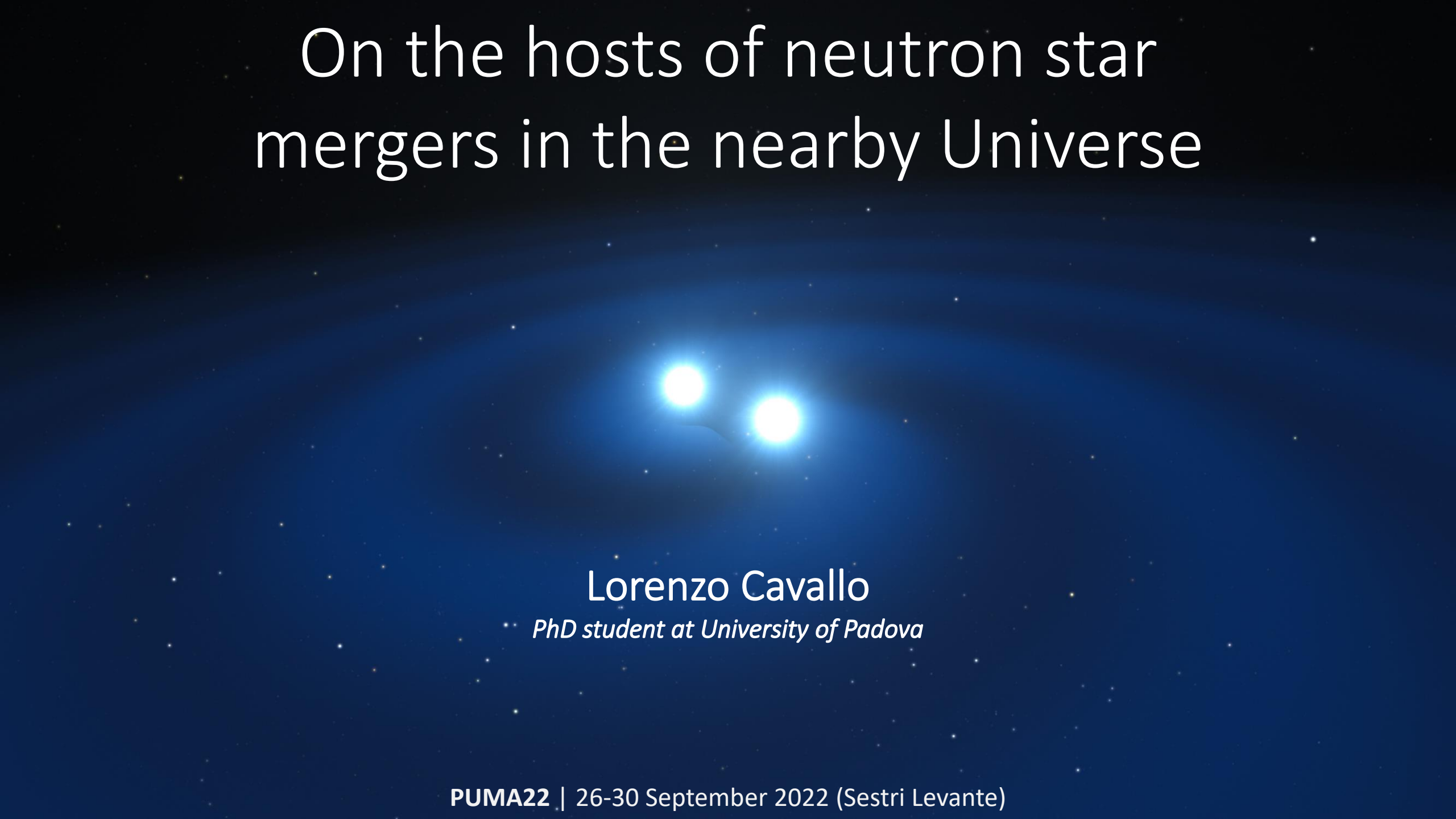
On the hosts of neutron star mergers in the nearby Universe

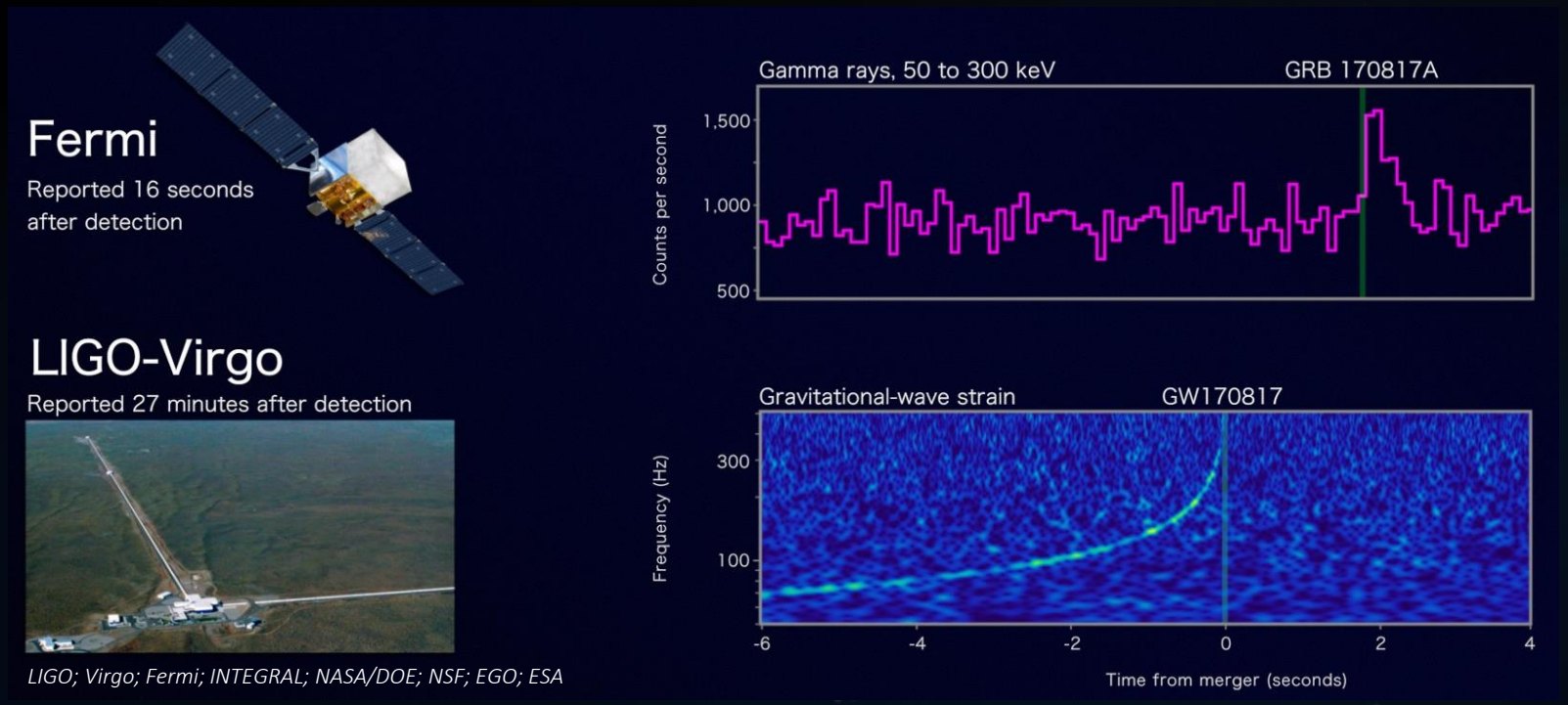


Lorenzo Cavallo

PhD student at University of Padova

PUMA22 | 26-30 September 2022 (Sestri Levante)

The dawn of a new era

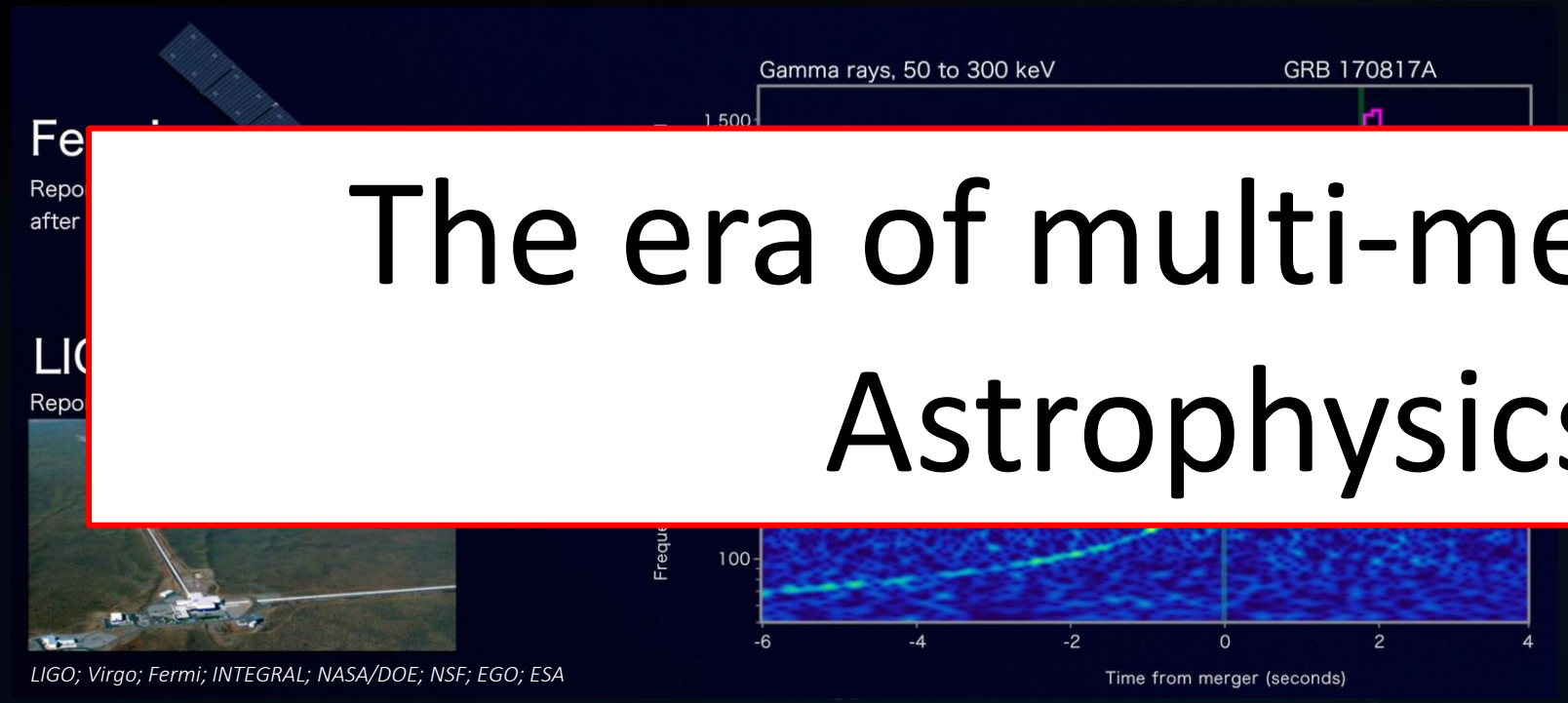


LIGO; Virgo; Fermi; INTEGRAL; NASA/DOE; NSF; EGO; ESA

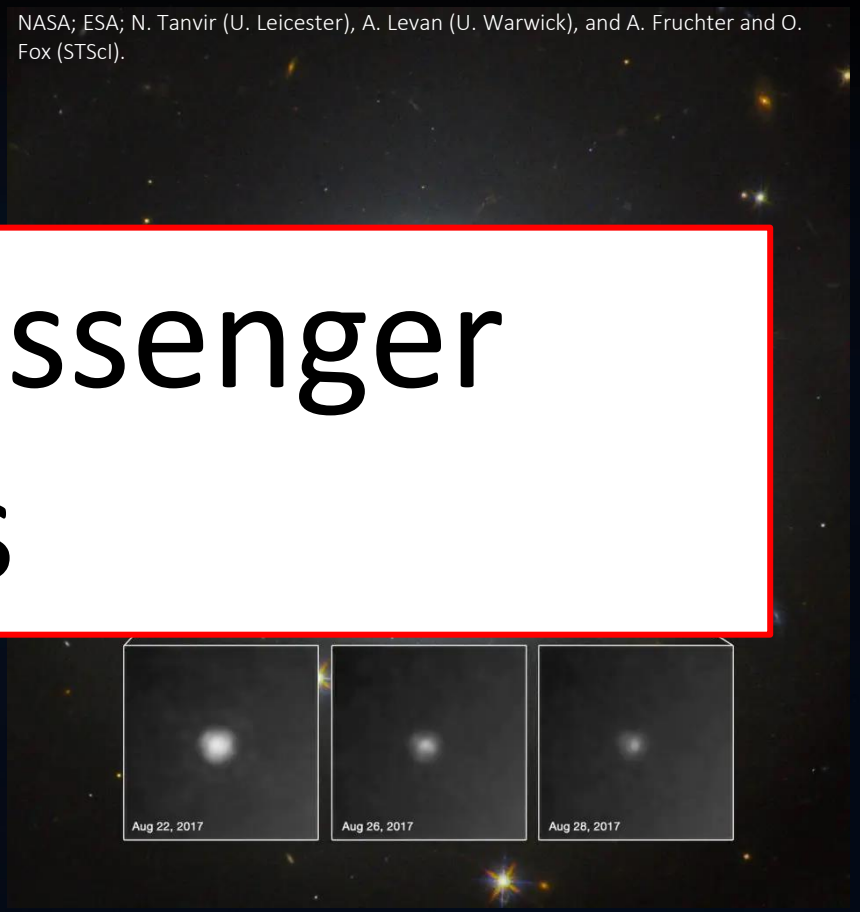
NASA; ESA; N. Tanvir (U. Leicester), A. Levan (U. Warwick), and A. Fruchter and O. Fox (STScI).

