Predicted rates of Merging Neutron Stars in galaxies

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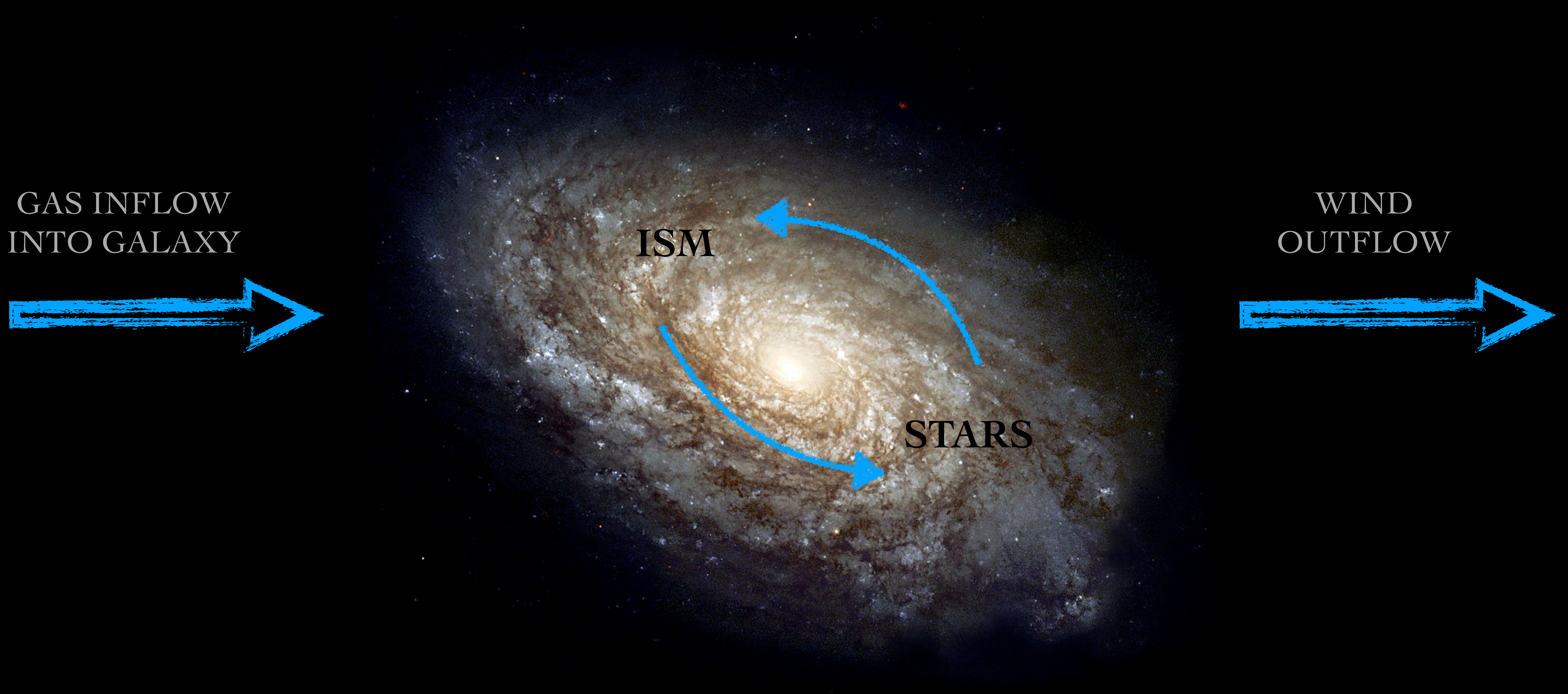
Chemical evolution of galaxies

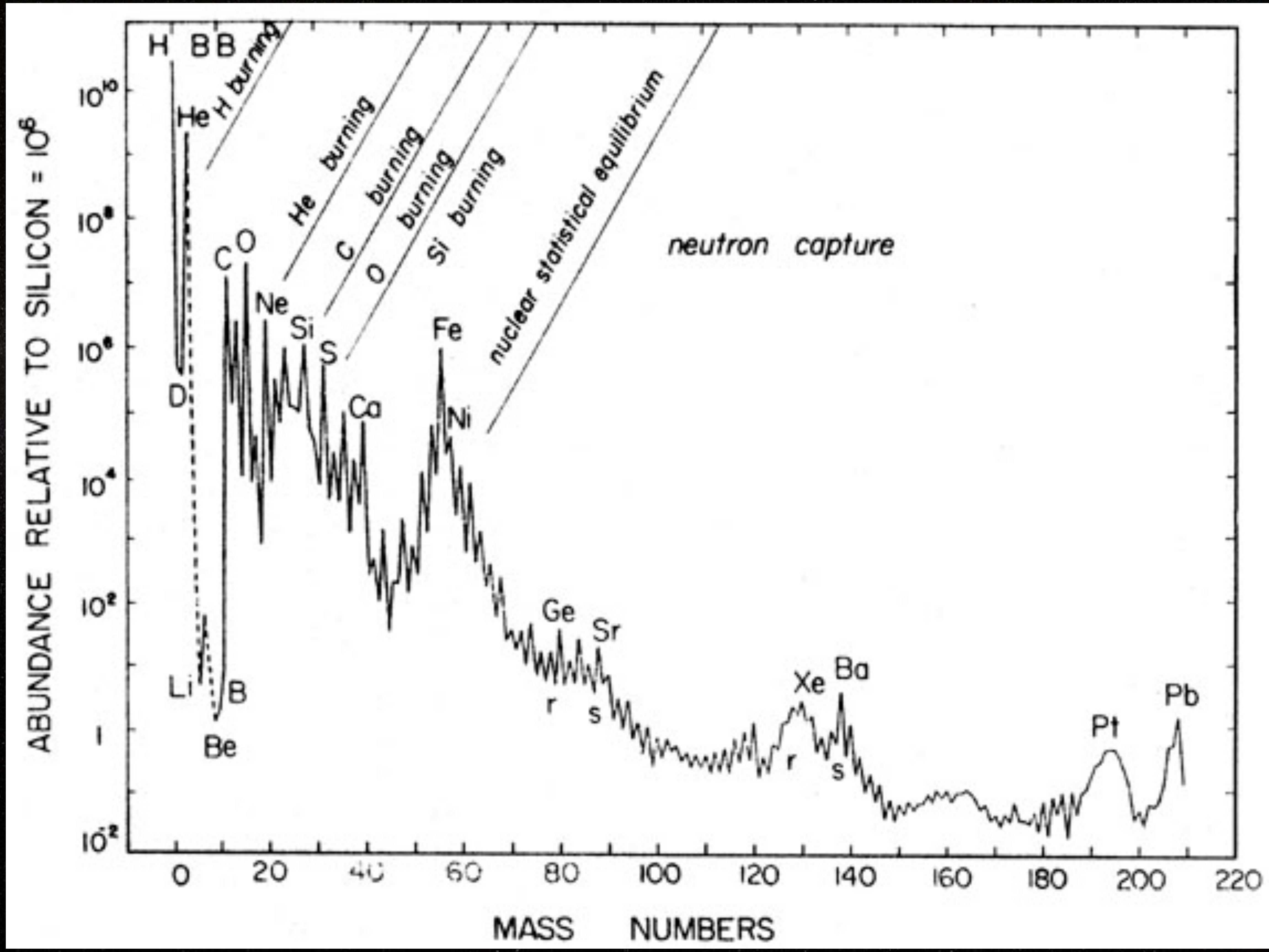


Equations of Chemical Evolution

$$\dot{M}_{\mathrm{gas},i}(t) = \boxed{-\psi(t)X_i(t)} + \boxed{X_{i,A}A(t)} - \boxed{X_i(t)W(t)} - \boxed{X_i(t)\dot{M}_{BH}(t)} + \boxed{\dot{R}_i(t)}$$

- Rate at which chemical elements are subtracted by the ISM to be included in star
- Rate at which chemical elements are accreted through infall of gas
- Rate at which chemical elements are lost through galactic wind
- Rate at which the material is accreted by the BH
- Rate of restitution of matter from stars to the ISM

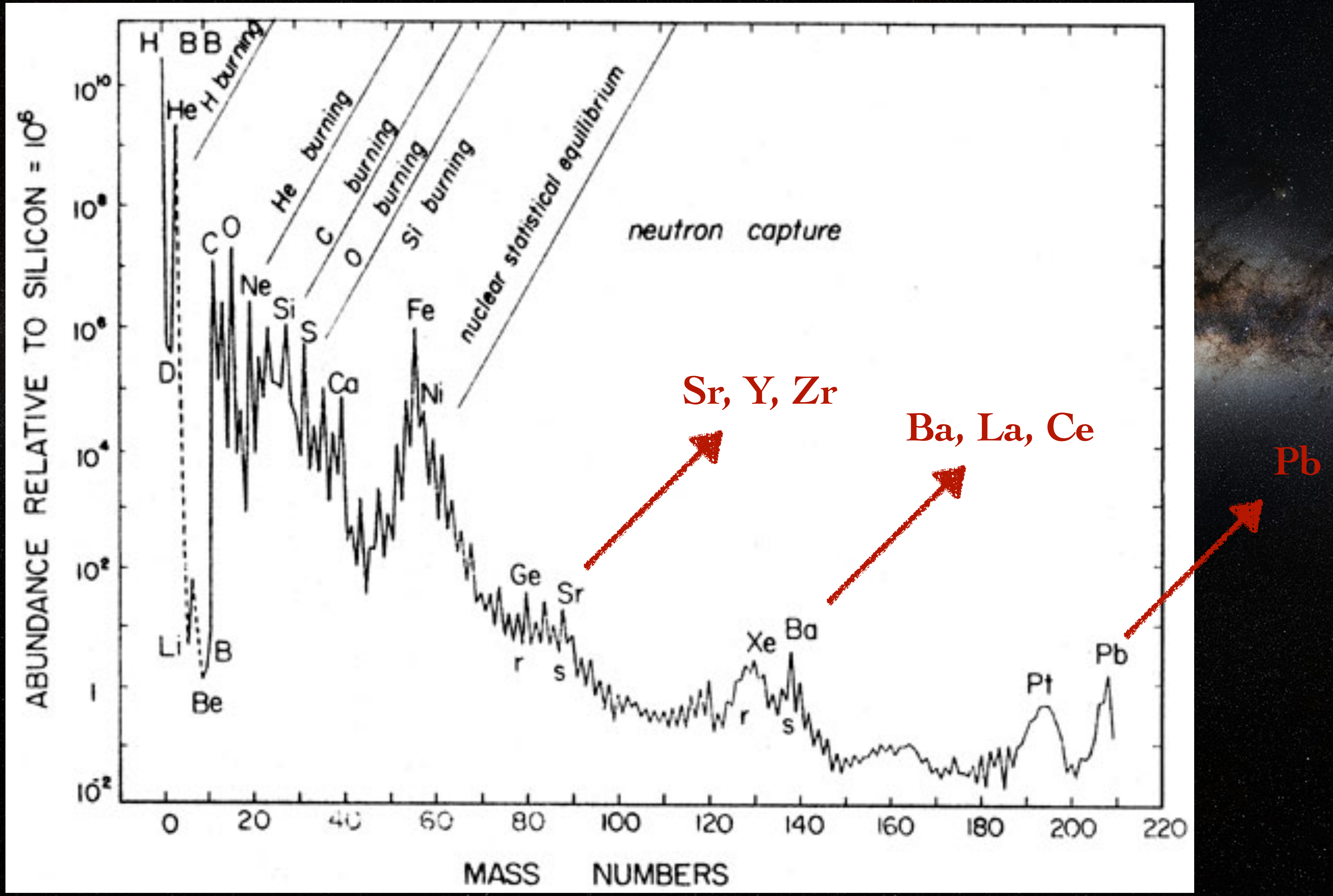
Neutron capture elements nucleosynthesis



s-process: the unstable nuclide created by neutron capture will decay in a stable nuclide before it has time to capture another neutron

r-process: there is time for multiple neutron captures before the first β-decay occurs

