

Cosmic collisions: nuclear astrophysics with gravitational waves

Philippe Landry ♦ Canadian Institute for Theoretical Astrophysics

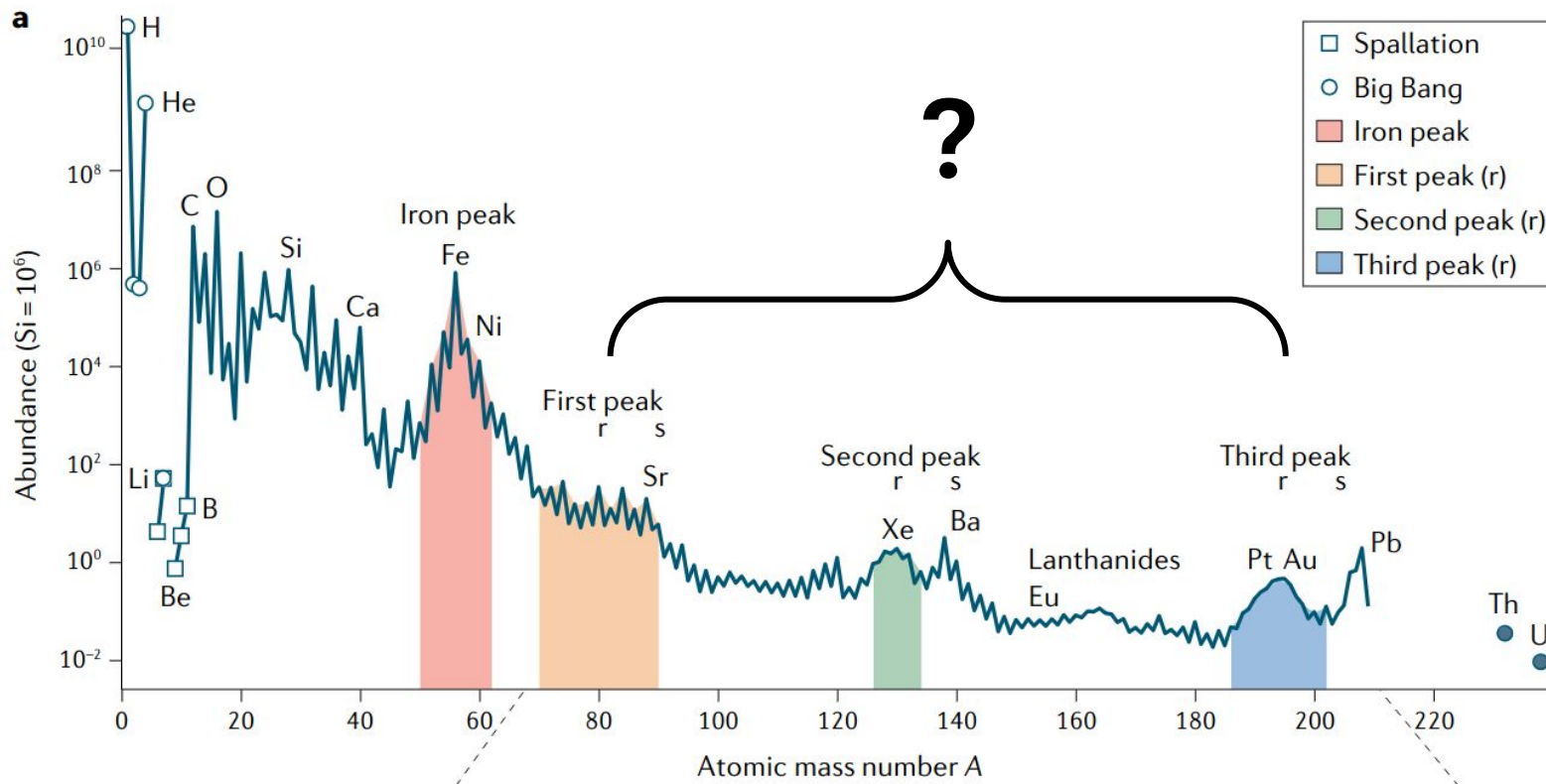


CaNPAN Annual Meeting – 3 May 2024

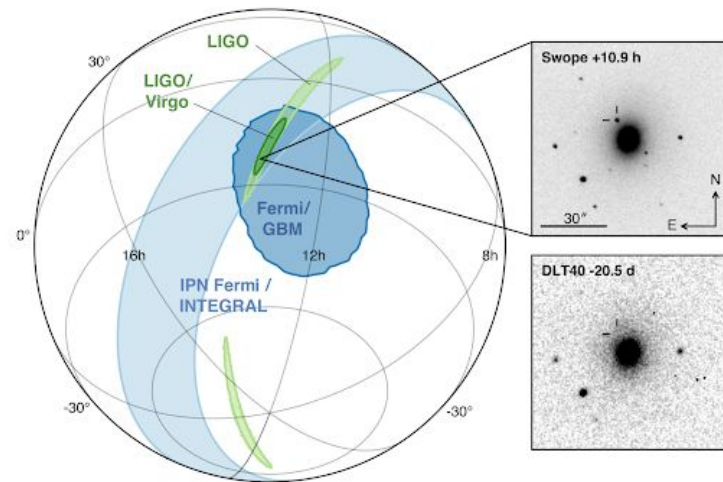


Where do the heavy elements come from?