The dawn of a new era

The era of multi-messenger Astrophysics



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).

Gravitational Wave Transient Catalog 3 (GWTC-3)

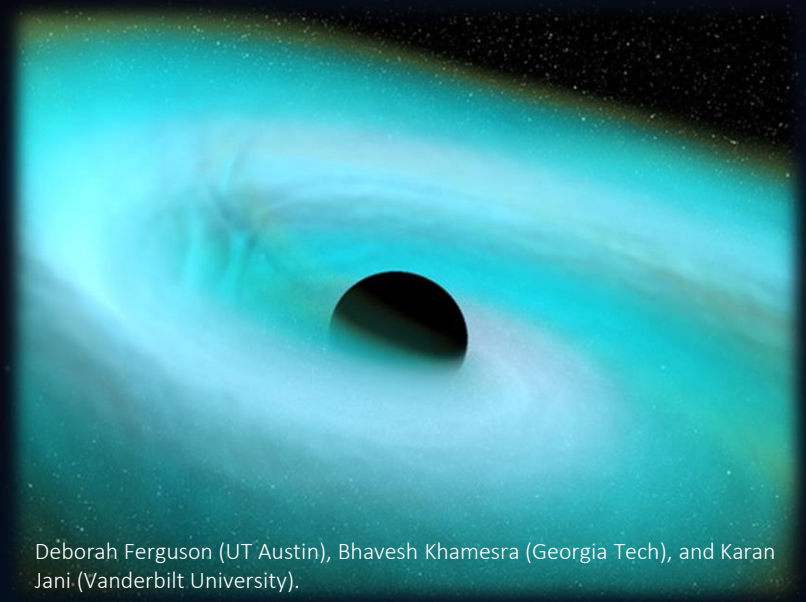
Abbott et al. (2021d), arXiv:2111.03606

Binary neutron star

University of Warwick/Mark Garlick

GW 170817
GW 190425

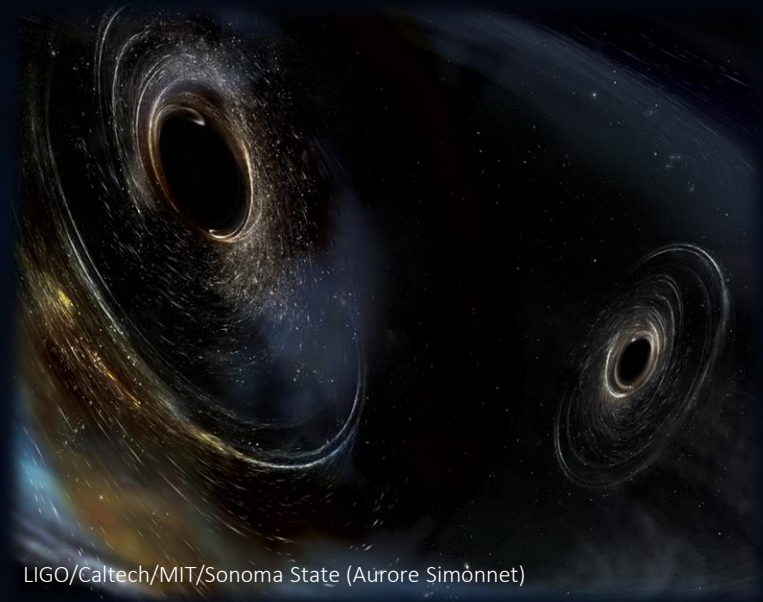
Neutron star–black hole



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

GW 200105
GW 200115

Binary black hole

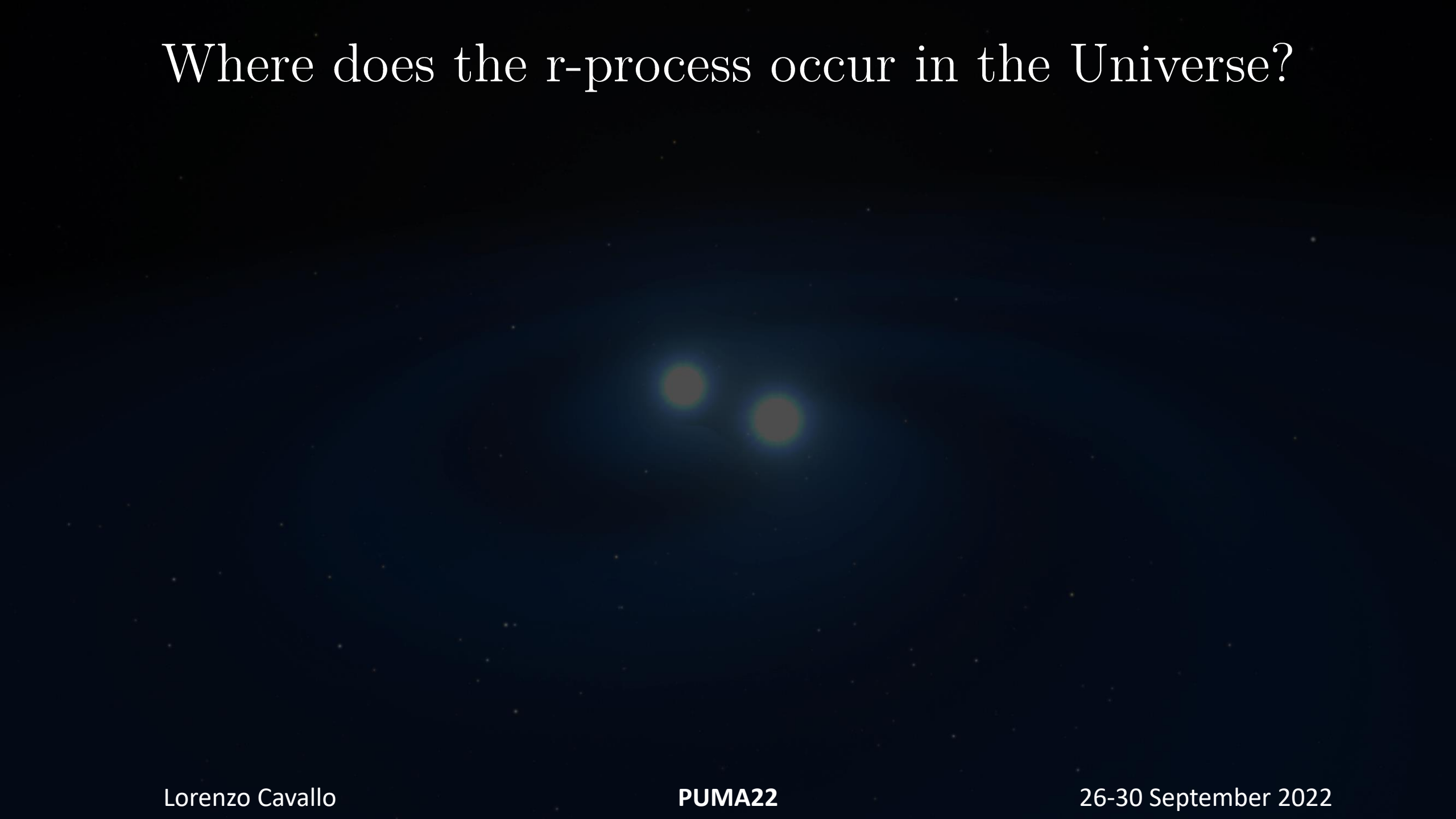


LIGO/Caltech/MIT/Sonoma State (Aurore Simonnet)

GW 150914
GW 151012
GW 151226
⋮
GW 200311

63 events

Where does the r-process occur in the Universe?

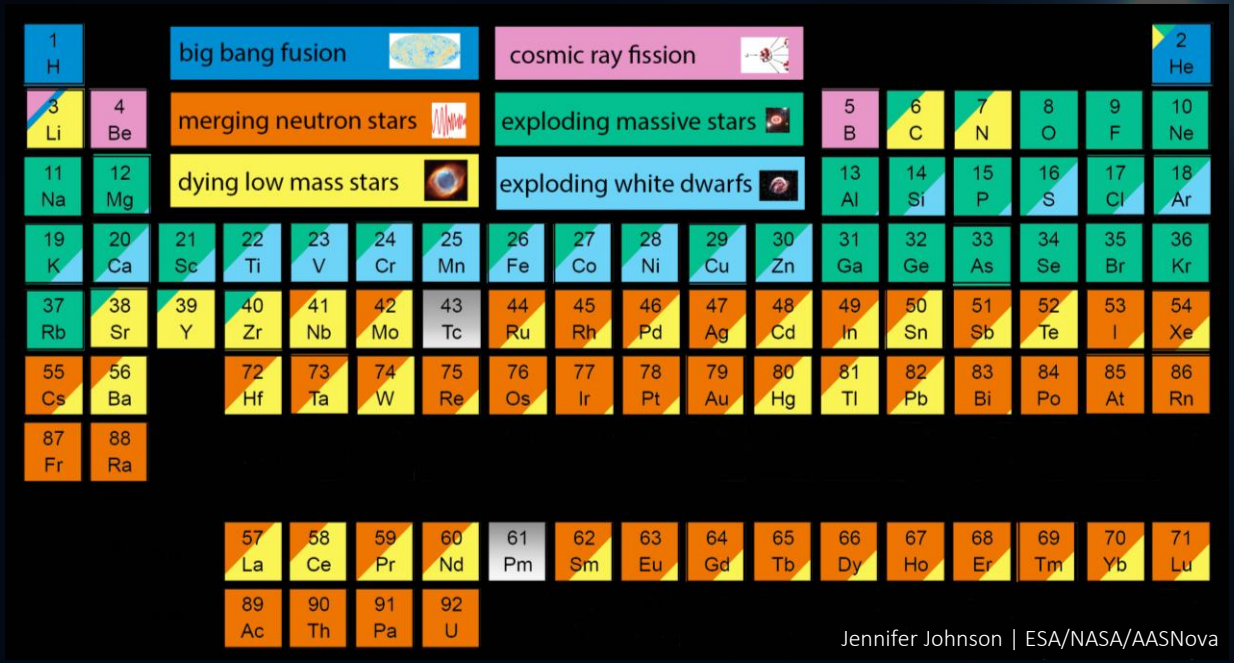


Where does the r-process occur in the Universe?