Neutron capture elements nucleosynthesis



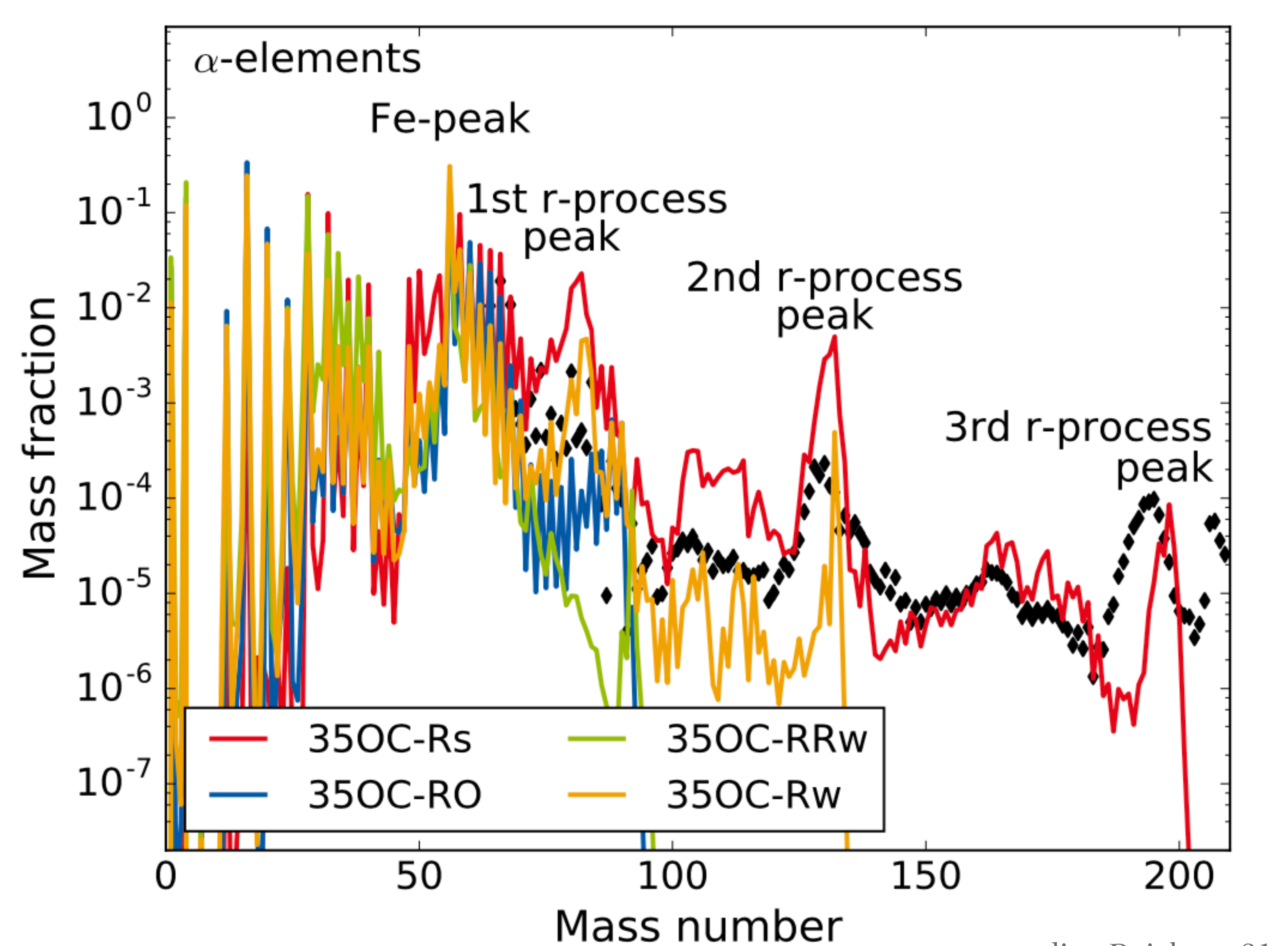
Weak s-process: (rotating) massive stars ($M > 8M_\odot$)

Main s-process: Low-intermediate mass stars (LIMS, $M < 8M_\odot$) during the AGB phase

Strong s-process: Low-metallicity low-mass AGB stars

Neutron capture elements nucleosynthesis

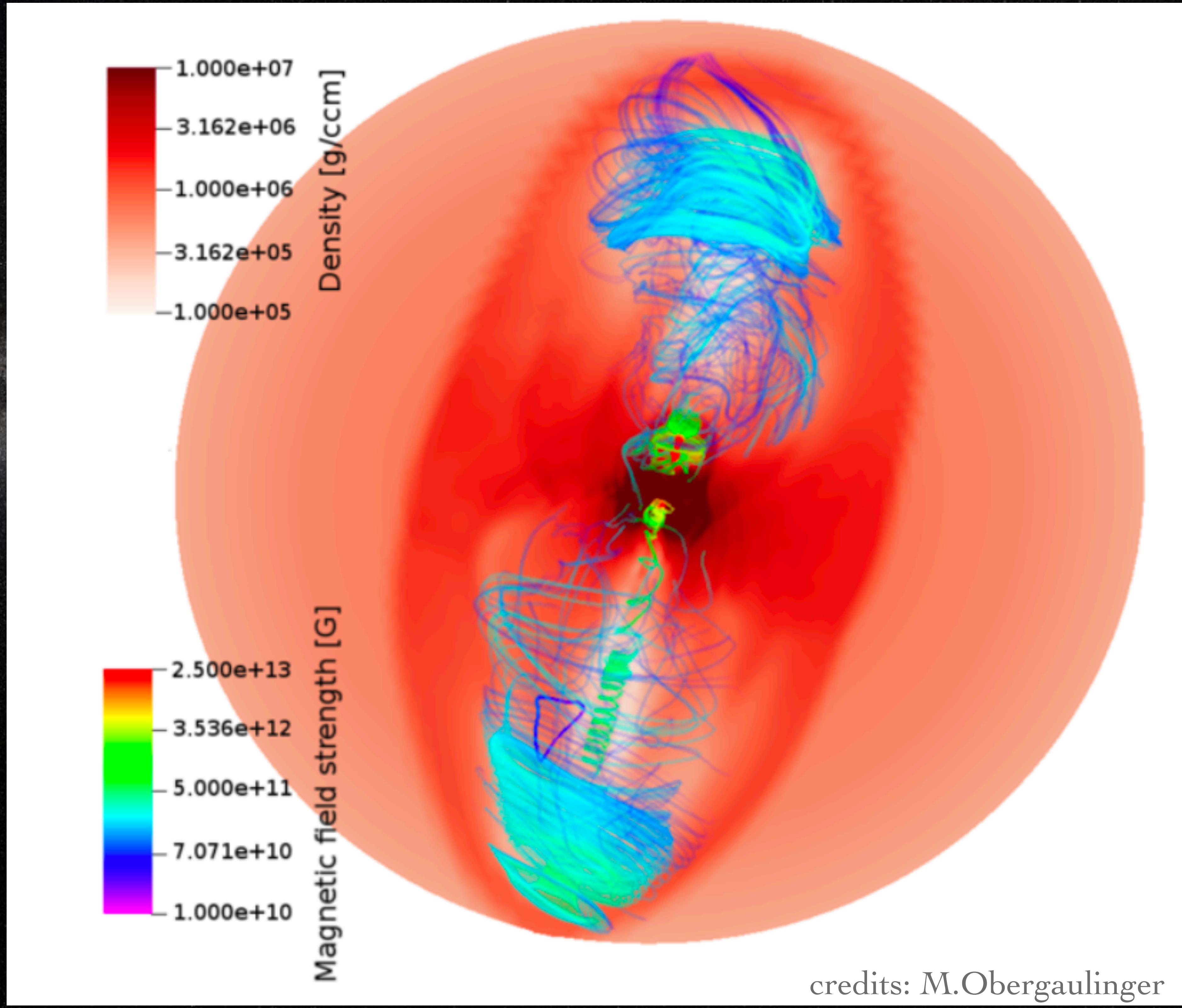
CC-SNe



credits: Reichert+21

Standard supernovae cannot produce elements beyond the second r-process peak: the eject is often proton rich with some small clumps of slightly neutron-rich material

