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A prompt channel for binary neutron star mergers

Evidence from galactic binaries and implications for r-process sources

Maoz & Nakar 2025

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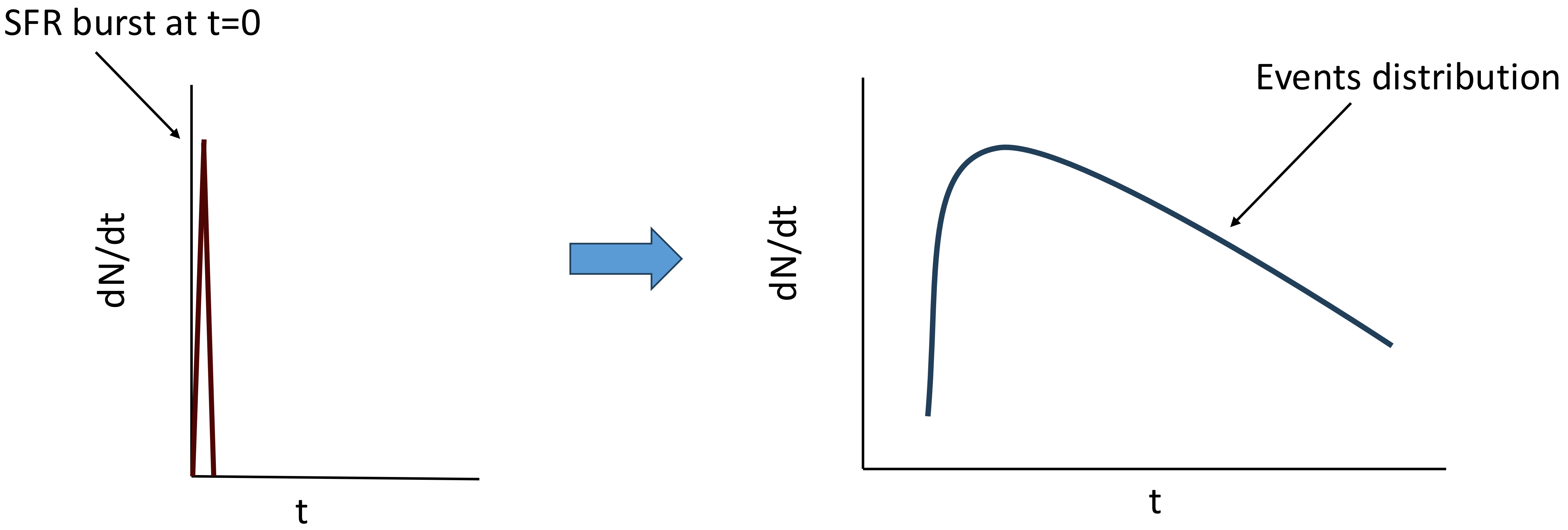
Delay time distribution (DTD): probability distribution of times between the formation of a system and the occurrence of a specific event.



DTD :Time distribution of the events (e.g., mergers) following a formation burst

Why do we care about the DTD of binary neutron star (BNS) mergers?

- The DTD may teach us about the formation channel(s)
- The DTD (together with the kick velocity) determines the merger environment
- The DTD plays a major role in the effect of BNS mergers on the chemical evolution history of r-process elements

Outline

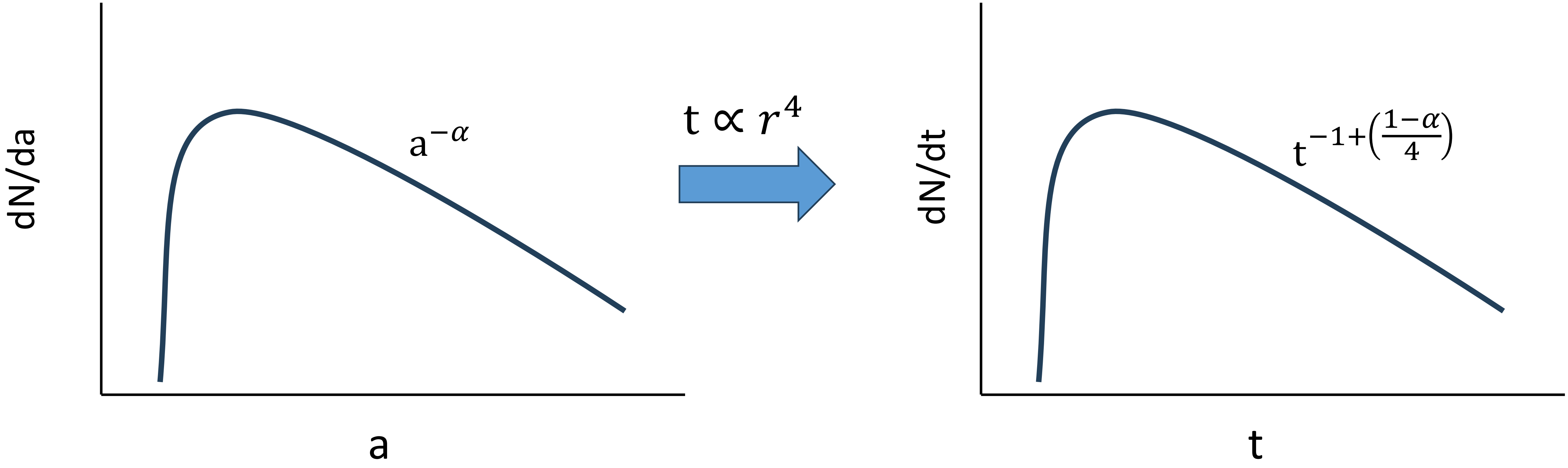
- The expected DTD of BNS mergers
- DTD and the Galactic chemical evolution
- BNS merger DTD from observed Galactic BNS systems

The expected DTD of BNS mergers

The expected DTD of BNS mergers

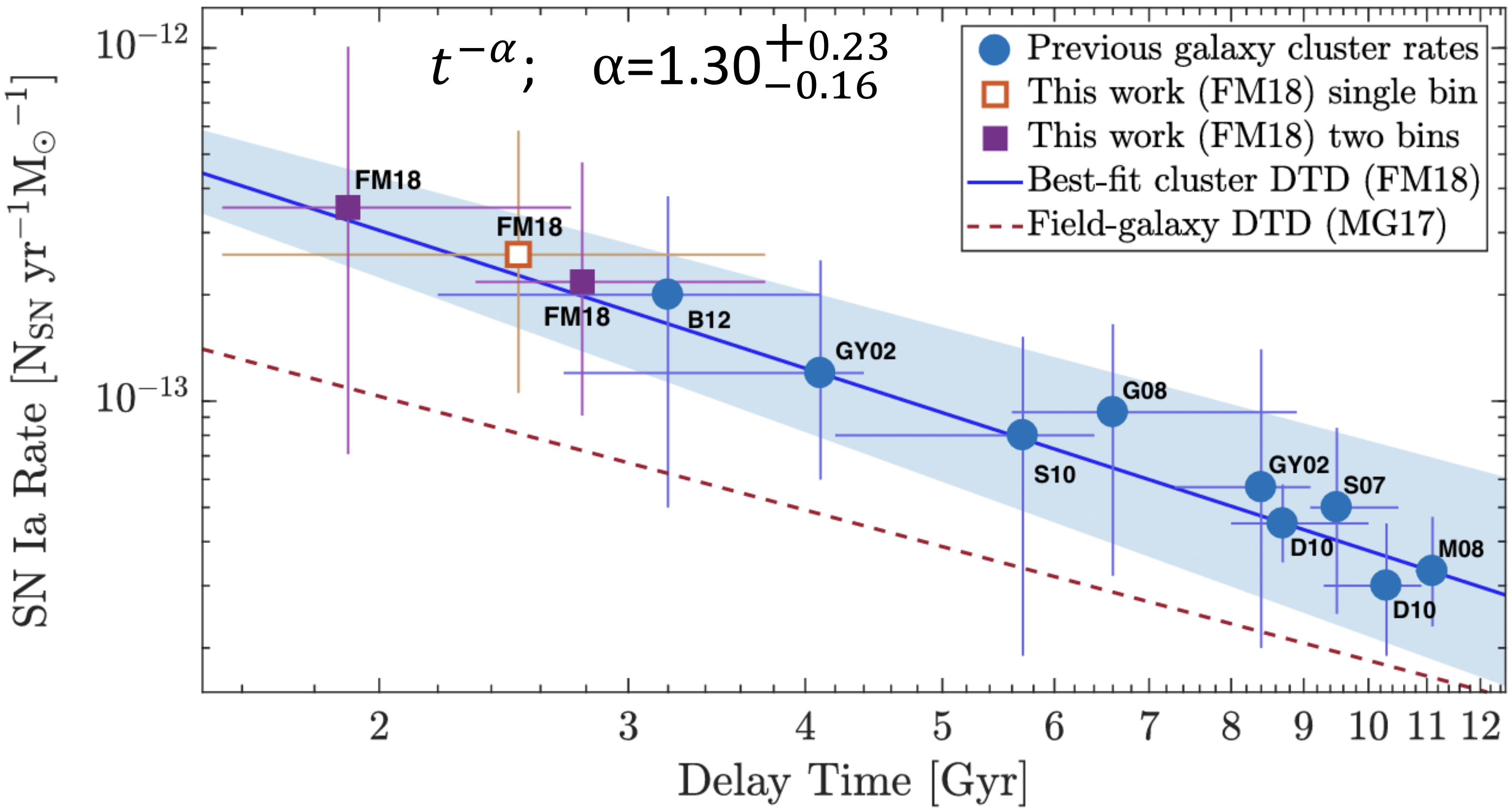
Binary separation distribution upon formation