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

Neutron capture process

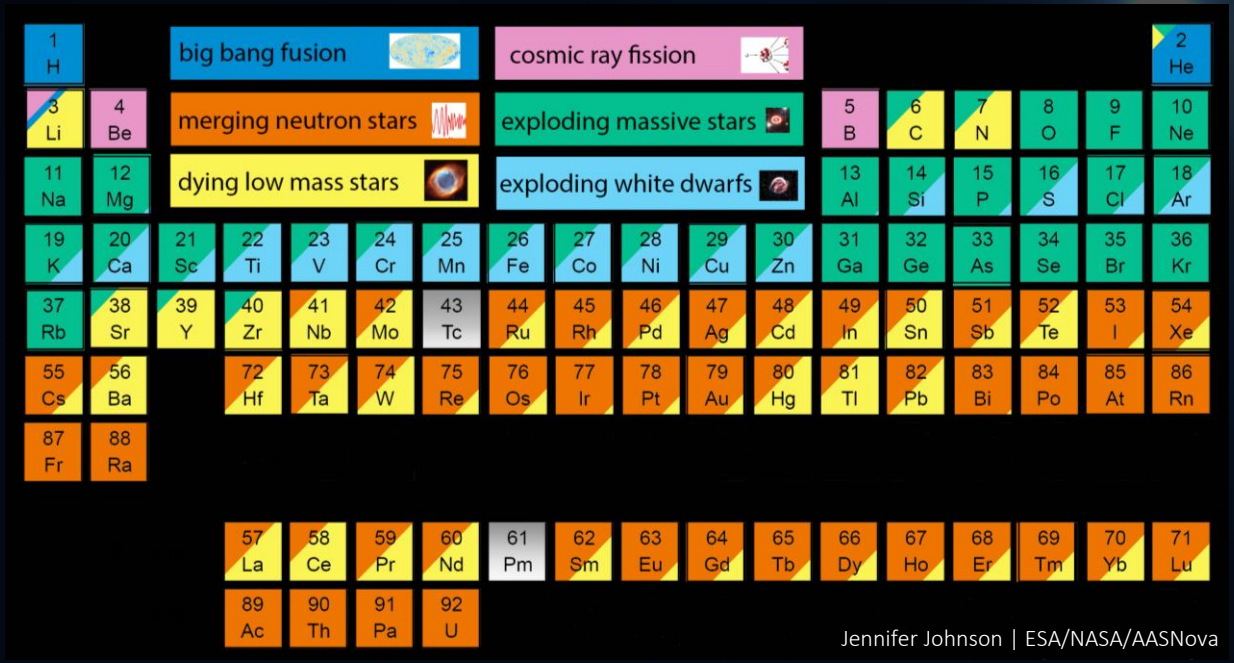
- Rapid-neutron capture process
- Slow-neutron capture process

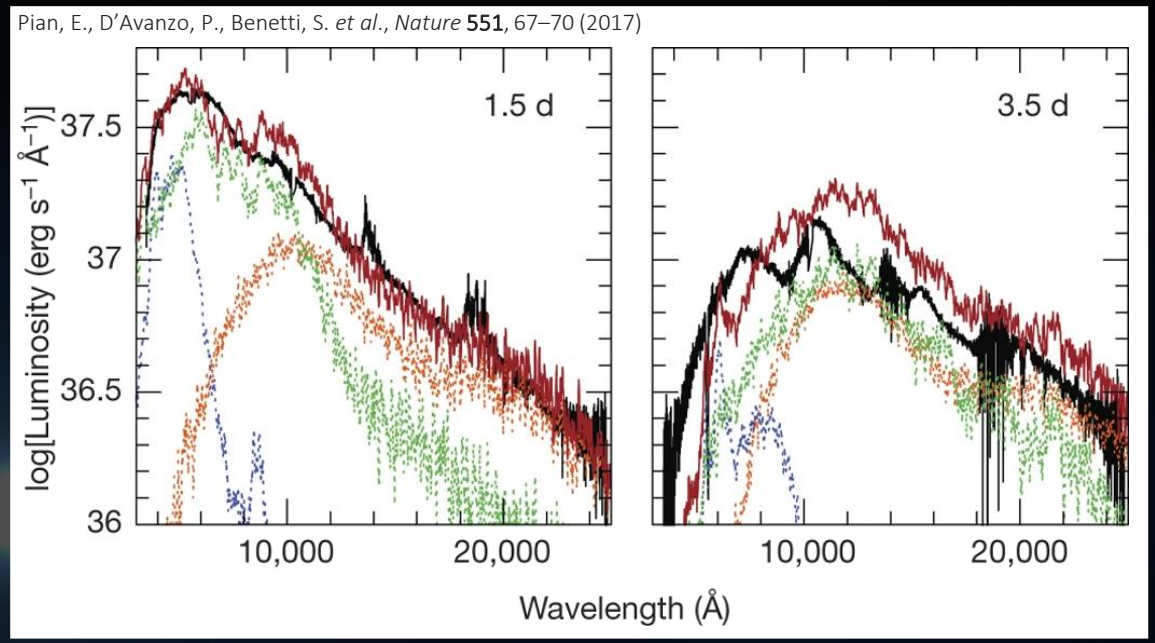


Where does the r-process occur in the Universe?

Neutron capture process → Rapid-neutron capture process

Neutron capture process → Slow-neutron capture process



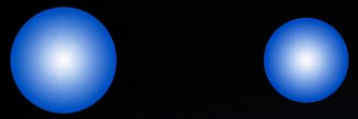


Kilonova evolution from blue to red has been generated by the presence of newly produced r-process elements.

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

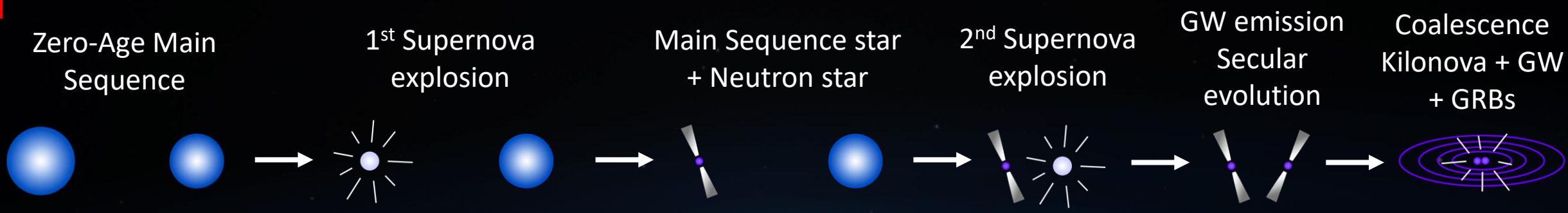
GW emission Secular evolution

Coalescence Kilonova + GW + GRBs

NUCLEAR TIME

GRAVITATIONAL TIME

DELAY TIME



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

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

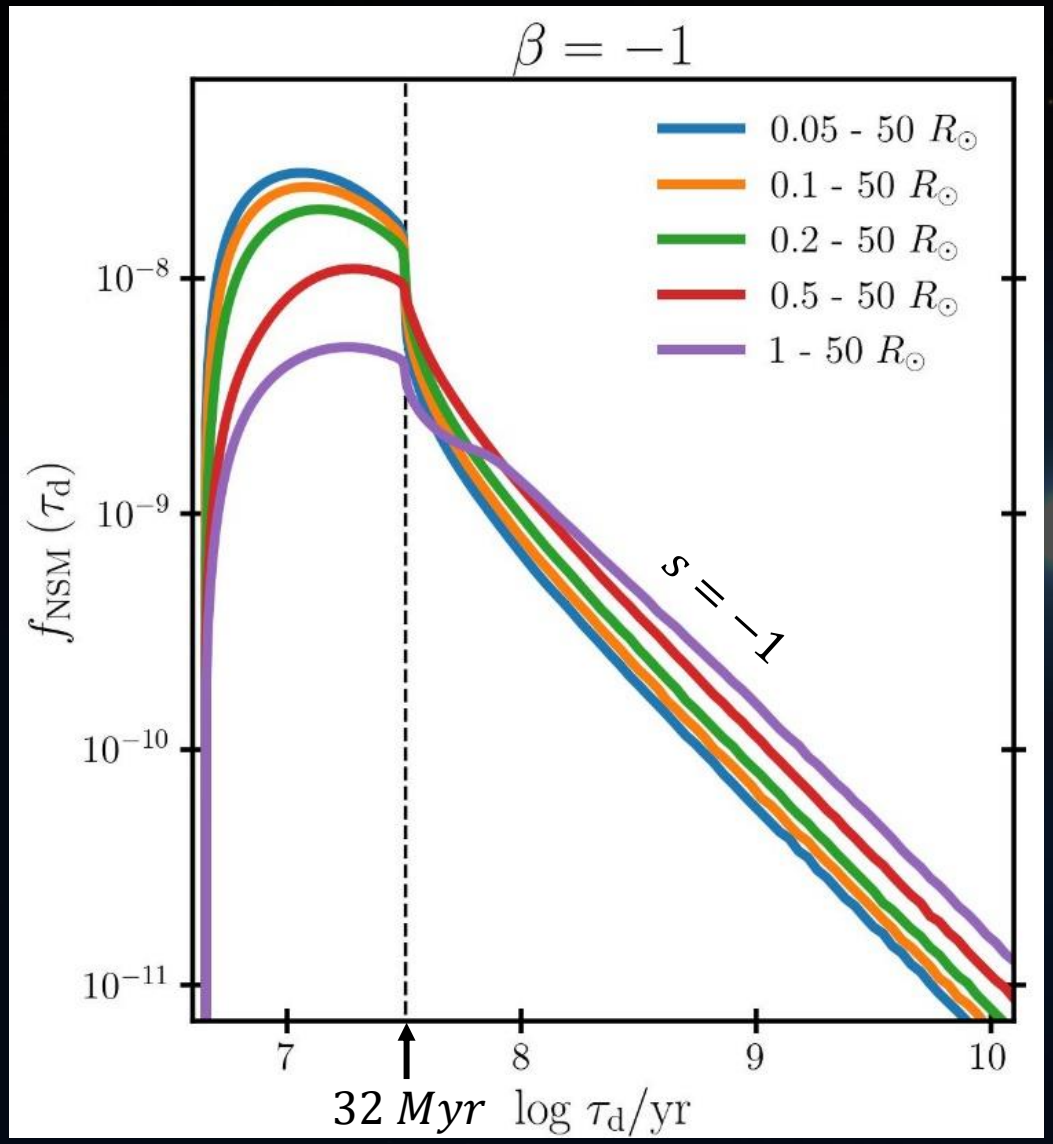
Slope of the power-law distribution:
$f(A) \propto A^{\beta}$