MRD-SNe

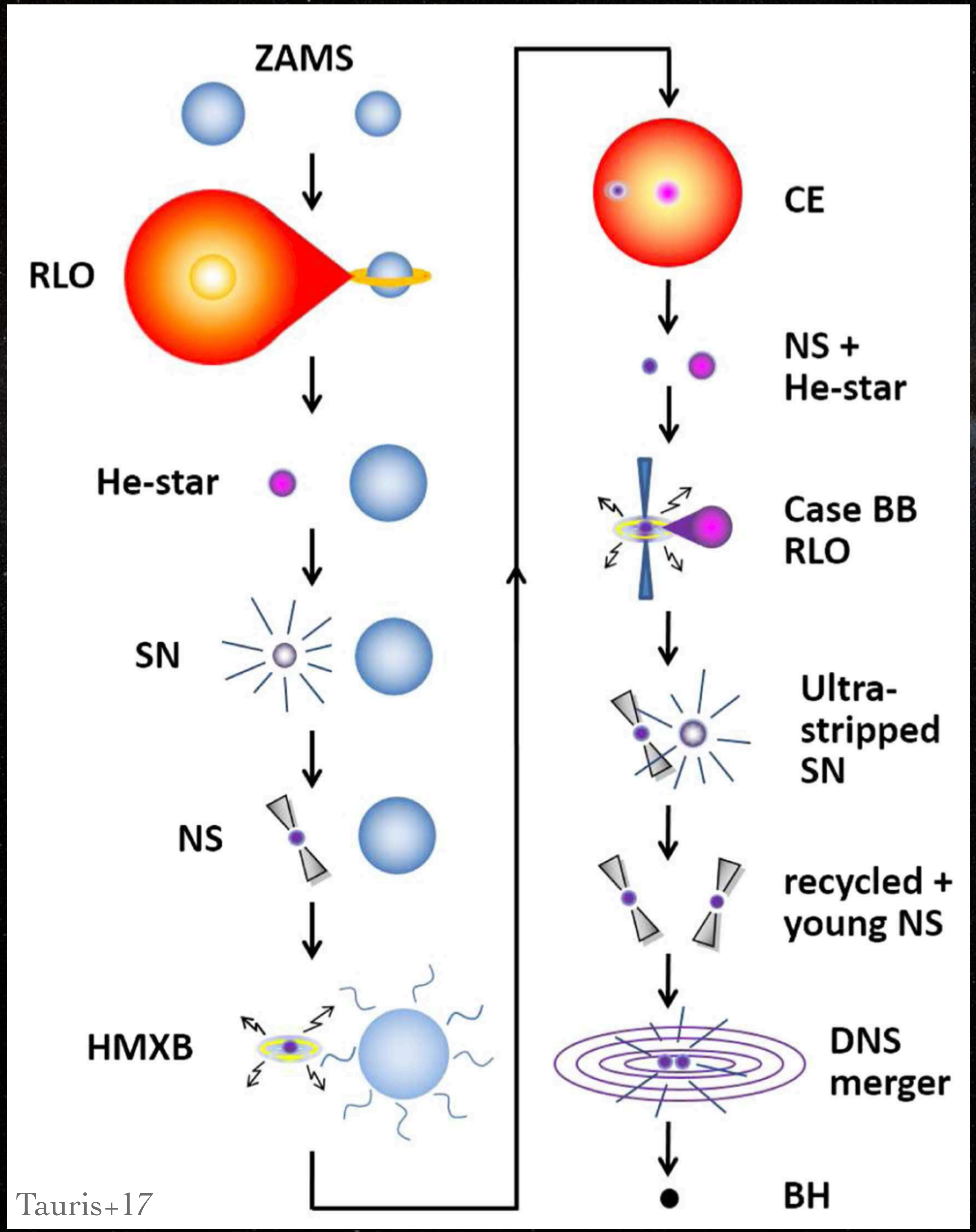


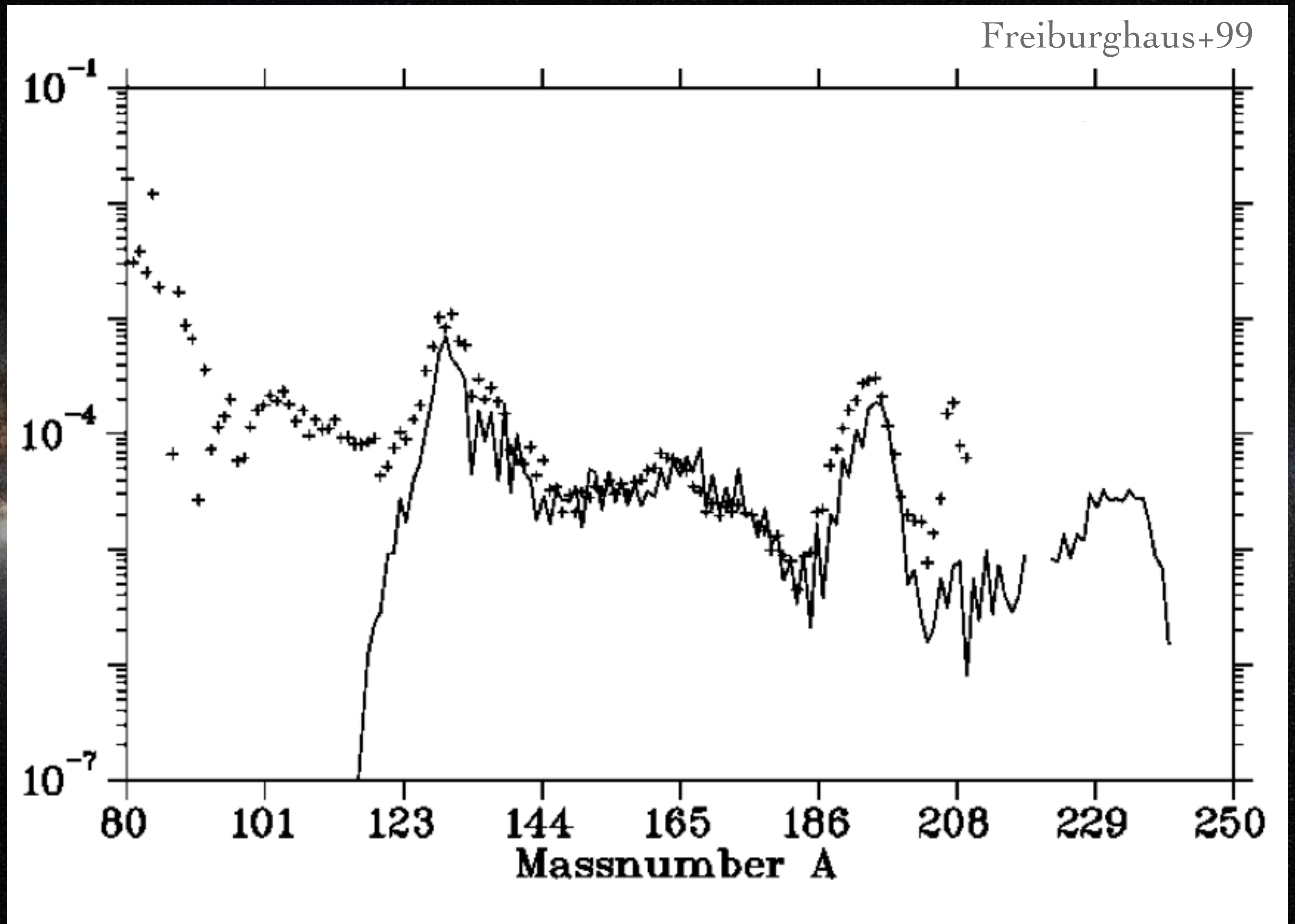
credits: M.Obergaulinger

In contrast to "typical" neutrino-driven CC-SNe, where matter is processed by neutrinos and therefore neutrons can react to protons, MRD-SNe may eject matter that is dominantly driven by magnetic pressure and therefore conserve neutron rich conditions

Neutron capture elements nucleosynthesis

MNS





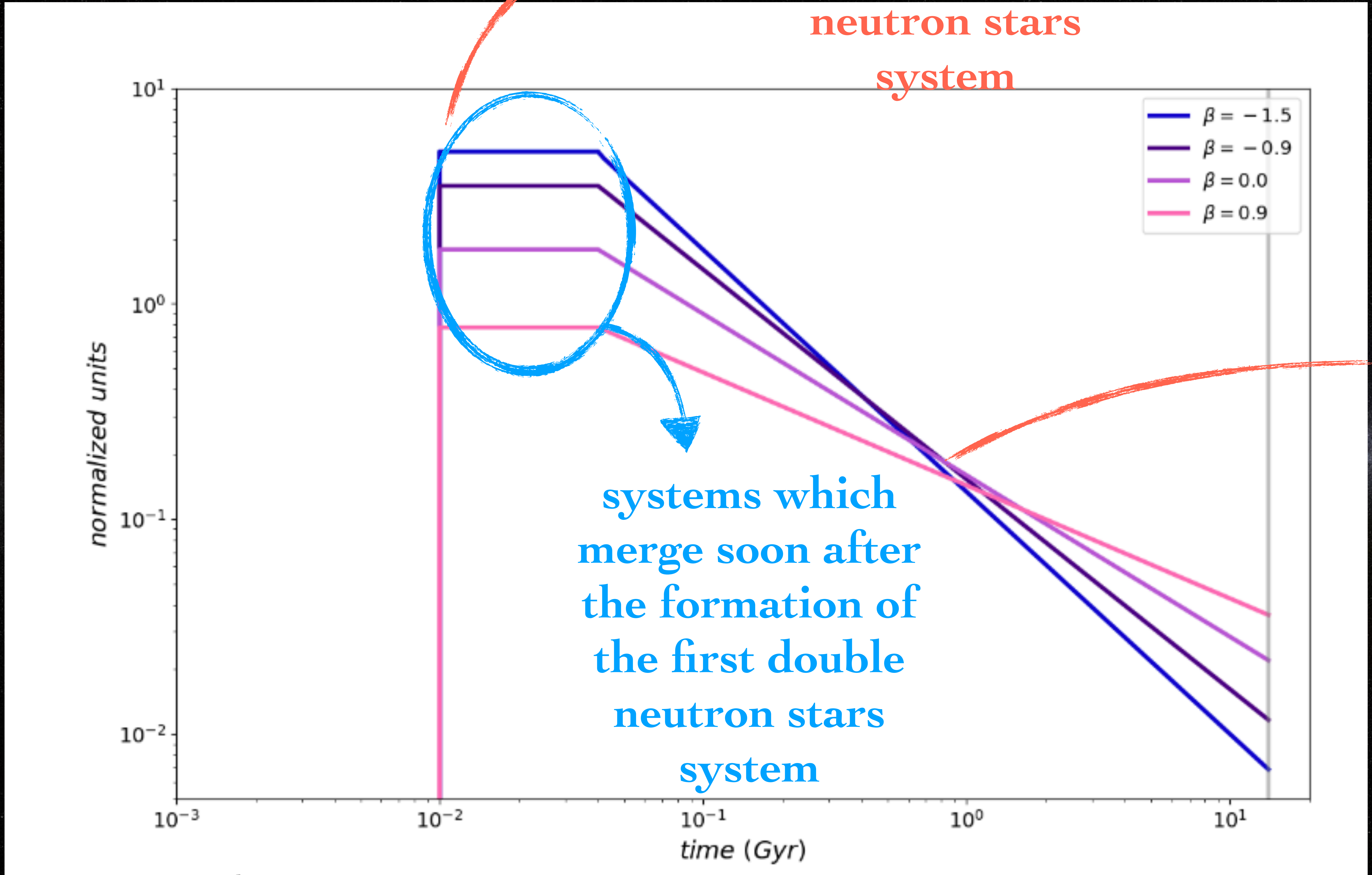
Consisting mainly out of material from the neutron star itself and being located far away from the colliding neutron stars, the tidally ejected and unshocked matter is to a minimum processed by neutrinos, therefore it is very neutron rich and an ideal host of the r-process

The Rate of Merging Neutron Stars

$$R_{MNS}(t) = k_\alpha \int_{\tau_i}^{min(t,\tau_x)} \alpha_{MNS}(\tau)\psi(t-\tau)f_{MNS}(\tau)\,\mathrm{d}\tau$$

- α_{MNS} the fraction of stars which gives rise to a merging event
- $f_{MNS}(\tau)$ the delay time distribution (DTD)
- $\tau = \tau_n + \tau_{gw}$ the delay time

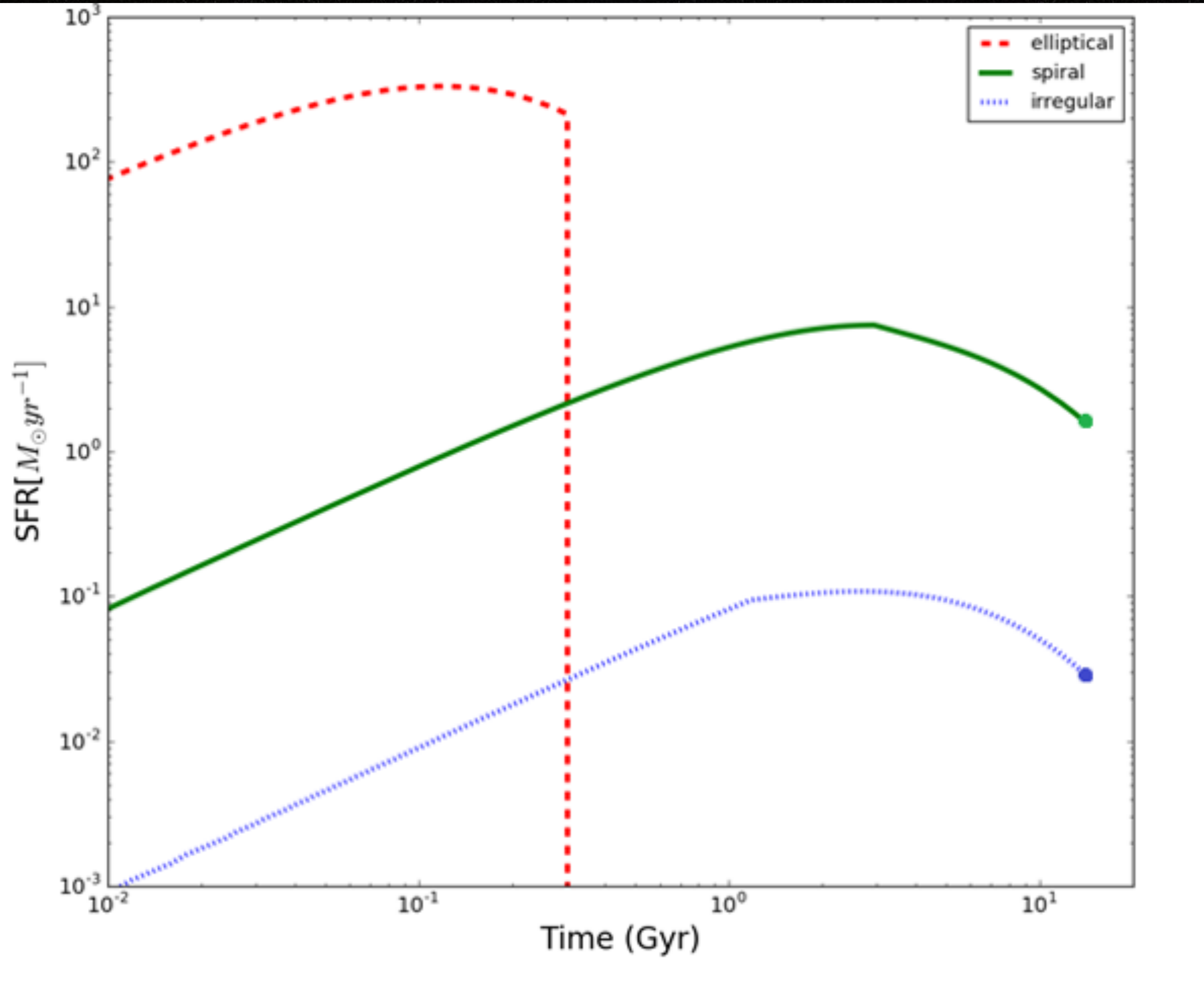
formation of the first double neutron stars system