merger DTD



The expectation is roughly **DTD** $\propto \boldsymbol{t^{-1}}$

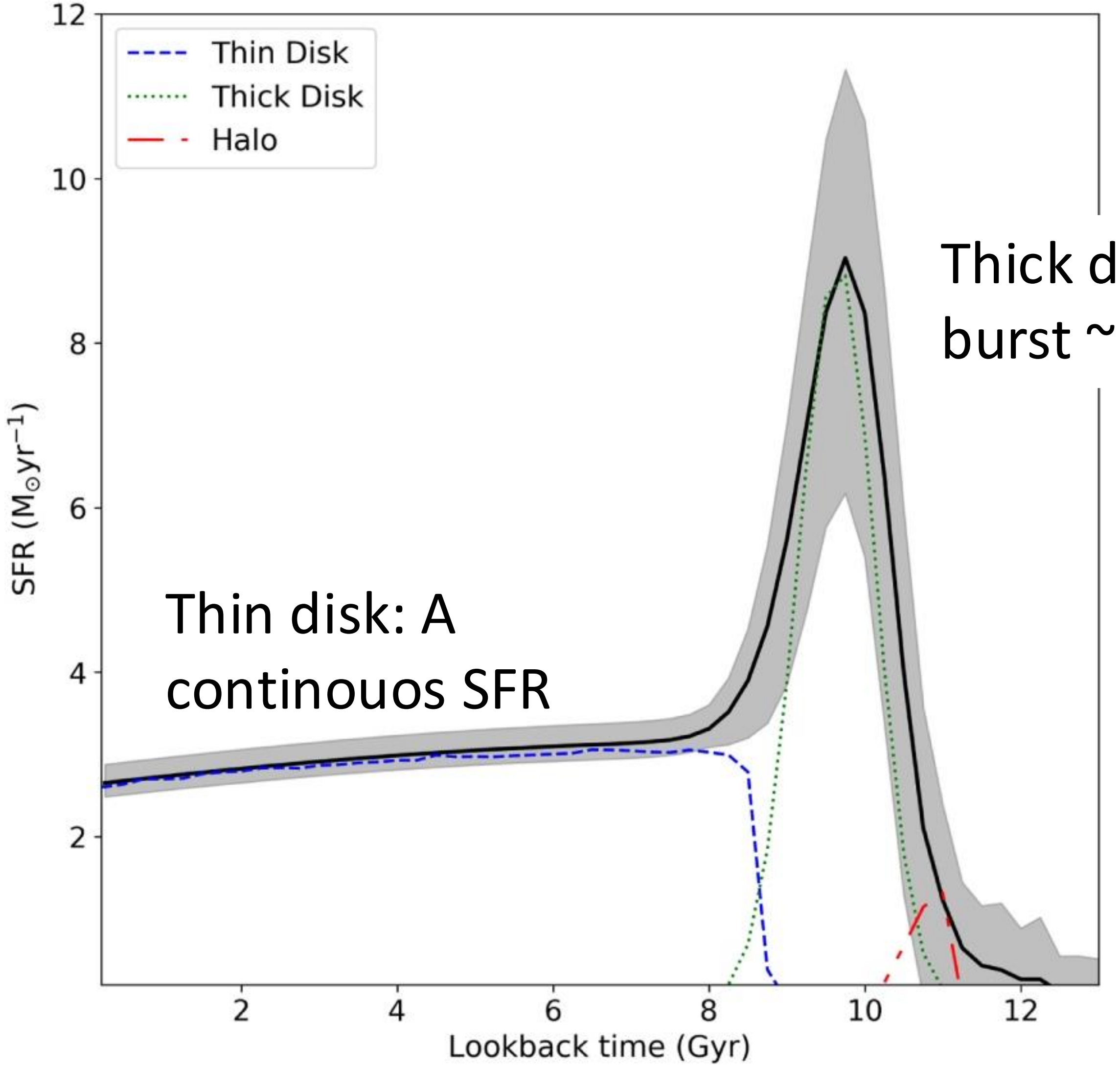
An example: type Ia SNe



Friedmann & Maoz 2018

DTD and the Galactic chemical evolution

The Milkey Way star formation history



Thin disk: A continouos SFR

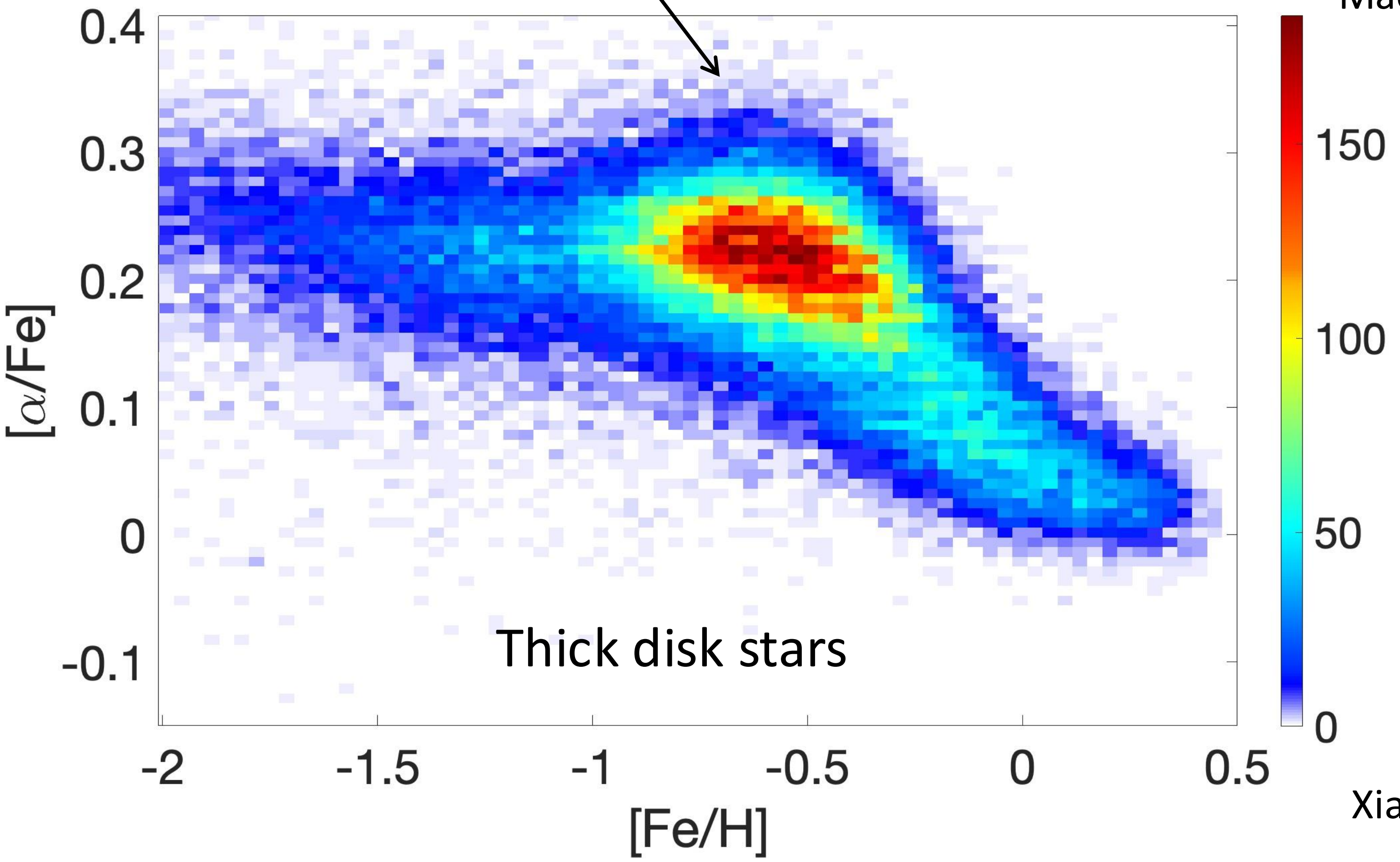
Thick disk: An SFR burst ~10Gyr ago

Fantin et al 2019

Galactic chemical evolution of α elements

A knee – the end of CCSNe or the ~~beginning of Ia SNe~~

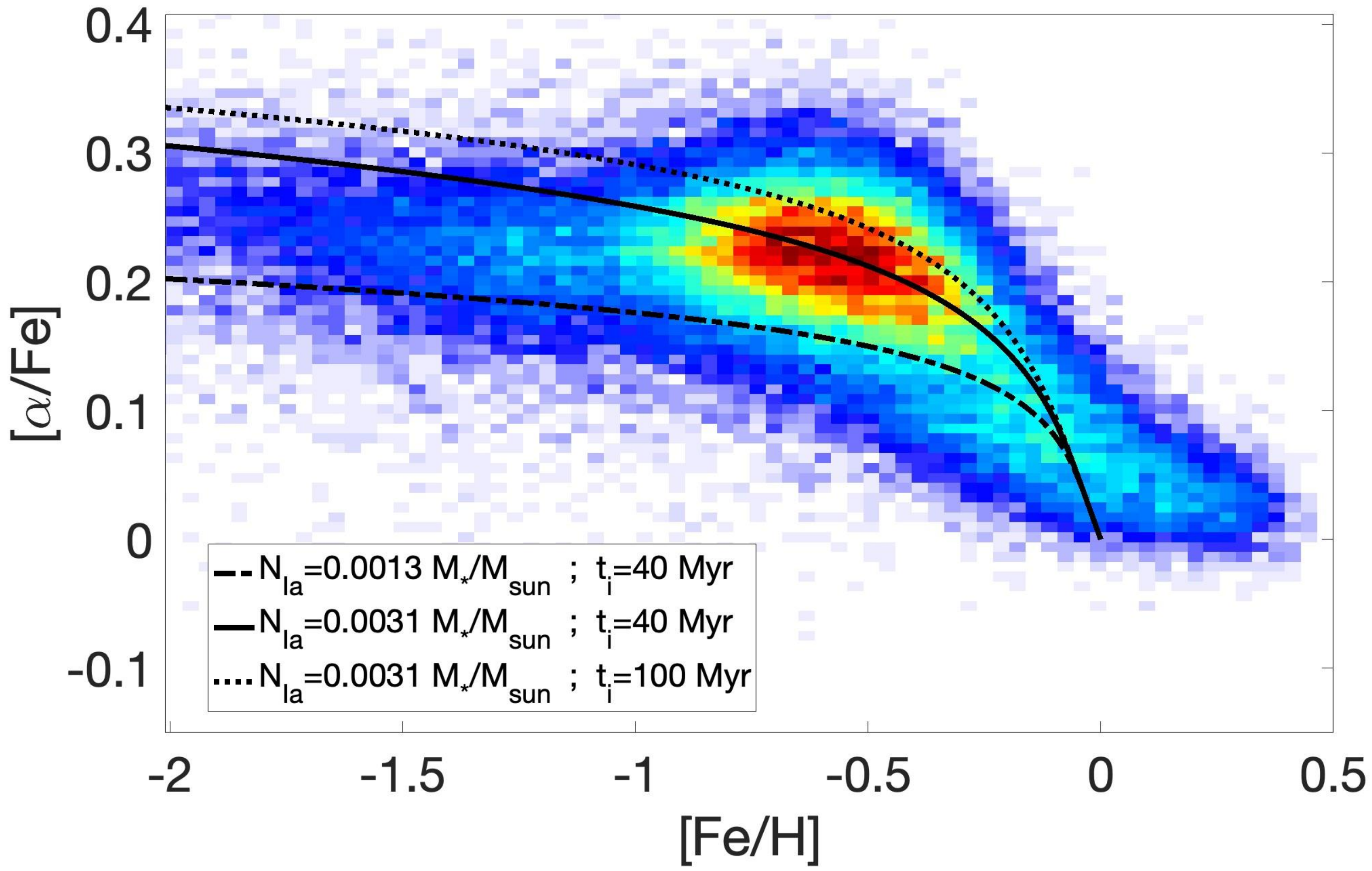
Maoz & Graur 2017



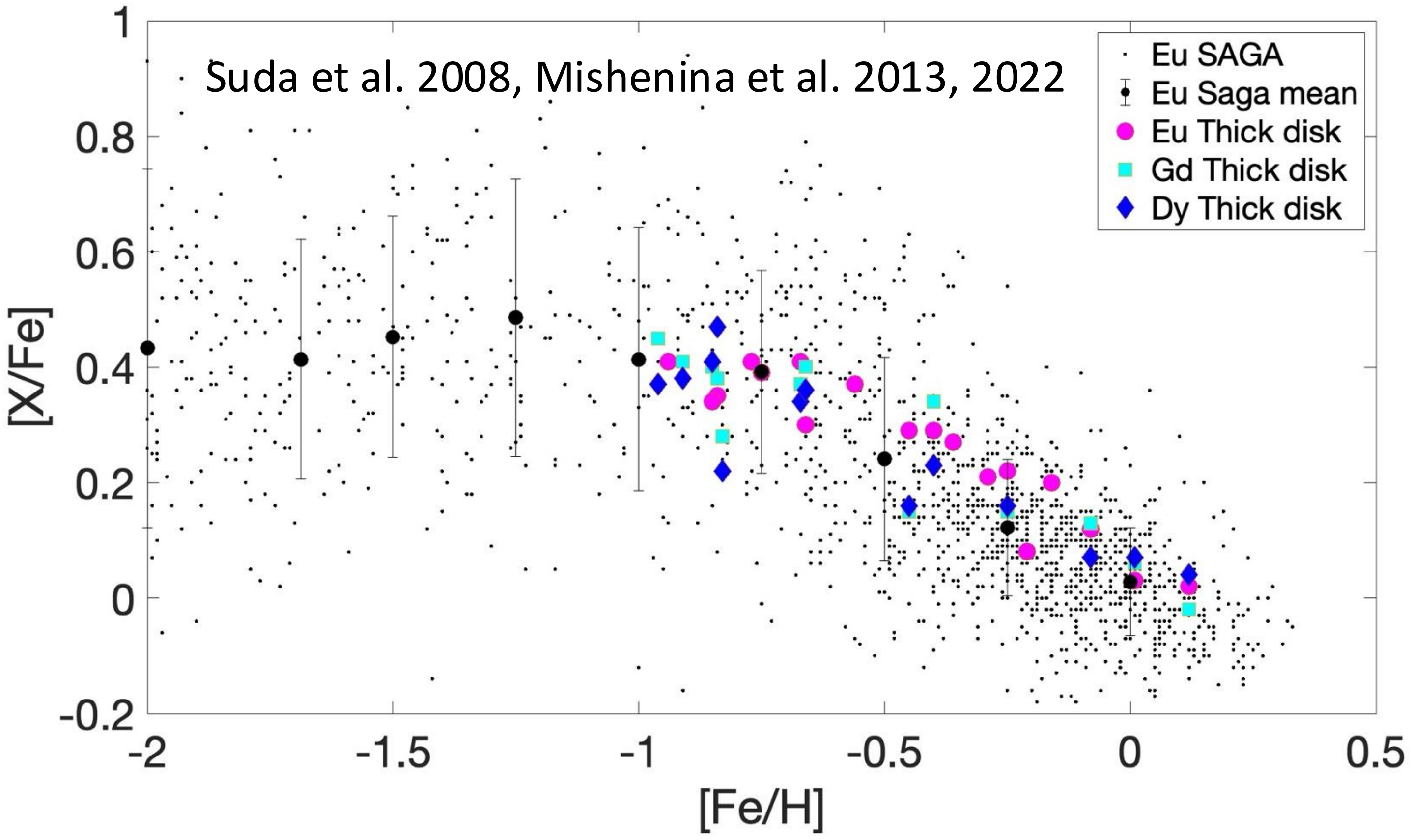
Xiang & Rix 2022

Galactic chemical evolution of α elements