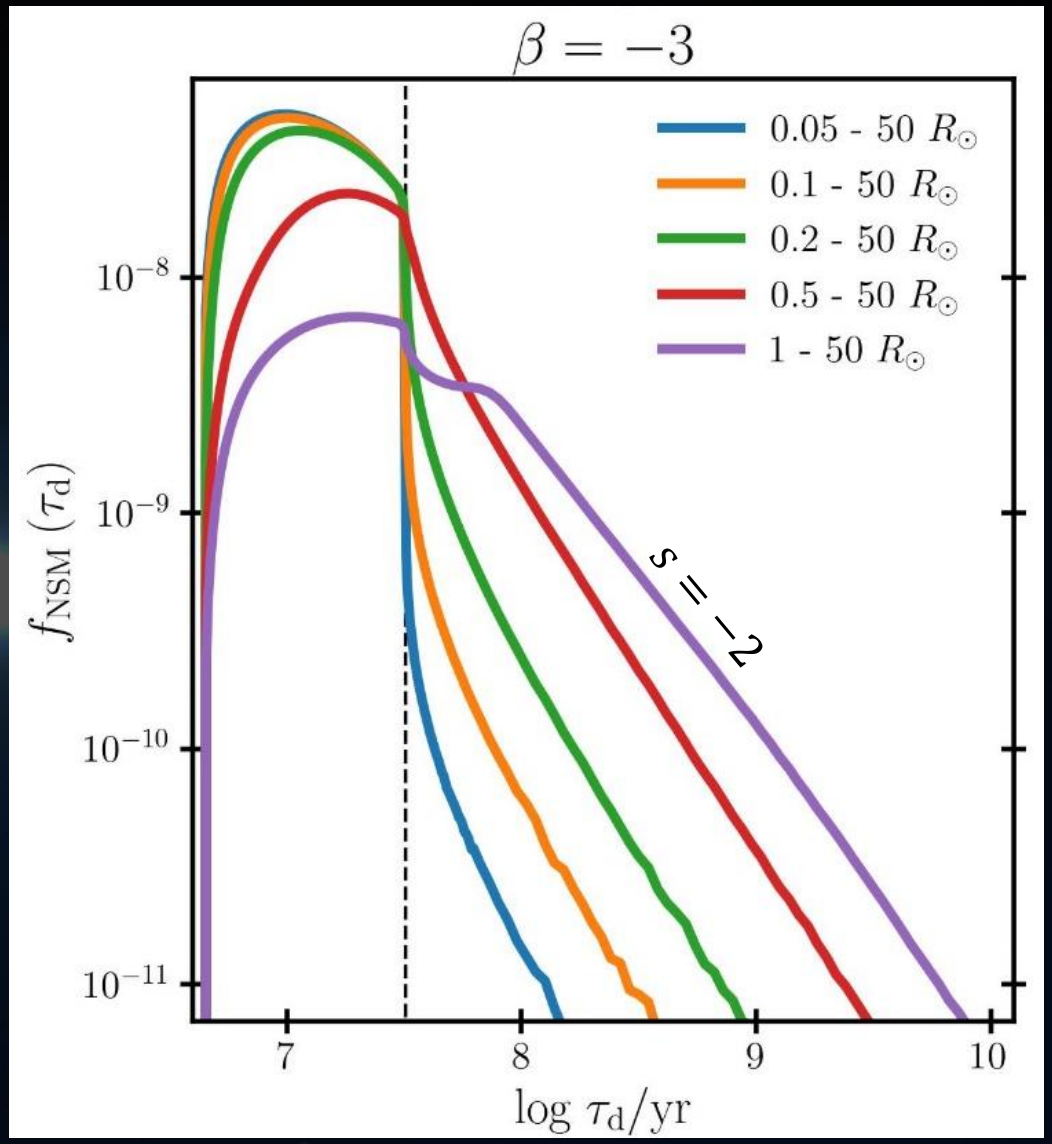
$\beta = -1$ $\beta = -2$ $\beta = -3$

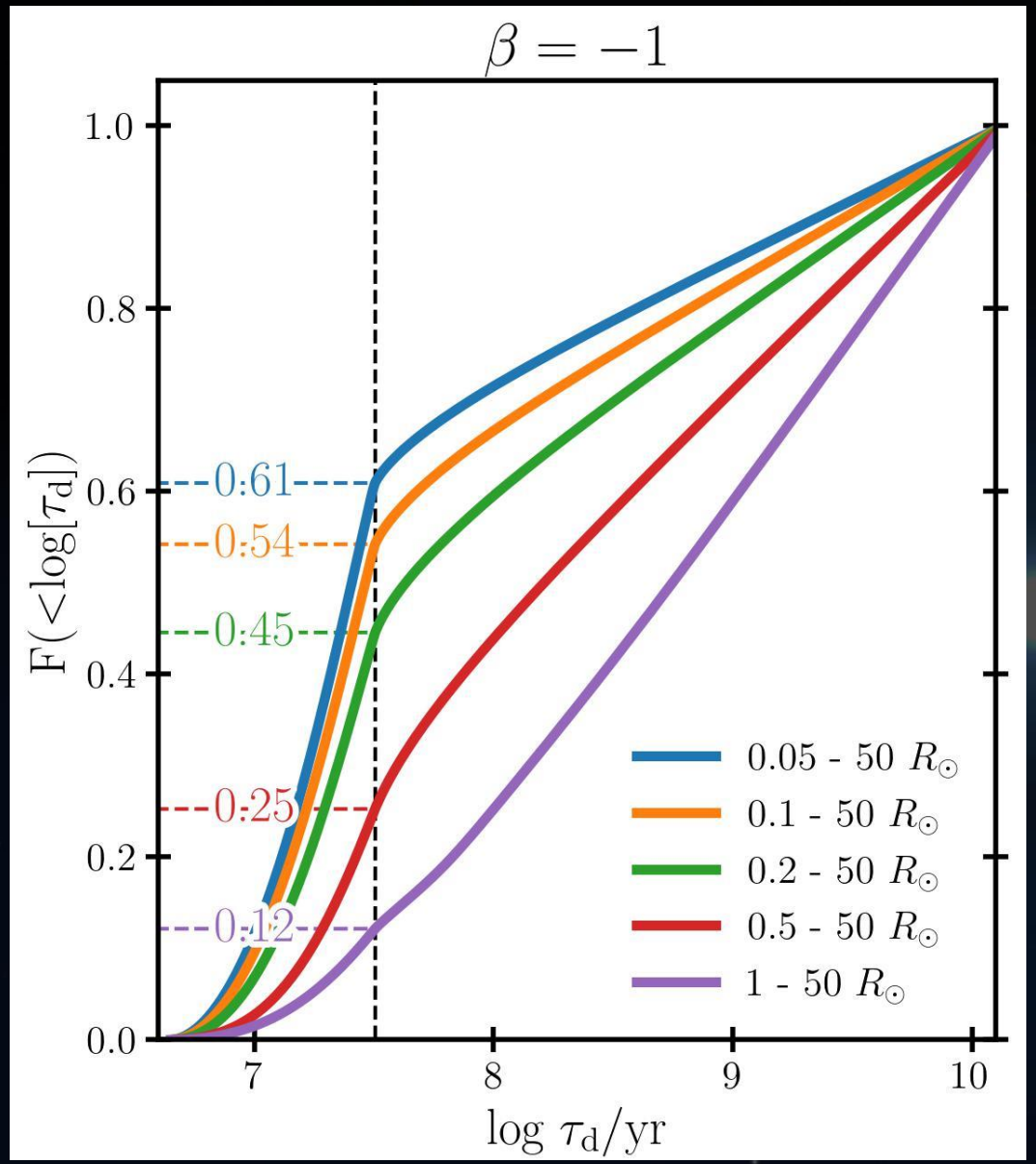
BPS models *Giacobbo & Mapelli 2018* *Belczynski et al. (2018)*

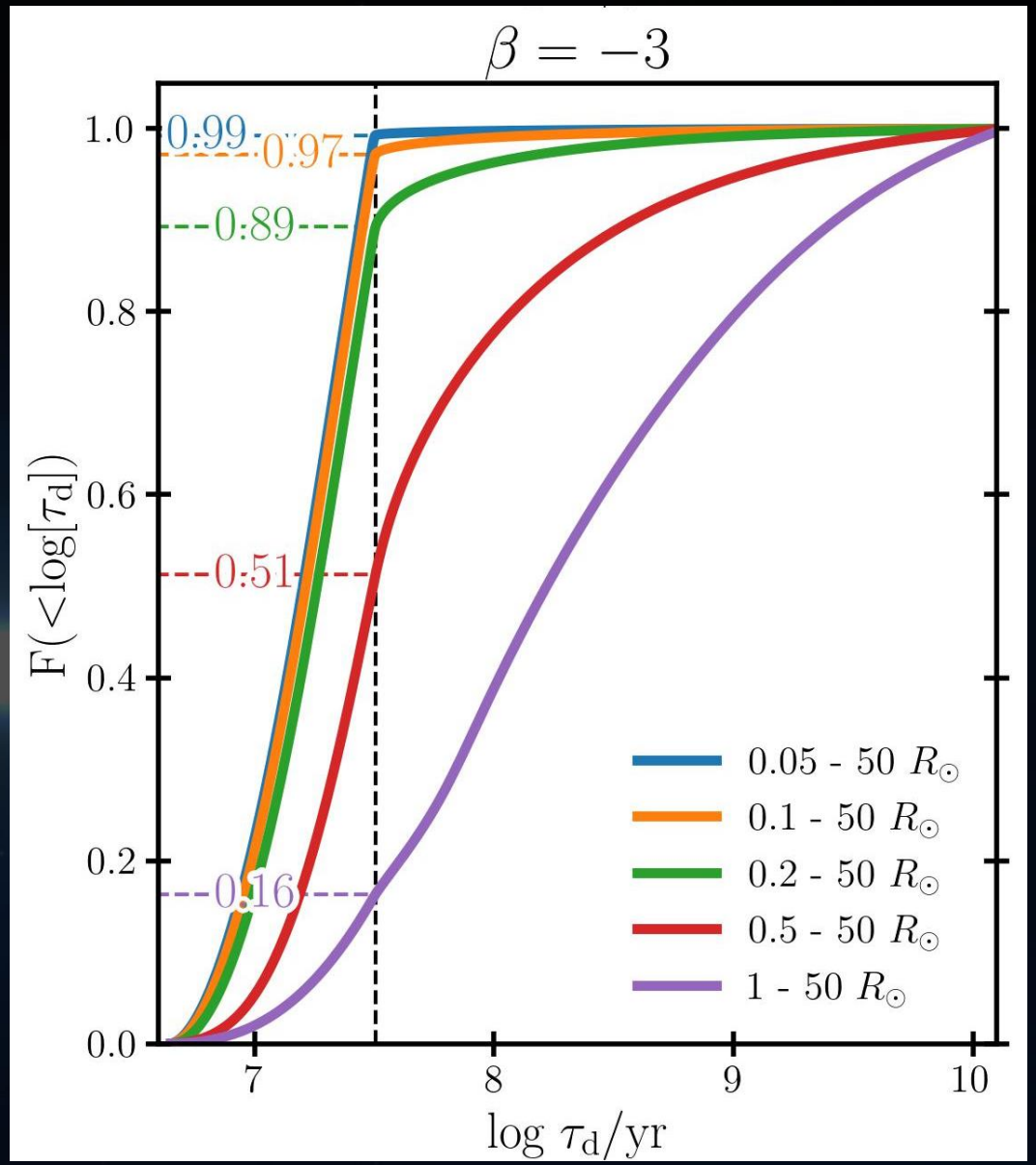
Range of separations:
$A_{min} - A_{max}$

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


$\beta = -1$
0.05 - 50 $R_\odot$
0.1 - 50 $R_\odot$
0.2 - 50 $R_\odot$
0.5 - 50 $R_\odot$
1 - 50 $R_\odot$
$s = -1$
$f_{\rm NSM}\,(\tau_{\rm d})$
10^{-8}
10^{-9}
10^{-10}
10^{-11}
7
8
9
10
32 Myr
$\log\,\tau_{\rm d}/{\rm yr}$


$\beta = -3$
0.05 - 50 $R_\odot$
0.1 - 50 $R_\odot$
0.2 - 50 $R_\odot$
0.5 - 50 $R_\odot$
1 - 50 $R_\odot$
$s = -2$
$f_{\rm NSM}\,(\tau_{\rm d})$
10^{-8}
10^{-9}
10^{-10}
10^{-11}
7
8
9
10
$\log\,\tau_{\rm d}/{\rm yr}$


$\beta = -1$
1.0
0.8
0.6
0.4
0.2
0.0
$F(<\log[\tau_d])$
0.61
0.54
0.45
0.25
0.12
7
8
9
10
$\log \tau_d/\mathrm{yr}$
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
$F(<\log[\tau_d])$
0.99
0.97
0.89
0.51
0.16
7
8
9
10
$\log \tau_d/\mathrm{yr}$
0.05 - 50 $R_\odot$
0.1 - 50 $R_\odot$
0.2 - 50 $R_\odot$
0.5 - 50 $R_\odot$
1 - 50 $R_\odot$