Simonetti+19; see also Greggio, Simonetti & Matteucci 2021

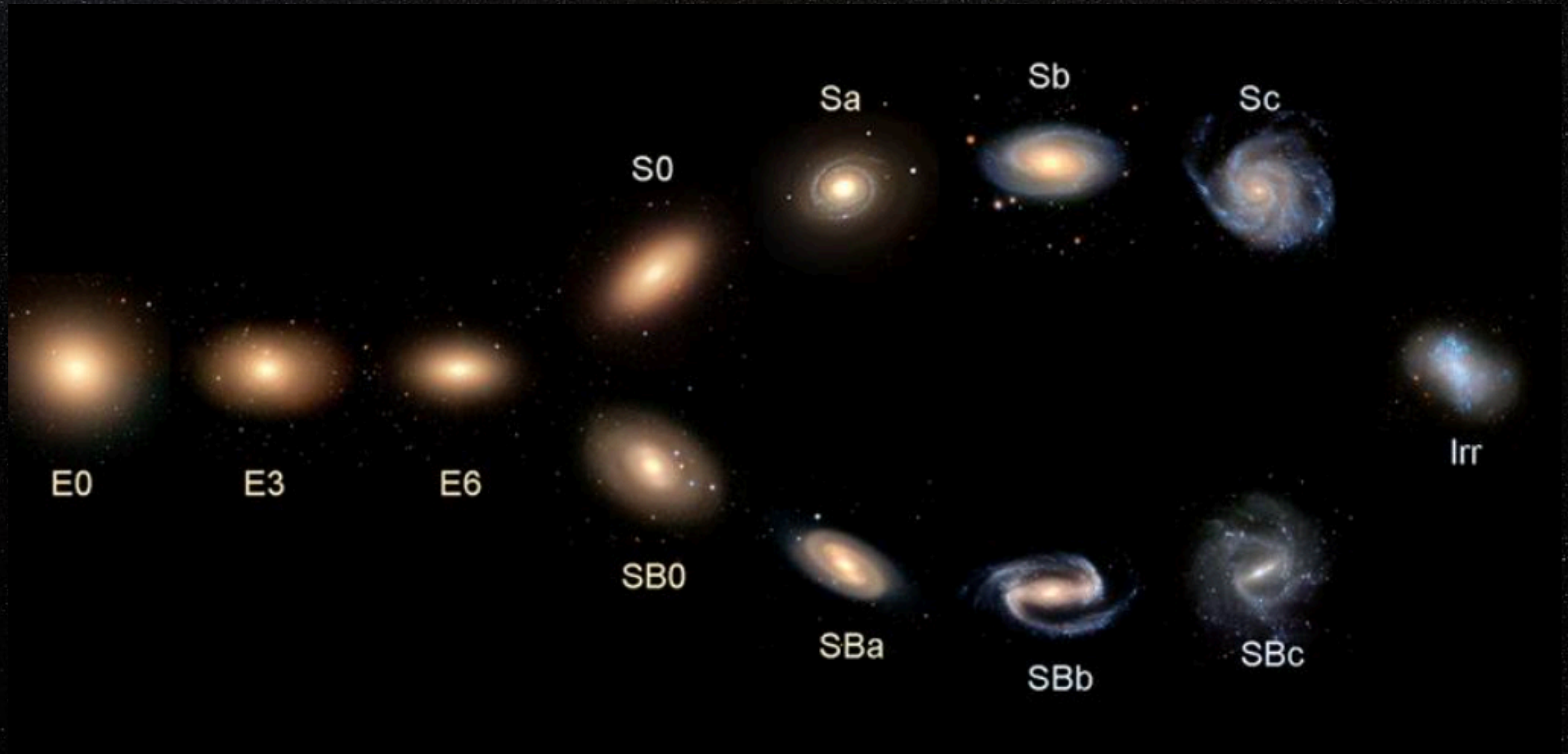
systems for which the delay is dominated by gravitational radiation

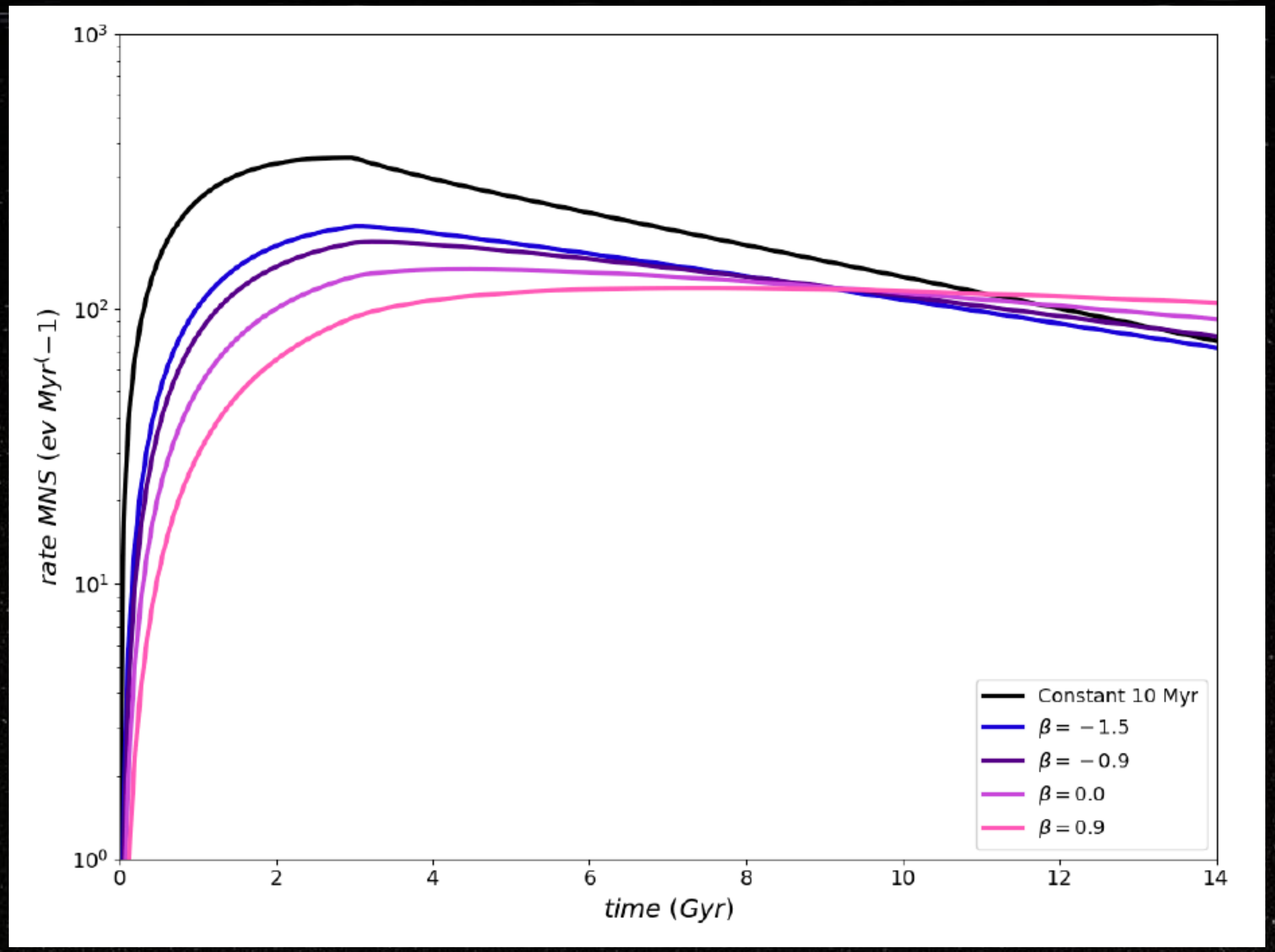
Galaxies of different morphological type



Chomiuk&Povich(2011); Rubele+15

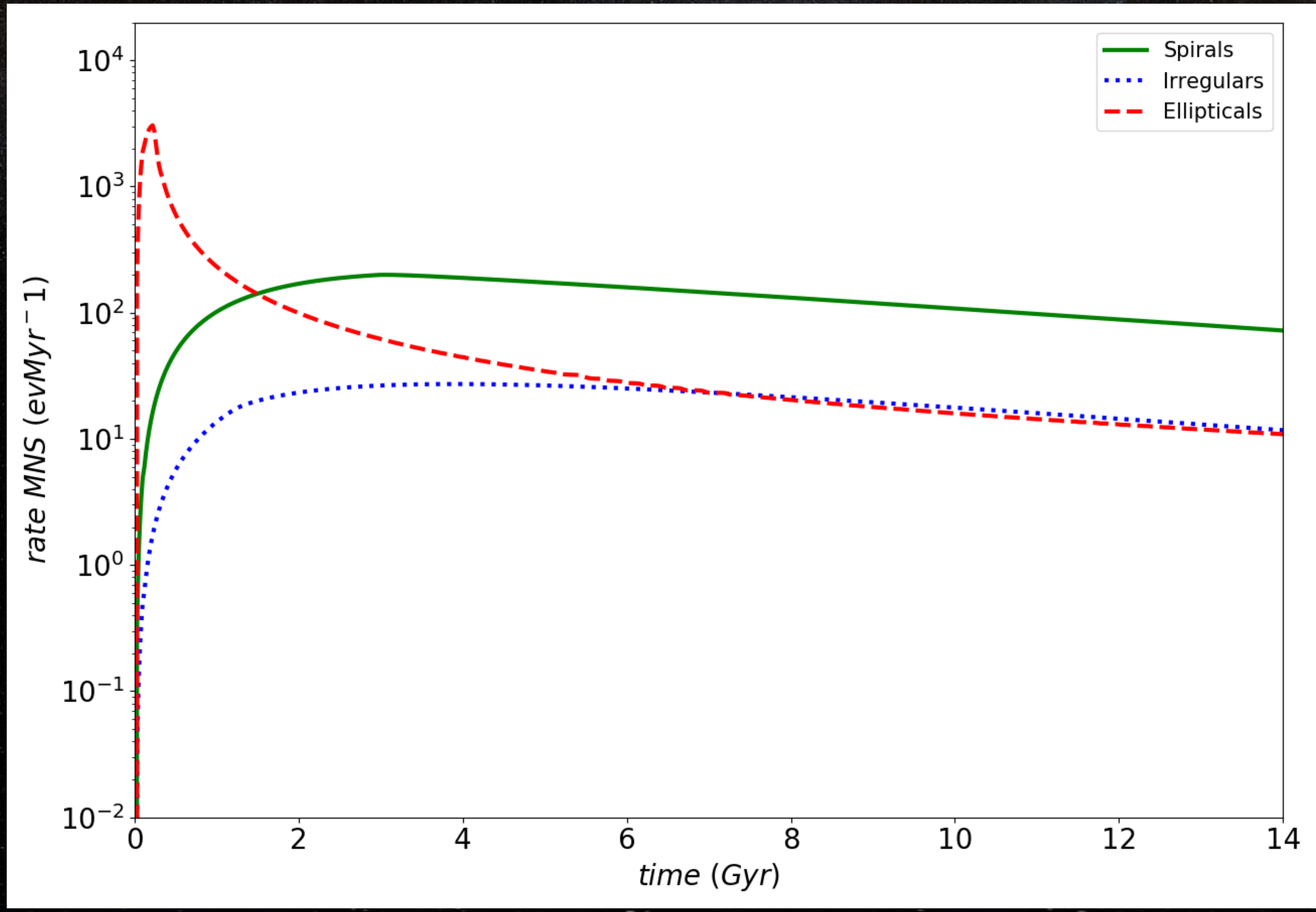
Type	M_{infall} $(M_\odot)$	ν (Gyr^{-1})	τ_{infall} (Gyr)
Spirals	5.0×10^{10}	1	7
Irregular	5.5×10^{8}	0.1	7
Ellipticals	5.0×10^{11}	17	0.2