The prediction of a homogenous close-box model with (almost) no free-parameters



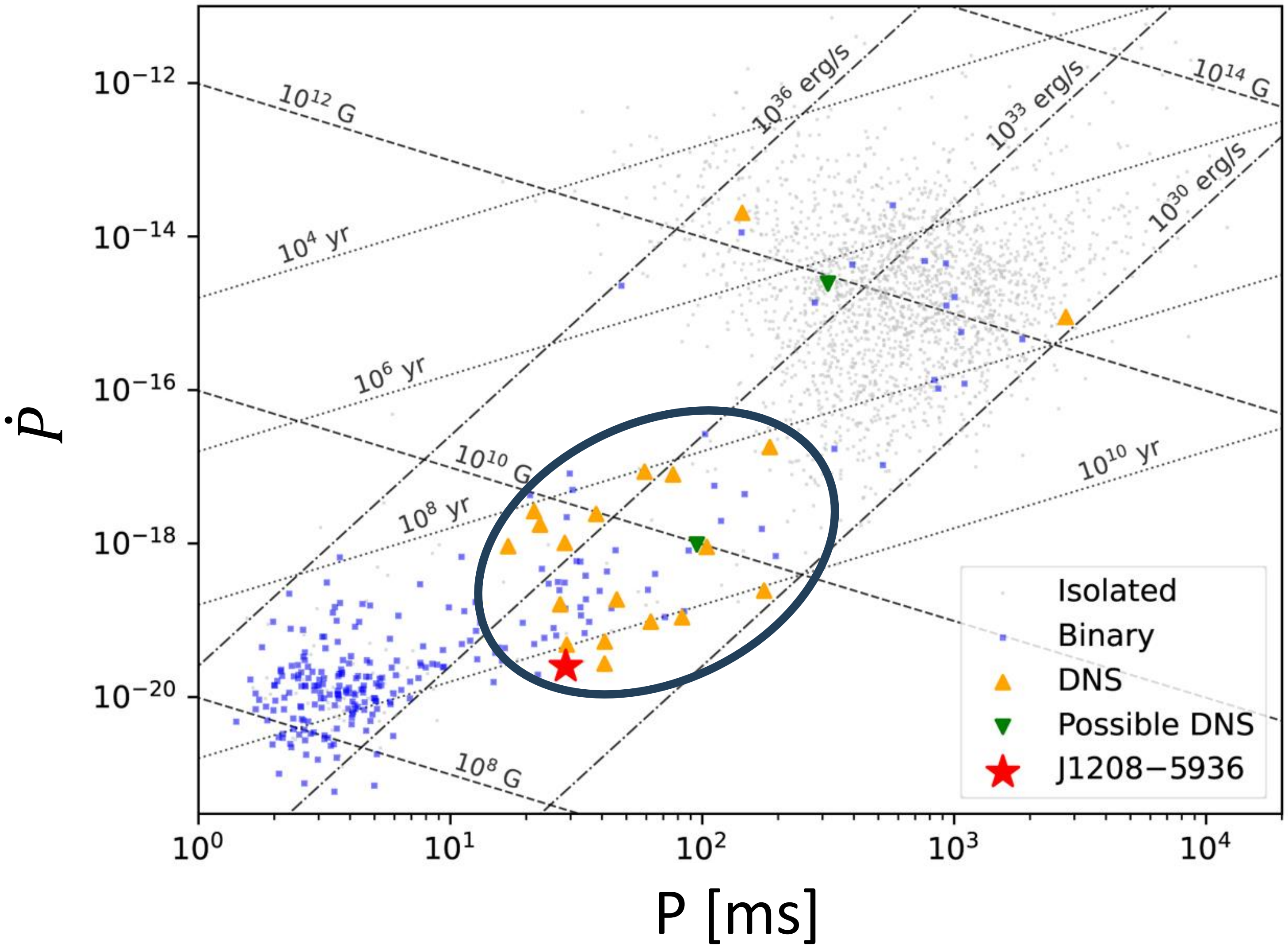
Galactic chemical evolution of r-process elements



Suggests a dominant r-process source that follows the SFR, similar to CCSNe (e.g., Hotokezaka et al 2018, and many others)

The main argument against BNS mergers as the dominant r-process sources

BNS merger DTD from observed Galactic BNS systems



Colom i Bernadich, et al., 2023

Almost all known Galactic BNS has a partially recycled pulsar

DNS	P_{orb} (days)	e	τ_{gw} (Gyr)	P_{spin} (ms)	$\dot{P}_{spin}$ (10^{-18})	τ_c (Gyr)
J1946+2052	0.078	0.064	0.045	17.0	0.9	0.30
J1757−1854	0.184	0.606	0.076	21.5	2.6	0.13
J0737−3039	0.102	0.088	0.086	22.7	1.8	0.20
B1913+16	0.323	0.617	0.30	59.0	8.6	0.11
J1913+1102	0.206	0.090	0.47	27.3	0.16	2.70
J0509+3801	0.380	0.586	0.58	76.5	7.9	0.15
J1756−2251	0.320	0.181	1.7	28.5	1.0	0.44
B1534+12	0.421	0.274	2.7	37.9	2.4	0.25
J1208−5936	0.632	0.348	7.2	28.7	< 0.04	> 11.2
J1829+2456	1.176	0.139	55	41.0	0.053	12.3
J1759+5036	2.043	0.308	177	176.0	0.243	11.5
J1325−6253	1.816	0.064	189	29.0	0.048	11.3
J1411−2551	2.616	0.170	466	62.5	0.096	10.3
J0453+1559	4.072	0.113	1450	45.8	0.19	3.90
J1811−1736	18.779	0.828	1800	104.2	0.90	1.83
J1518+4904	8.634	0.249	8840	40.9	0.027	23.8
J1018−1523	8.984	0.228	10^4	83.152	0.11	12.0
J1930−1852	45.060	0.399	5×10^5	185.5	18.0	0.16

Two time scales:

Characteristic age: $\tau_c = \frac{P}{2\dot{P}}$

Time since formation; Unclear accuracy

Gravitational Wave lifetime: τ_{GW}

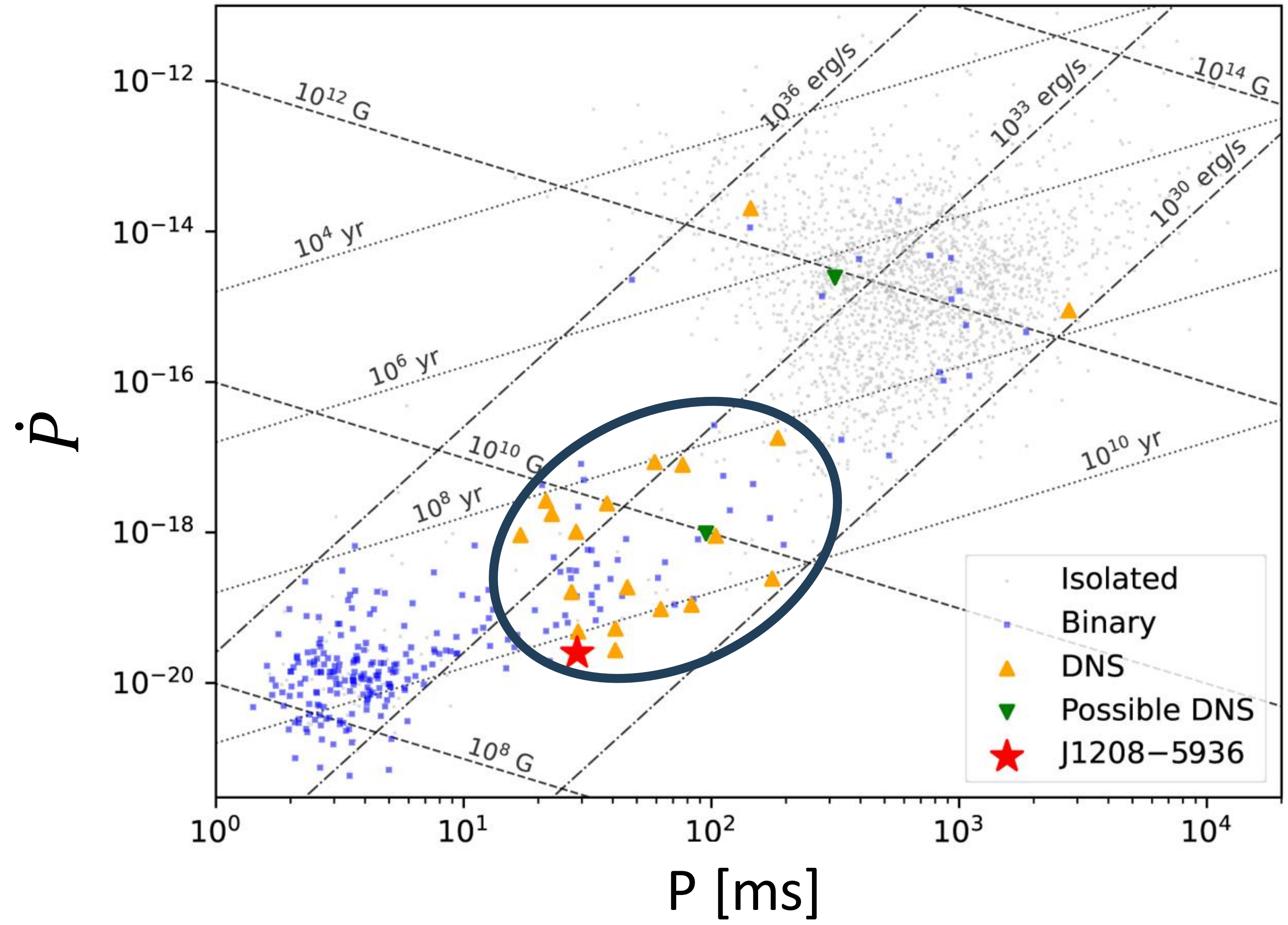
Time till merger; Highly accurate

If there are no selection effects, each of the observed time distributions τ_c (if accurate enough) and τ_{GW}, provides an independendent measurment of the DTD

Possible types of selection effects and systematics:

- systematic inaccuracy in τ_c
- limited pulsar lifetime (without the pulsar the BNS is undetectable)
- A correlation between τ_c and τ_{GW} and the probability for BNS detection – known selection effects prevent detection of binaries with very short period ($\tau_{GW} \lesssim 50 Myr$)

Characteristic age distribution



Colom i Bernadich, et al., 2023

Two samples

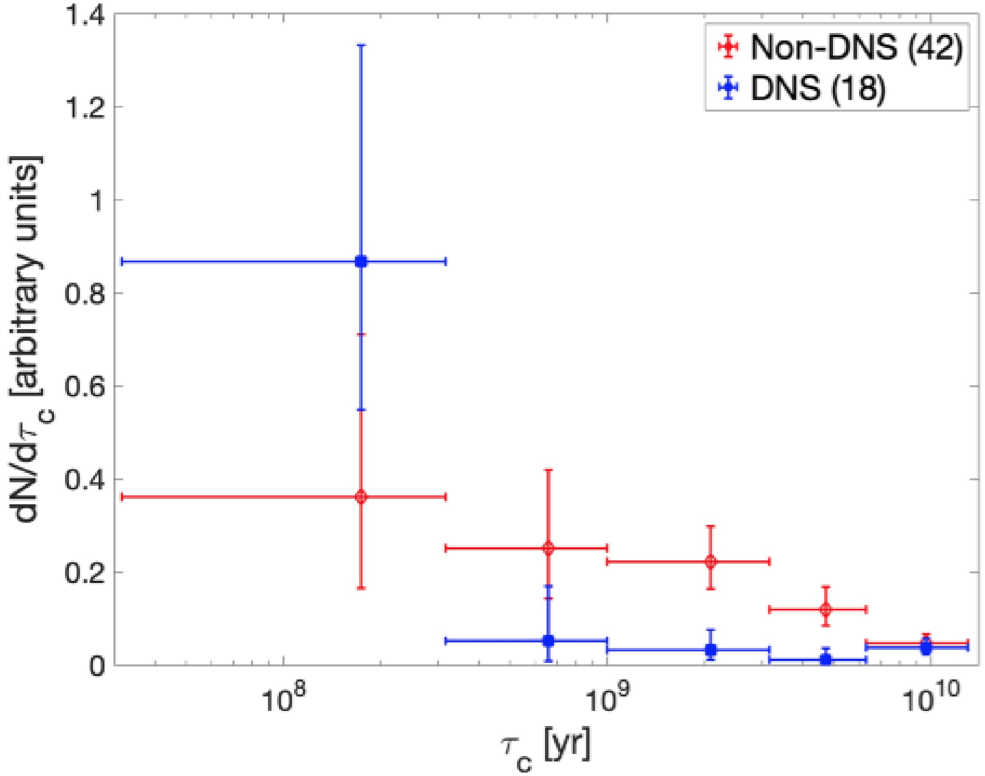
1. BNS with partialy recycled pulsars
2. NS-No Ns binaries at the same region of the $P\dot{P}$ diagram (a control sample)

Characteristic age distribution

A Uniform SFR starting at t_0=10Gyr ago

Non-BNS: No merger within Hubble time → $\frac{dN}{d\tau_c} = const$ if $\tau_c < 10Gyr$, otherwise 0

BNS: $DTD \propto t^{-\alpha}$ → $\frac{dN}{d\tau_c} \propto \tau_c^{-\alpha+1} - t_0^{-\alpha+1}$ if $\tau_c < 10Gyr$, otherwise 0



If BNS and Non-BNS partially recycled pulsars are not fundamentally different:

1. τ_c is a reasonable age estimator
2. No sign of limited pulsar lifetime
3. The access of young BNS systems (<300 Myr) is not a result of selection effects