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

To do that we first developed

↓

MOCK UNIVERSE

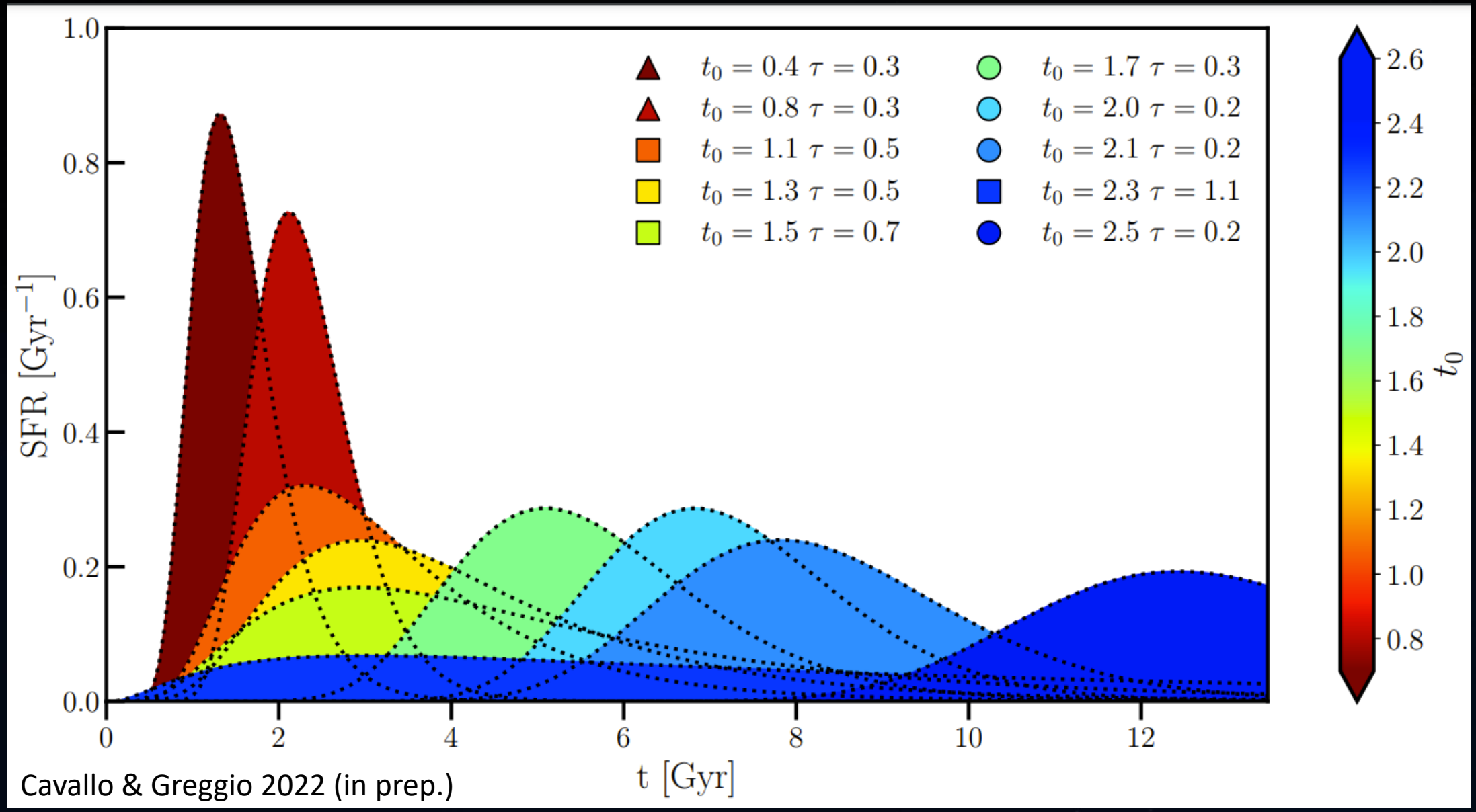
↓

composed of a sample of galaxies that fulfils major observational facts

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 2022 (in prep.)

To do that we first developed

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MOCK UNIVERSE

↓

composed of a sample of galaxies that fulfils major observational facts

To do that we first developed

MOCK UNIVERSE

composed of a sample of galaxies that fulfils major observational facts

- Star formation rate density (SFRD) — *Madau & Dickinson (2014)*
- Mass distribution function (MDF) observed for nearby galaxies — *Peng et al. (2015)*
- Star-forming main sequence of galaxies — *Renzini & Peng (2015)*

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

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

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

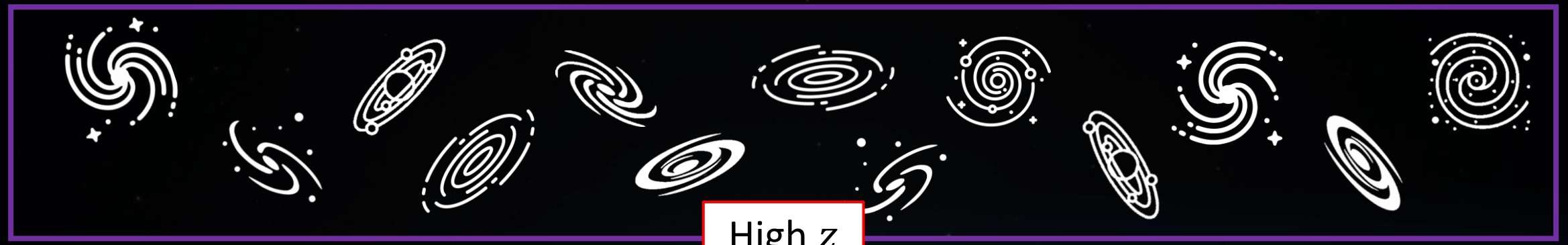
$$\mathcal{R} = 320^{+490}_{-240}\ Gpc^{-3} yr^{-1}$$

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

Tacchella et al. (2022)

$D(z) < 1/3$ → **Early-type**

$D(z) \geq 1/3$ → **Late-type**



High z

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

Tacchella et al. (2022)

$D(z) < 1/3$ → **Early-type**

$D(z) \geq 1/3$ → **Late-type**

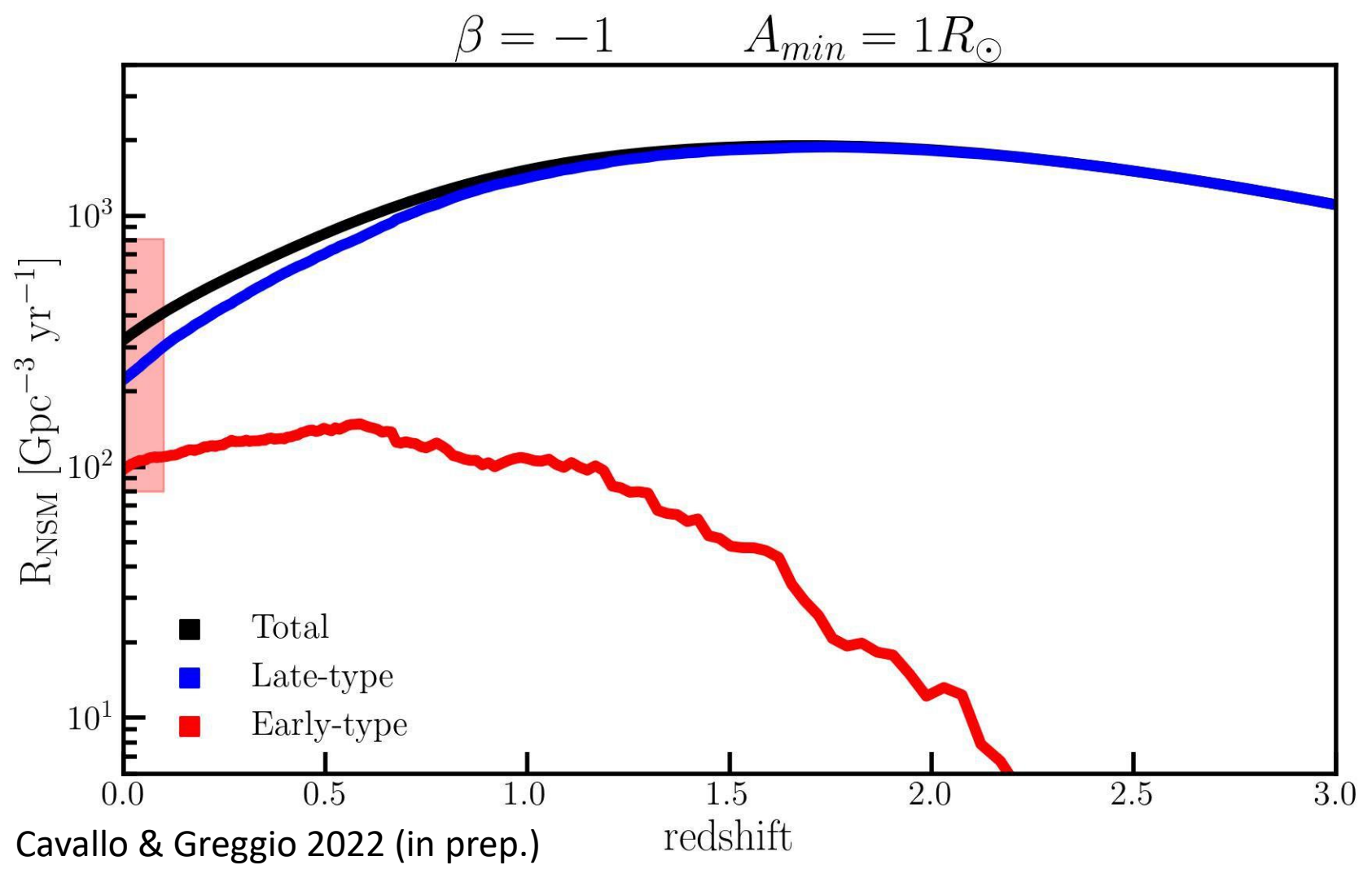
Nearby Universe

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

Tacchella et al. (2022)

$D(z) < 1/3$ → **Early-type**

$D(z) \geq 1/3$ → **Late-type**

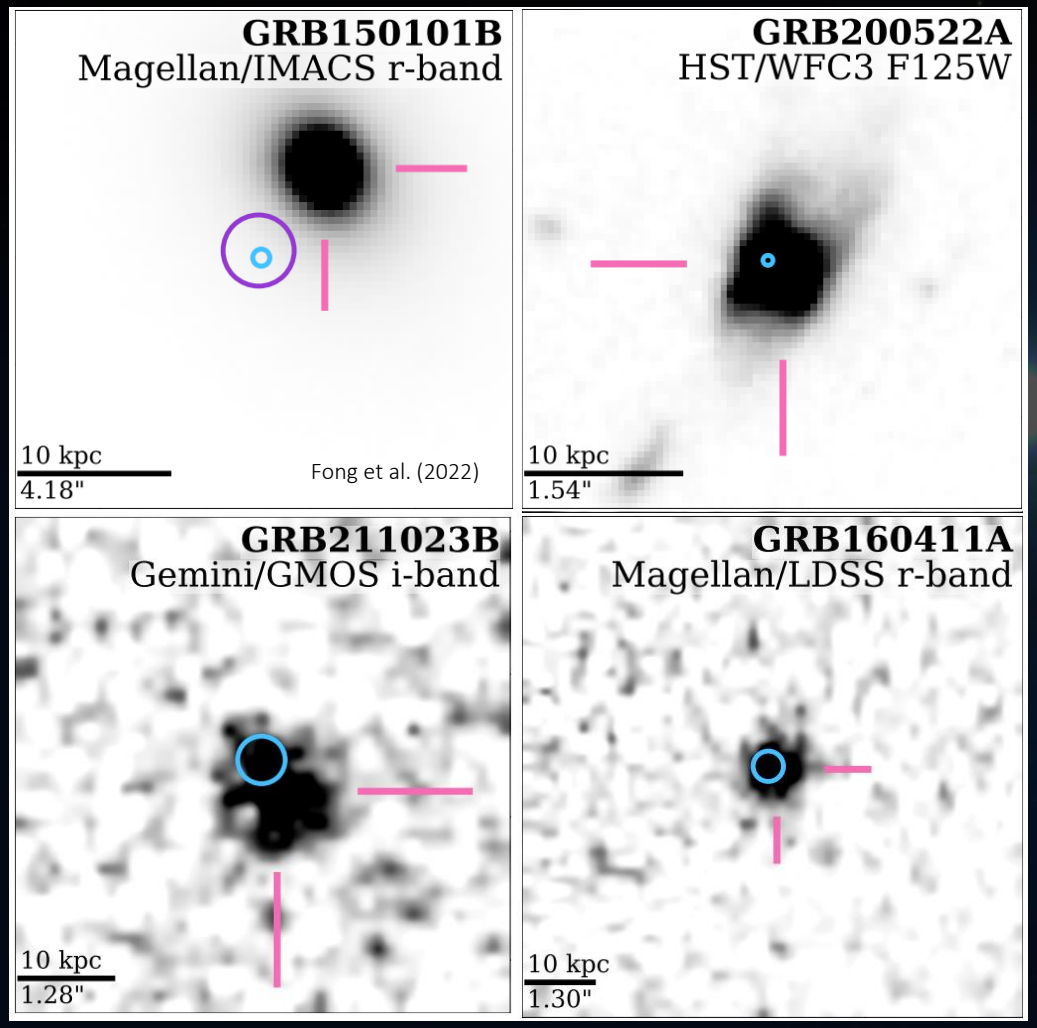


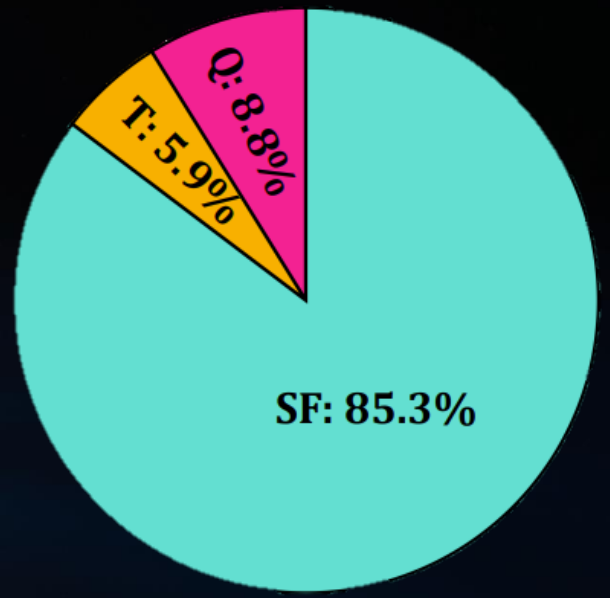
Cavallo & Greggio 2022 (in prep.)

