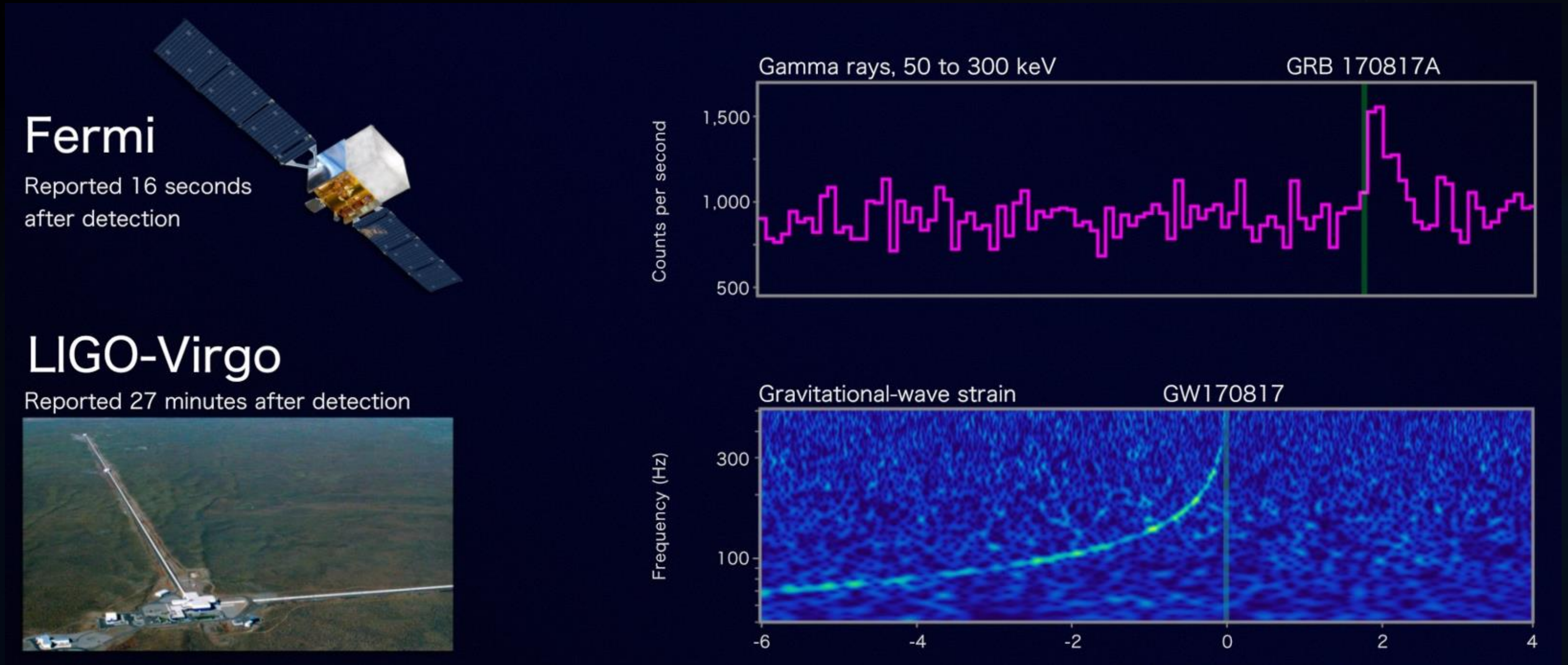
On the hosts of neutron star mergers in the nearby Universe

Lorenzo Cavallo

PhD student at University of Padova

9-13 January 2023 (Sexten)

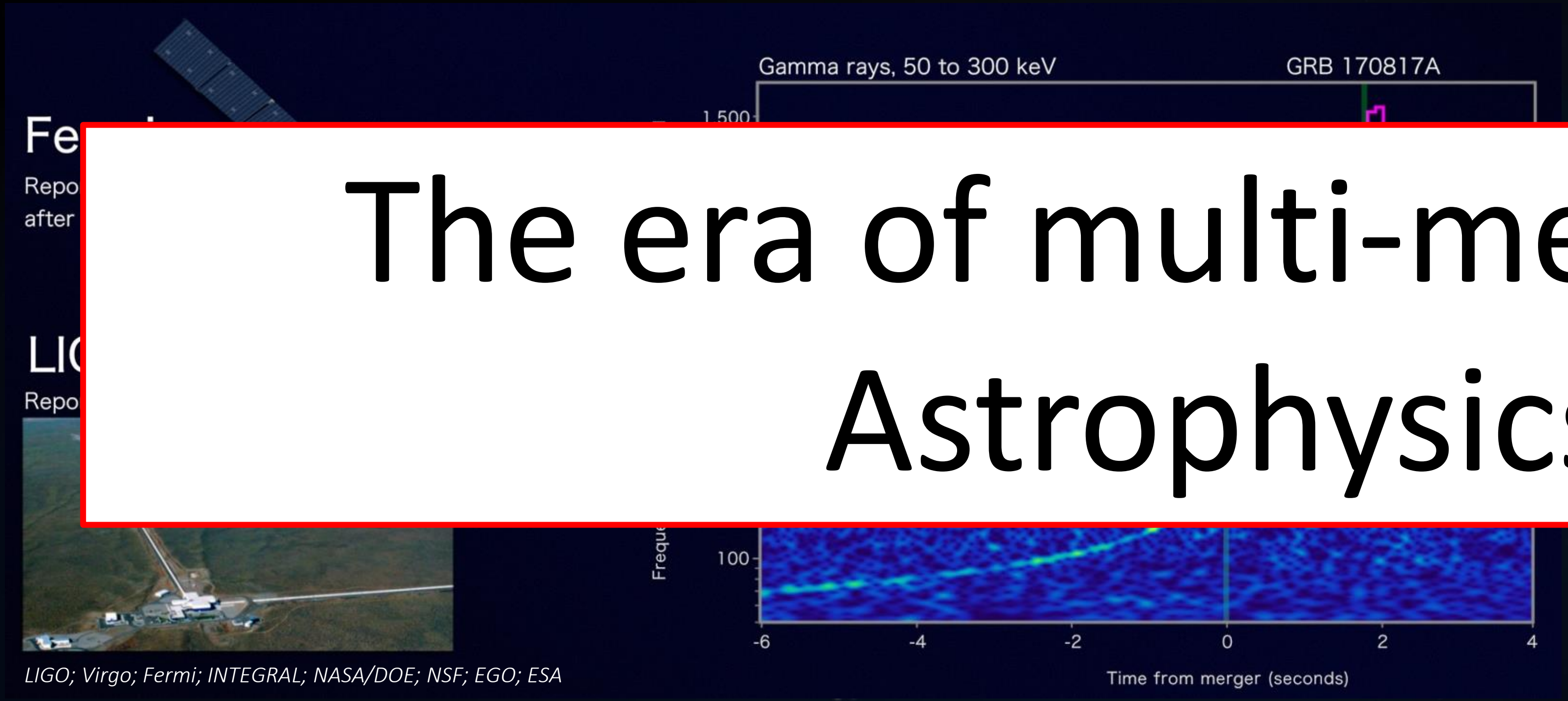
The dawn of a new era

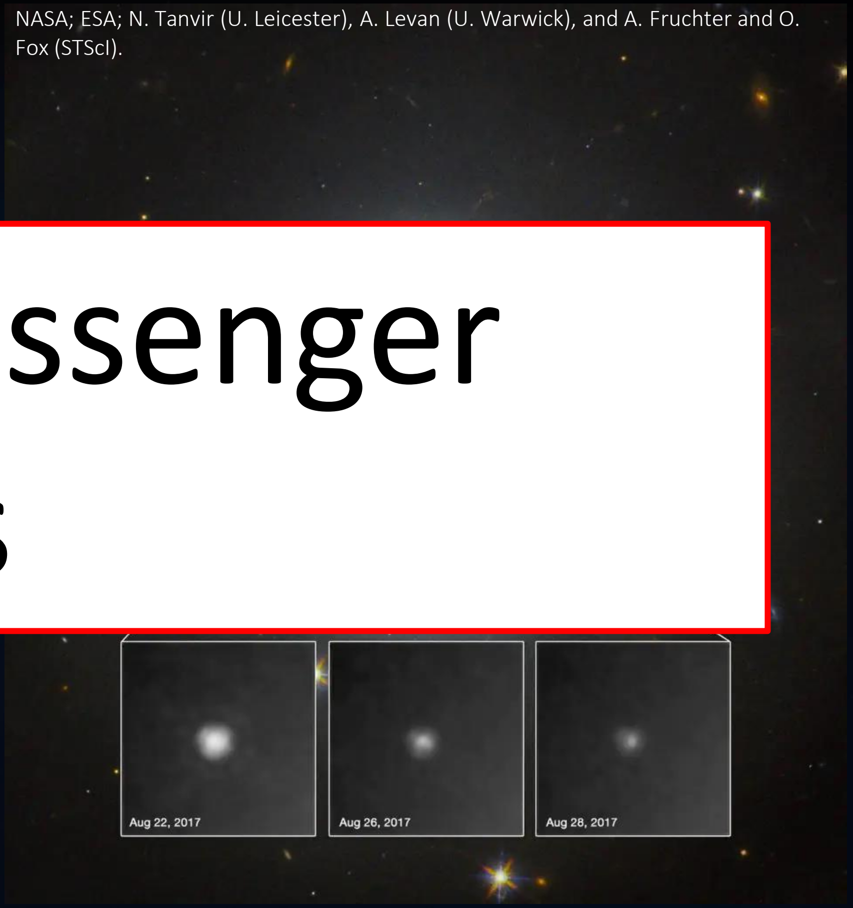


LIGO; Virgo; Fermi; INTEGRAL; NASA/DOE; NSF; EGO; ESA

NASA; ESA; N. Tanvir (U. Leicester), A. Levan (U. Warwick), and A. Fruchter and O. Fox (STScI).

The dawn of a new era





The era of multi-messenger Astrophysics

Gravitational Wave Transient Catalog 3 (GWTC-3)

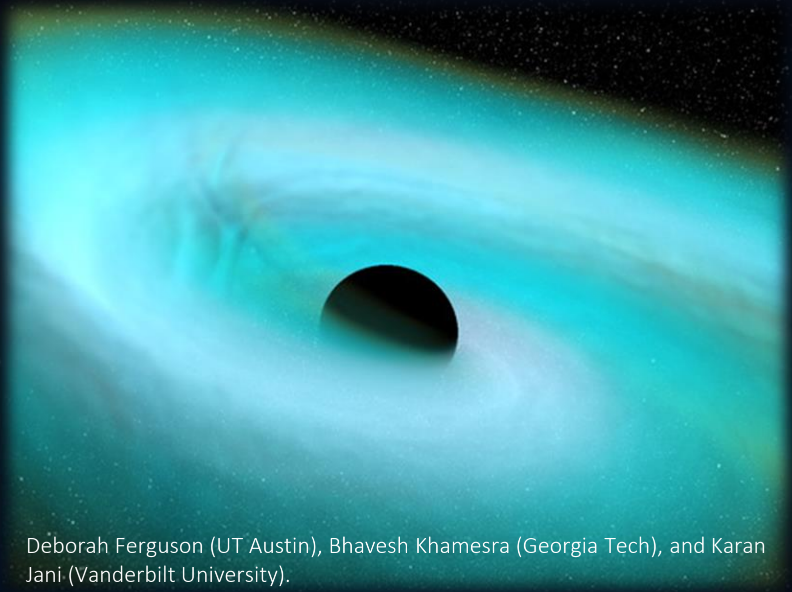
Abbott et al. (2021d), arXiv:2111.03606

Binary neutron star

University of Warwick/Mark Garlick

GW 170817
GW 190425

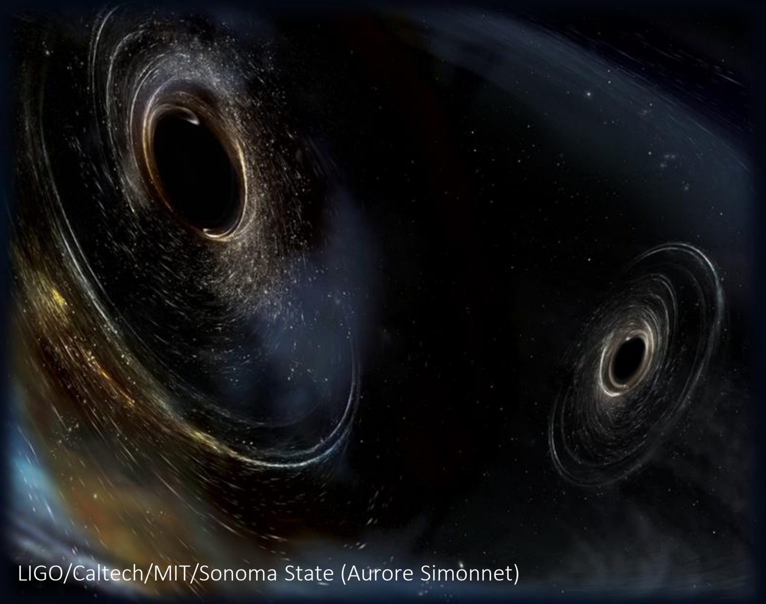
Neutron star–black hole



Deborah Ferguson (UT Austin), Bhavesh Khamesra (Georgia Tech), and Karan Jani (Vanderbilt University).

GW 200105
GW 200115

Binary black hole



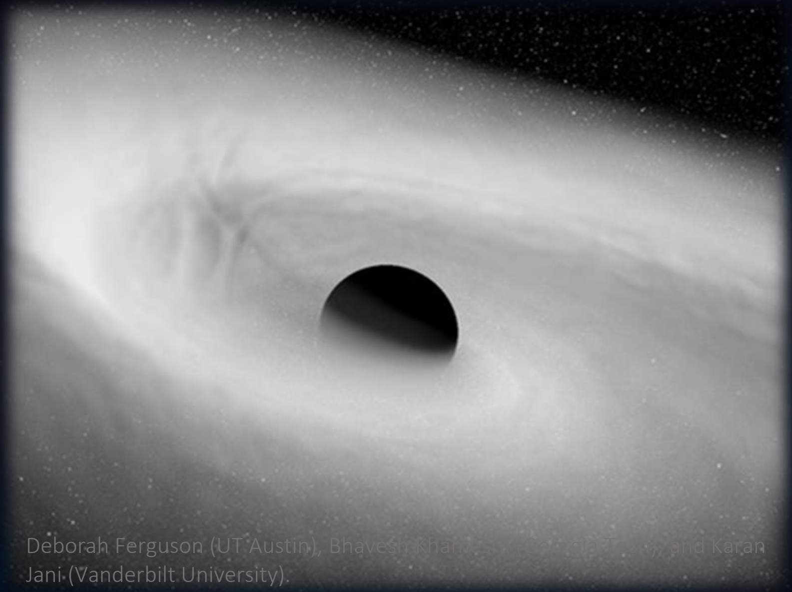
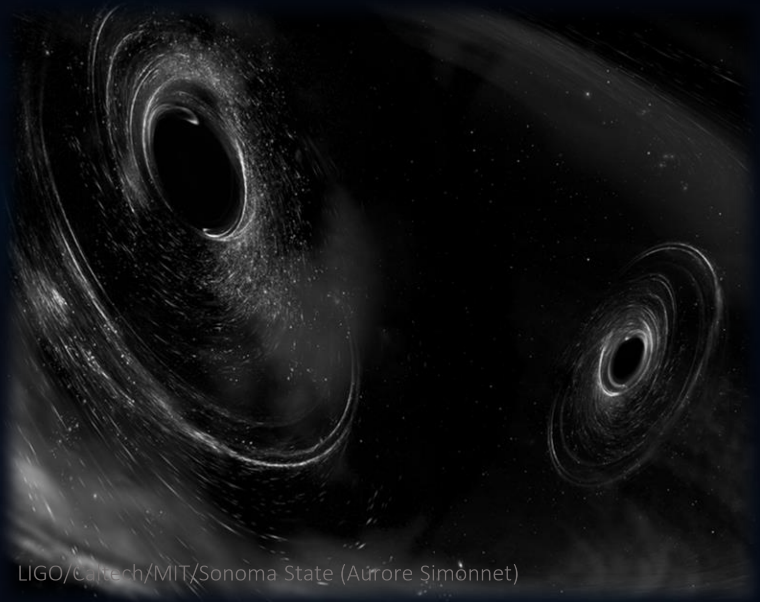
LIGO/Caltech/MIT/Sonoma State (Aurore Simonnet)

GW 150914
GW 151012
GW 151226
⋮
GW 200322

86 events

Gravitational Wave Transient Catalog 3 (GWTC-3)

Abbott et al. (2021d), arXiv:2111.03606

Binary neutron star	Neutron star–black hole	Binary black hole
		

GW 170817 GW 190425	GW 200105 GW 200115	GW 150914 GW 151012 GW 151226 ⋮ GW 200322 — 86 events

Lorenzo Cavallo — Sexten — 9-13 January 2023

Where does the r-process occur in the Universe?