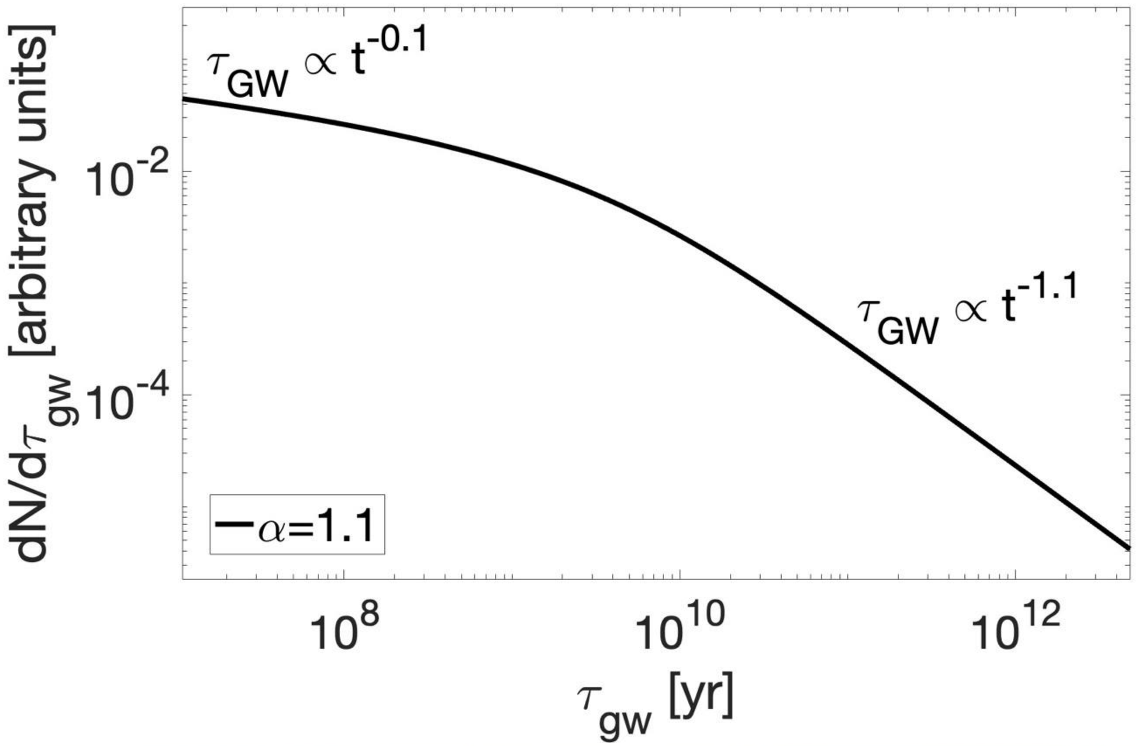
⇩

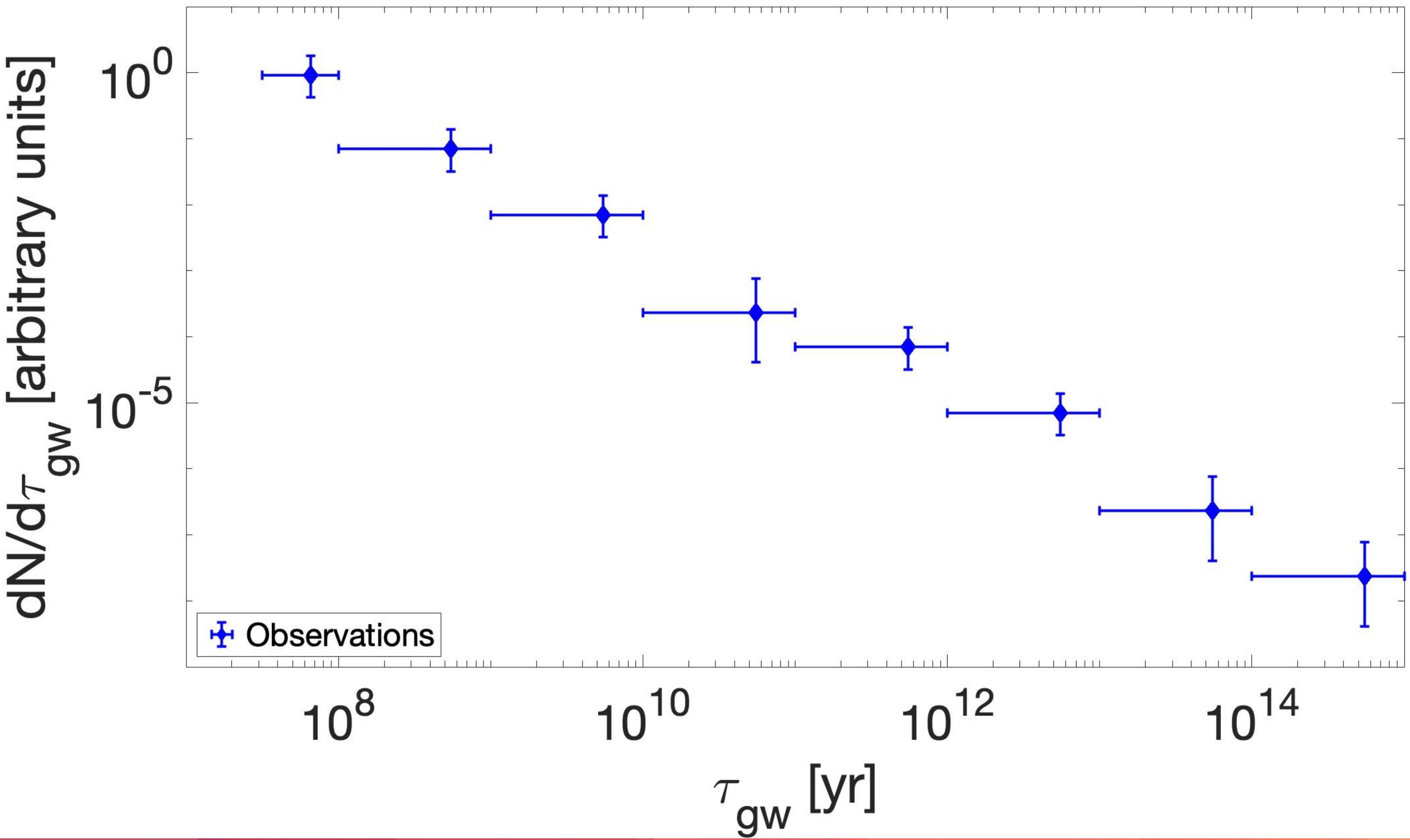
Suggests a significant population of <1 Gyr mergers

Gravitational wave lifetime (time till merger)

Uniform SFR starting at t_0=10Gyr ago + $DTD \propto t^{-\alpha}$

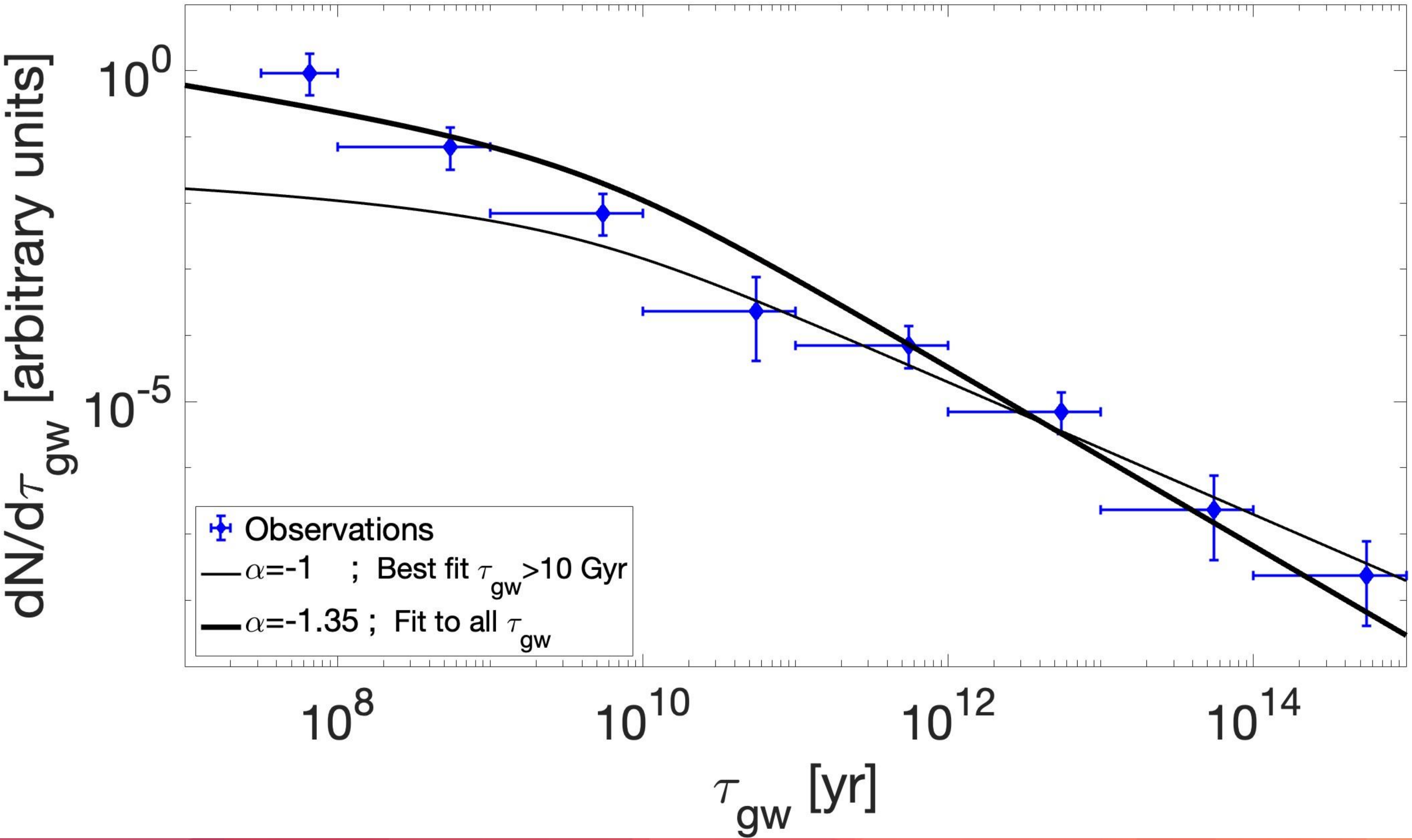
$$\frac{dN}{d\tau_{GW}} \propto \tau_{GW}^{-\alpha+1} - (\tau_{GW} + t_0)^{-\alpha+1} \propto \begin{cases} \tau_{GW}^{-\alpha+1} & ; \tau_{GW} \ll t_0 \\ \tau_{GW}^{-\alpha} & ; \tau_{GW} \gg t_0 \end{cases}$$