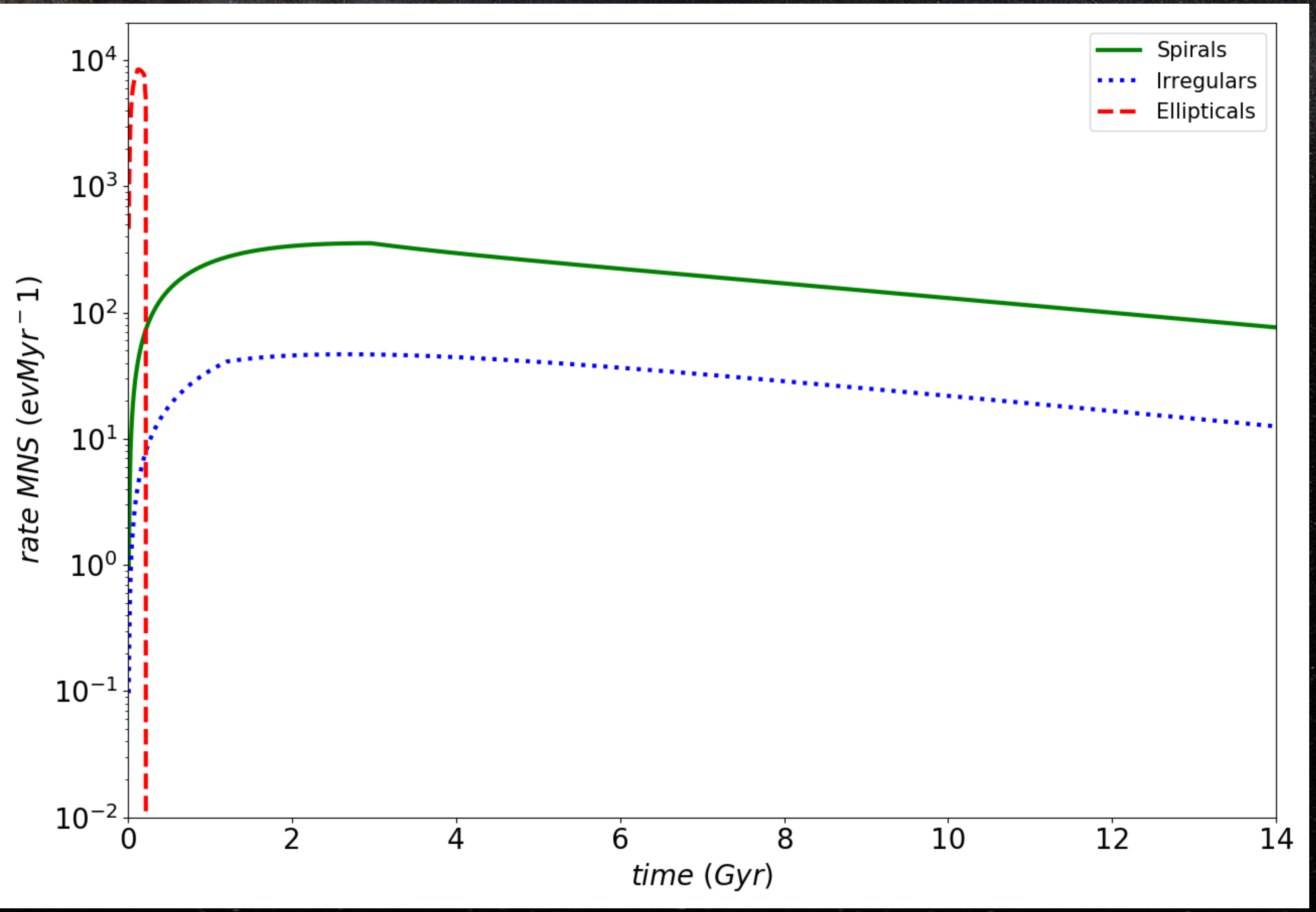


Model	Galaxy Type	MNS DTD	α_{MNS} ($\times 10^{-2}$)	MNS rate ($M\,yr^{-1}$)
1Sa	Spiral	$\beta = -1.5$	5.58	72
2Sa	Spiral	$\beta = -0.9$	5.42	80
3Sa	Spiral	$\beta = 0.0$	5.21	92
4Sa	Spiral	$\beta = 0.9$	5.06	105
5Sa	Spiral	Constant 10 Myr	6.15	77
1Ia	Irregular	$\beta = -0.9$	5.58	12
2Ia	Irregular	Constant 10 Myr	6.15	13
1Ea	Elliptical	$\beta = -0.9$	5.58	15
2Ea	Elliptical	Constant 10 Myr	6.15	0

DTD

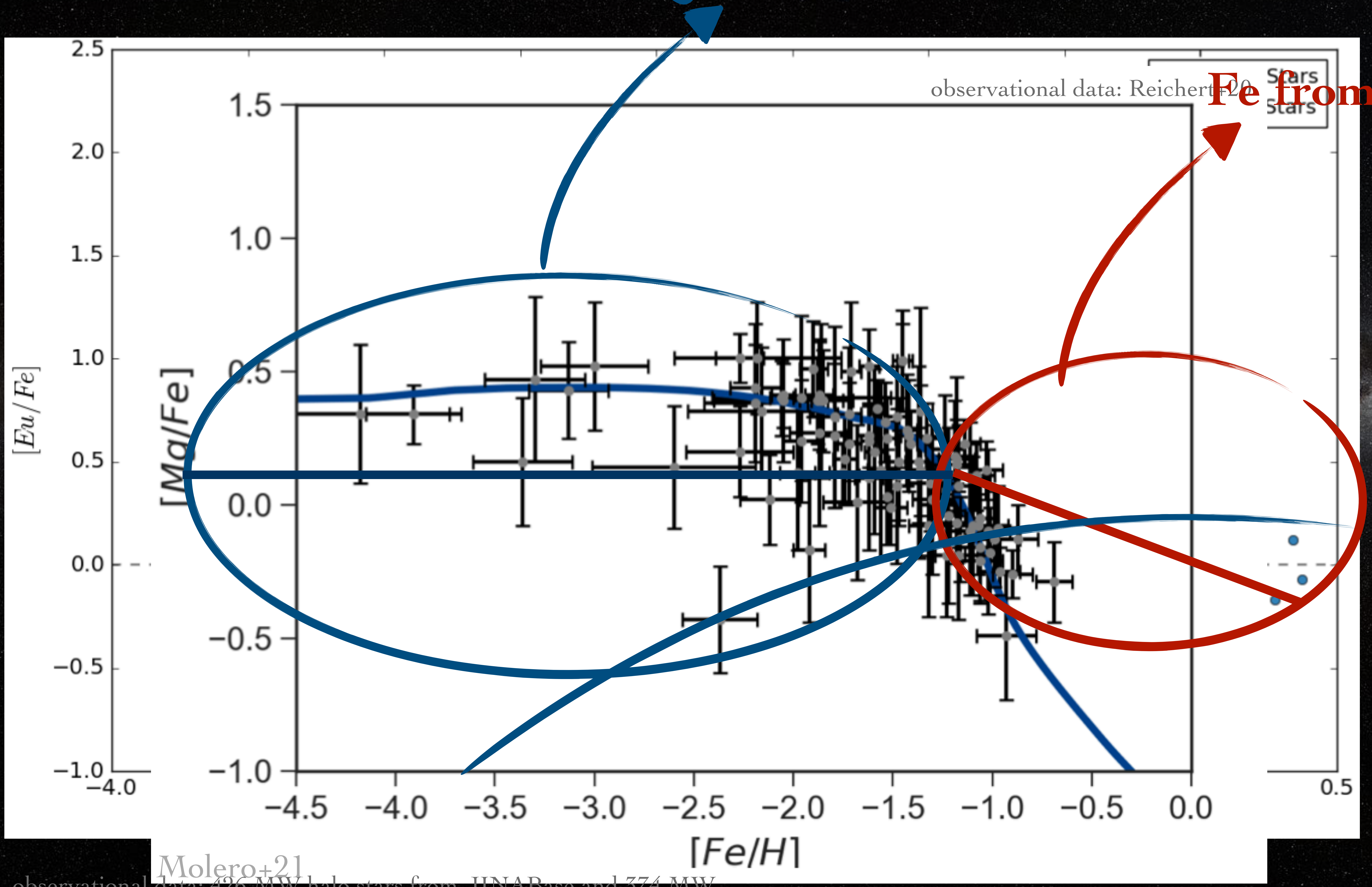


no DTD



[Eu/Fe] vs [Fe/H] in the Milky Way

QUICK SOURCE!



observational data: 426 MW halo stars from JINABase and 374 MW thin disk stars from Battistini&Bensby+16

CC-SNe:

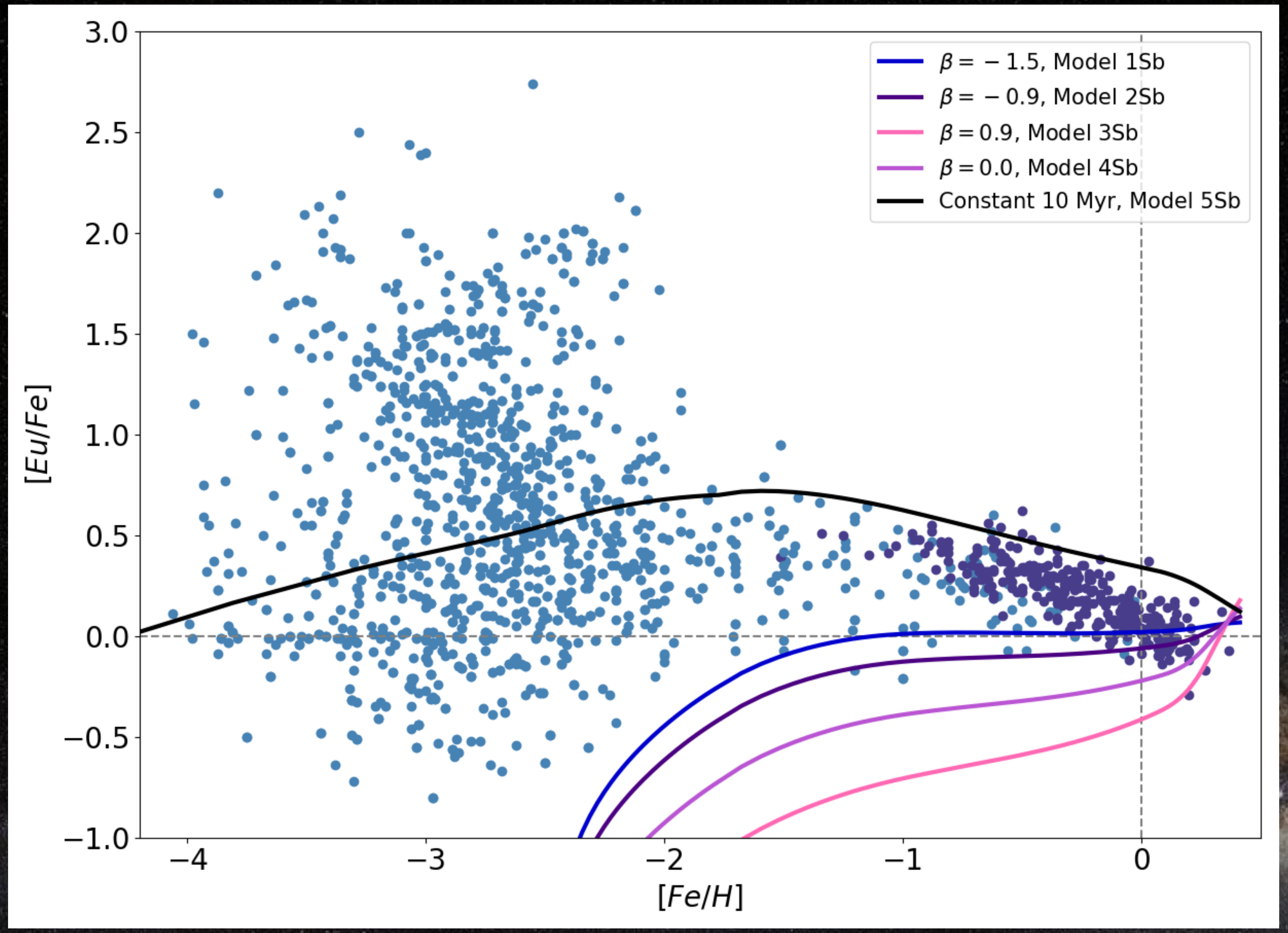
- Main producers of α-elements
- 1/3 of Fe producers
- From massive stars (short lifetime)