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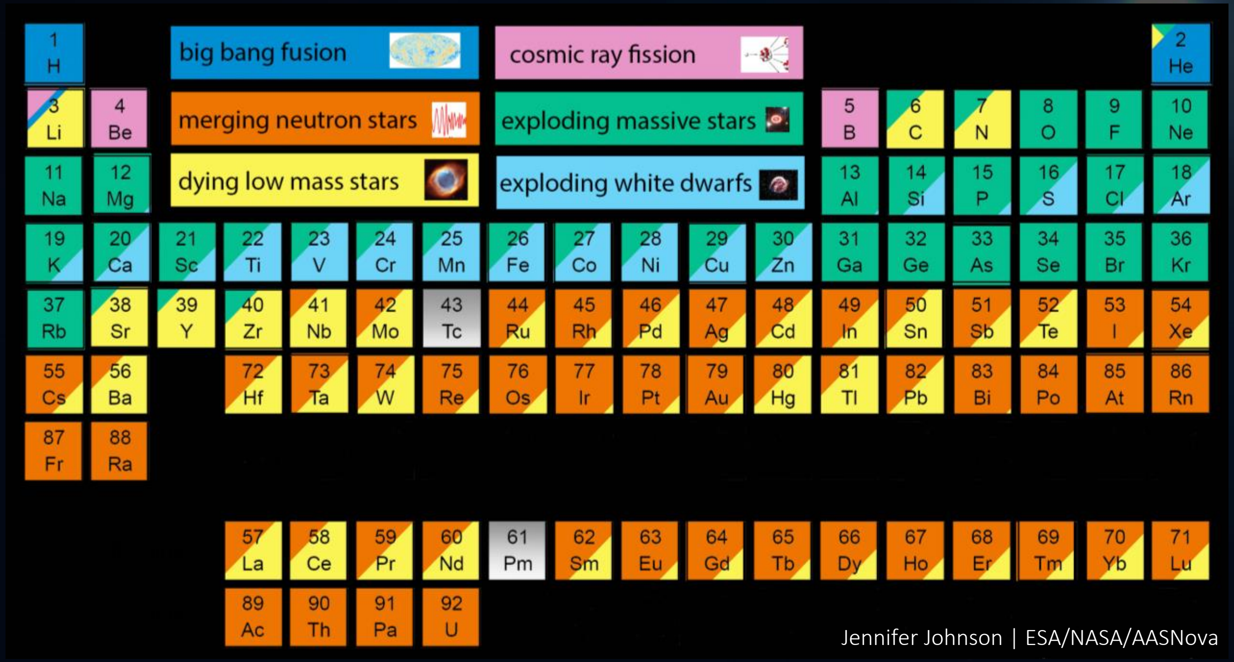
Neutron capture process

- Rapid-neutron capture process
- Slow-neutron capture process



Where does the r-process occur in the Universe?

Neutron capture process
- Rapid-neutron capture process
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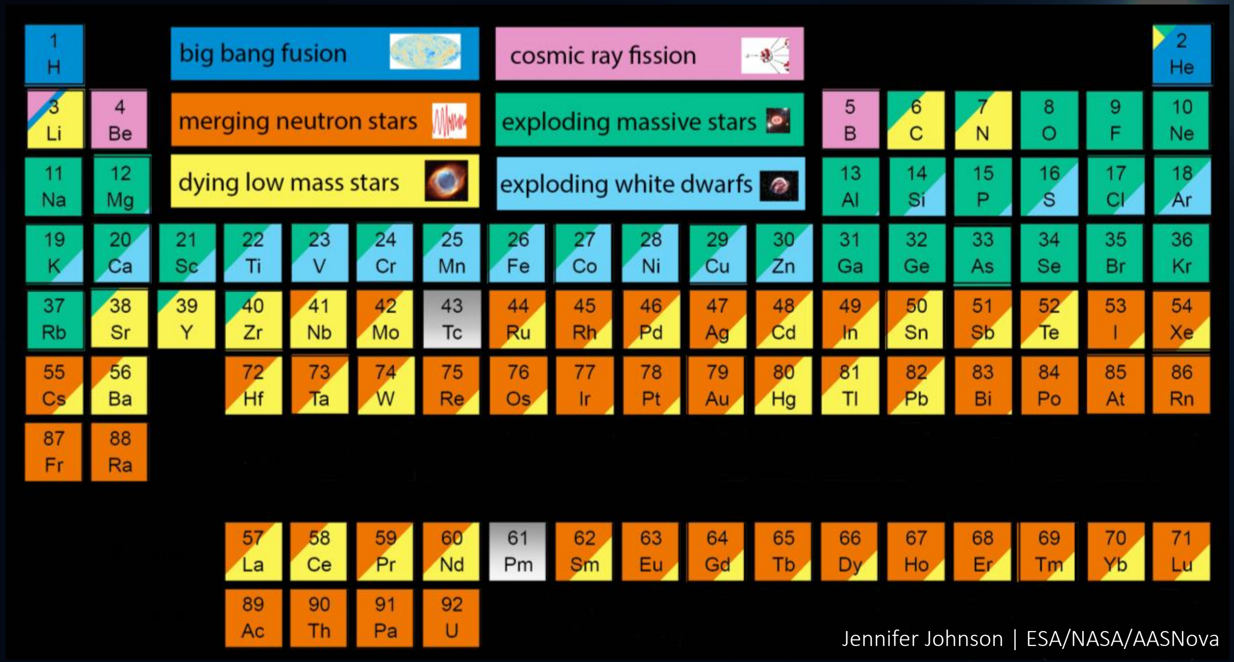
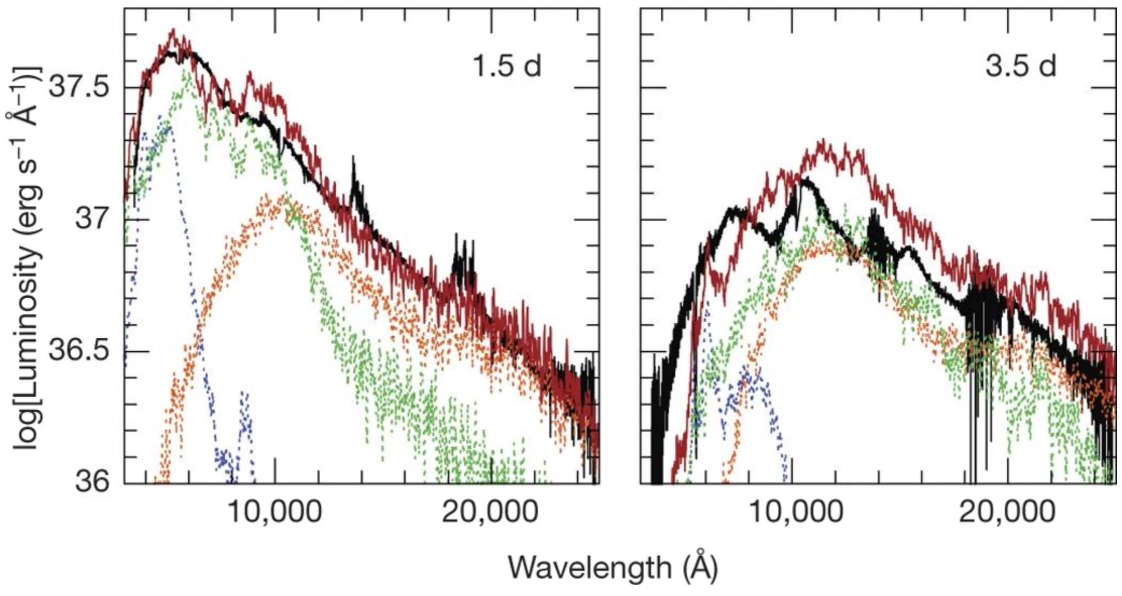


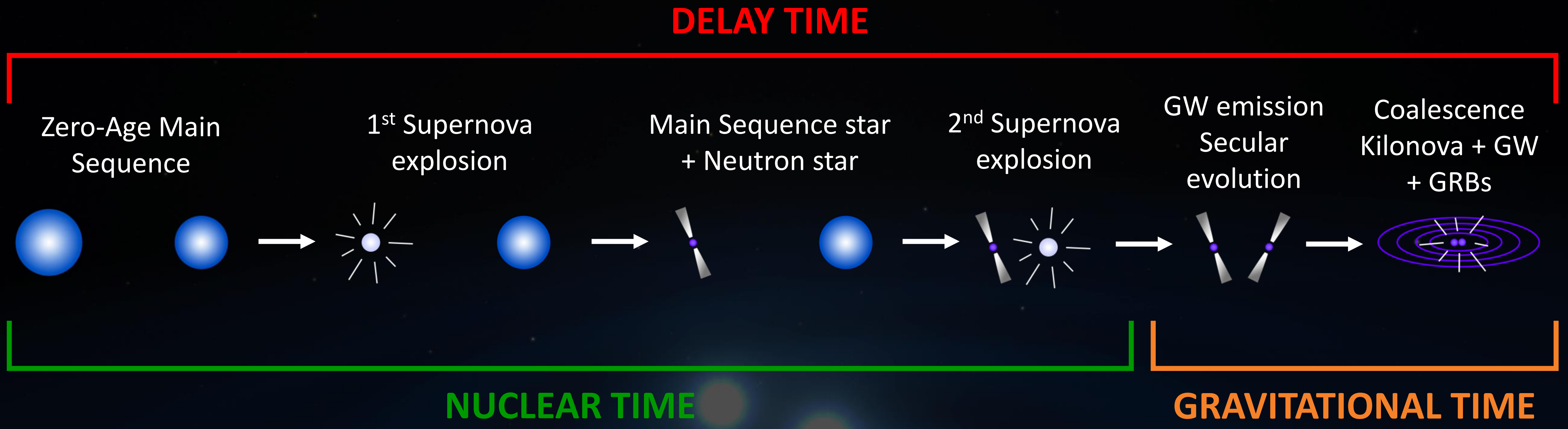
Pian, E., D'Avanzo, P., Benetti, S. *et al.*, *Nature* **551**, 67–70 (2017)



Kilonova evolution from blue to red has been generated by the presence of newly produced r-process elements

Pian, D'Avanzo et al. (2017)


DELAY TIME
Zero-Age Main Sequence
Coalescence
Kilonova + GW
+ GRBs


DELAY TIME
Zero-Age Main Sequence
1st Supernova explosion
Main Sequence star + Neutron star
2nd Supernova explosion
GW emission Secular evolution
Coalescence Kilonova + GW + GRBs
NUCLEAR TIME
GRAVITATIONAL TIME

DELAY TIME

Zero-Age Main Sequence | 1st Supernova explosion | Main Sequence star + Neutron star | 2nd Supernova explosion | GW emission Secular evolution | Coalescence Kilonova + GW + GRBs

NUCLEAR TIME

Depends on the assumption of the mass range of NS progenitors

GRAVITATIONAL TIME

Depends on the orbital parameters of the NS-NS system at formation

Separation, Total mass, and eccentricity

With this work we aim to investigate if the **demographic of SGRBs** can be used to constrain the main characteristics of the **delay time distribution** (DTD) of neutron star mergers (NSMs).

To do that we first developed

↓

MOCK UNIVERSE

↓

composed of a sample of galaxies that fulfils major observational facts

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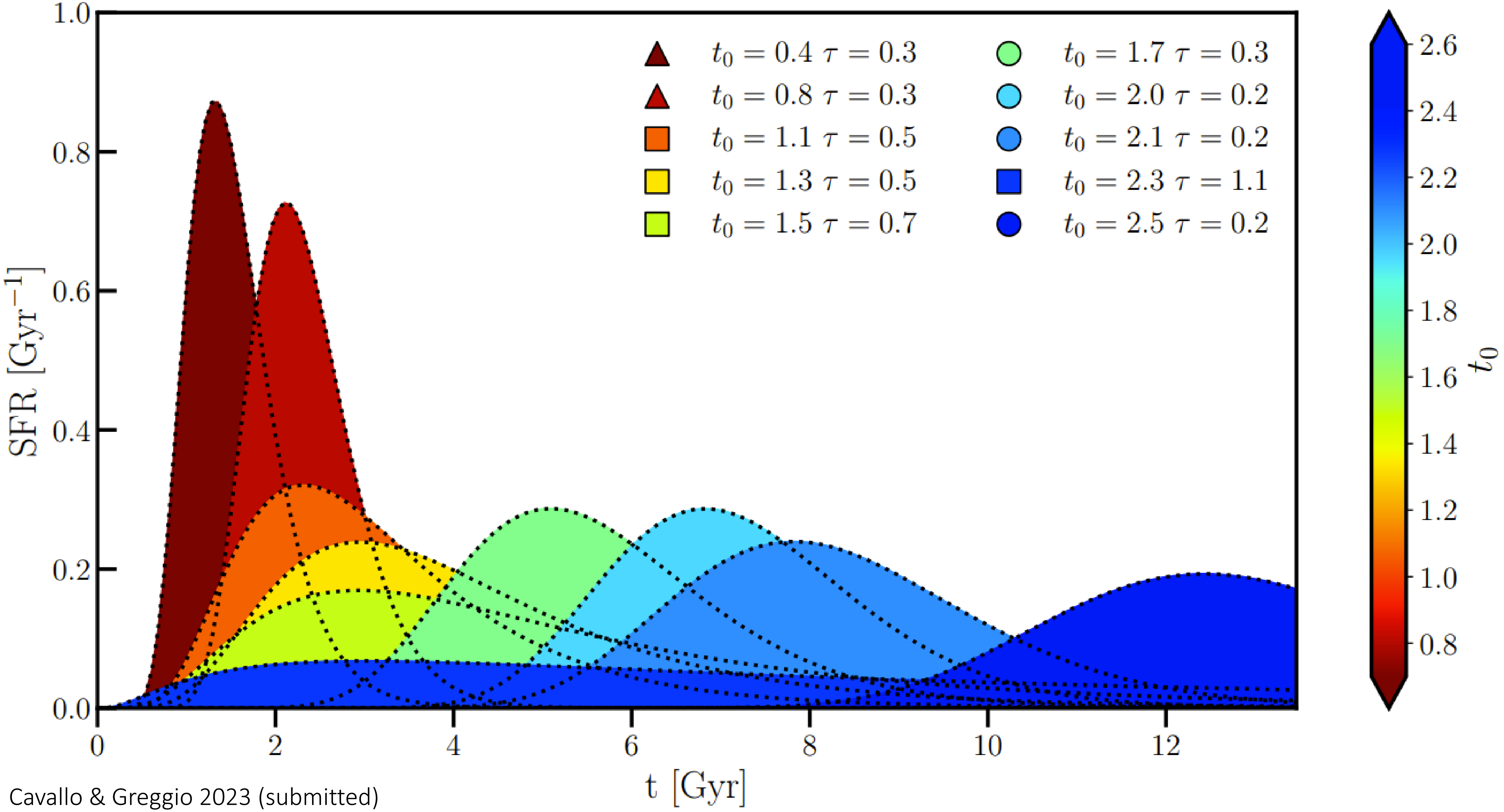
Log-normal star formation history

$$\mathrm{SFR}(t, t_0, \tau) = \frac{1}{t\tau} e^{-\frac{(\ln t - t_0)^2}{2\tau^2}}$$