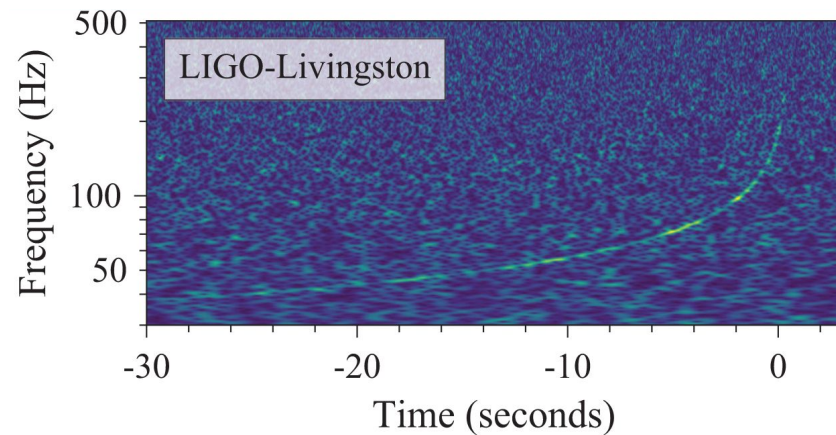
Siegel+ NatRevPhys 2022



GW170817: a multi-messenger binary neutron star merger

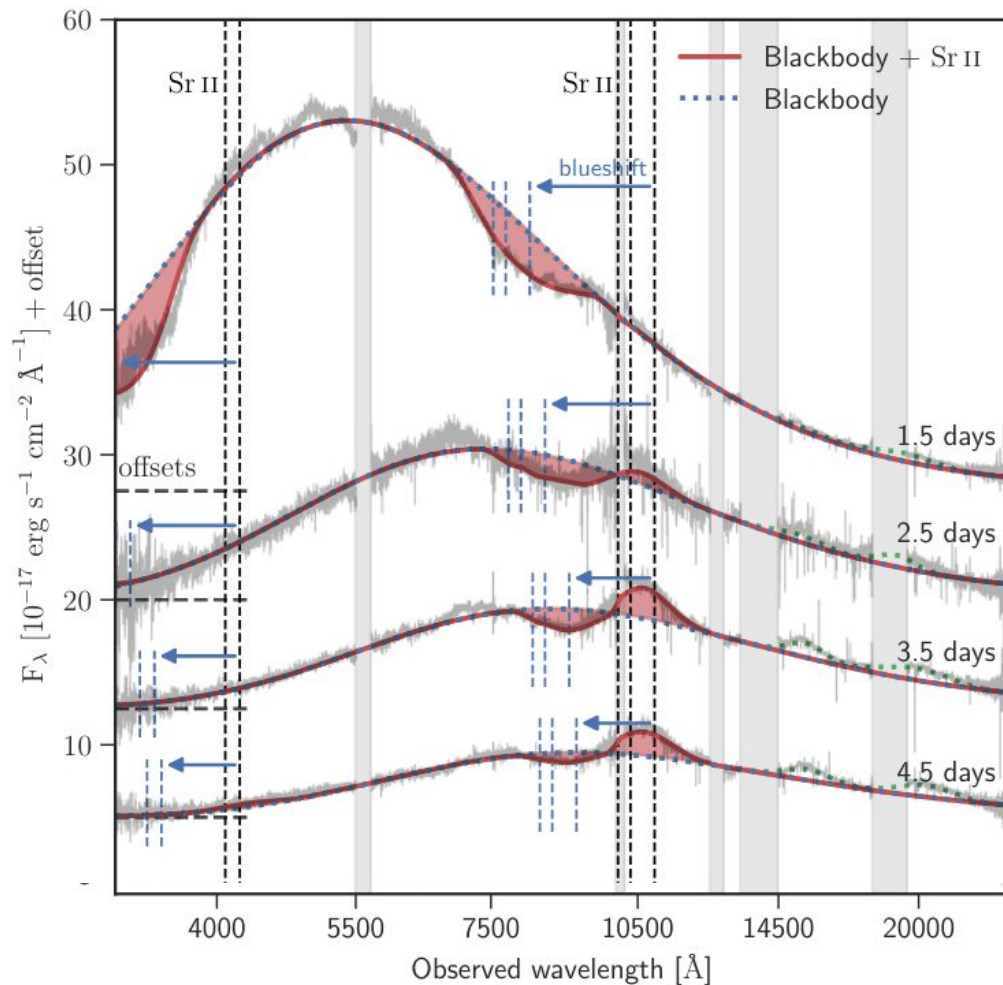


LVC PRL 2017

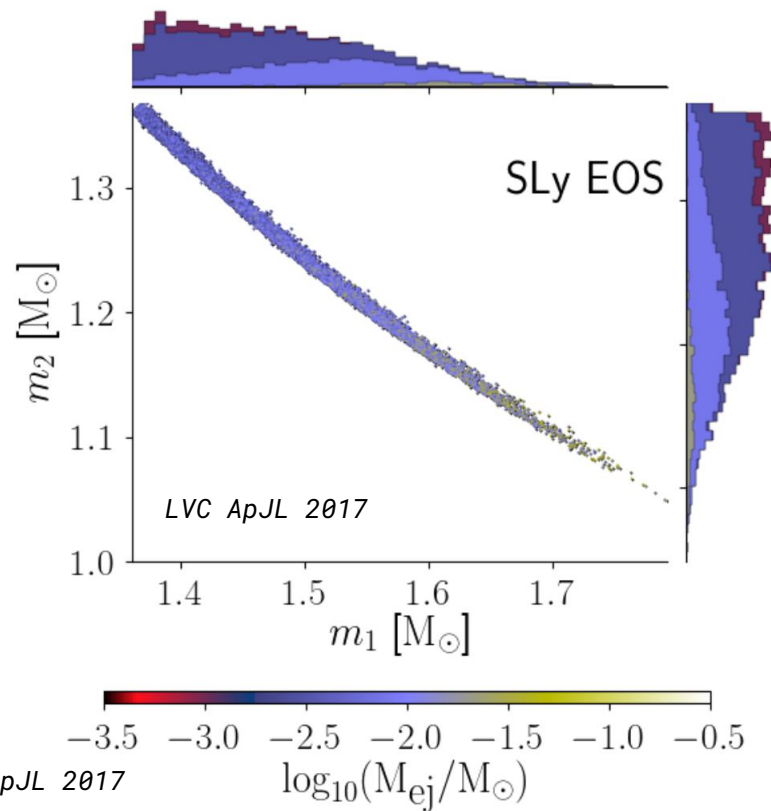
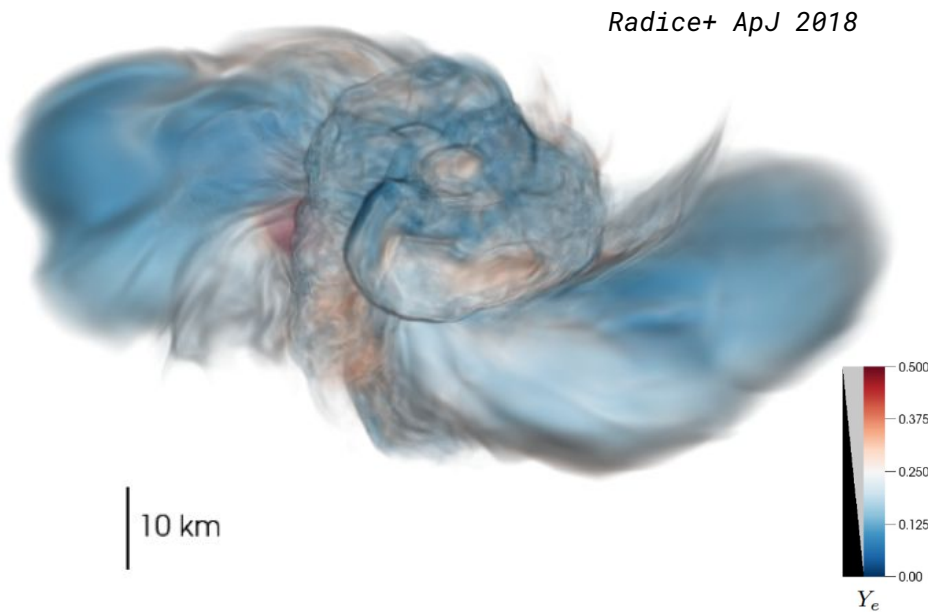


Evidence for r-process absorption in the kilonova spectrum

Watson+ Nat 2019



Heavy element production in GW170817



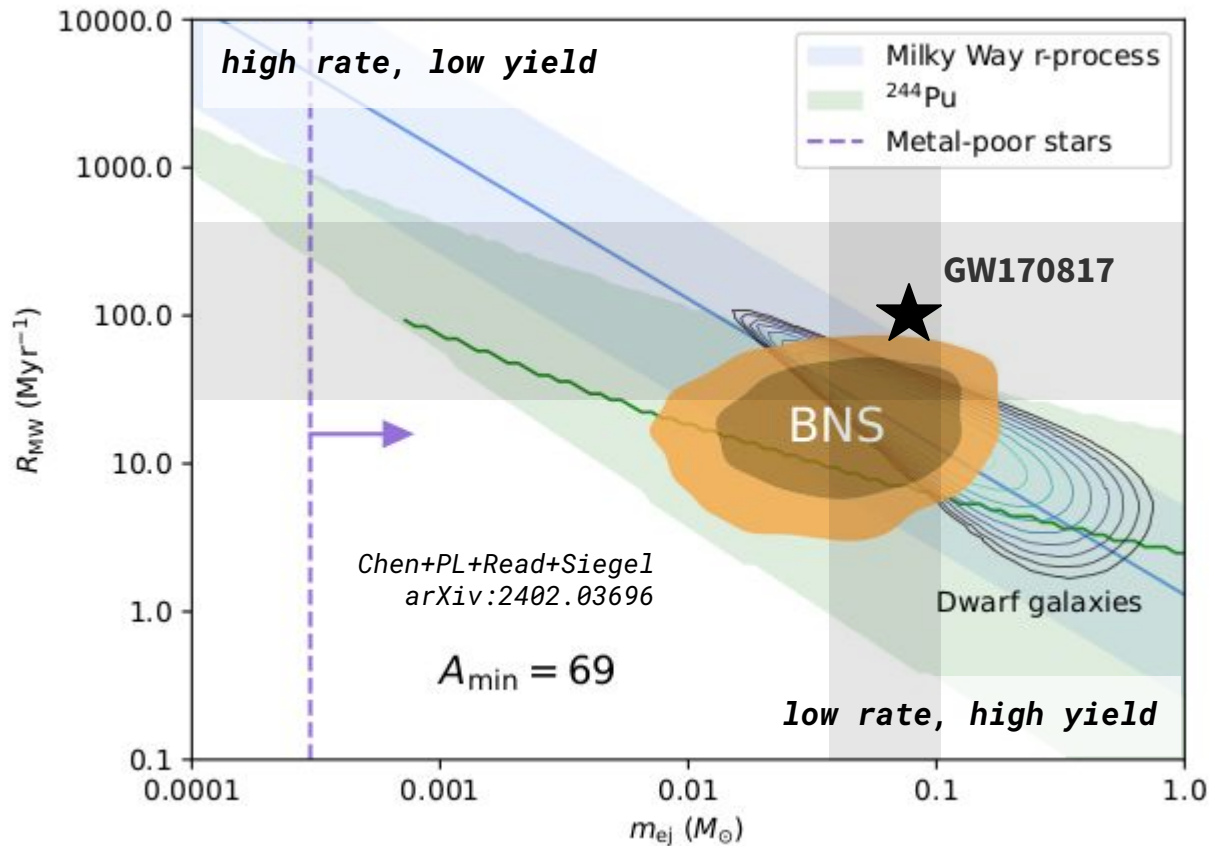
models predict up to $0.1 M_\odot$ of dynamical ejecta for GW170817

LVC ApJL 2017

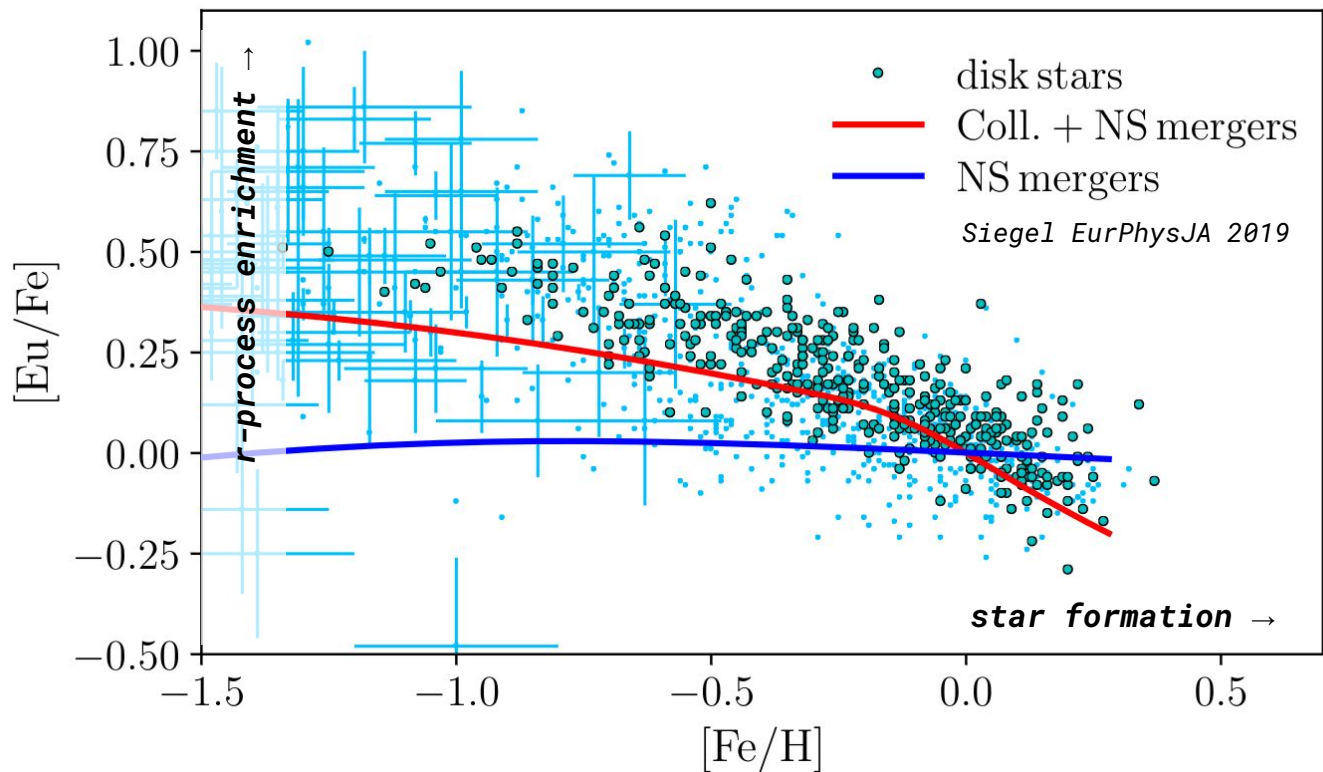
Can BNSs match r-process observations?