Fraction of NSMs in late-type galaxies

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

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.

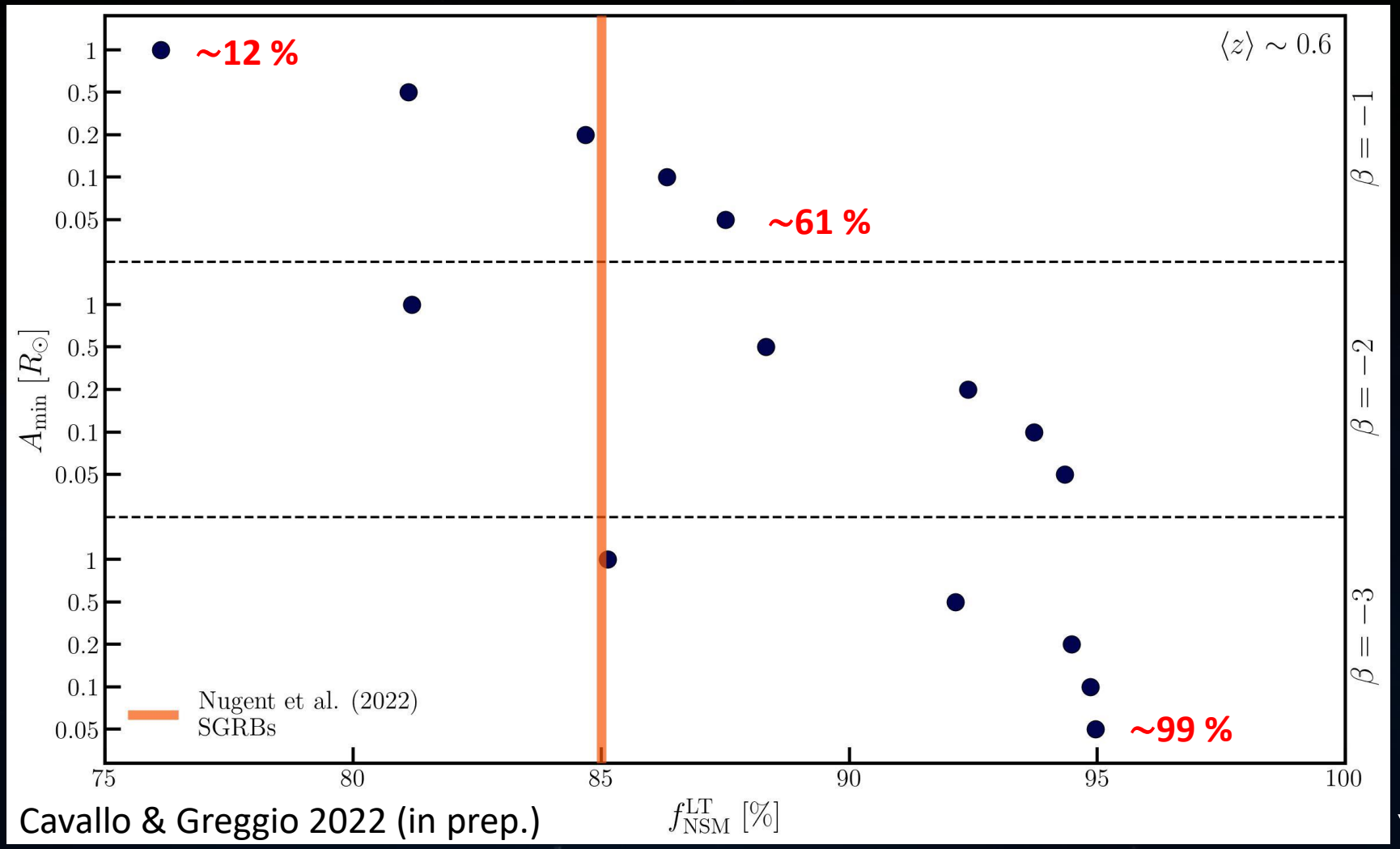


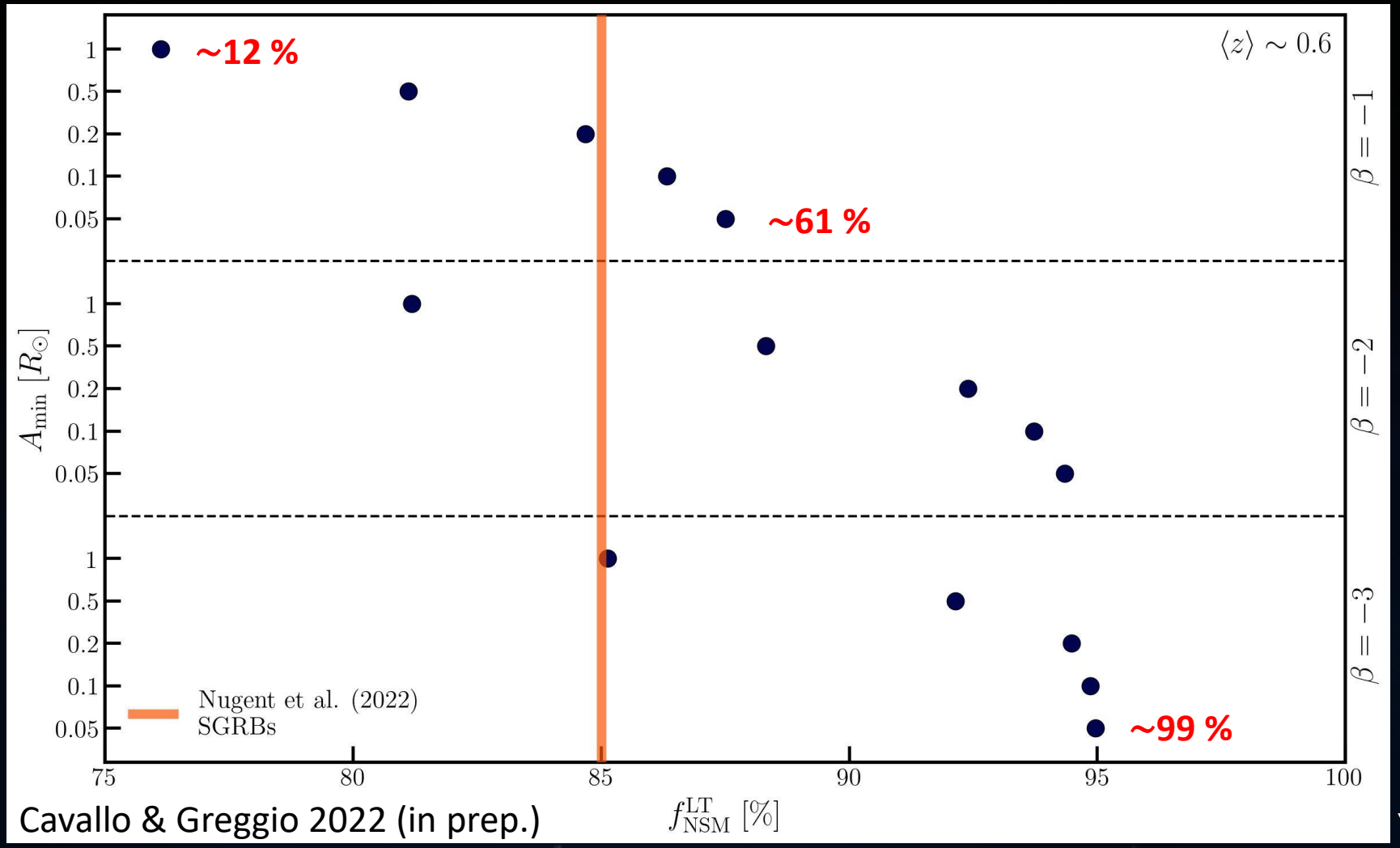


Nugent et al. (2022)

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**

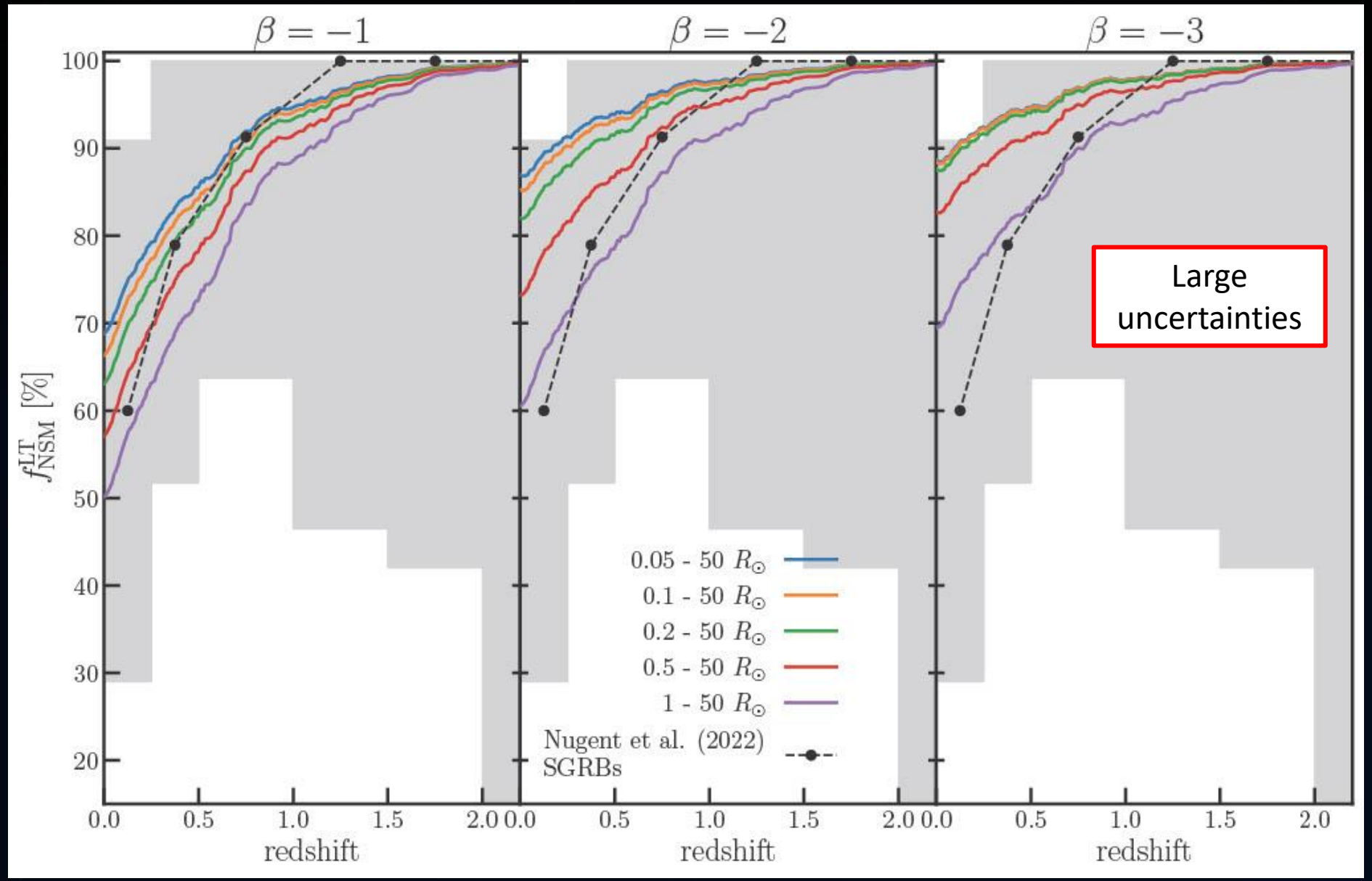

~12 %
~61 %
~99 %
$\langle z \rangle \sim 0.6$
$\beta = -1$
$\beta = -2$
$\beta = -3$
$A_{\rm min}$ $[R_\odot]$
Nugent et al. (2022)
SGRBs
$f^{\rm LT}_{\rm NSM}$ [%]
Cavallo & Greggio 2022 (in prep.)
less
Prompt events
more