$[t_0, \tau]$ from *Abramson et al. (2016)*



Cavallo & Greggio 2023 (submitted)

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Star formation rate density (SFRD)

Madau & Dickinson (2014)

Mass distribution function (MDF) observed for nearby galaxies

Peng et al. (2010)

Star-forming main sequence of galaxies

Renzini & Peng (2015)

Gladders et al. (2013)

2094 galaxies

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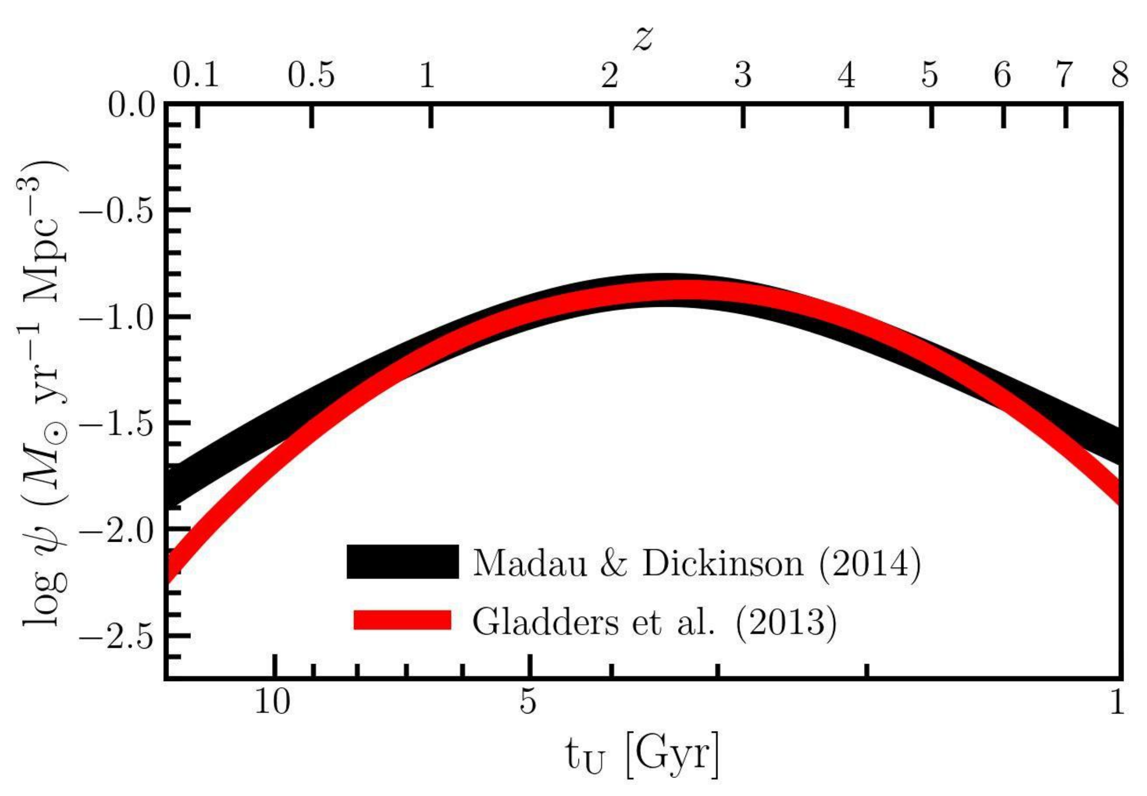
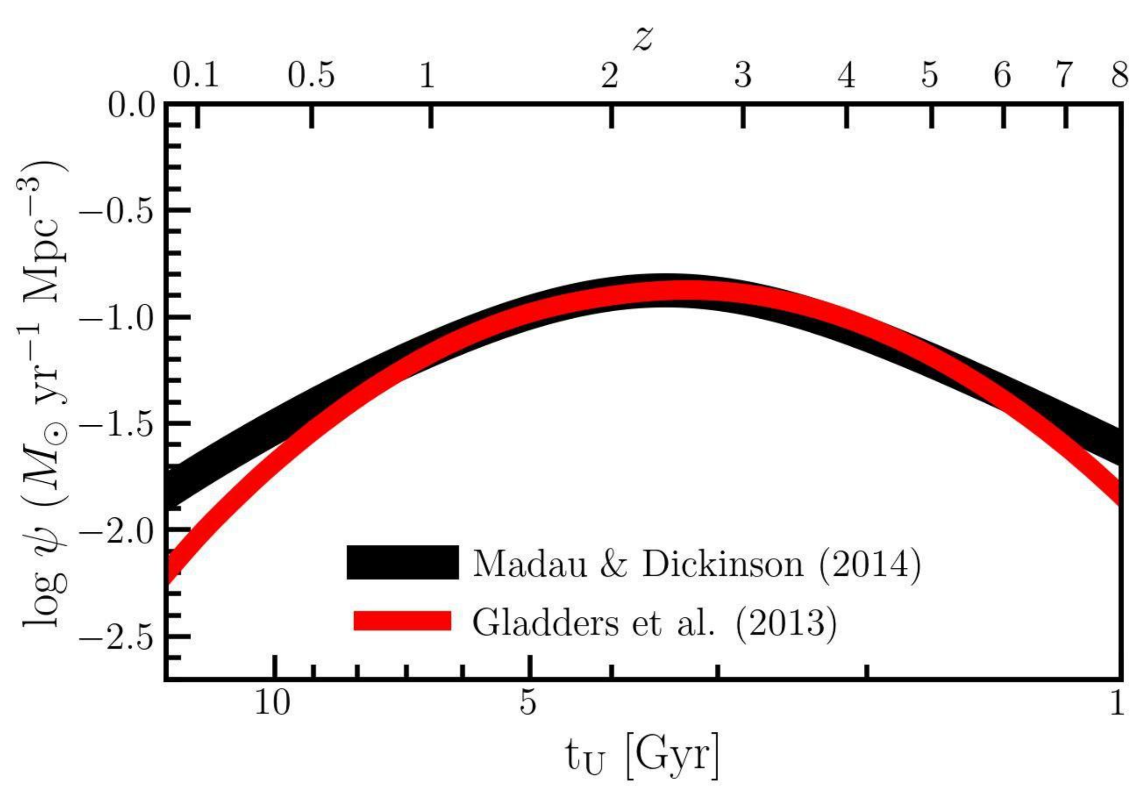
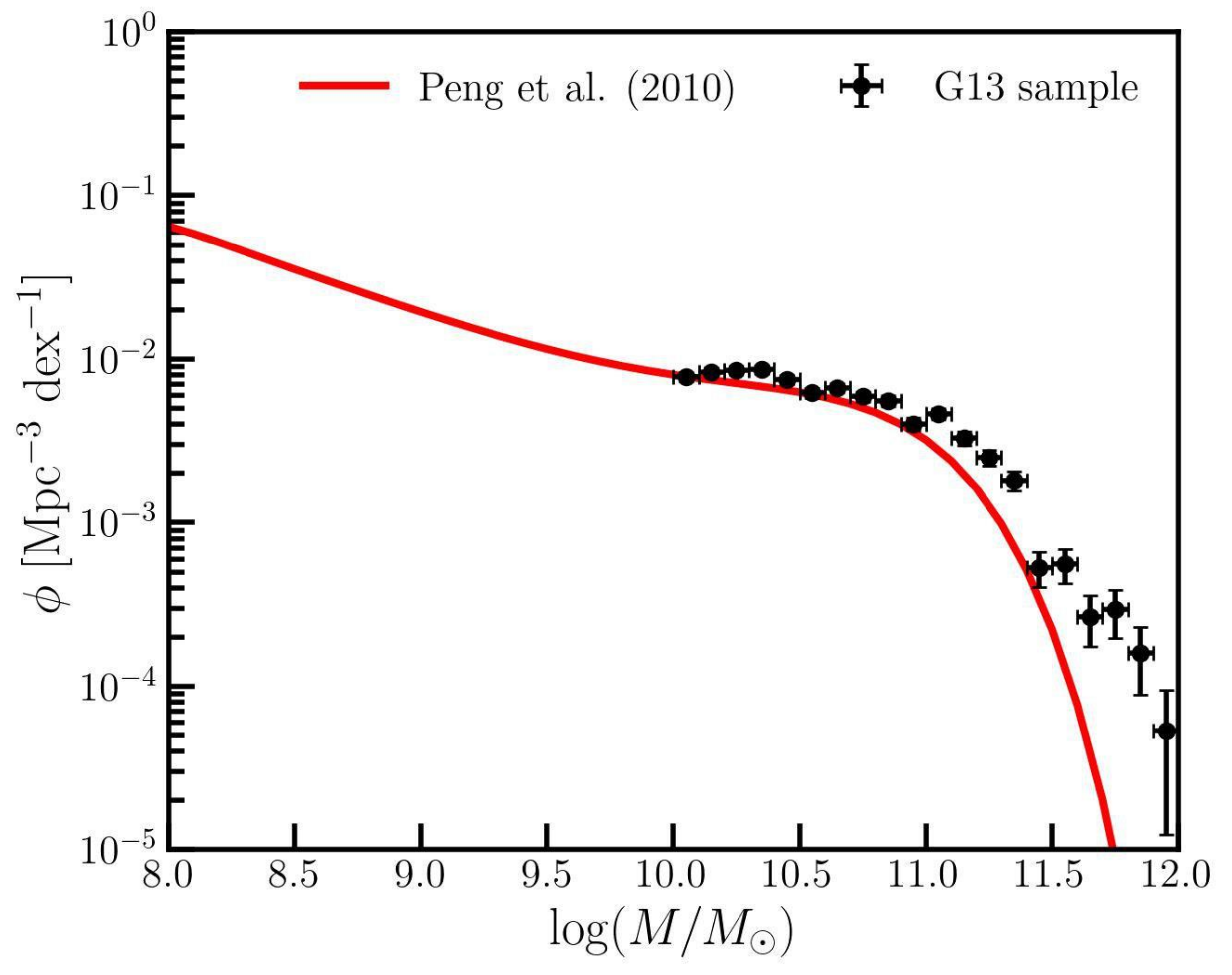
2094 galaxies



Gladders et al. (2013)

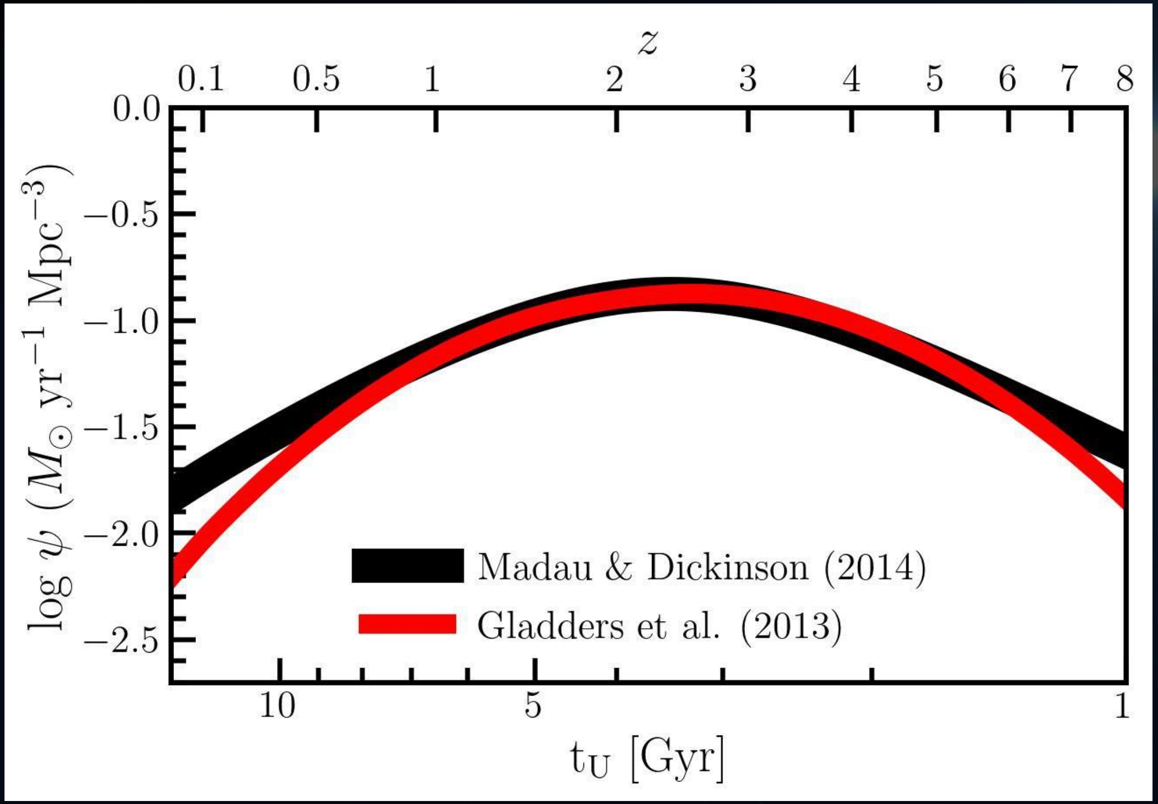
2094 galaxies

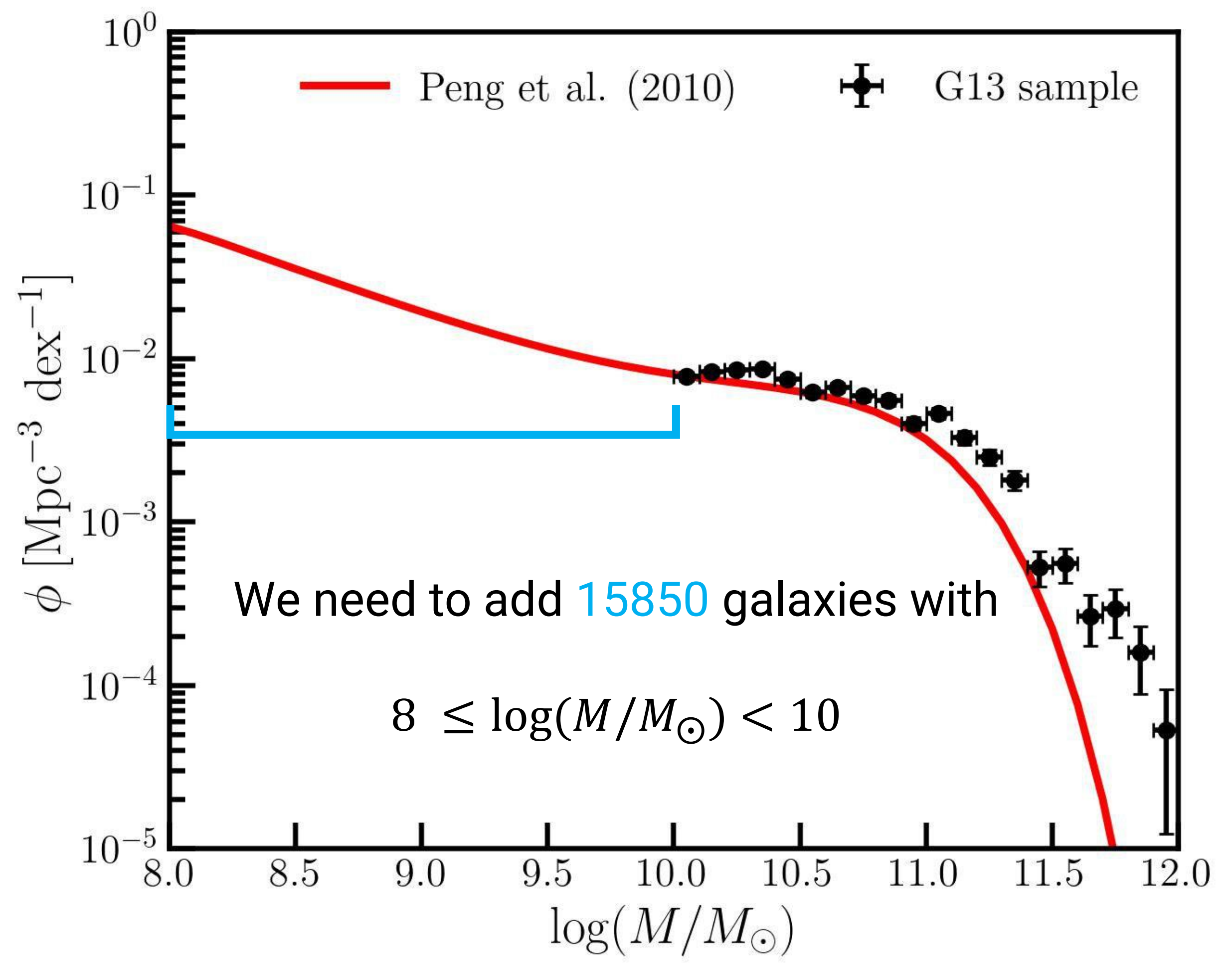




Gladders et al. (2013)