SNe Ia:

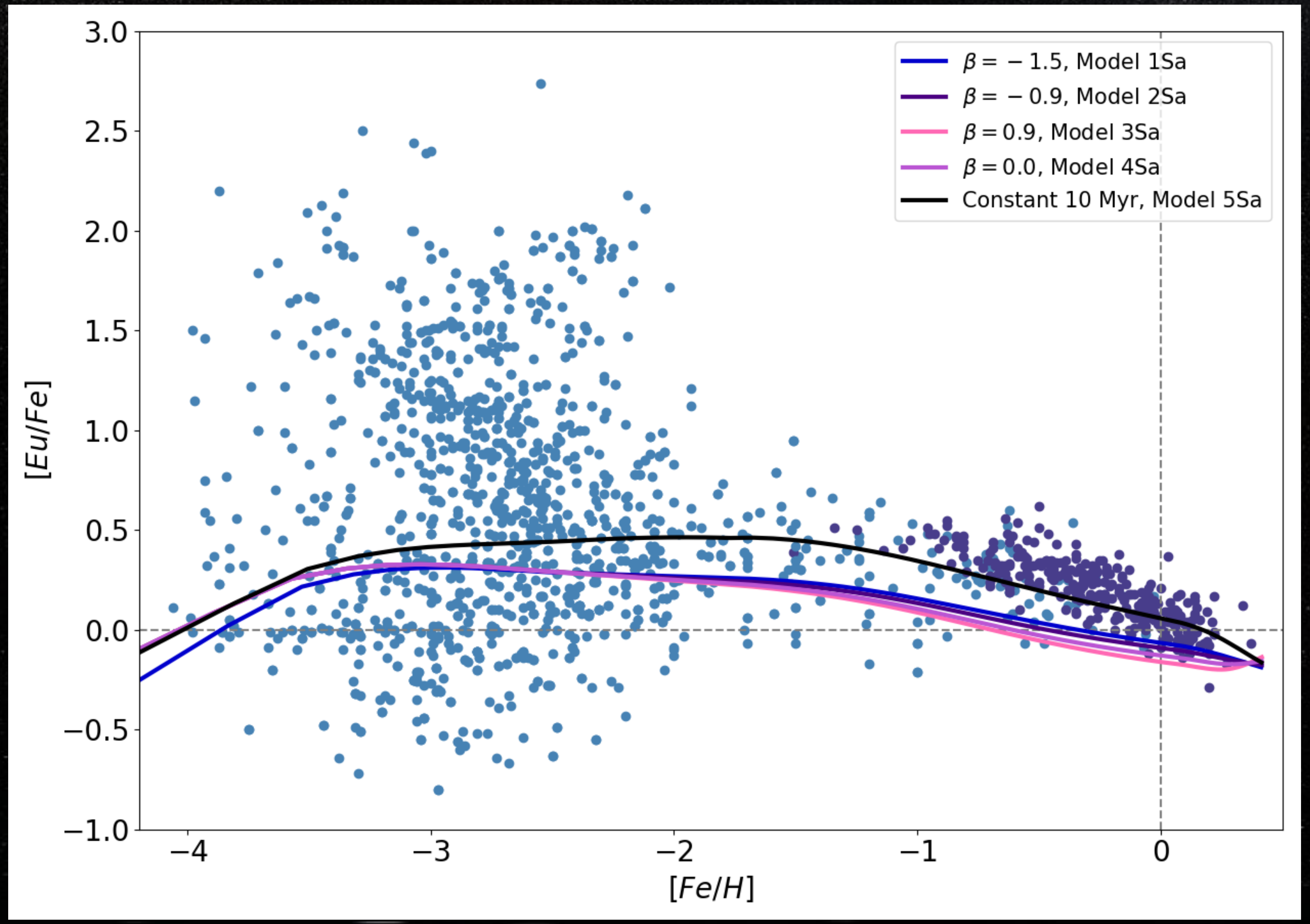
- Main producers of Fe
- From low-mass stars (long lifetime)

[Eu/Fe] vs [Fe/H] in the Milky Way

only MNS



MNS + Massive stars



- When MNS are the sole producers of Eu, the model which better reproduces the [Eu/Fe] vs [Fe/H] pattern is the one with a constant and short delay

- When MS co-produce Eu with MNS, they become the main production site and dominate the relation

Either NS all merge on short timescales or they cannot be the major producers of Eu

Cosmic Rates

Cosmic rate: the rate in a coming unitary volume of the Universe

Galaxy number density

$$n_k = n_{k,0}(1+z)^{\beta_k}$$

Type	n_k ($\times 10^{-3}$) Mpc^{-3}	β_k
Spirals	8.4	0.9
Irregular	0.6	0.0
Ellipticals	2.24	−2.5

Gioannini, Matteucci, Calura 2017

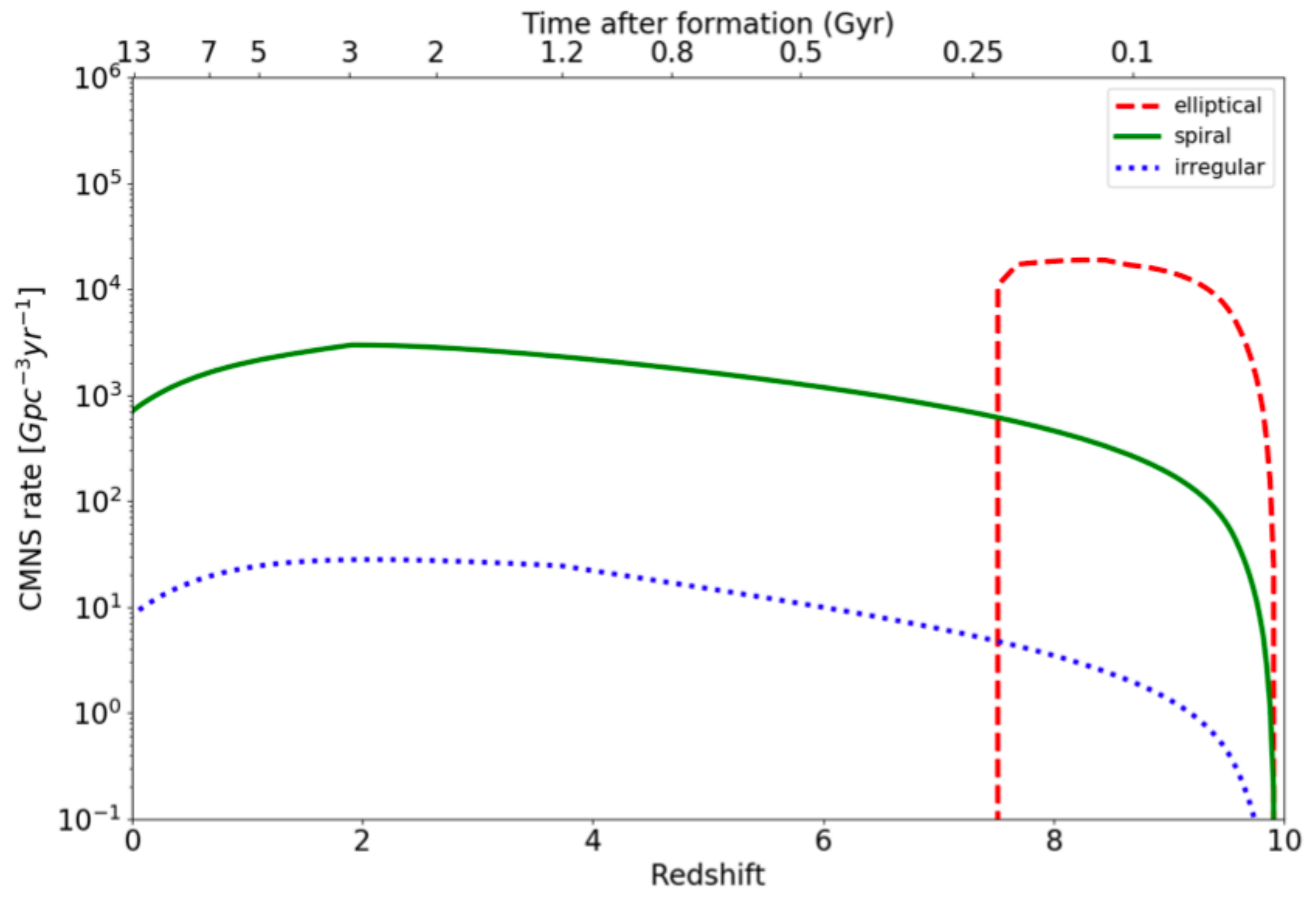
- PLE (pure luminosity evolution) scenario, $\beta_k = 0$;
- DE (density evolution-hierarchical clustering) scenario, $\beta_k \neq 0$;
- Alternative scenario (Pozzi+15)