**rate and yield
inferred from
GW170817
agree with
observations**

e.g. Siegel *EurPhysJA* 2019



Can BNSs match r-process observations?



***extrapolation
of GW170817
rate-yield back
over Galactic
history is a
poor match to
metal-poor star
r-process
abundances***

Can BNSs match r-process observations?

Is the GW170817-inferred r-process rate-yield representative?

- *How often do BNS mergers occur?*
- *What is the mass distribution of merging neutron stars?*
- *How compact are neutron stars?*

How does the BNS merger rate vary over cosmic history?

- *What is the BNS delay time distribution?*

Are r-process sites other than BNSs important?

- *What about collapsars? NSBH mergers?*

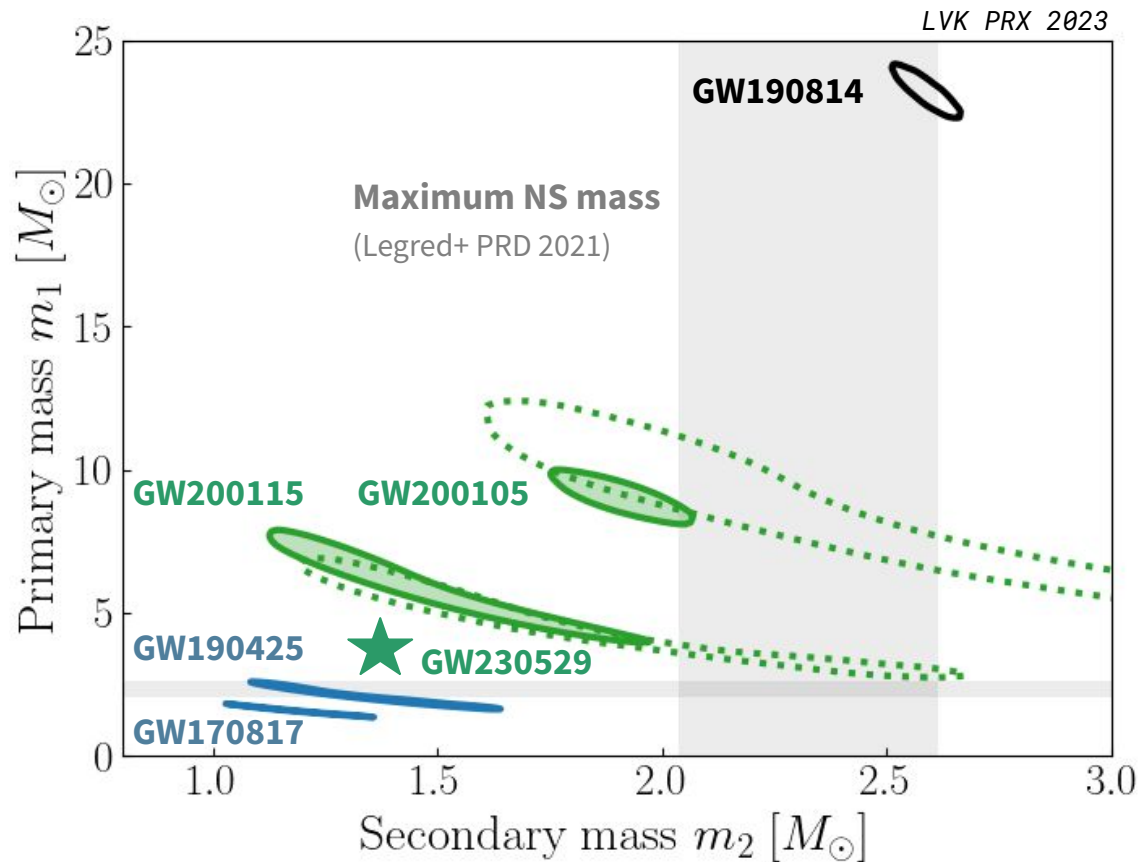
LIGO-Virgo- KAGRA BNS merger rate

post-GW170817:

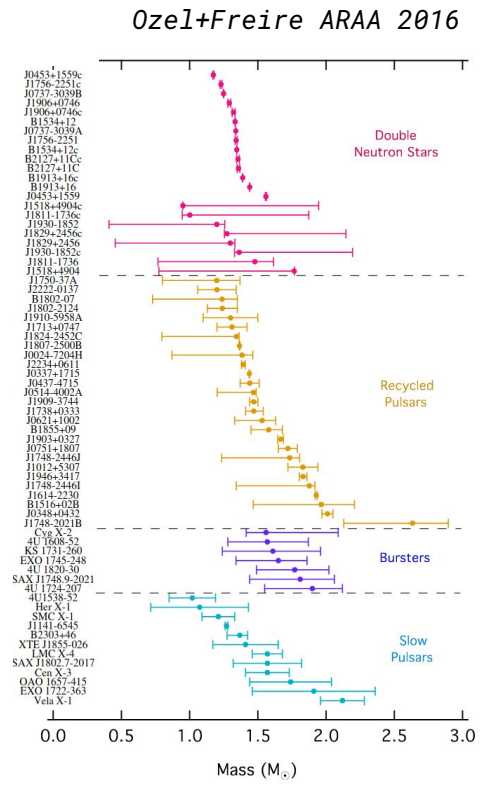
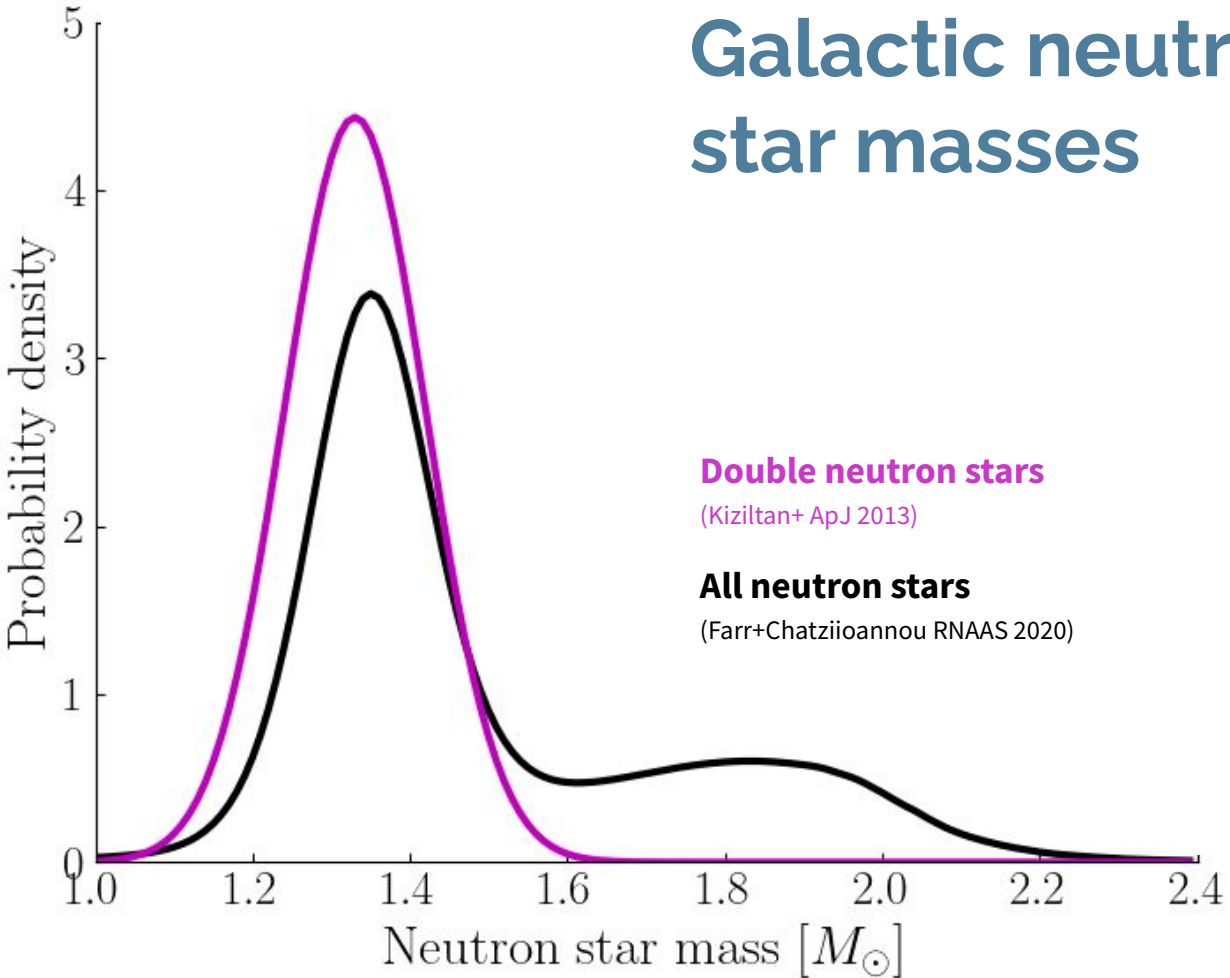
$3800 \text{ Gpc}^{-3} \text{ yr}^{-1}$

post-LVK O3b:

$440 \text{ Gpc}^{-3} \text{ yr}^{-1}$



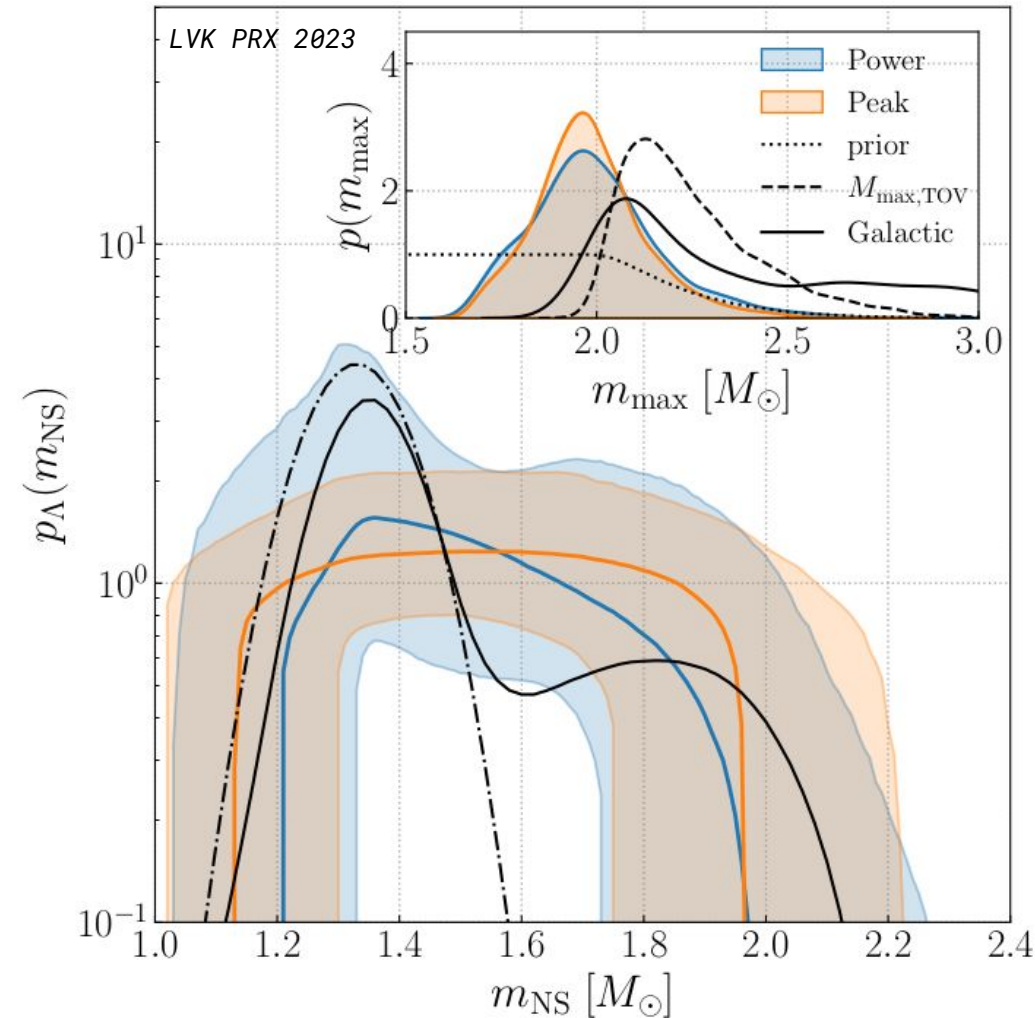
Galactic neutron star masses



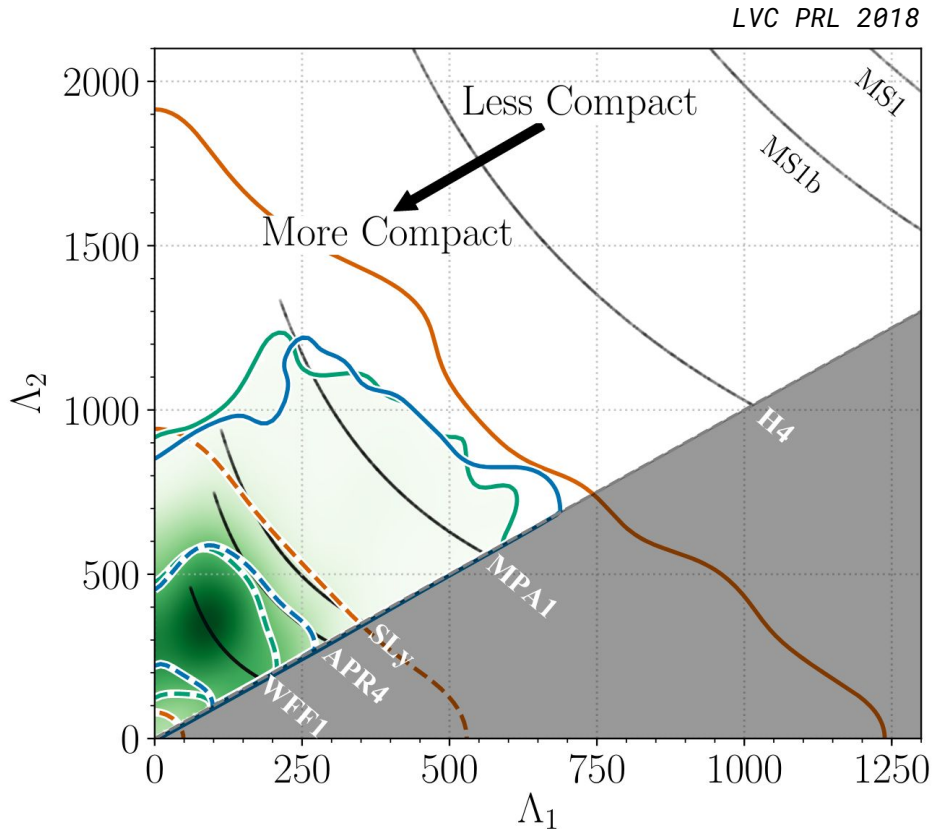
LIGO-Virgo-KAGRA neutron star masses

*the mass distribution for
merging neutron stars
does not appear to be
strongly peaked, unlike
the one for Galactic
double neutron stars*

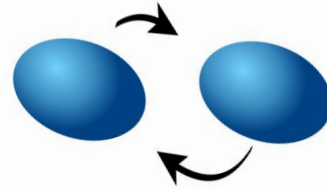
PL+Read ApJL 2021



How compact are neutron stars?