2094 galaxies





We need to add 15850 galaxies with

$8 \leq \log(M/M_\odot) < 10$

Extract M_{gal} from the MDF

Peng et al. (2010)

From the SFMS of galaxies we retrive $SFR(t_{now})$

Renzini & Peng (2015)

M_{gal} $SFR(t_{now})$

Grid Search

t_0 vs τ plane

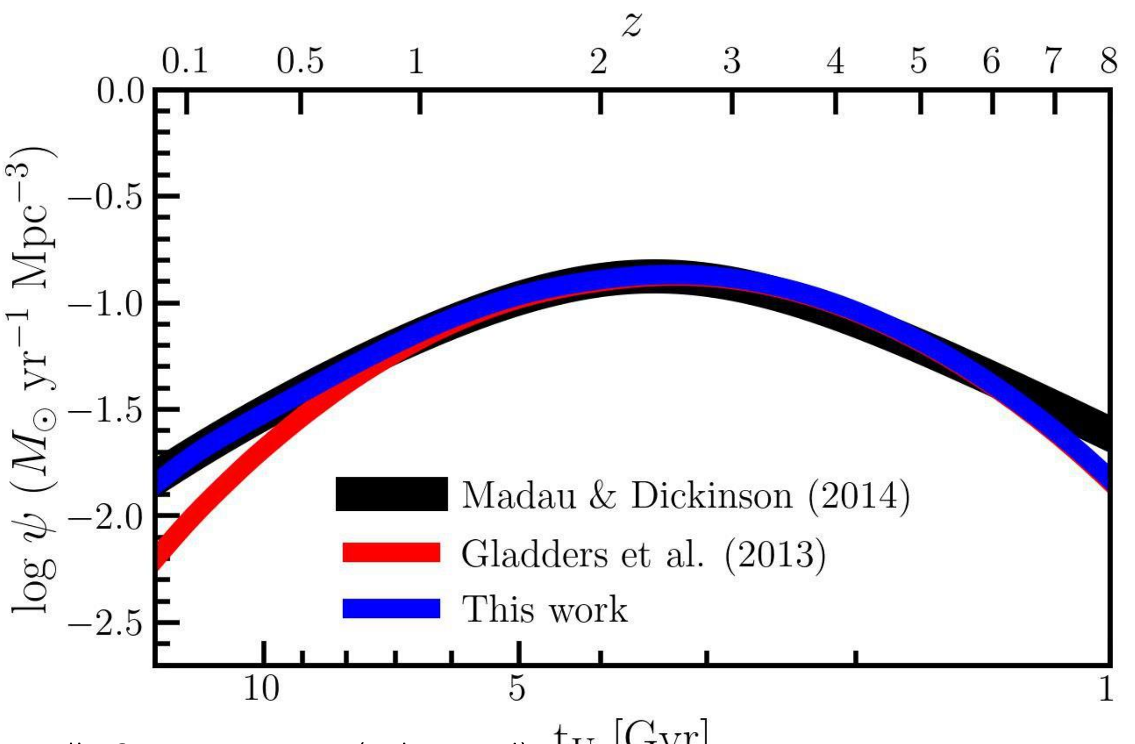
$$M_{gal} = 0.7 \times \int_0^{t_{now}} SFR(t)\, dt$$

$$\mathrm{SFR}(t_{now}, t_0, \tau) = M_{gal} \frac{1}{t_{now}\tau} e^{-\frac{(\ln t_{now} - t_0)^2}{2\tau^2}}$$

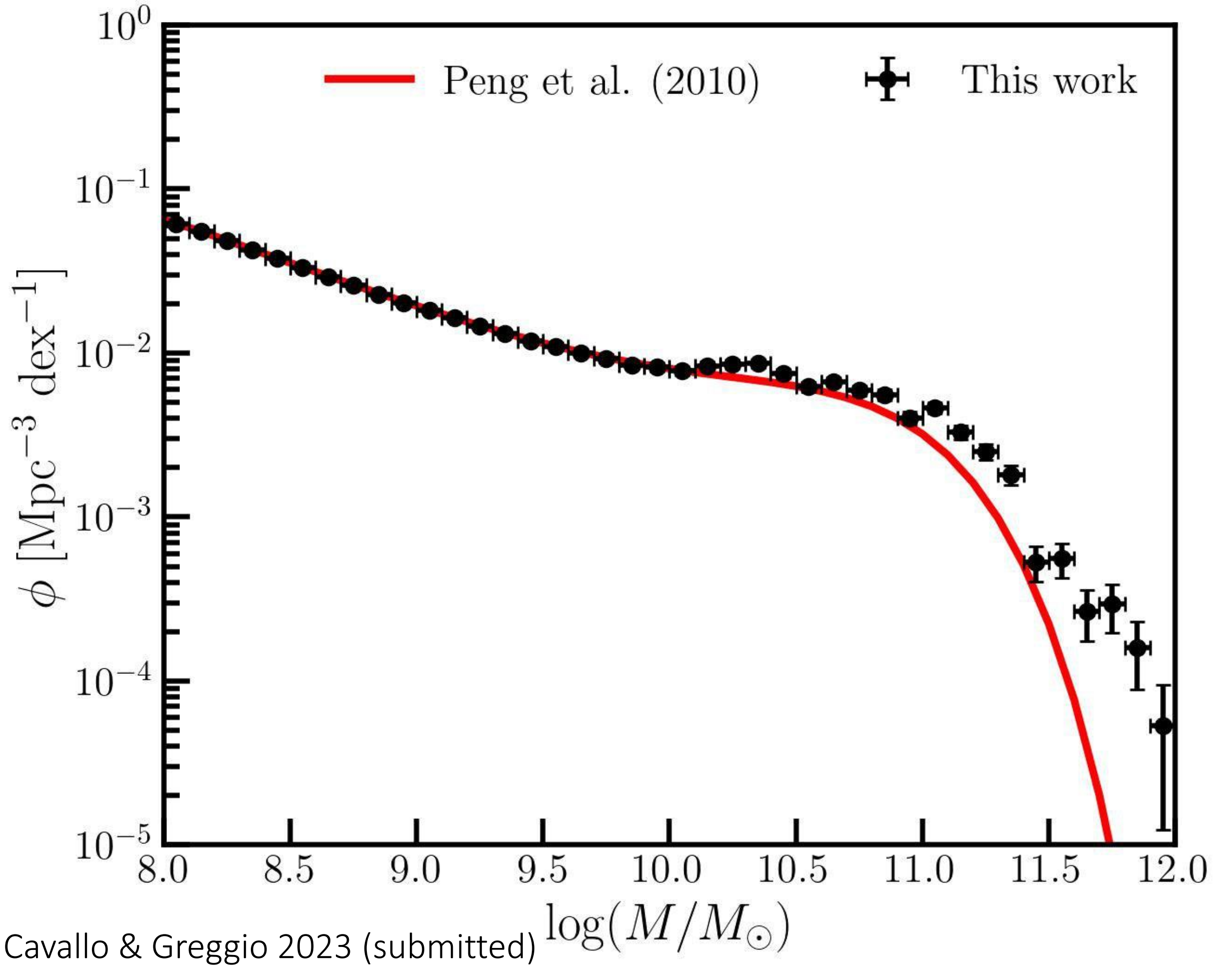
$$[t_0, \tau]$$

Our sample

17944 galaxies



Cavallo & Greggio 2023 (submitted)



Cavallo & Greggio 2023 (submitted)

To do that we first developed

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composed of a sample of galaxies that fulfils major observational facts

Star formation rate density (SFRD)

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Mass distribution function (MDF) observed for nearby galaxies

Peng et al. (2010)

Star-forming main sequence of galaxies

Renzini & Peng (2015)

$$R_{NSM}(t) \propto \int_0^t SFR(t-\tau)\, f_{NSM}(\tau)\, d\tau$$

See Laura Talk!

Greggio et al. 2021 have developed an analytical DTD for NSM

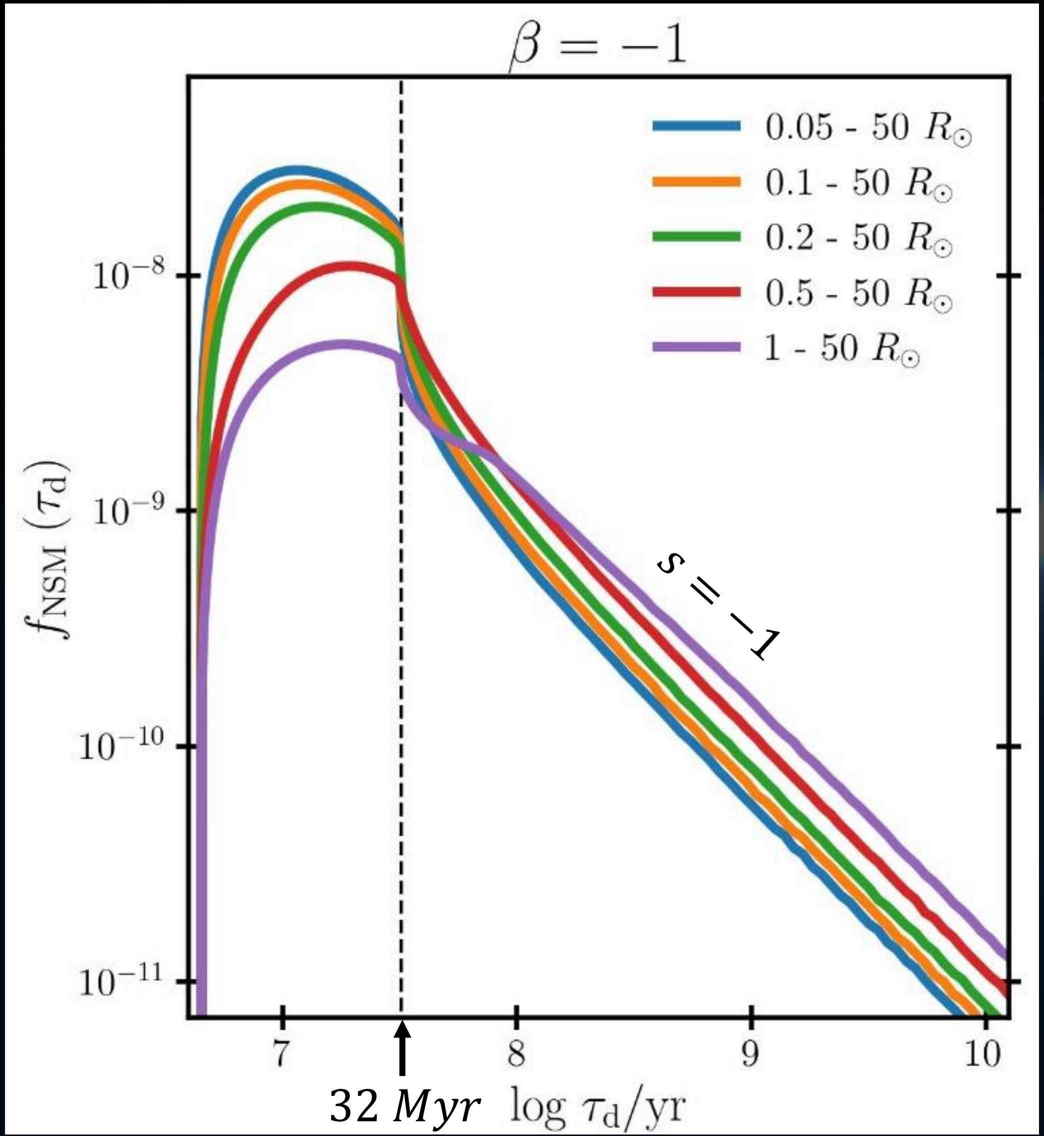
Slope of the power-law distribution of separations:
$f(A) \propto A^{\beta}$

$\beta = -1$ $\beta = -2$ $\beta = -3$

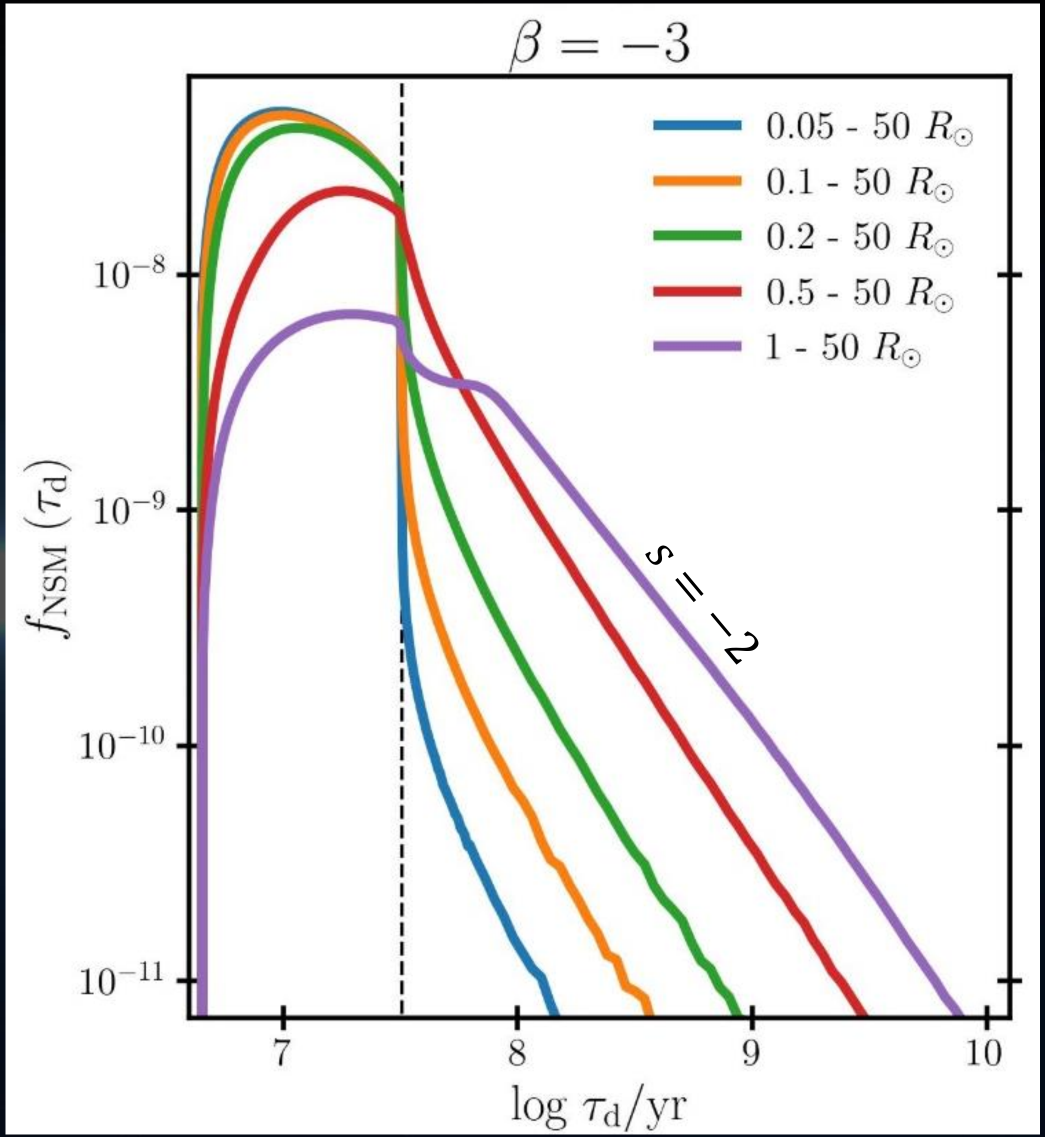
BPS models *Giacobbo & Mapelli 2018* *Belczynski et al. (2018)*