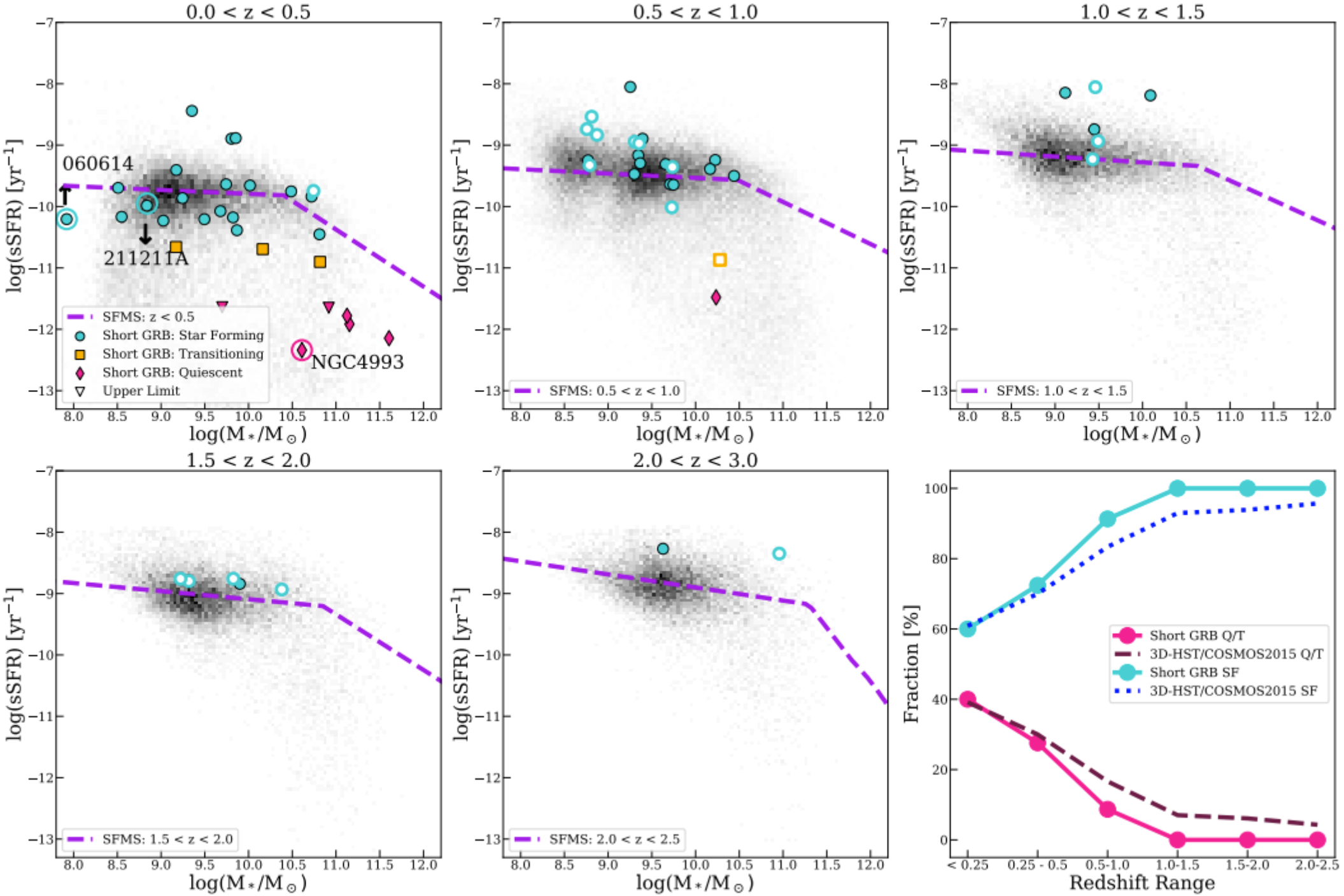
The fraction of short-GRBs observed in late-type galaxies favors DTDs with a fair fraction of prompt events.

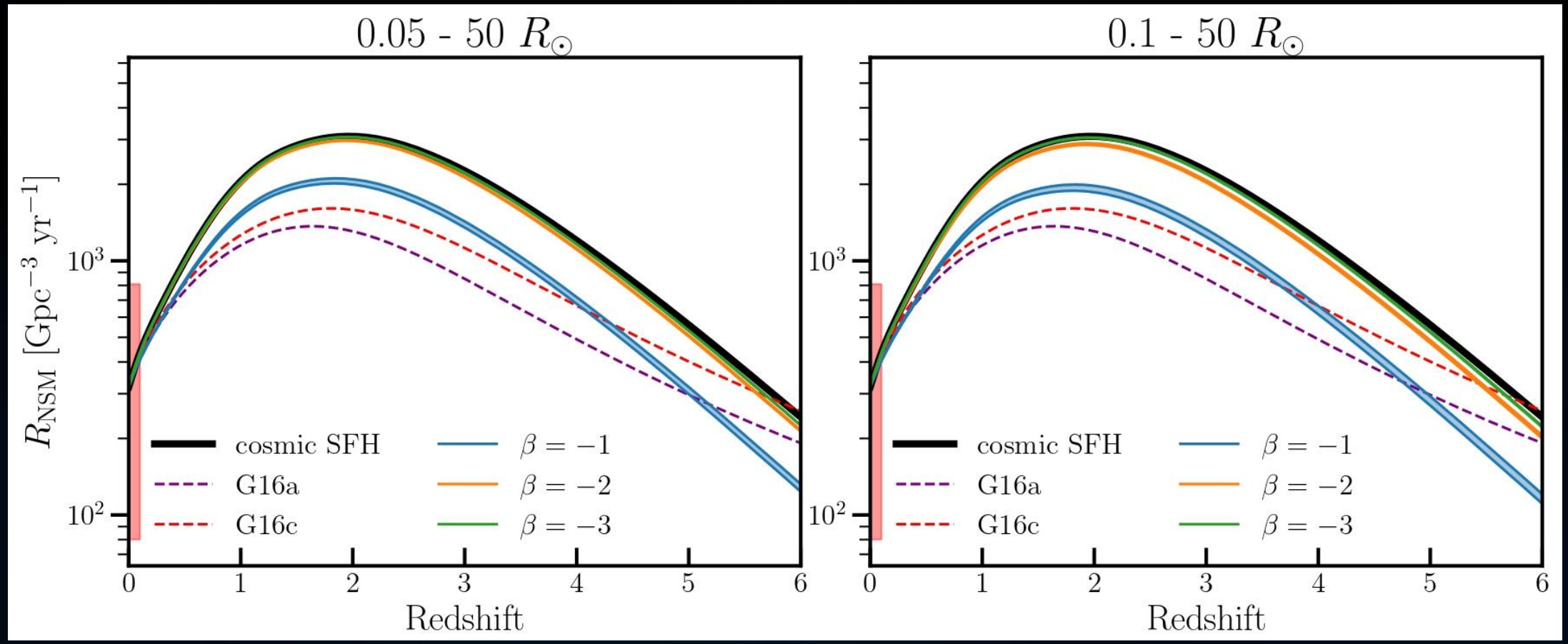
We notice that a similar indication is obtained from chemical evolution models.

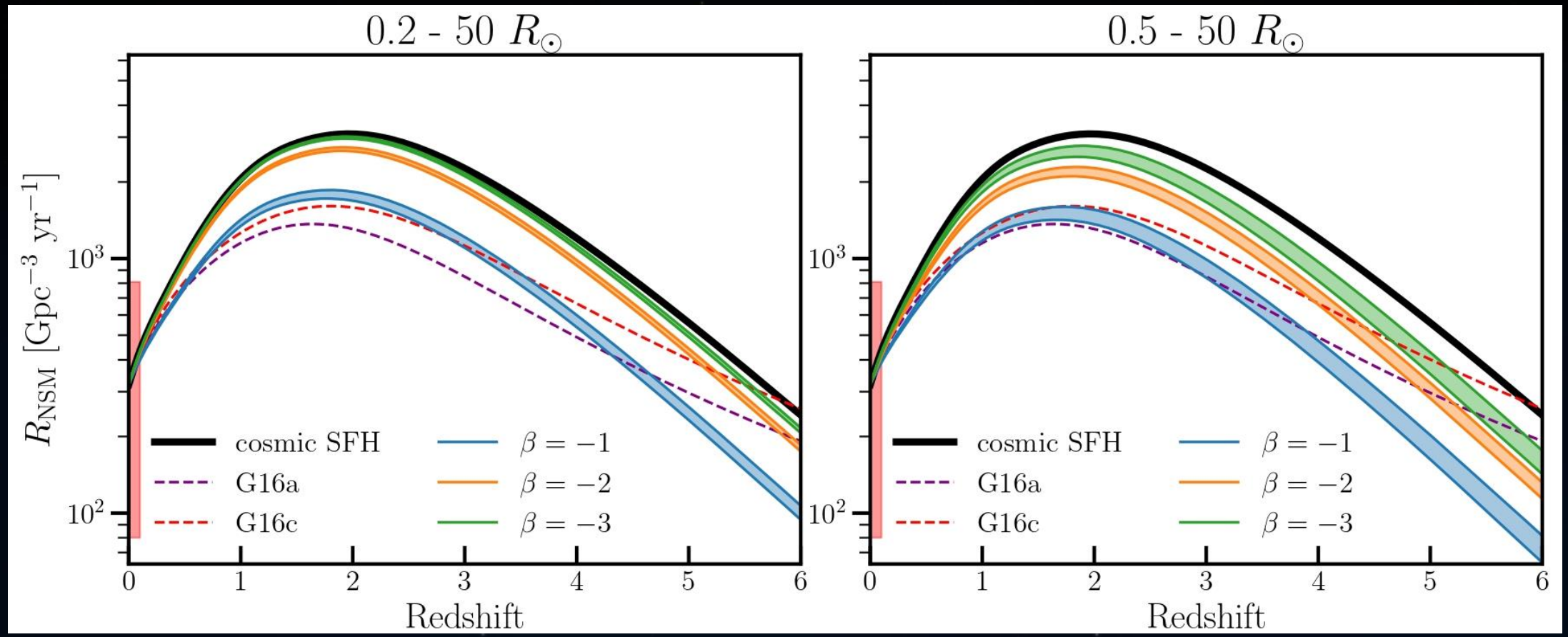
Future (?)