Mass ejection depends on the NS compactness Gm/c^2R , a measure of self-gravity

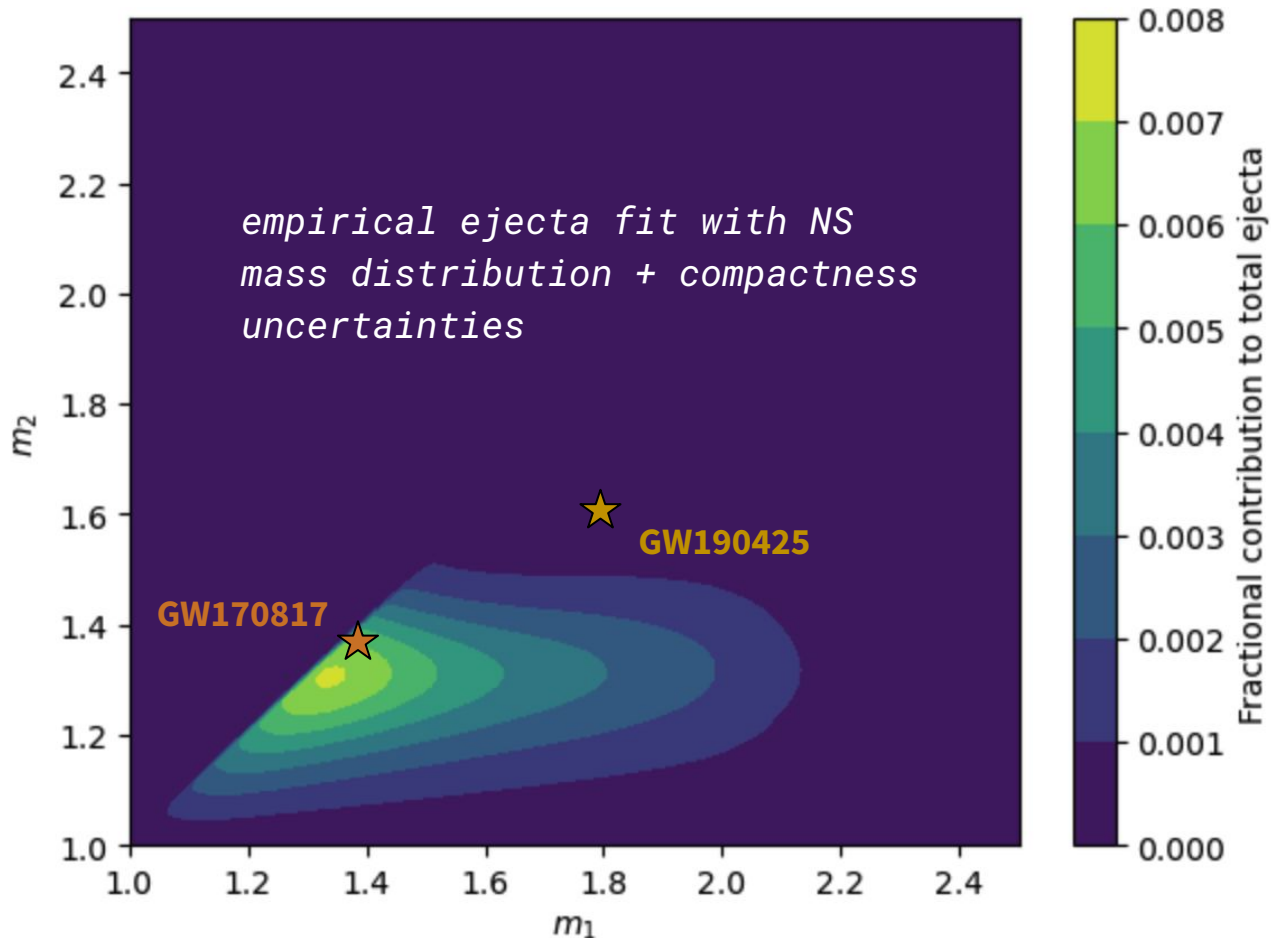


GW measurements of tidal deformability Λ , a proxy for the radius, indicate that NSs are relatively compact

Ejecta mass varies across BNS mergers

GW170817 is not necessarily representative

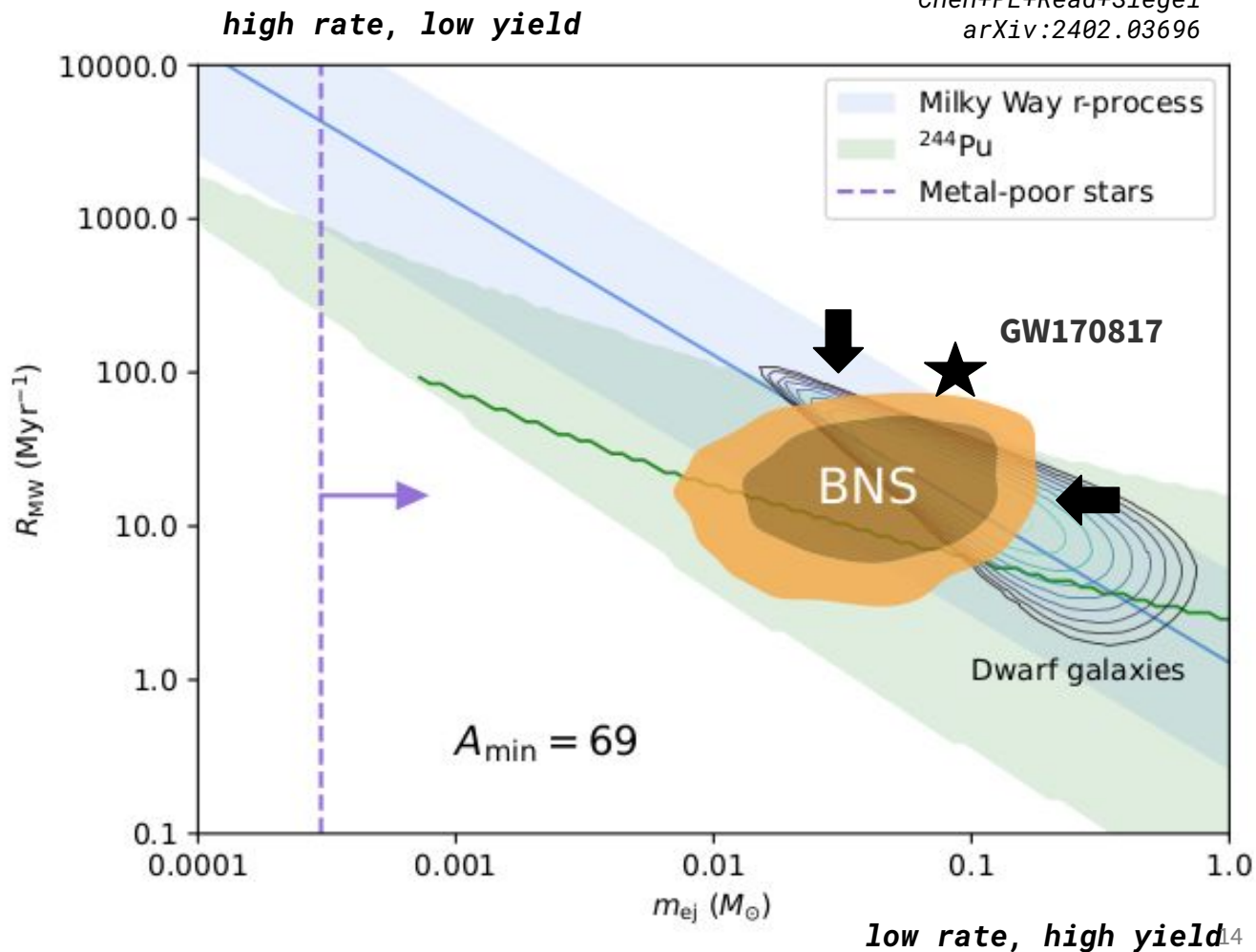
Chen+PL+Read+Siegel
arXiv:2402.03696



Updated BNS rate and yield

***BNS rate and
average ejecta
mass agree with
stellar, galactic
and geophysical
constraints***

Chen+PL+Read+Siegel
arXiv:2402.03696



Can BNSs match r-process observations?

Is the GW170817-inferred r-process rate-yield representative?

- *How often do BNS mergers occur?*
- *What is the mass distribution of merging neutron stars?*
- *How compact are neutron stars?*

NO 

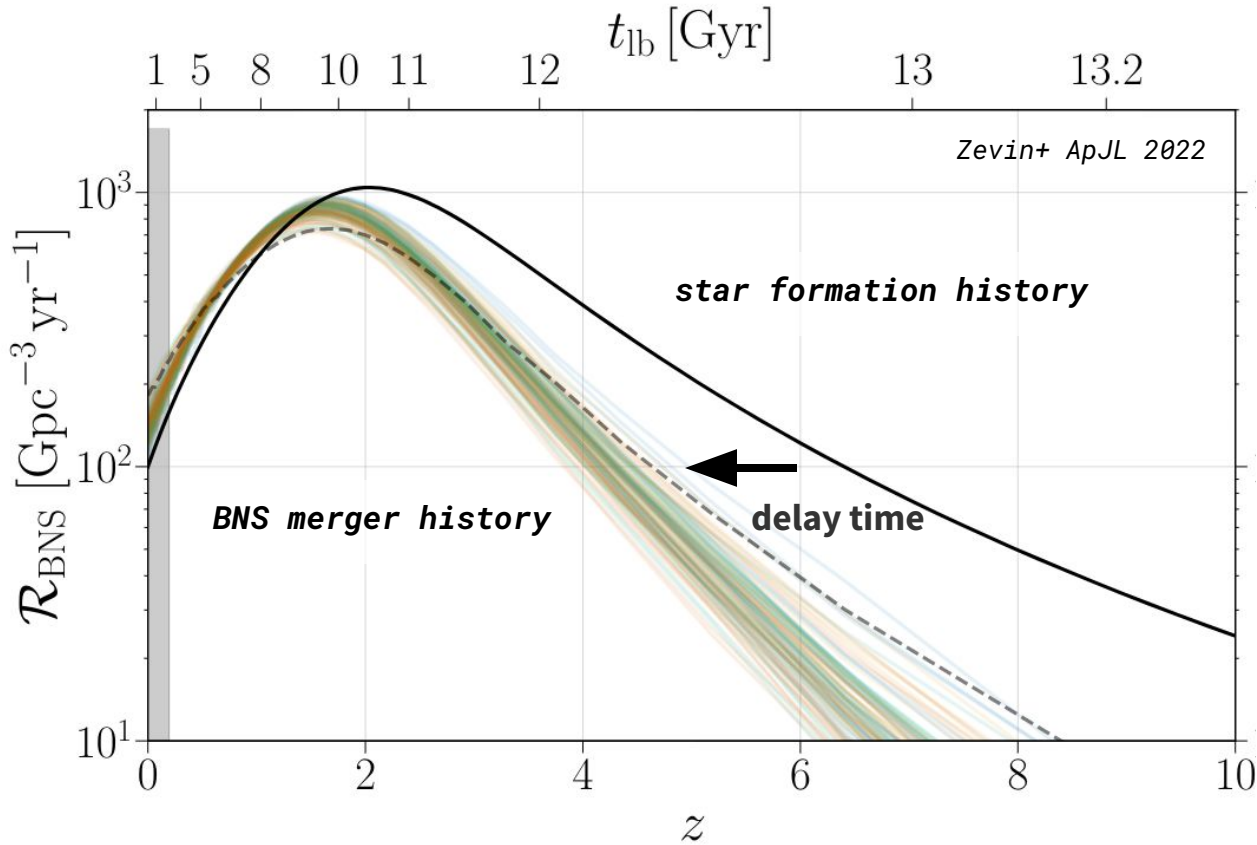
How does the BNS merger rate vary over cosmic history?