Range of separations:
$A_{min} - A_{max}$

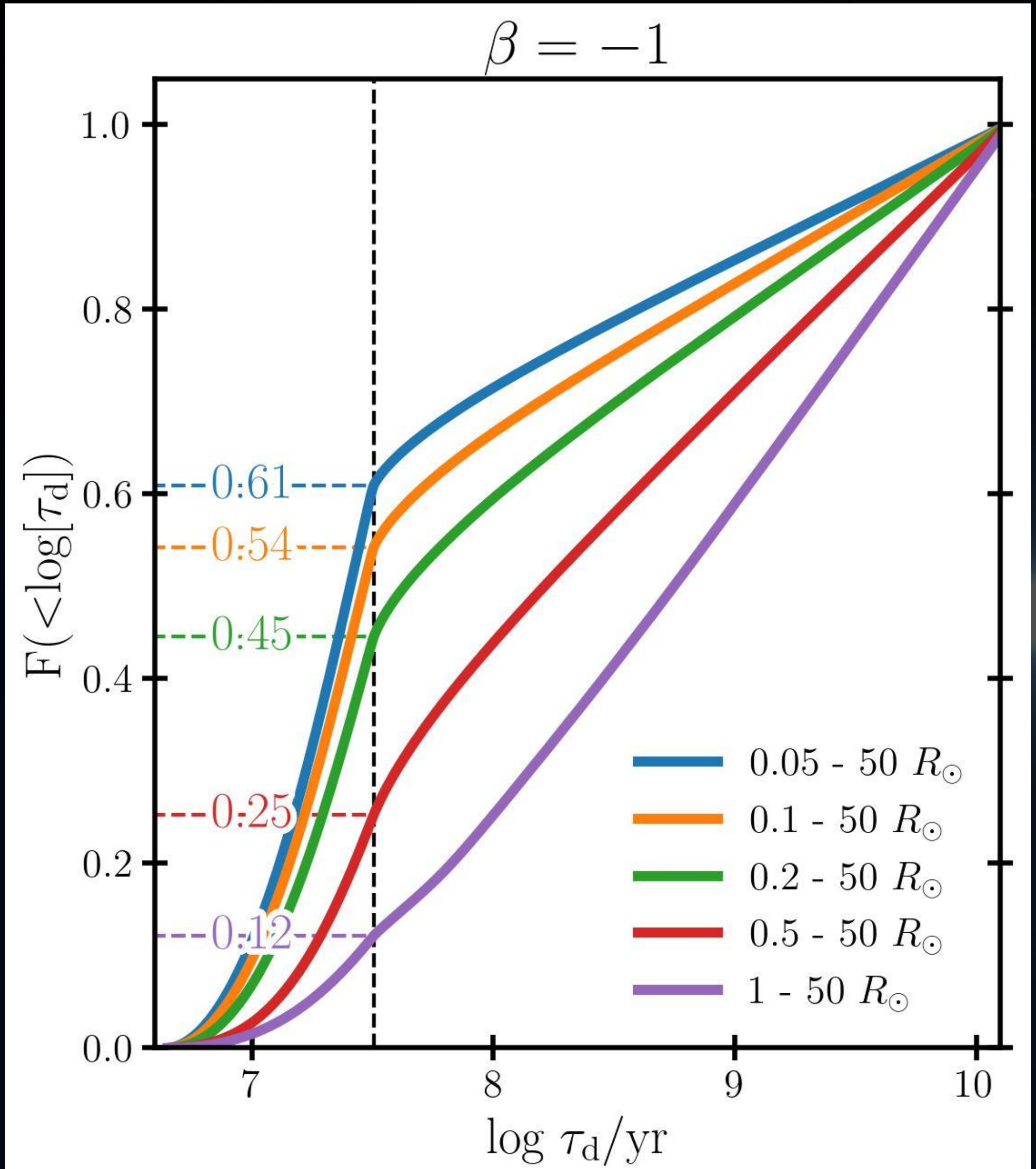
$0.05\ R_{\odot}$ $0.2\ R_{\odot}$ $1\ R_{\odot}$

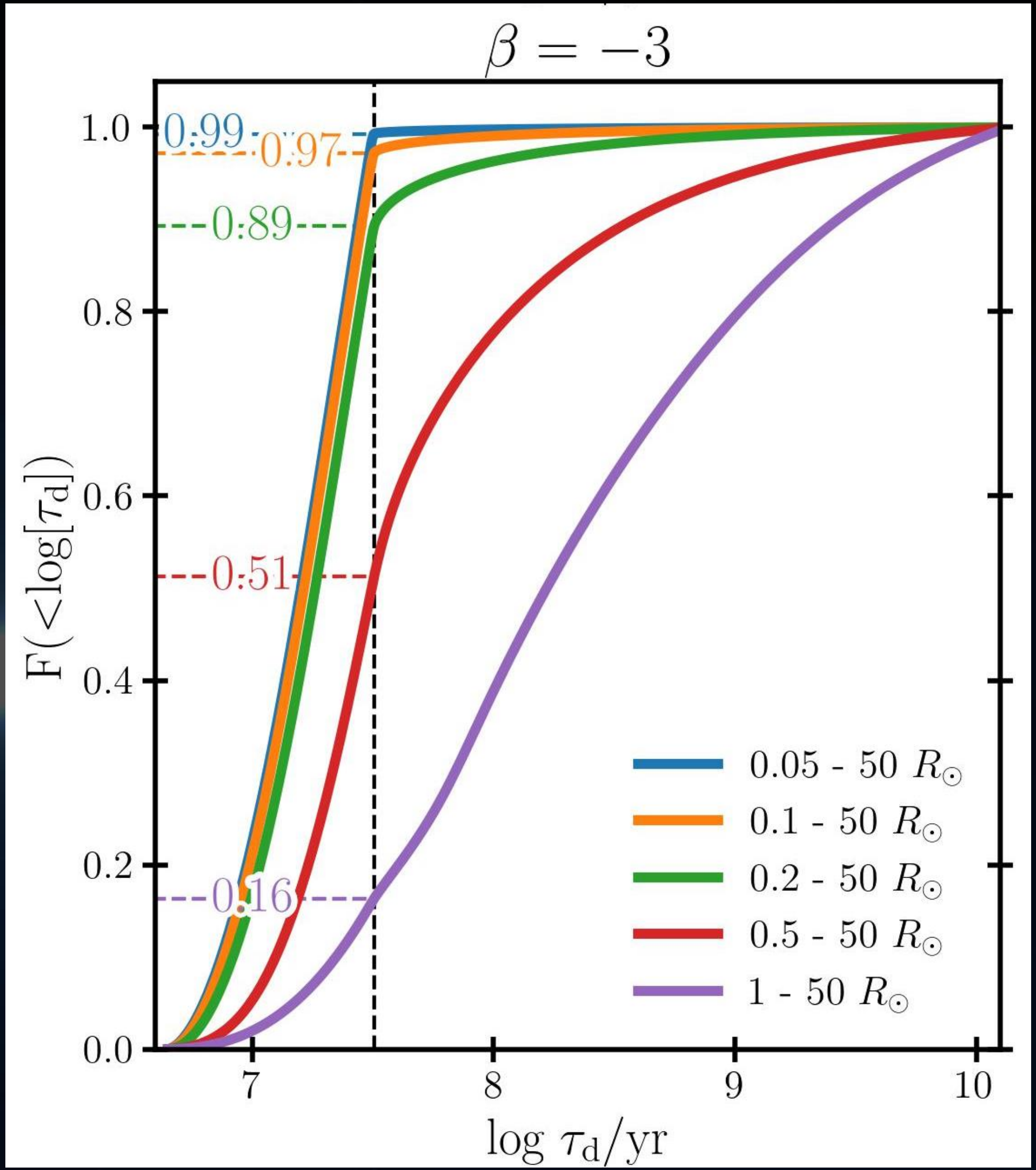


$\beta = -1$
0.05 - 50 $R_\odot$
0.1 - 50 $R_\odot$
0.2 - 50 $R_\odot$
0.5 - 50 $R_\odot$
1 - 50 $R_\odot$
$s = -1$
$f_{\rm NSM}(\tau_{\rm d})$
$\log \tau_{\rm d}/{\rm yr}$
32 Myr



$\beta = -3$
0.05 - 50 $R_\odot$
0.1 - 50 $R_\odot$
0.2 - 50 $R_\odot$
0.5 - 50 $R_\odot$
1 - 50 $R_\odot$
$s = -2$
$f_{\rm NSM}(\tau_{\rm d})$
$\log \tau_{\rm d}/{\rm yr}$


$\beta = -1$
1.0
0.8
0.6
0.4
0.2
0.0
F(<log[τ_d])
0.61
0.54
0.45
0.25
0.12
7
8
9
10
log τ_d/yr
0.05 - 50 $R_\odot$
0.1 - 50 $R_\odot$
0.2 - 50 $R_\odot$
0.5 - 50 $R_\odot$
1 - 50 $R_\odot$


$\beta = -3$
1.0
0.8
0.6
0.4
0.2
0.0
F(<log[τ_d])
0.99
0.97
0.89
0.51
0.16
7
8
9
10
log τ_d/yr
0.05 - 50 $R_\odot$
0.1 - 50 $R_\odot$
0.2 - 50 $R_\odot$
0.5 - 50 $R_\odot$
1 - 50 $R_\odot$

$$R_{NSM}(t) = k_{\alpha}\ \alpha_{NS} \int_0^t SFR(t-\tau)\, f_{NSM}(\tau)\, d\tau$$

$$R_{NSM}(t) = k_\alpha\, \alpha_{NS} \int_0^t SFR(t-\tau)\, f_{NSM}(\tau)\, d\tau$$

Number of neutron stars progenitors per unit mass in a stellar generation

$$k_\alpha = \int_{m_1}^{m_2} \varphi(\mathrm{m})\, \mathrm{dm}$$

Salpeter (1955) IMF and NS progenitors ranging from 9 to 50 $M_\odot$

$$k_\alpha \simeq 0.006\, M_\odot{}^{-1}$$

$$R_{NSM}(t) = k_{\alpha}\, \alpha_{NS} \int_0^t SFR(t-\tau)\, f_{NSM}(\tau)\, d\tau$$

Number of neutron stars progenitors per unit mass in a stellar generation

$$k_{\alpha} = \int_{m_1}^{m_2} \varphi(\mathrm{m})\, \mathrm{dm}$$

Salpeter (1955) IMF and NS progenitors ranging from 9 to 50 $M_{\odot}$

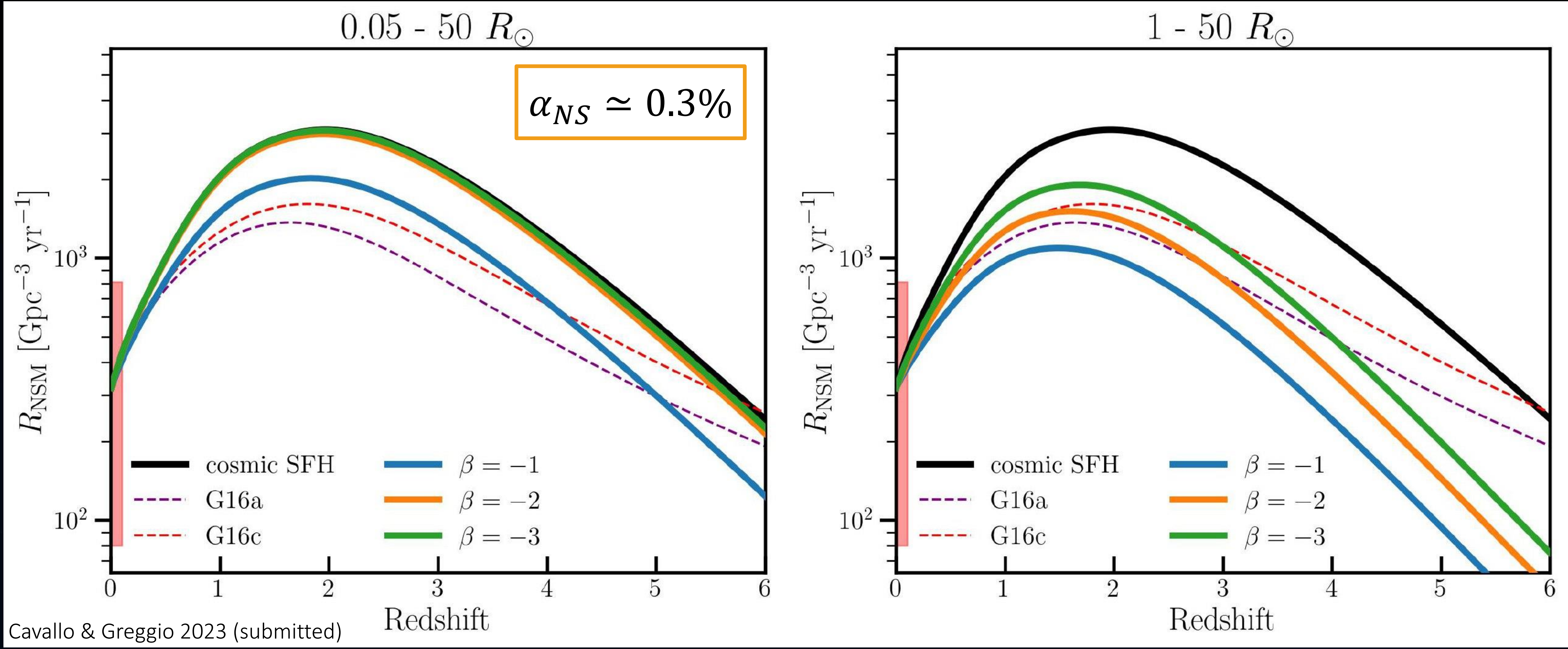
$$k_{\alpha} \simeq 0.006\, {M_{\odot}}^{-1}$$

Fraction of massive stars with the right characteristics to lead to a NSM

R_{NSM} = R_{GW} by *Abbott et al. (2021)*

$$\mathcal{R} = 320^{+490}_{-240}\ Gpc^{-3} yr^{-1}$$

Redshift evolution of the NSM rate



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$$D(z) = sSFR(z) \times t_U(z)$$

Tacchella et al. (2022)

