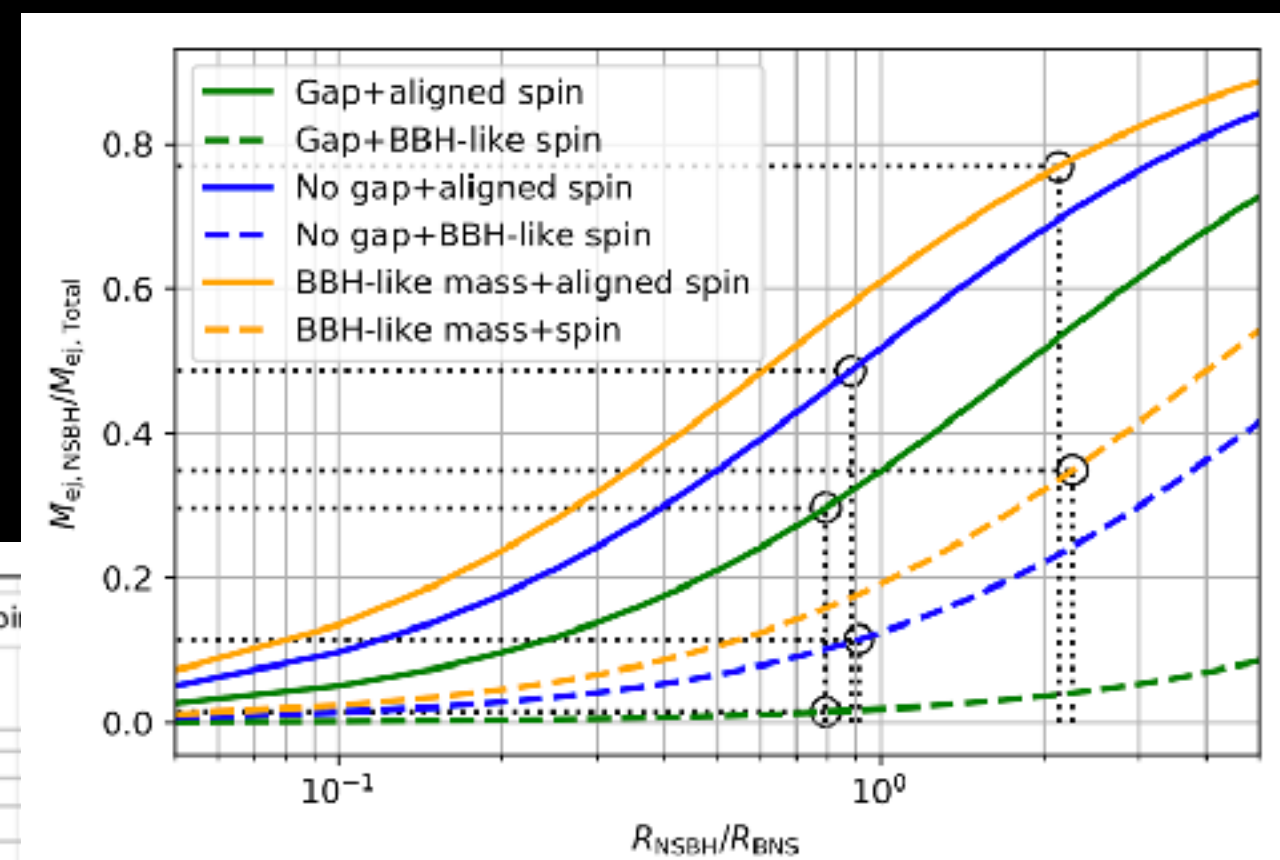


-Varying merger rates



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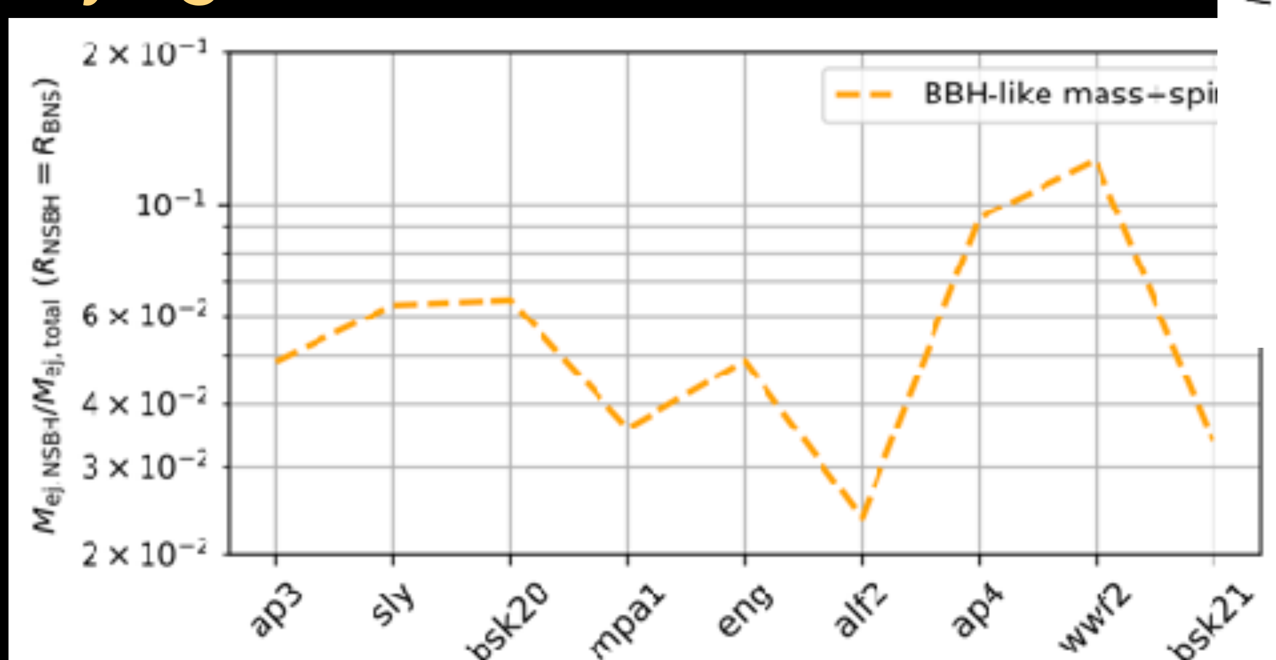

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Comparing the total amount of ejecta

Black hole mass *Black hole spin*

Label	m_1	$\lvert\chi_1\rvert$	Tilt	$M_{\rm ej,NSBH}/M_{\rm ej,Total}$
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	11%
BBH-like mass+aligned spin	BBH-like	Uniform in [0,0.95]	Aligned	77%
BBH-like mass+spin	BBH-like	BBH-like	BBH-like	35%

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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.