- *What is the BNS delay time distribution?*

Are r-process sites other than BNSs important?

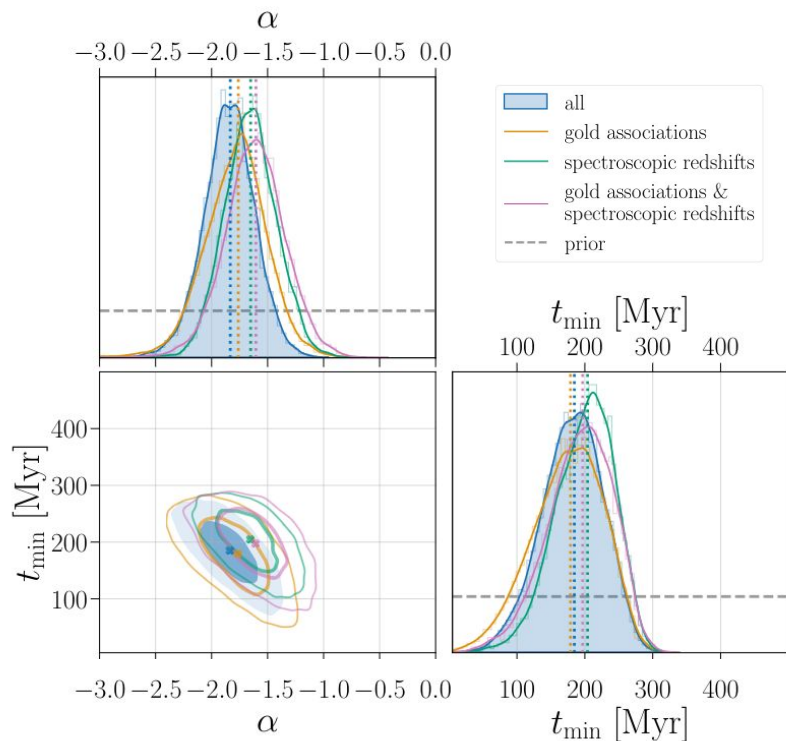
- *What about collapsars? NSBH mergers?*

BNS merger delay times



***cosmic history of
BNS mergers is
given by star
formation history +
delay time from
birth of progenitor
to merger***

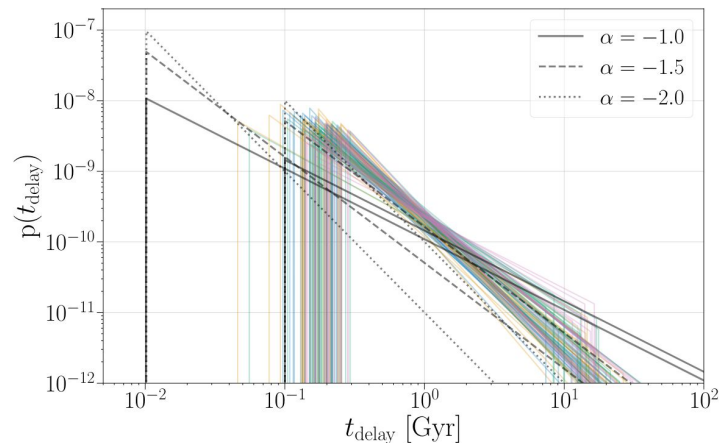
BNS merger delay times



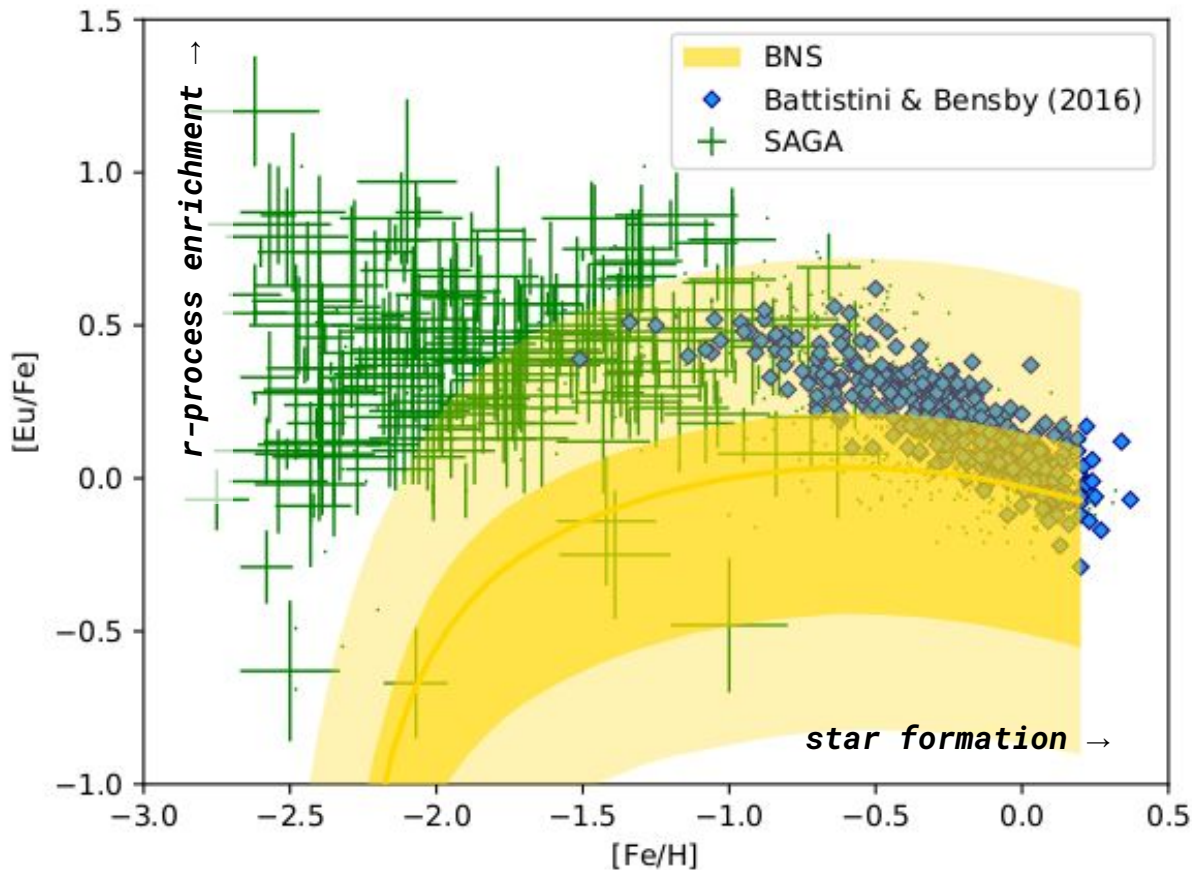
GW170817 confirmed that BNS mergers can power sGRBs

sGRB afterglow host associations favour delay times of $O(100 \text{ Myr})$

Zevin+ ApJL 2022



BNS mergers: r-process enrichment history



***BNS mergers with
sGRB-informed delay
times can't explain
low-metallicity
r-process enrichment***

Chen+PL+Read+Siegel
arXiv:2402.03696

Can BNSs match r-process observations?

Is the GW170817-inferred r-process rate-yield representative?

- *How often do BNS mergers occur?*
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NO 

How does the BNS merger rate vary over cosmic history?

- *What is the BNS delay time distribution?*

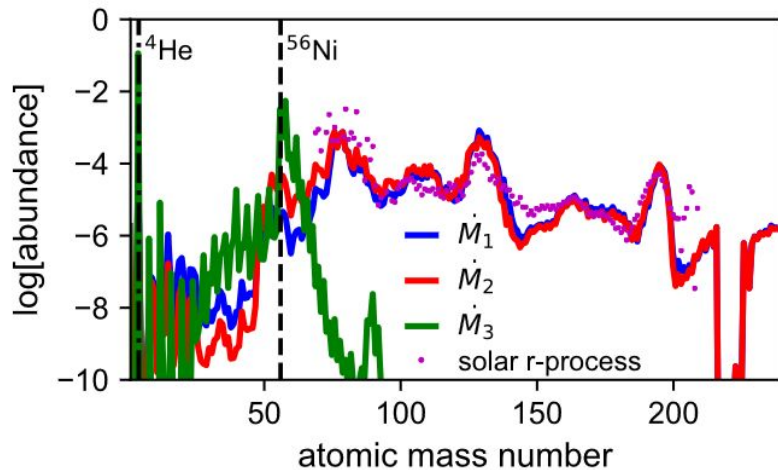


Are r-process sites other than BNSs important?