$D(z) < 1/3$ → **Passive**

$D(z) \geq 1/3$ → **Star-forming**

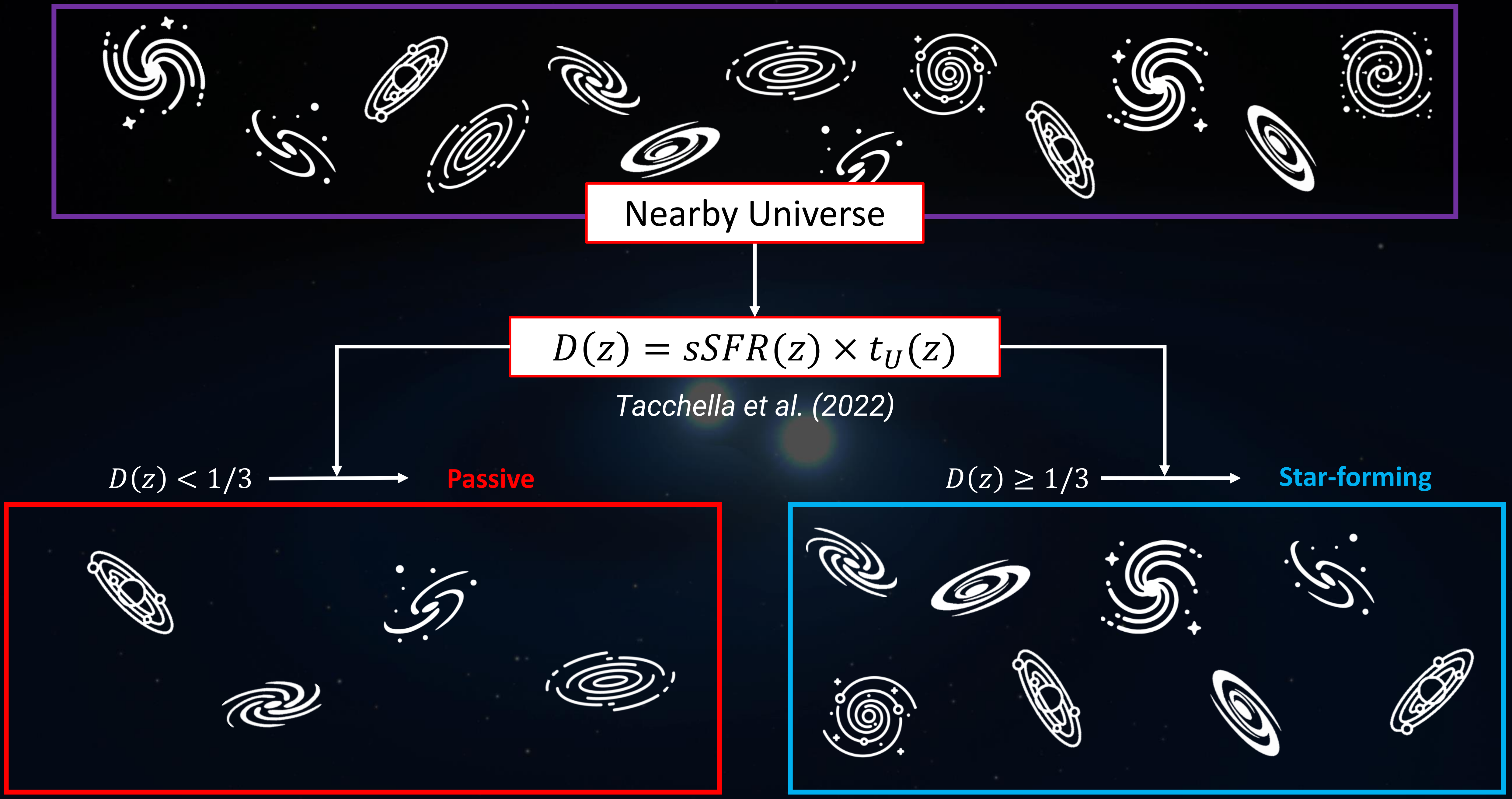
High z

$$D(z) = sSFR(z) \times t_U(z)$$

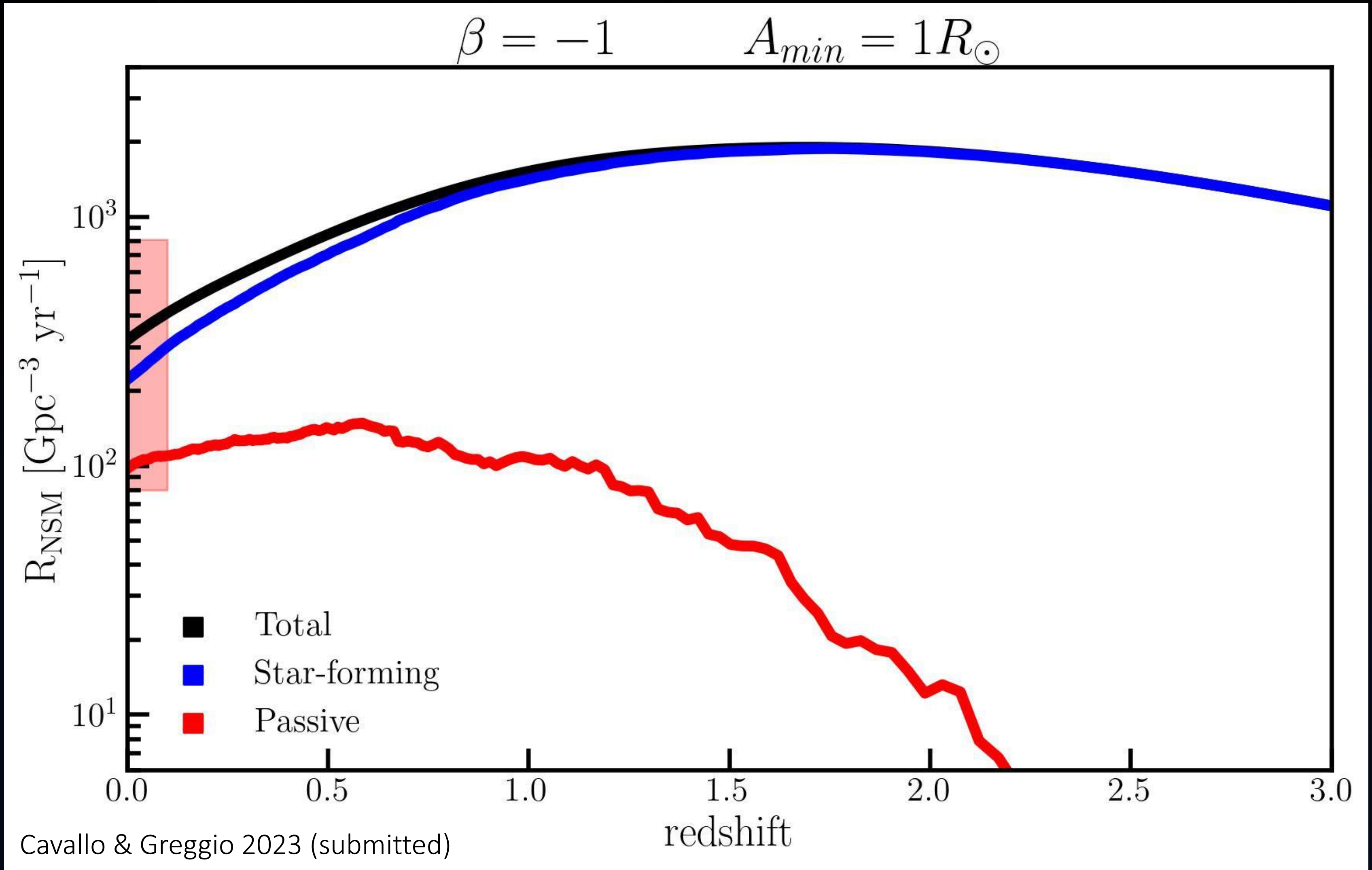
Tacchella et al. (2022)

$D(z) < 1/3$ → **Passive**

$D(z) \geq 1/3$ → **Star-forming**



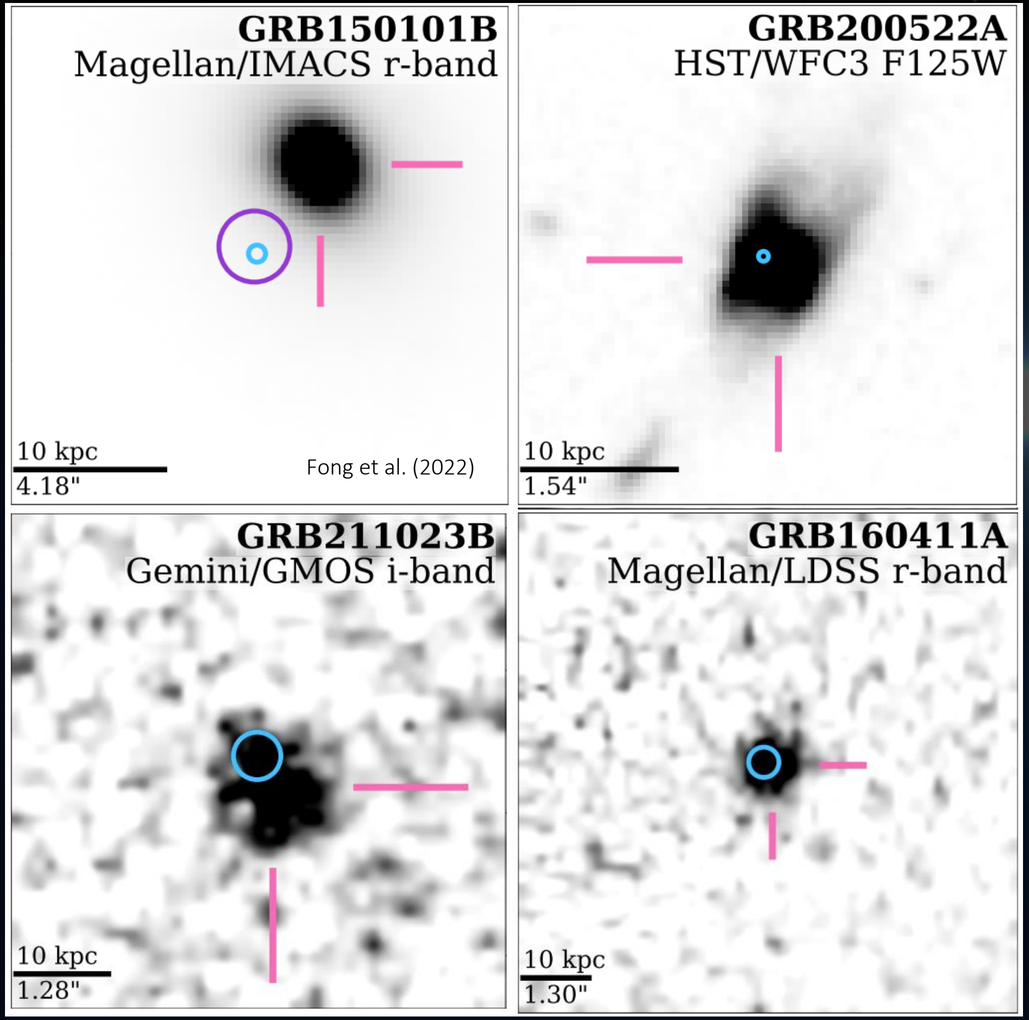
Nearby Universe
$D(z) = sSFR(z) \times t_U(z)$
Tacchella et al. (2022)
$D(z) < 1/3$
Passive
$D(z) \geq 1/3$
Star-forming

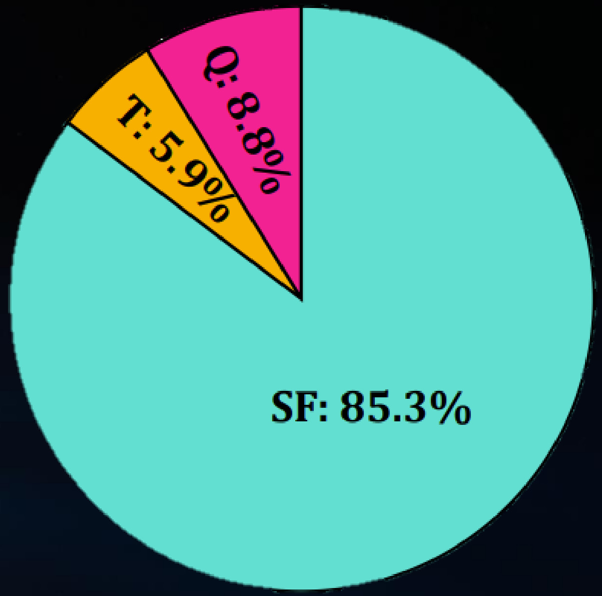


Fraction of NSMs in late-type galaxies

$$\frac{\mathcal{R}_{SF}(z)}{\mathcal{R}_{TOT}(z)} = f_{SF}(z)$$

Fong et al. (2022) have presented a census of the 90 SGRBs observed from 2005 to 2021 that have an association with an host galaxy.



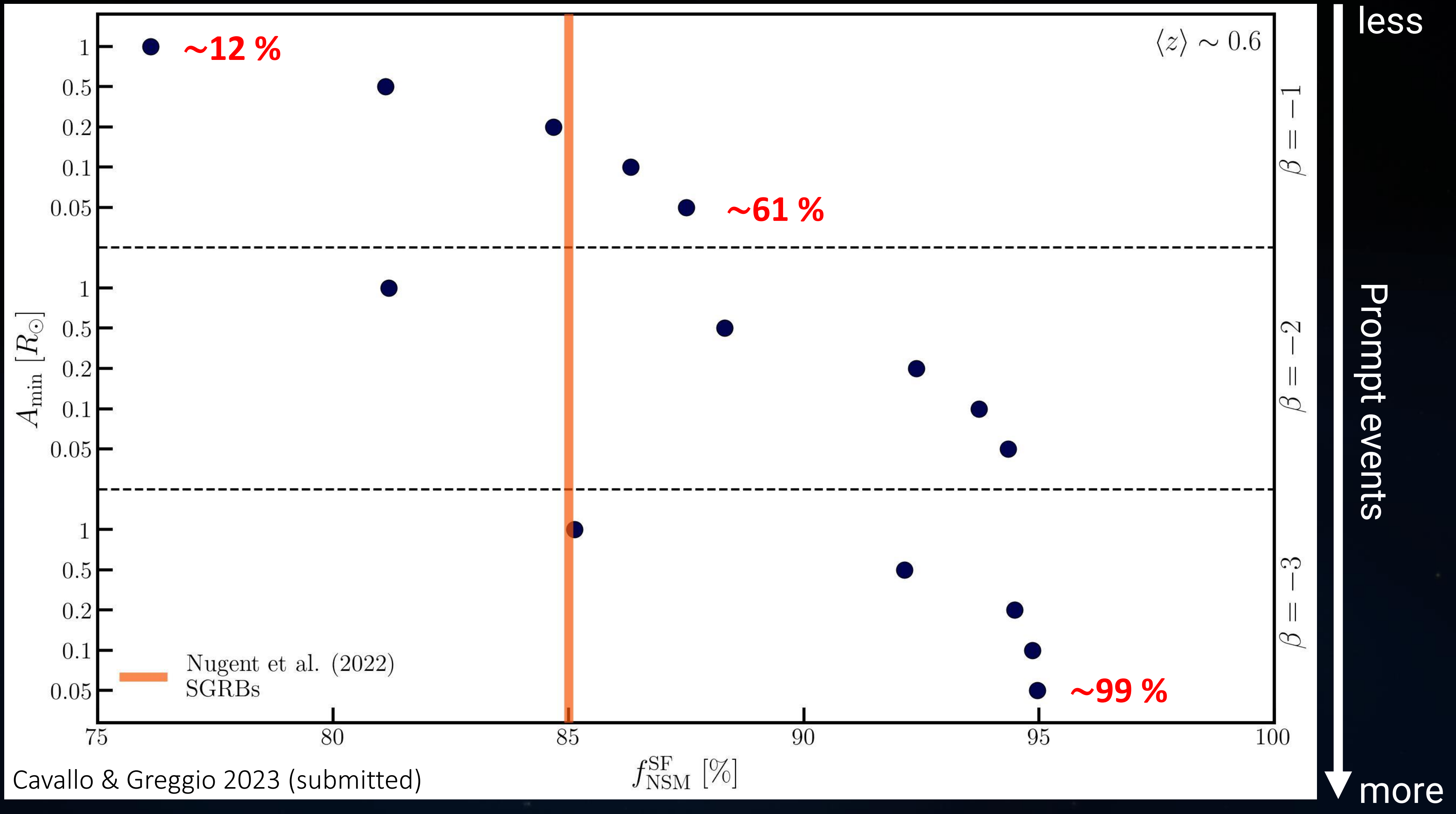


Nugent et al. (2022)