Cosmic Rates

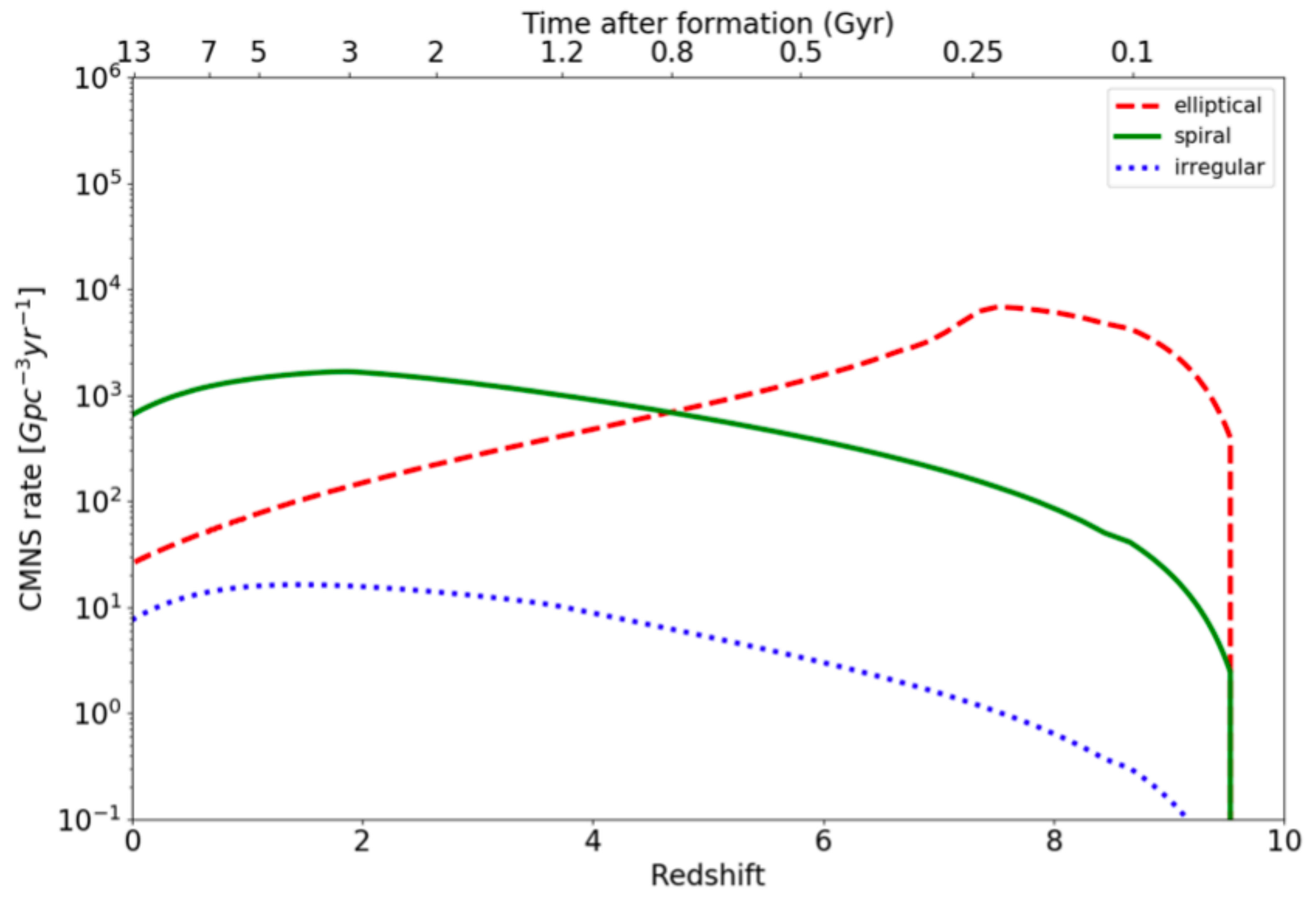
- PLE (pure luminosity evolution) scenario, $\beta_k = 0$

$$n_k = n_{k,0}(1+z)^{\beta_k} = n_{k,0}$$

Type	n_k $(\times 10^{-3})$ Mpc^{-3}	β_k
Spirals	8.4	0.9
Irregular	0.6	0.0
Ellipticals	2.24	−2.5



(a)



(b)

Cosmic Rates

- DE (density evolution-hierarchical clustering) scenario,

  $\beta_k \neq 0$

$$n_k = n_{k,0}(1+z)^{\beta_k}$$

Type	n_k ($\times 10^{-3}$) Mpc^{-3}	β_k
Spirals	8.4	0.9
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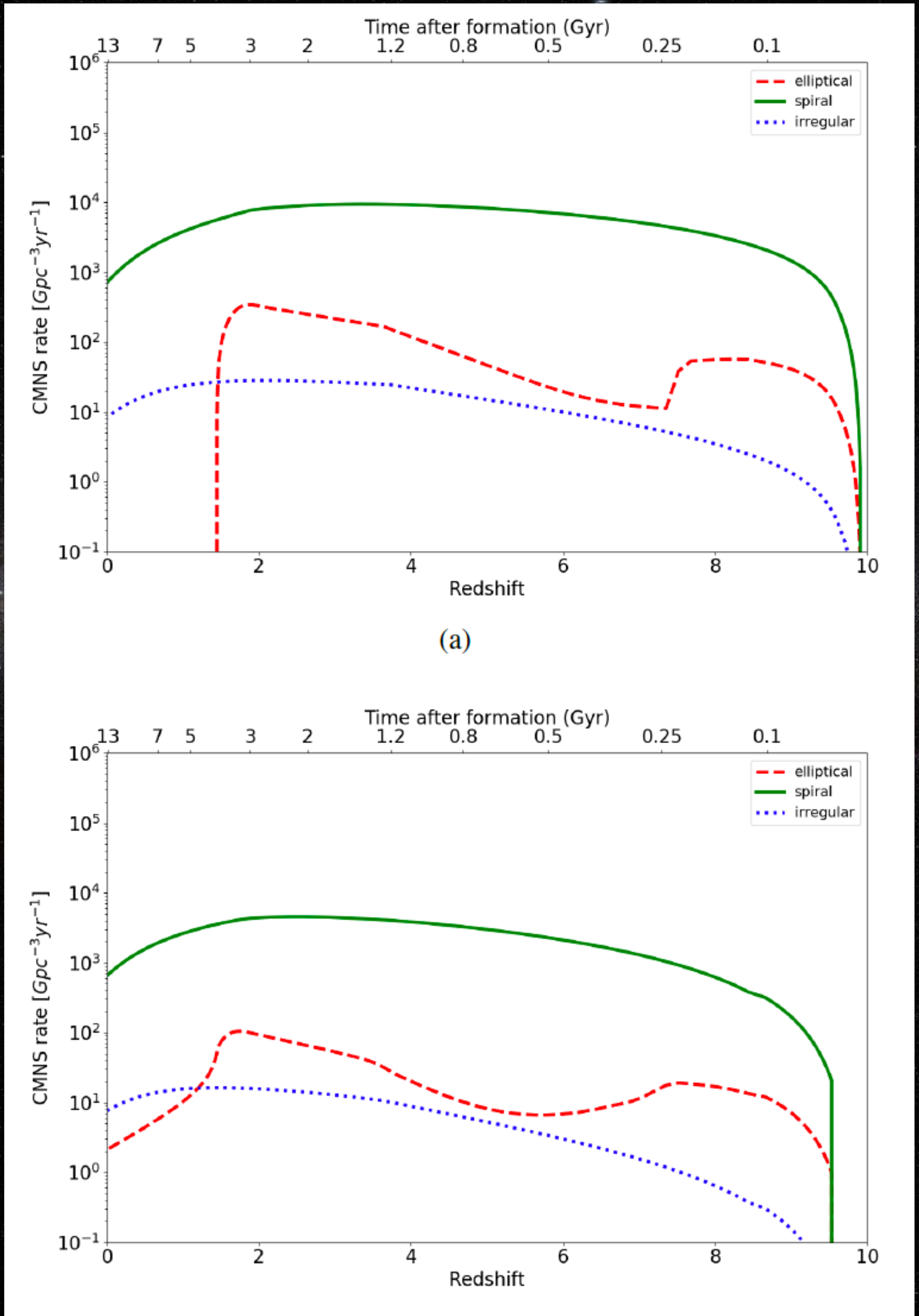
Ellipticals	2.24	−2.5

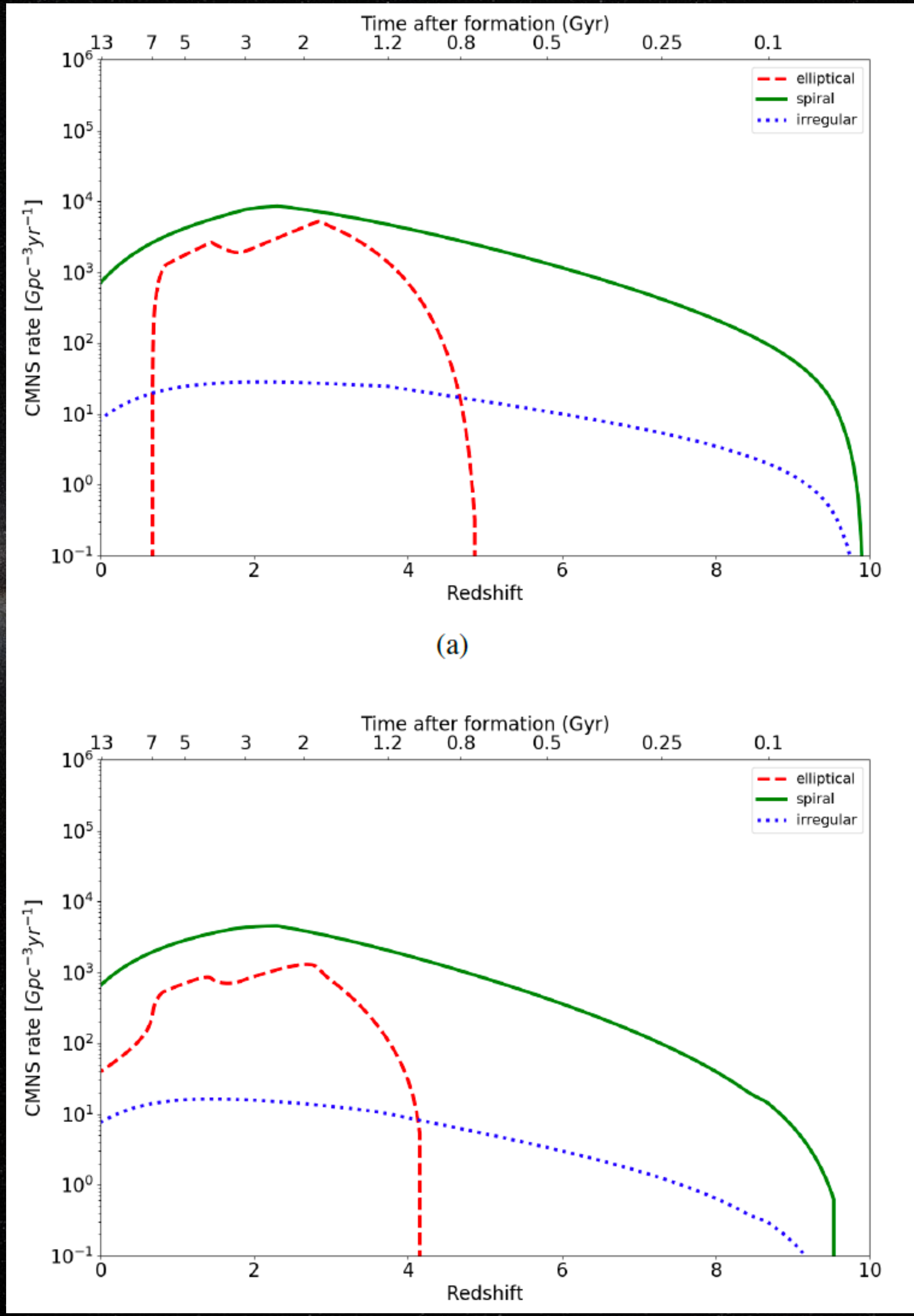


Cosmic Rates

- Alternative scenario observational derived (Pozzi+15):

$$n_s = \begin{cases} n_{0,s}(1+z)^{\beta_s} & 0 < z < 2.3 \\ n_{0,s}(1+z)e^{-(1+z)/2} & z > 2.3 \end{cases}$$

Ellipticals are assumed to stars forming at z=5 and half of them form in the range 1 < z < 2



Cosmic Rates

Considering the sky areas and volumes patrolled by LSST and VST (see Della Valle+18) we can compute the predicted number of Kilonovae detections for those surveys

Kilonovae are intrinsically weak objects detectable at low redshift where our number of MNS in spirals and irregulars cannot be used to disentangle among different scenarios

Observations of MNS in early-type galaxies are of the utmost importance because they can effectively help to discriminate models