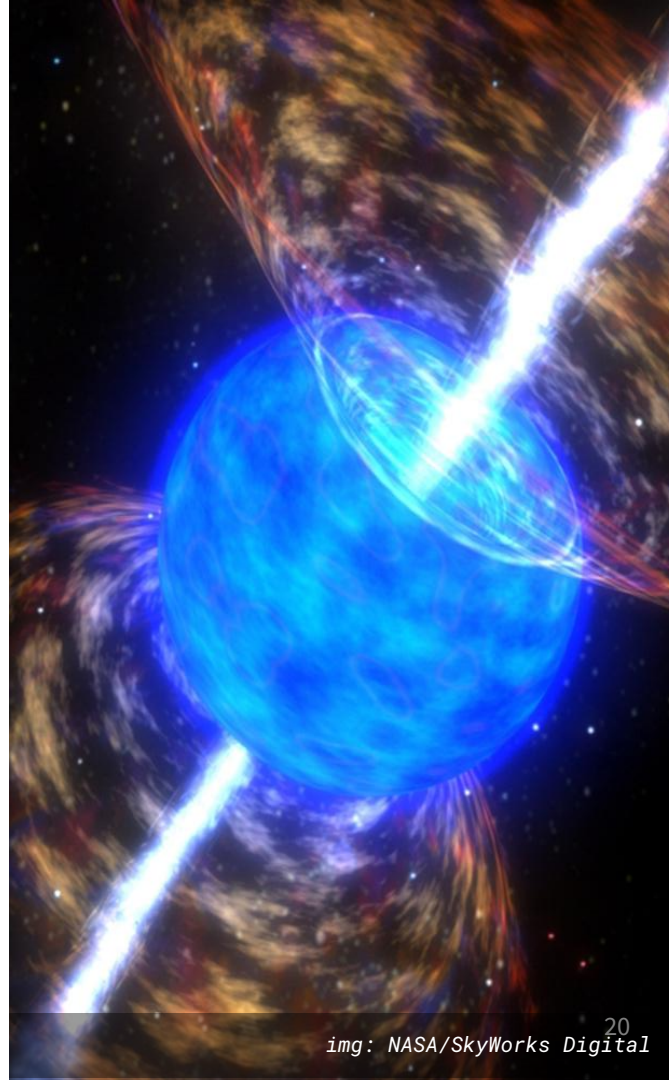
- *What about collapsars? NSBH mergers?*

Collapsars as r-process sites

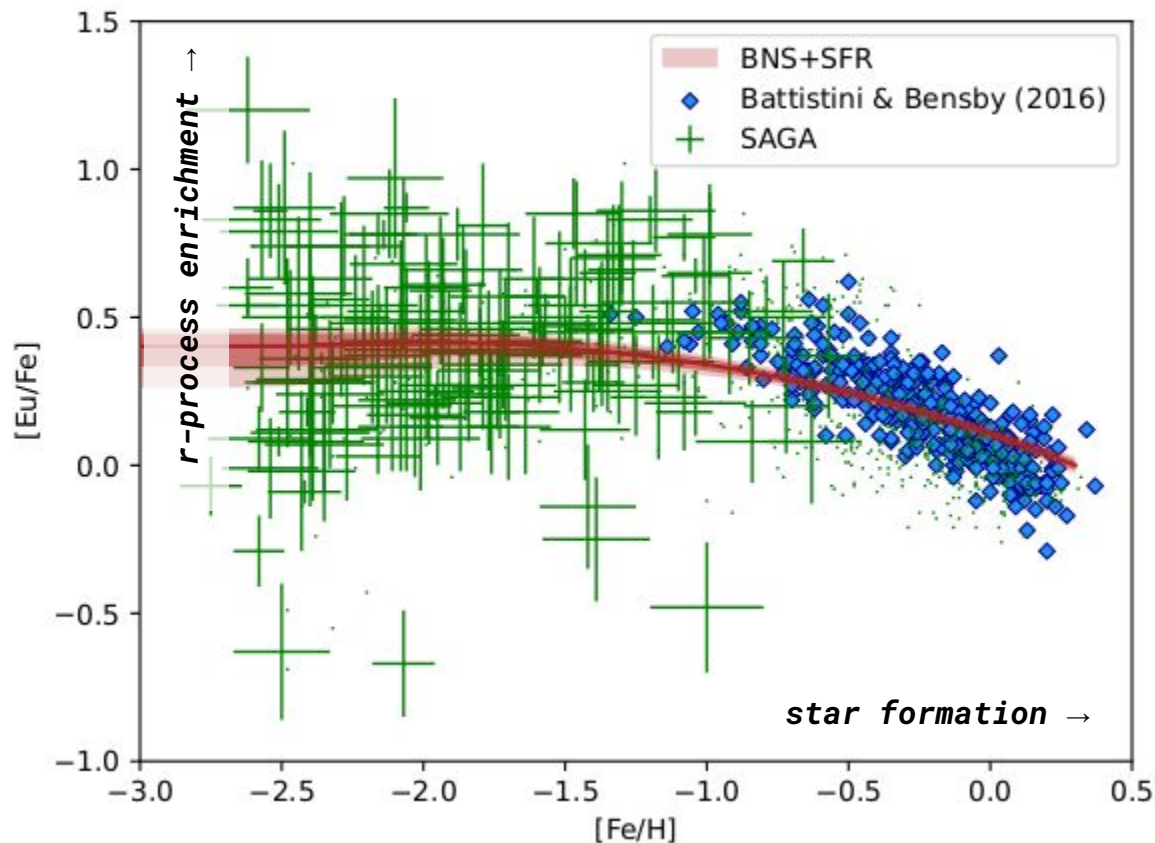
Rare type of superluminous supernova associated with IGRBs: core-collapse of a rapidly rotating massive star forms a BH with a neutron-rich accretion disk



collapsar
abundance
predictions
from Siegel+
Nat 2019



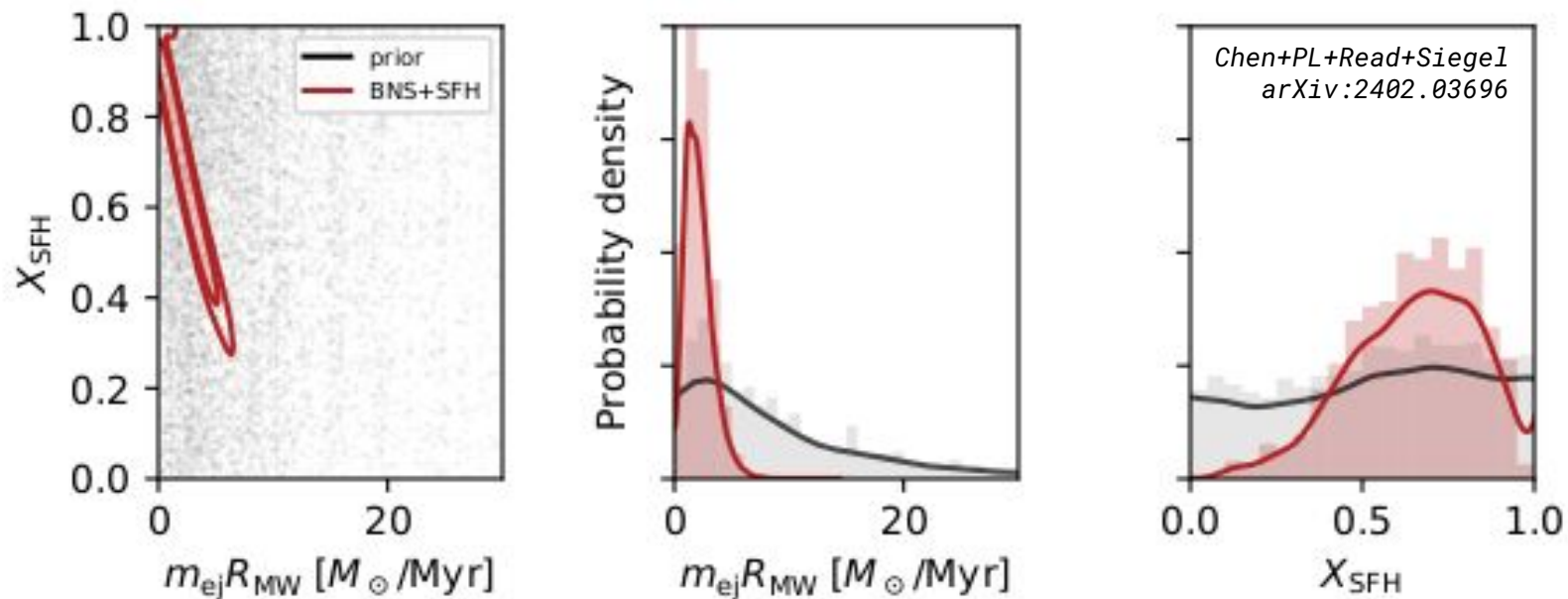
Two-channel scenario: BNSs + collapsars



adding a second channel with no delay time relative to star formation resolves the low-metallicity tension

Chen+PL+Read+Siegel
arXiv:2402.03696

Two-channel scenario: BNSs + collapsars



GW + sGRB + metal-poor star observations combine to favour similar r -process contributions from both channels!

Can BNSs match r-process observations?

Is the GW170817-inferred r-process rate-yield representative?

- *How often do BNS mergers occur?*
- *What is the mass distribution of merging neutron stars?*
- *How compact are neutron stars?*

NO 

How does the BNS merger rate vary over cosmic history?

- *What is the BNS delay time distribution?*



Are r-process sites other than BNSs important?

- *What about collapsars? NSBH mergers?*

YES 

Can BNSs match r-process observations?

Is the GW170817-inferred r-process rate-yield representative?

- *No, but improved BNS rate, mass distribution and compactness knowledge lead to better alignment with rate-yield observations*

NO 

How does the BNS merger rate vary over cosmic history?

- *sGRBs favour delay times too long to explain metal-poor star r-process enrichment, but are they unbiased BNS merger tracers?*



Are r-process sites other than BNSs important?