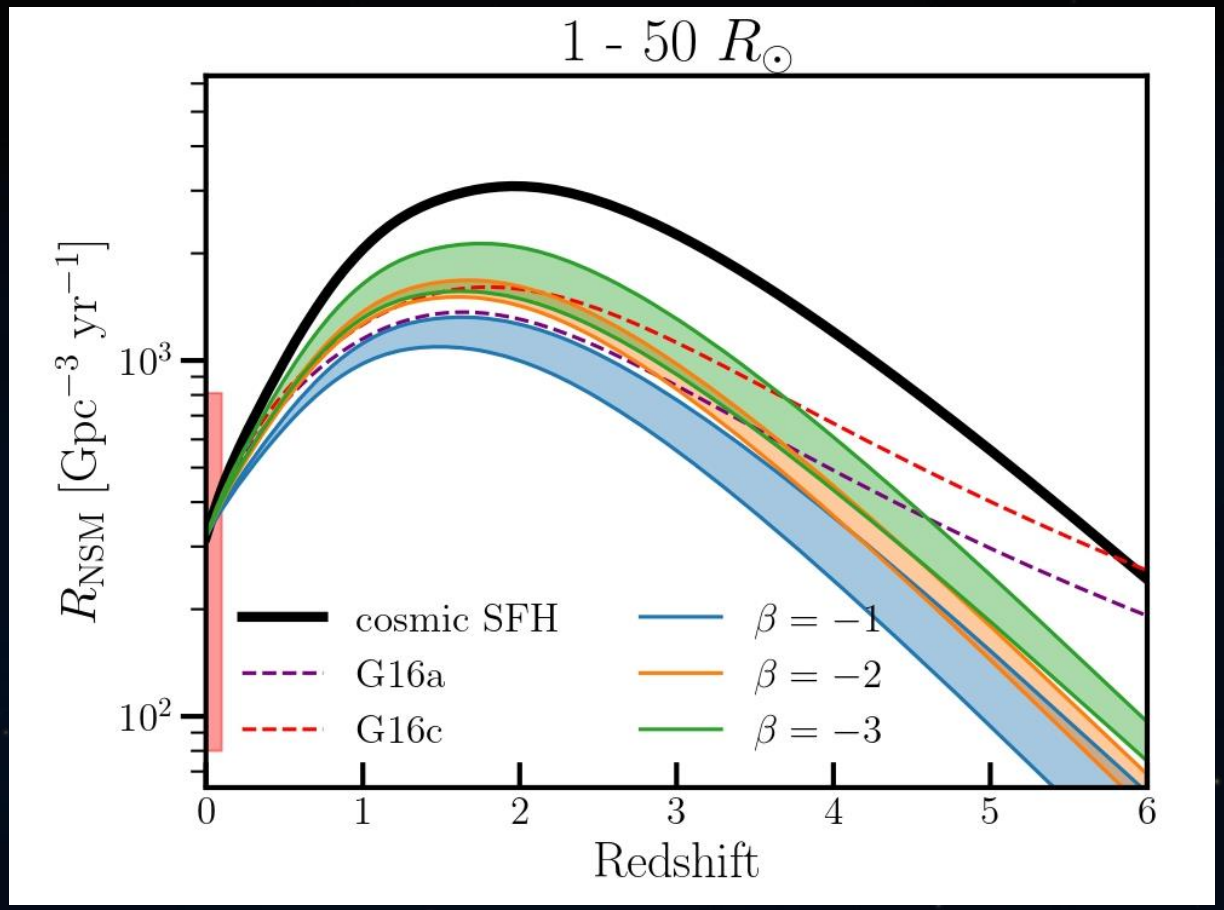

$\beta = -1$
$\beta = -2$
$\beta = -3$
$f^{\rm LT}_{\rm NSM}$ [%]
100
90
80
70
60
50
40
30
20
0.0
0.5
1.0
1.5
2.0
redshift
0.05 - 50 $R_\odot$
0.1 - 50 $R_\odot$
0.2 - 50 $R_\odot$
0.5 - 50 $R_\odot$
1 - 50 $R_\odot$
Nugent et al. (2022)
SGRBs
Large uncertainties

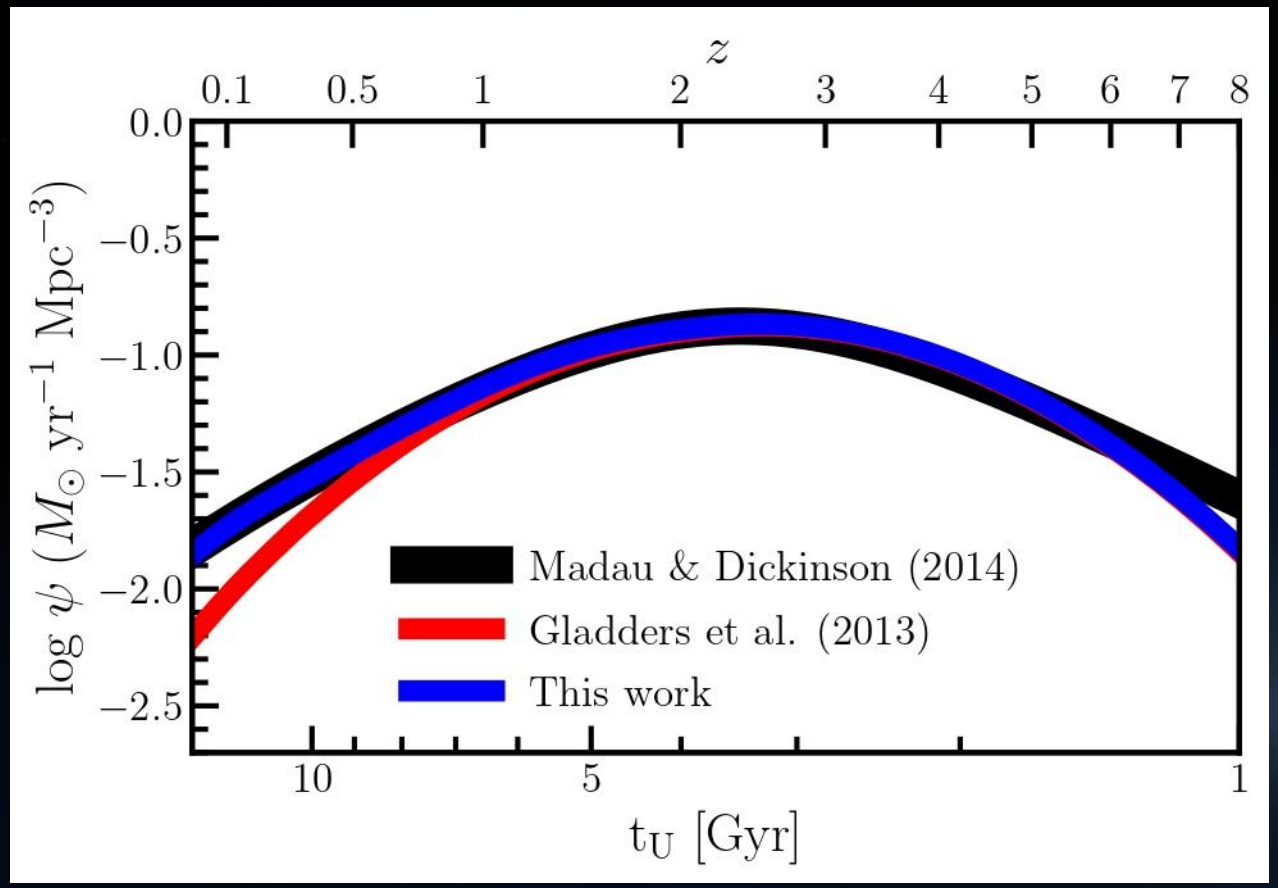
BACKUP

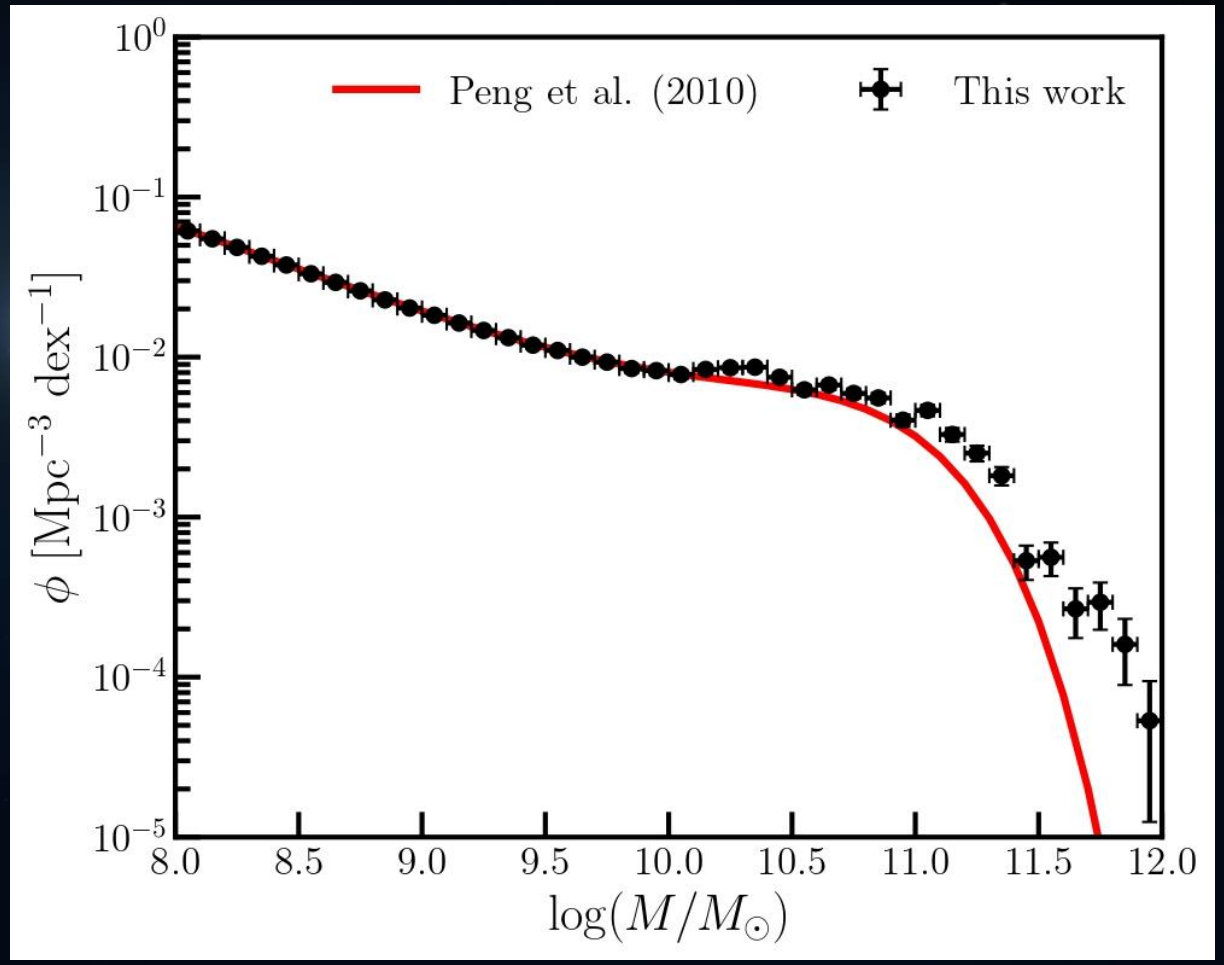

0.0 < z < 0.5
0.5 < z < 1.0
1.0 < z < 1.5
1.5 < z < 2.0
2.0 < z < 3.0
log(sSFR) [yr^{-1}]
log(M$_*$/M$_\odot$)
060614
211211A
NGC4993
SFMS: z < 0.5
SFMS: 0.5 < z < 1.0
SFMS: 1.0 < z < 1.5
SFMS: 1.5 < z < 2.0
SFMS: 2.0 < z < 2.5
Short GRB: Star Forming
Short GRB: Transitioning
Short GRB: Quiescent
Upper Limit
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
cosmic SFH
G16a
G16c
$\beta = -1$
$\beta = -2$
$\beta = -3$
0
1
2
3
4
5
6
Redshift


z
0.1
0.5
1
2
3
4
5
6
7
8
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
log ψ ($M_\odot$ yr^{-1} Mpc^{-3})
Madau & Dickinson (2014)
Gladders et al. (2013)
This work
10
5
1
t_U [Gyr]


Peng et al. (2010)
This work
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
ϕ [Mpc^{-3} dex^{-1}]
8.0
8.5
9.0
9.5
10.0
10.5
11.0
11.5
12.0
log($M/M_\odot$)