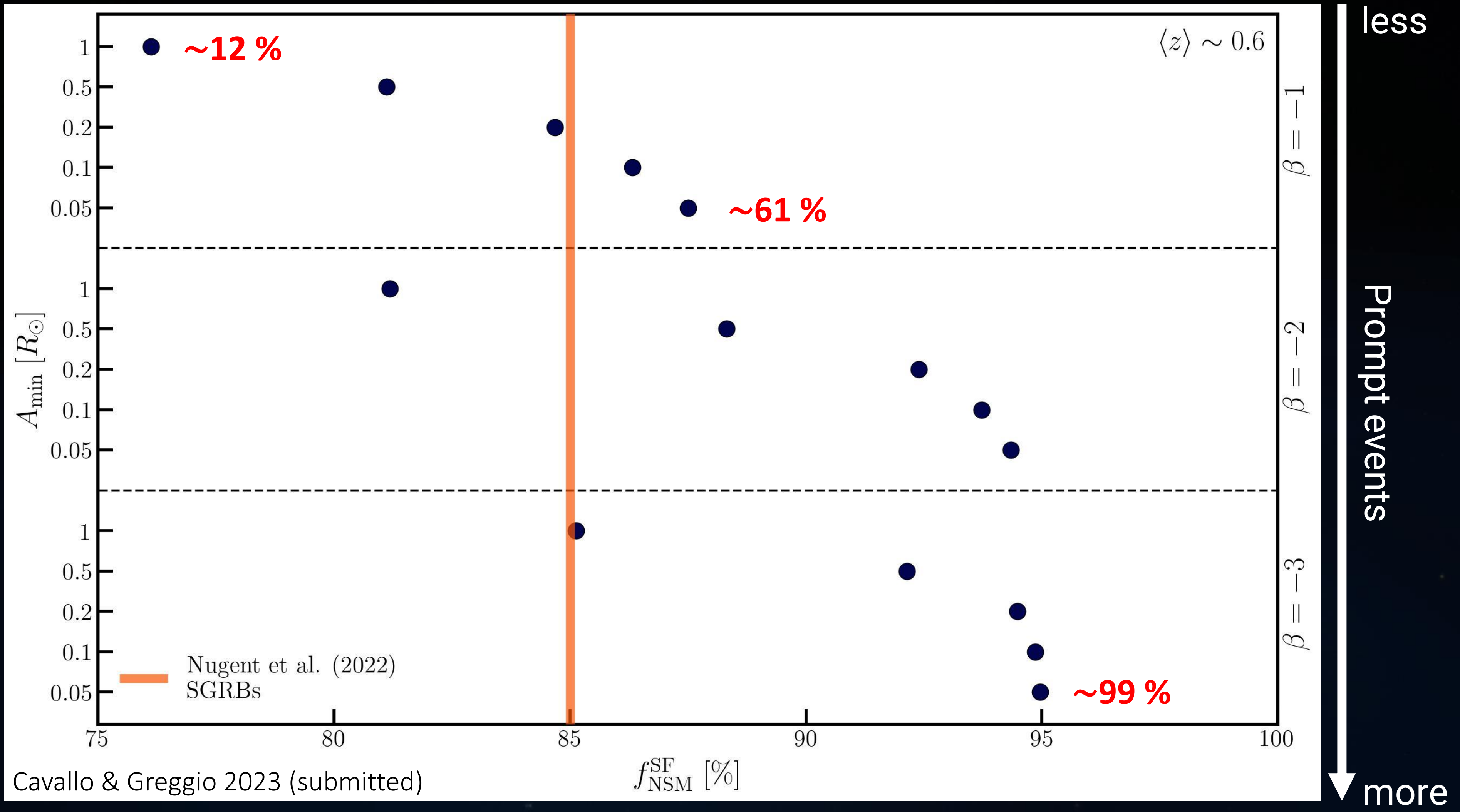
Nugent et al. (2022) used spectroscopy and optical and near-infrared photometry to characterize the stellar population properties of the host galaxies of SGRBs.

↓

~ **85%** of the population of hosts are **star forming galaxies**



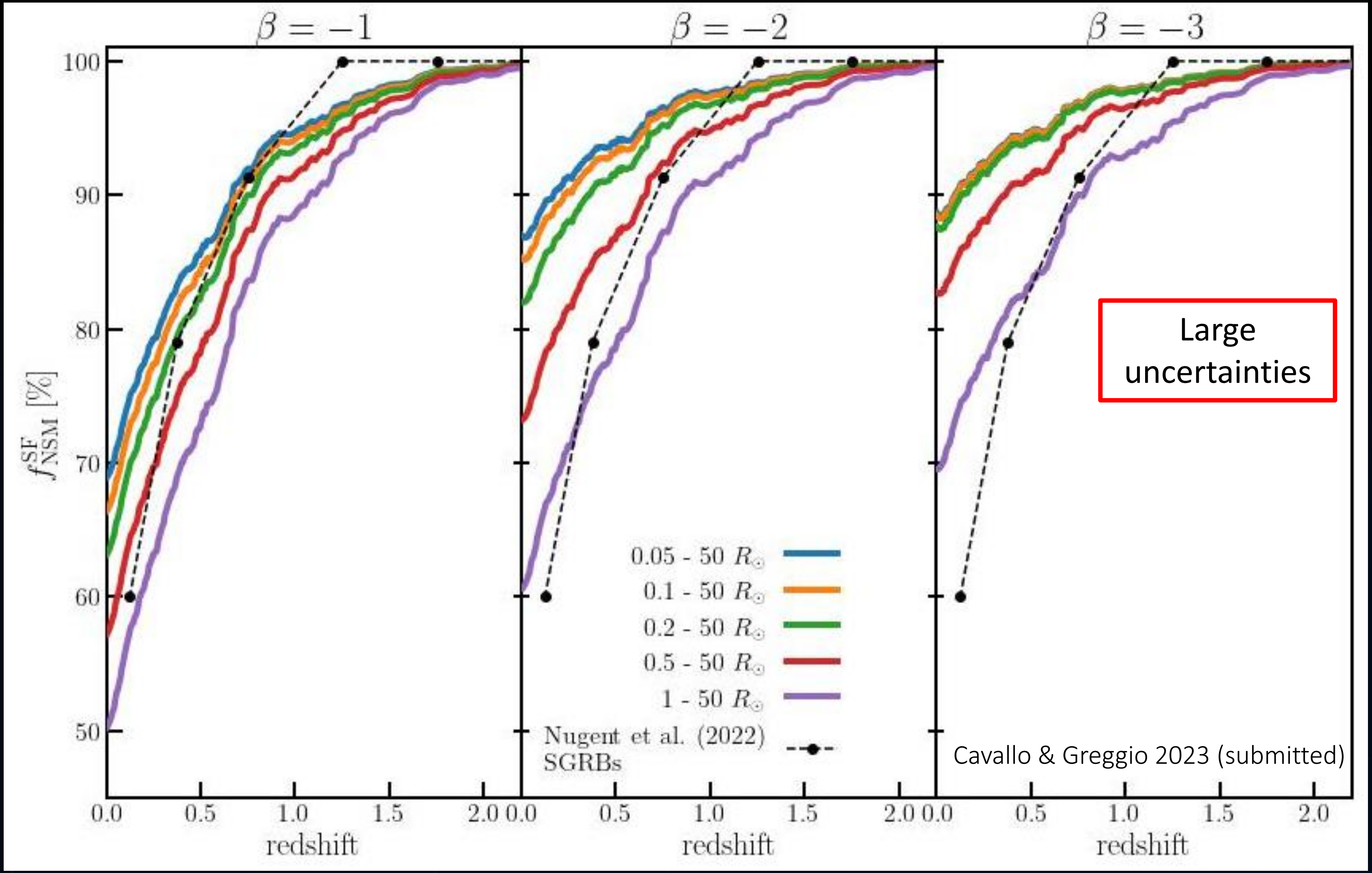
~12 %
~61 %
~99 %
$\langle z \rangle \sim 0.6$
$\beta = -1$
$\beta = -2$
$\beta = -3$
$A_{\rm min}\ [R_\odot]$
1
0.5
0.2
0.1
0.05
Nugent et al. (2022)
SGRBs
75
80
85
90
95
100
$f^{\rm SF}_{\rm NSM}$ [%]
Cavallo & Greggio 2023 (submitted)
less
Prompt events
more



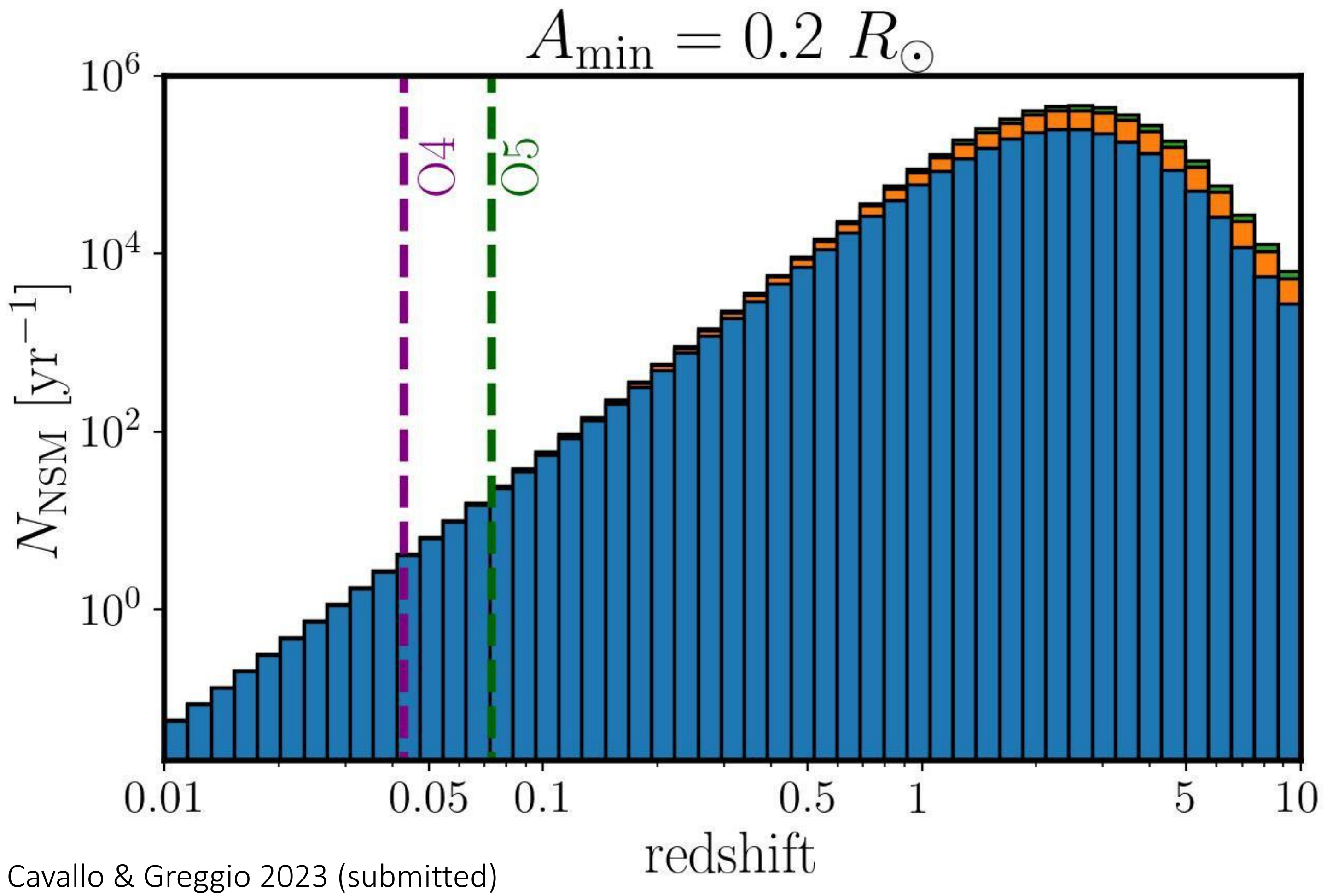
The fraction of short-GRBs observed in late-type galaxies favors DTDs with a fair fraction of prompt events.

We notice that a similar indication is obtained from chemical evolution models.

Future (with GRBs)



Future (with GW)



Cavallo & Greggio 2023 (submitted)

Summary

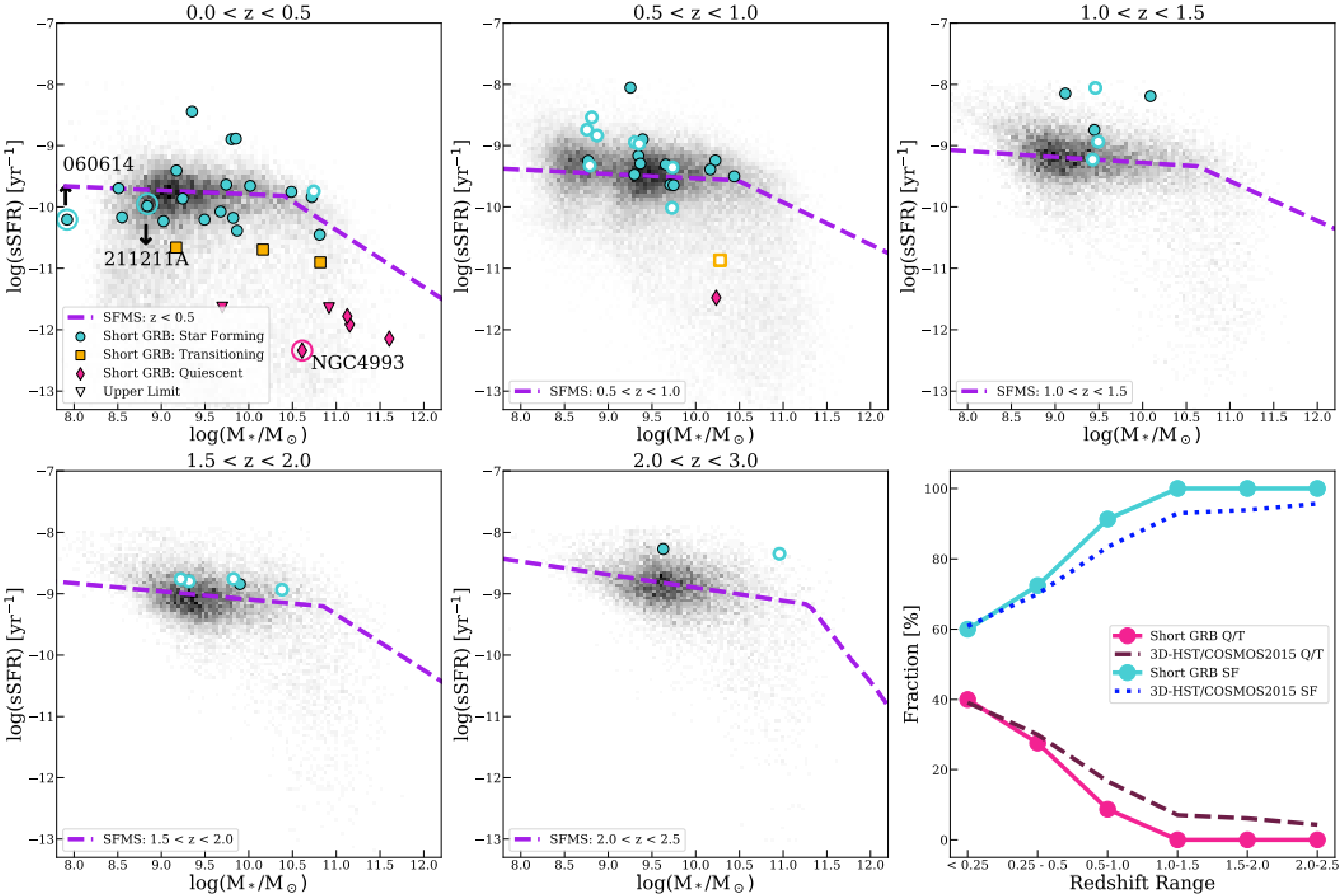
- Assuming that NSMs are the progenitors of SGRBs, we compare our theoretical curves with the redshift evolution of the rate of SGRBs computed by *Ghirlanda et al. (2016)*. This constraint favours DTD with $\beta = -1$, as found in *Greggio et al. (2021)*

- Adopting the current estimate for the rate of NSMs in the local Universe, we estimate that 0.3% of neutron star progenitors living in binary systems with the right characteristics to lead to a NSM within a Hubble time. We found a weak dependence on the DTD parameters β and A_{min}