- *A star-formation-history tracking channel, like collapsars, must account for 50-90% of the local r-process abundance*

YES 

GW astronomy for nuclear astrophysics



CITA (Toronto), UBC,
UManitoba, UMontreal,
Perimeter Institute (Waterloo)

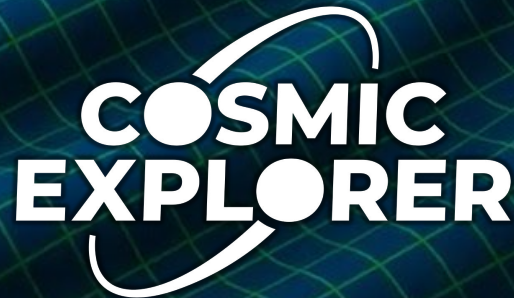
**NS structure and
dense matter physics**

**Low-latency GW
localization for
KN observations**

**BNS merger
simulations and KN
lightcurve modeling**

**BNS merger population
and redshift evolution**

North America's
next-generation GW
observatory project

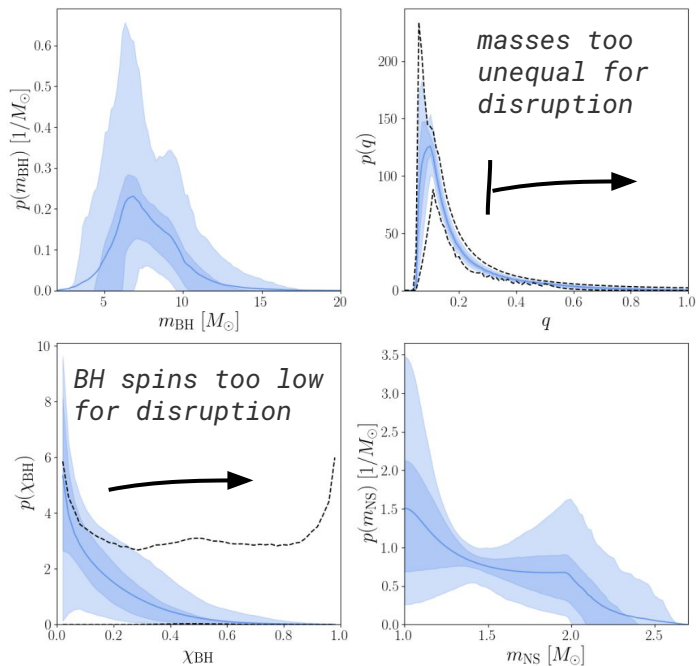


Thanks!

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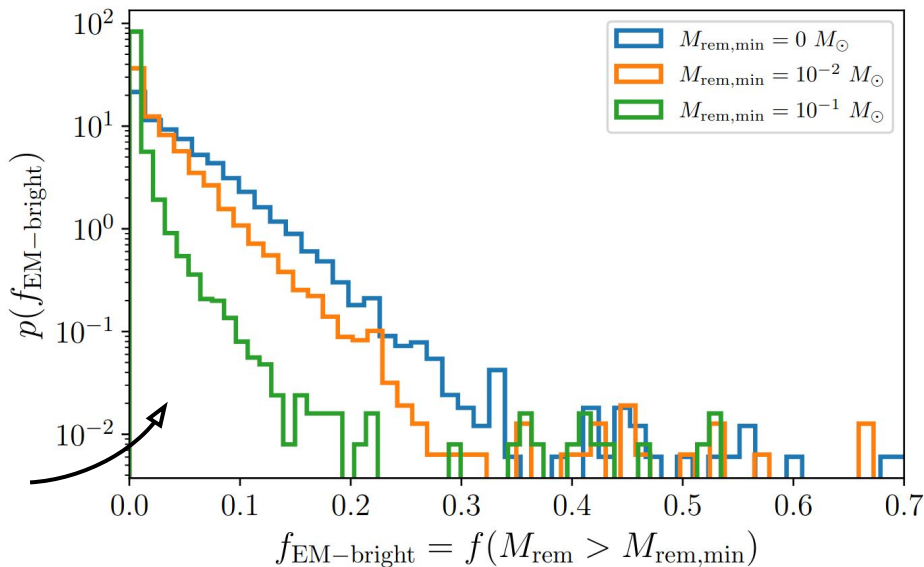
Many collaborators inside and outside the LIGO-Virgo-KAGRA collaboration are acknowledged, especially Hsin-Yu Chen (UT Austin), Jocelyn Read (CSUF) and Daniel Siegel (U Greifswald).

NSBH mergers as r-process sites

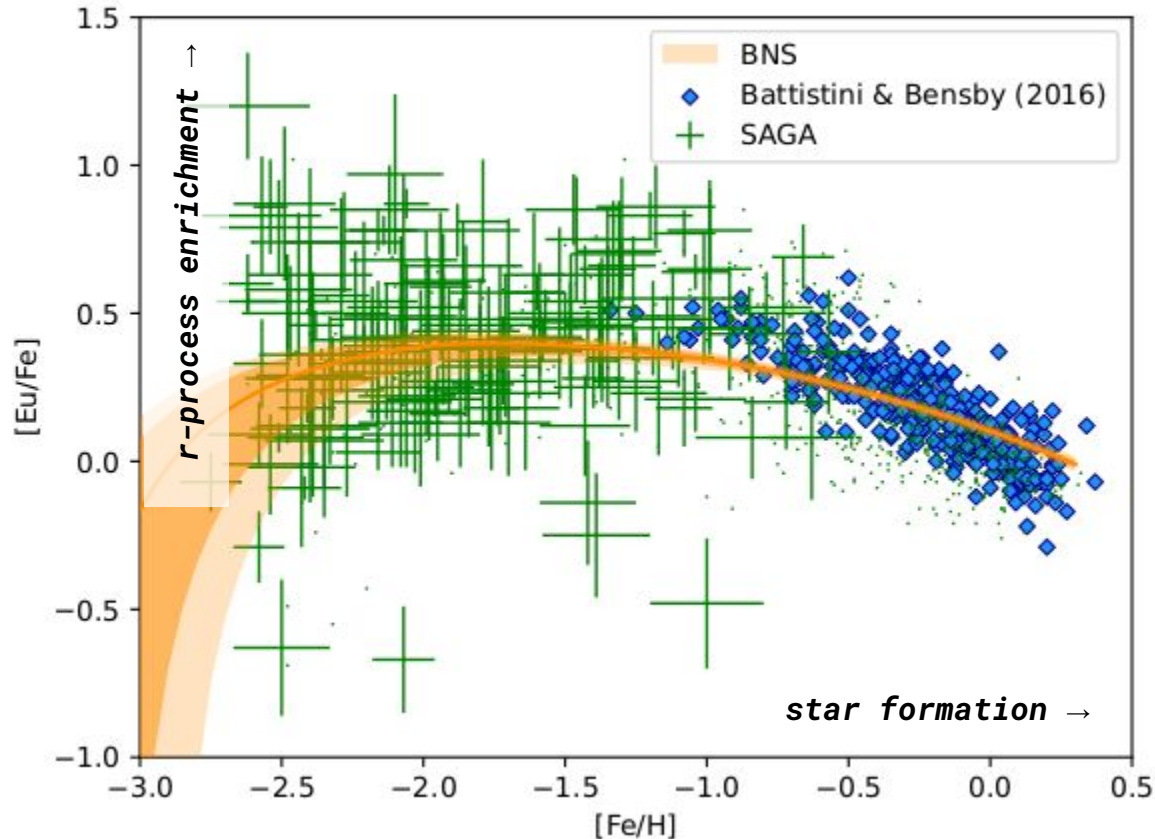


90% credible bound on fraction of NSBH population with any ejecta is $\sim 10\%$ in Biscoveanu+PL+Vitale arXiv:2207.01568

do NSBH mergers contribute significantly to r-process nucleosynthesis?



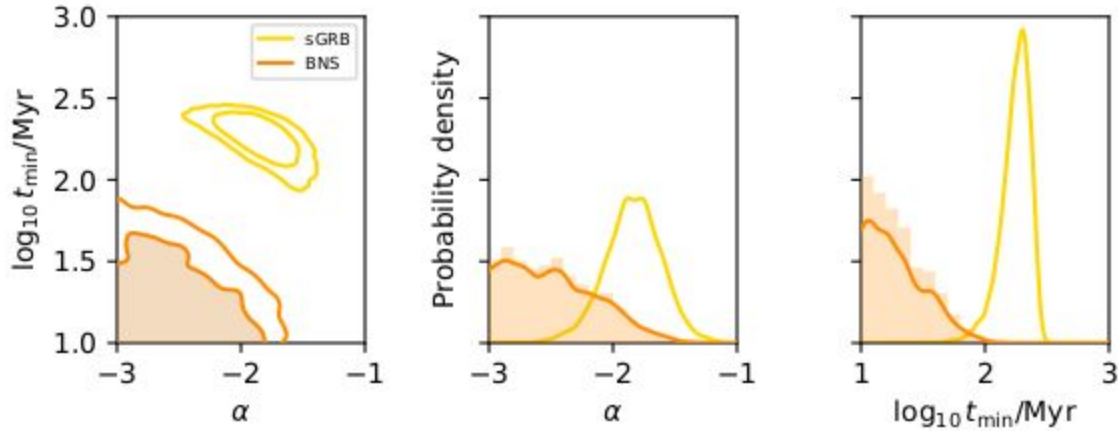
BNS mergers with short delay times



what delay time distribution is needed to match metal-poor star observations with BNS mergers alone?

Chen+PL+Read+Siegel
arXiv:2402.03696

BNS mergers with short delay times



preferred delay times are too short for standard (isolated) BNS formation scenario... but maybe birth kicks are the answer?

Beniamini+Piran arXiv:2312.02269

standard theory of DNS formation from Tauris+ ApJ 2017