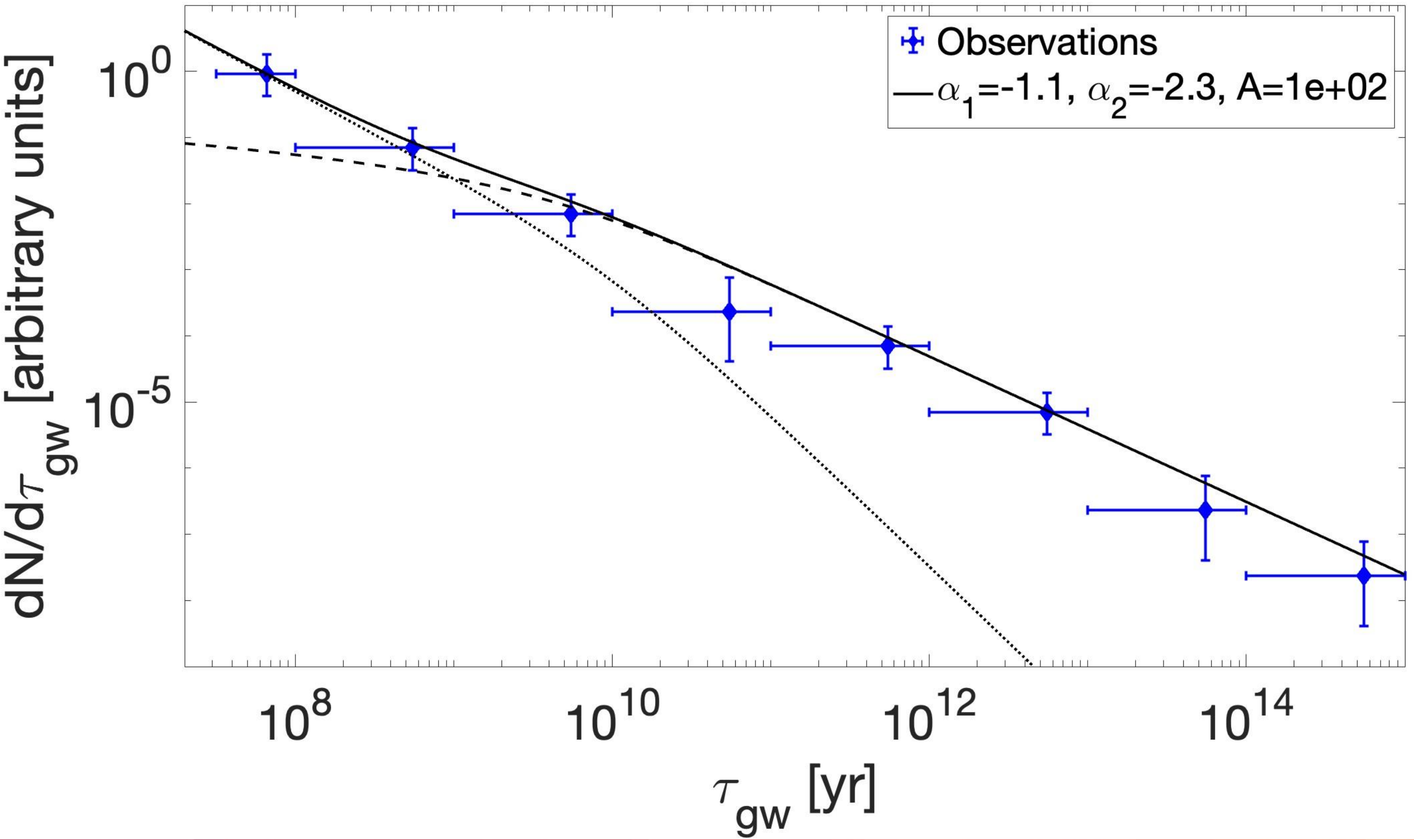


dN/dτgw [arbitrary units]
10^0
10^-5
10^8
10^10
10^12
10^14
τgw [yr]
Observations