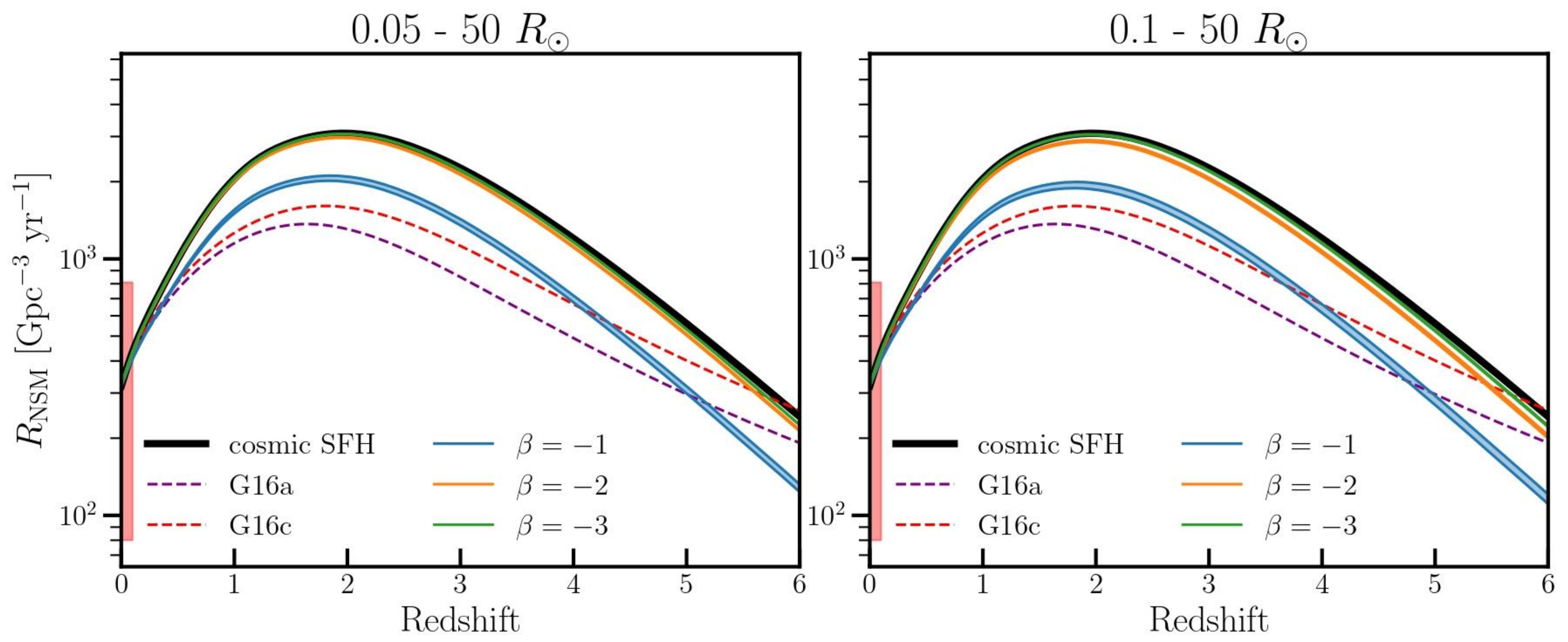
- We find that the fraction of SGRBs observed in star-forming galaxies favours DTDs with a fair fraction of prompt events ($\beta = -2/-3$)

- The evolution with redshift of the fraction of NSMs in star-forming galaxies depends on the criterion used to define them and on the DTD. Current empirical estimates of this trend (*Nugent et al. 2022*) are affected by large uncertainties caused by the poor statistics so that all our models are compatible with the data. Larger datasets will allow exploiting this trend to constrain the DTD

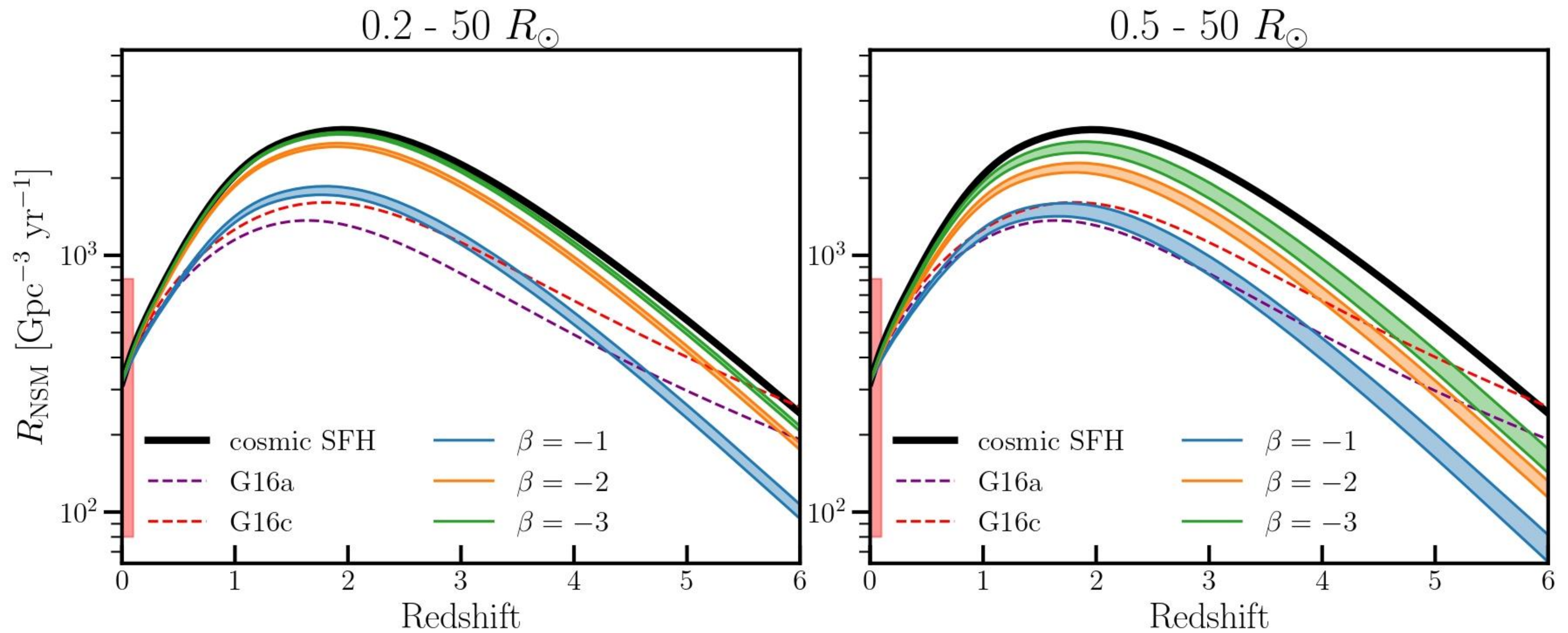
BACKUP



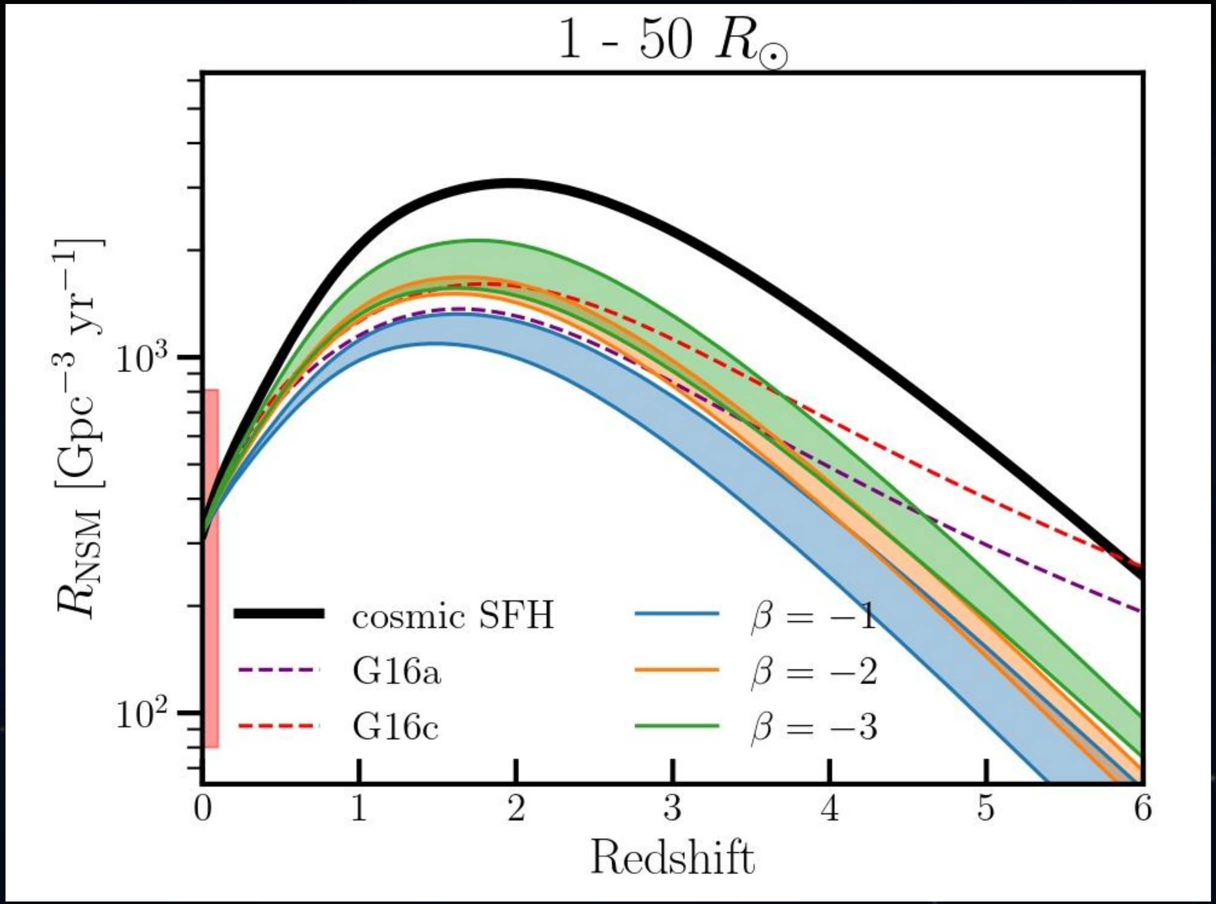
0.0 < z < 0.5
0.5 < z < 1.0
1.0 < z < 1.5
1.5 < z < 2.0
2.0 < z < 3.0
log(sSFR) [yr^{-1}]
log(M$_*$/M$_\odot$)
060614
211211A
NGC4993
SFMS: z < 0.5
Short GRB: Star Forming
Short GRB: Transitioning
Short GRB: Quiescent
Upper Limit
SFMS: 0.5 < z < 1.0
SFMS: 1.0 < z < 1.5
SFMS: 1.5 < z < 2.0
SFMS: 2.0 < z < 2.5
Fraction [%]
Redshift Range
< 0.25
0.25 - 0.5
0.5-1.0
1.0-1.5
1.5-2.0
2.0-2.5
Short GRB Q/T
3D-HST/COSMOS2015 Q/T
Short GRB SF
3D-HST/COSMOS2015 SF



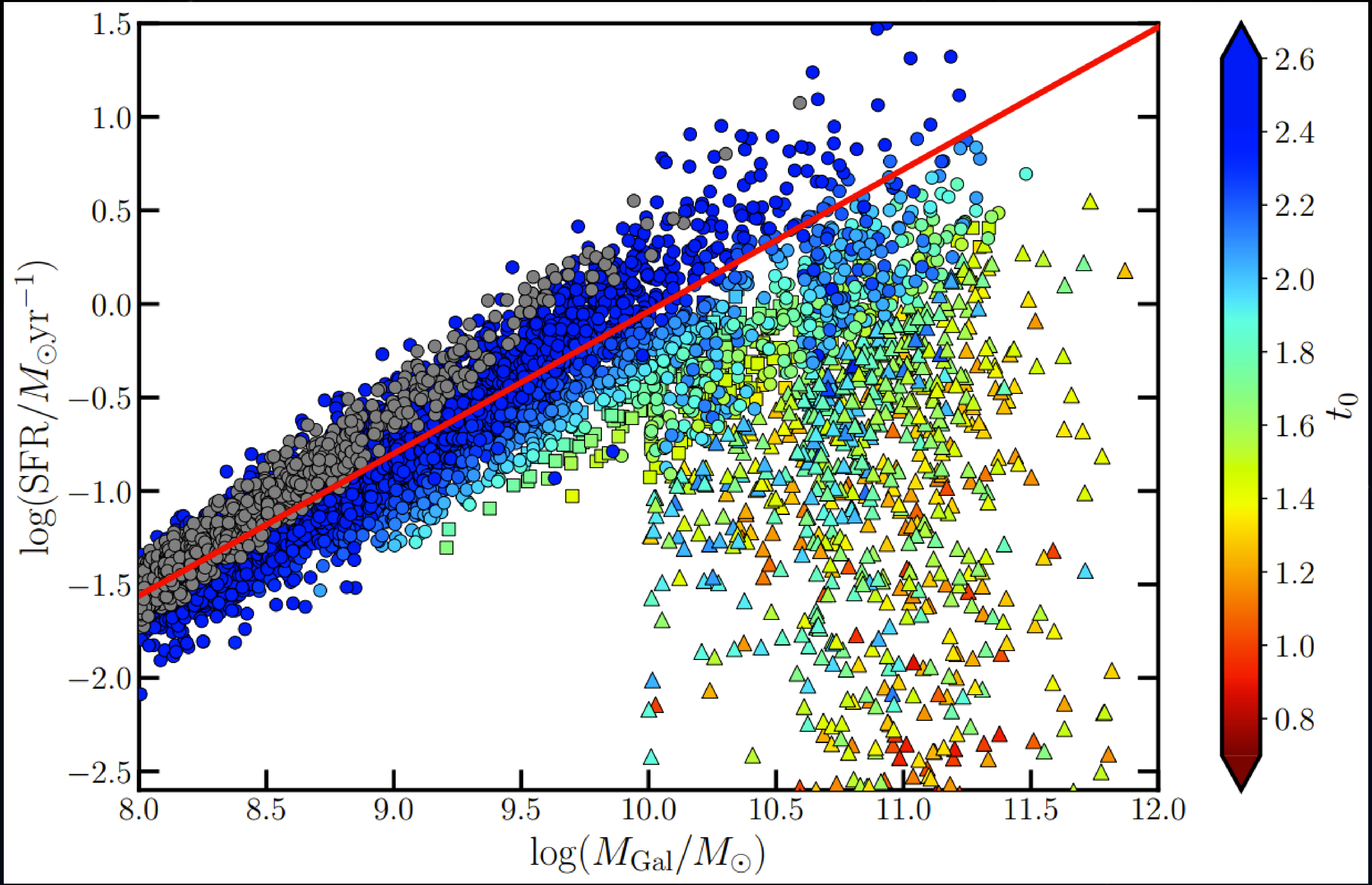
0.05 - 50 $R_\odot$
0.1 - 50 $R_\odot$
$R_{\rm NSM}$ [Gpc^{-3} yr^{-1}]
10^3
10^2
0
1
2
3
4
5
6
Redshift
cosmic SFH
G16a
G16c
$\beta = -1$
$\beta = -2$
$\beta = -3$



0.2 - 50 $R_\odot$
0.5 - 50 $R_\odot$
$R_{\rm NSM}$ [Gpc^{-3} yr^{-1}]
10^3
10^2
0 1 2 3 4 5 6
Redshift
cosmic SFH
G16a
G16c
$\beta = -1$
$\beta = -2$
$\beta = -3$



1 - 50 $R_\odot$
$R_{\rm NSM}$ [Gpc^{-3} yr^{-1}]
10^3
10^2
0
1
2
3
4
5
6
Redshift
cosmic SFH
G16a
G16c
$\beta = -1$
$\beta = -2$
$\beta = -3$



1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
$\log(\mathrm{SFR}/M_\odot \mathrm{yr}^{-1})$
8.0
8.5
9.0
9.5
10.0
10.5
11.0
11.5
12.0
$\log(M_\mathrm{Gal}/M_\odot)$
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
t_0