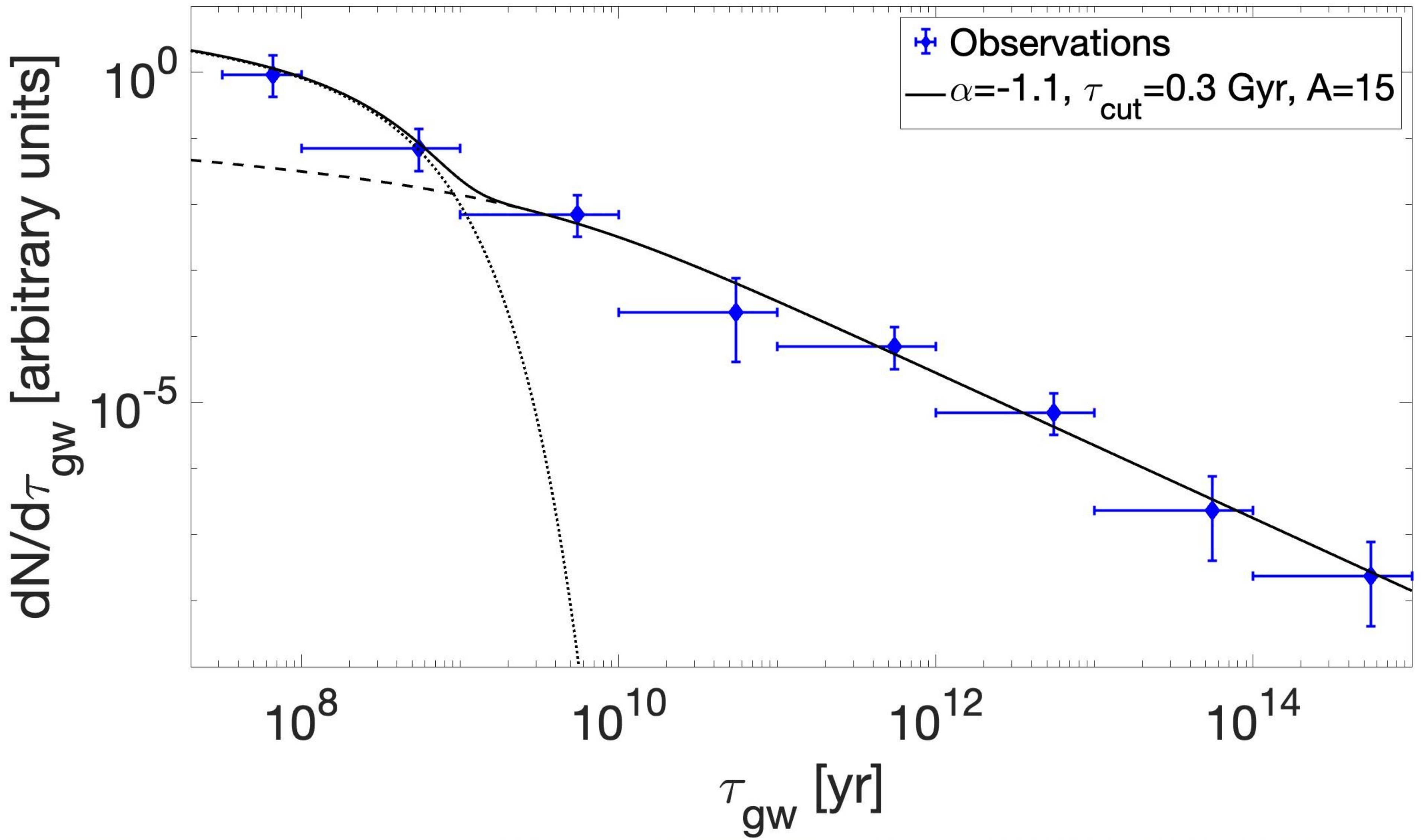
A single power-law



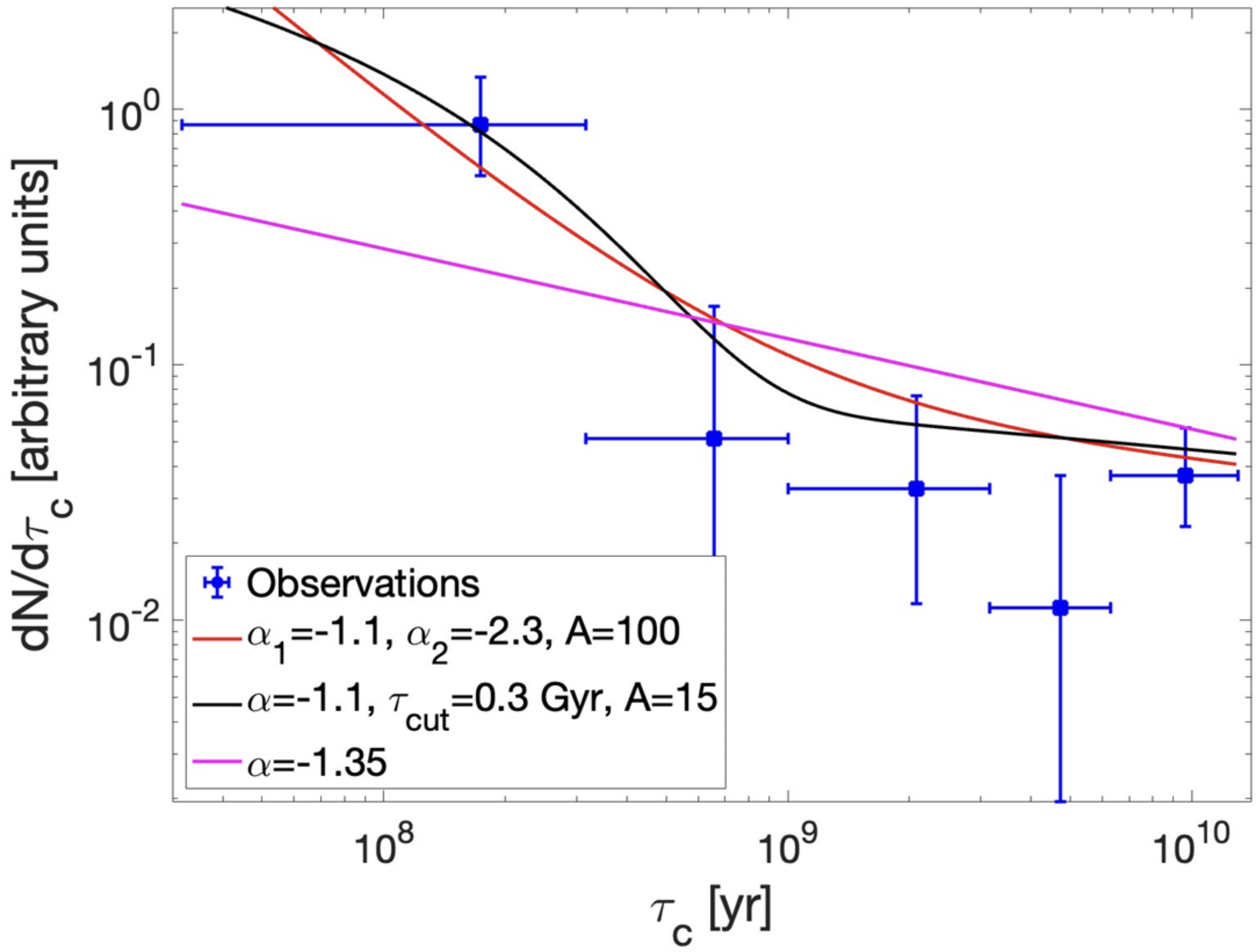
2 power-laws


Observations
α_1=-1.1, α_2=-2.3, A=1e+02
10^0
10^{-5}
10^8
10^{10}
10^{12}
10^{14}
$dN/d\tau_{gw}$ [arbitrary units]
τ_{gw} [yr]

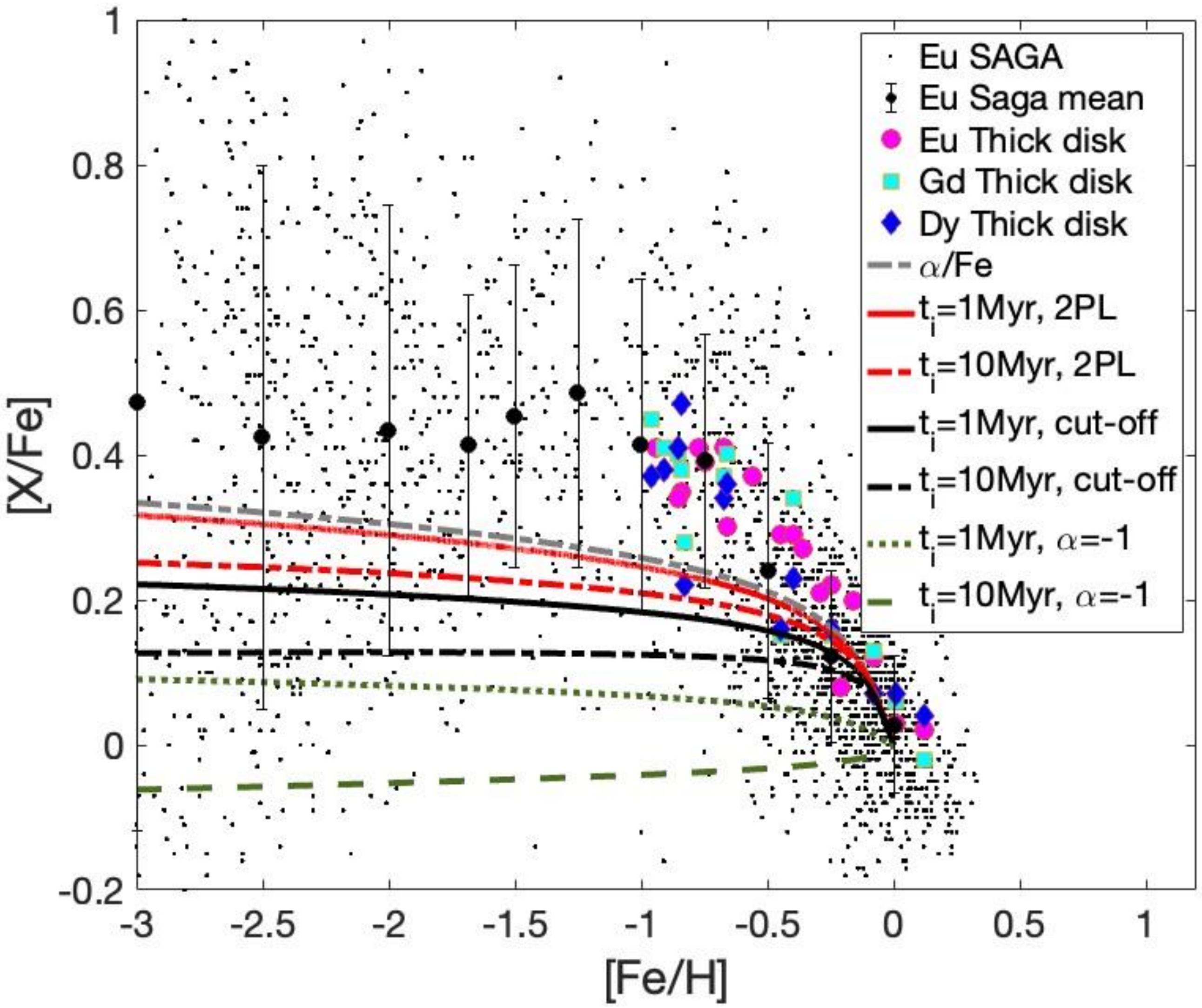
power-law + exponential cut-off



Characteristic age distribution



Implications for chemical evolution of r-process elements



Conclusion

- Two different time scales of the observed Galactic BNS point at a dominant short-lived BNS population and a sub-dominant population with: $DTD \propto t^{-1}$

- In this picture, the total fraction of BNS systems a lifetimetime < 1Gyr is larger than 90%.

- If there is such a populationtion of prompt mergers it may be the source of the observed chemichal evolution of r-process elements.