DTD

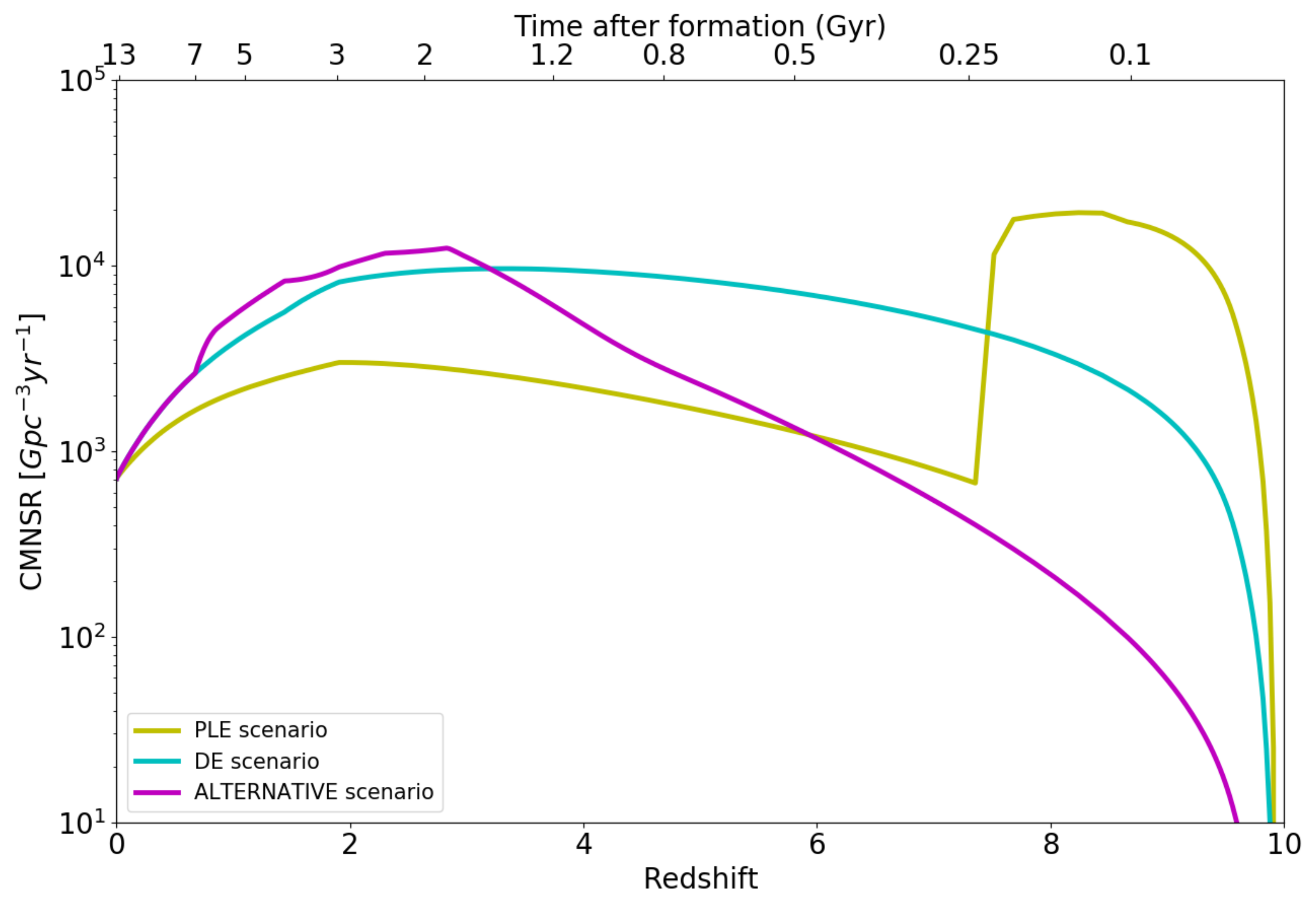
Type	Scenario	LSST	VST
Spiral	PLE	1850	91
Irregular	PLE	21	1
Elliptical	PLE	74	4
Elliptical	DE	17	0
Elliptical	alternative	130	6

no DTD

Type	Scenario	LSST	VST
Spiral	PLE	2215	100
Irregular	PLE	28	1
Elliptical	PLE	0	0
Elliptical	DE	0	0
Elliptical	alternative	0	0

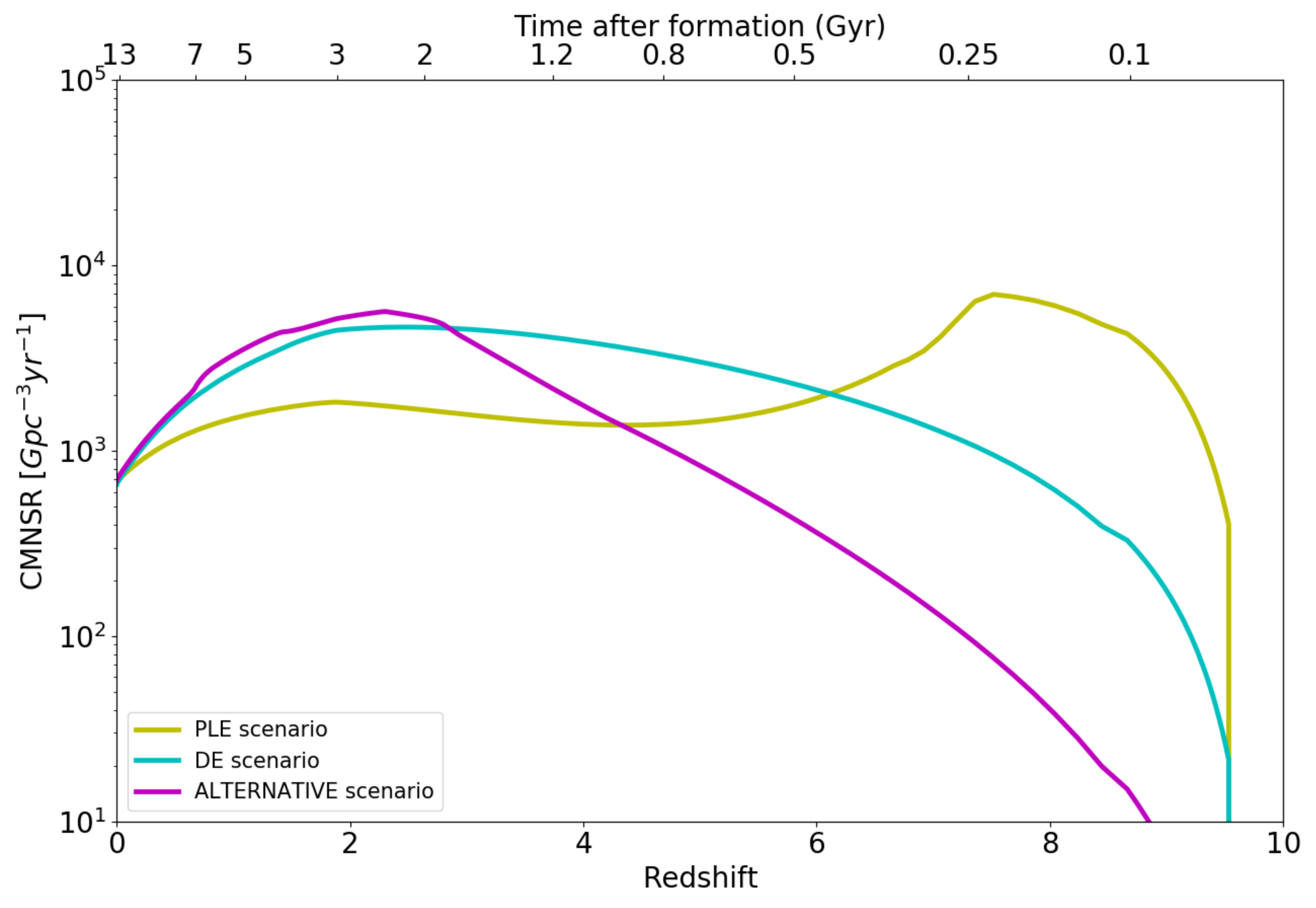
$$CMNSR = \sum_k R_{MNS,k}(t)n_k$$

No DTD



- PLE scenario with constant delay: first peak at $z \sim 8$ due to the high redshift formation of ellipticals. When the SF in ellipticals stops, the CMNSR abruptly decreases and its evolution is then due to spirals, leading to a second peak at $z \sim 2$

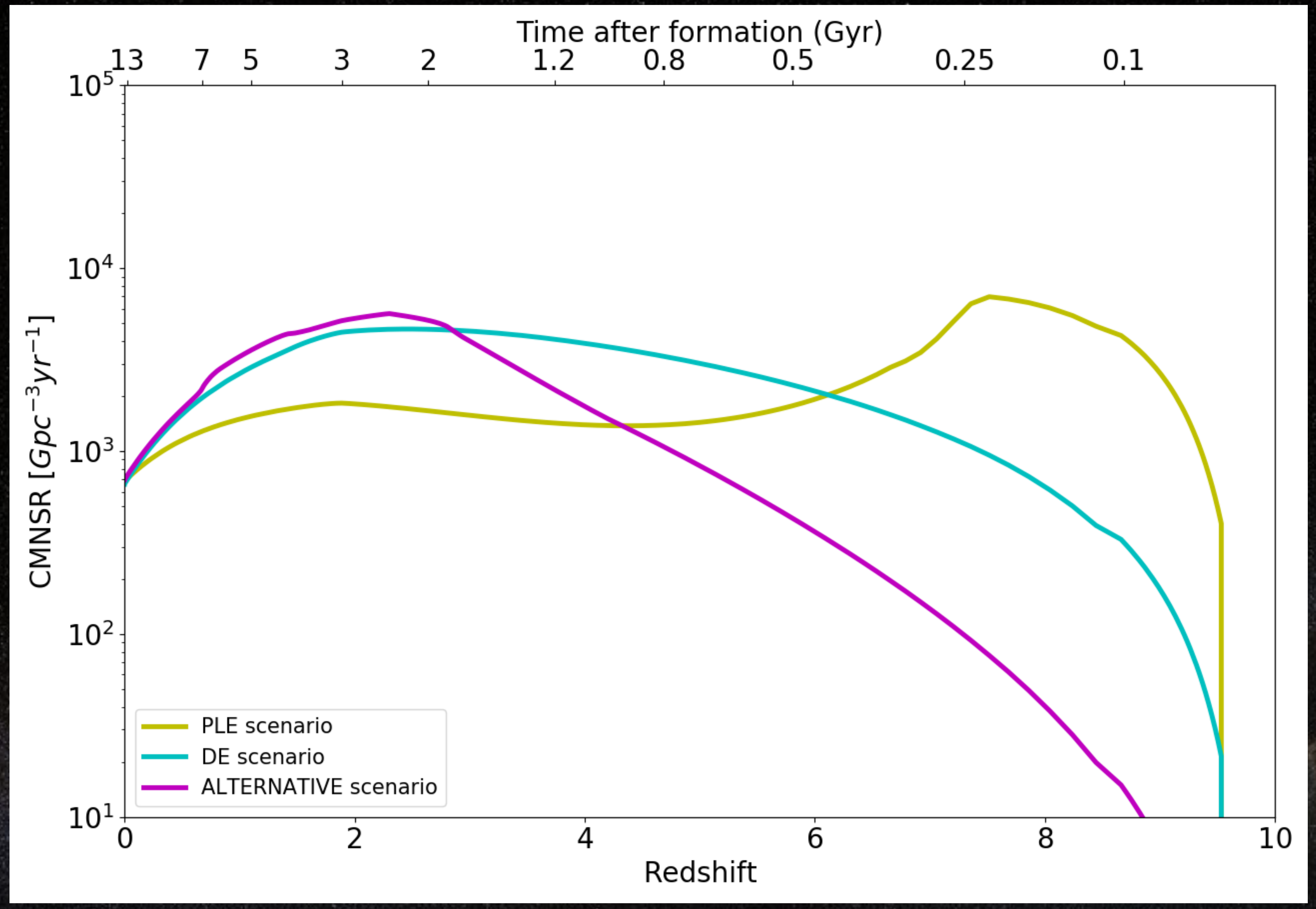
DTD



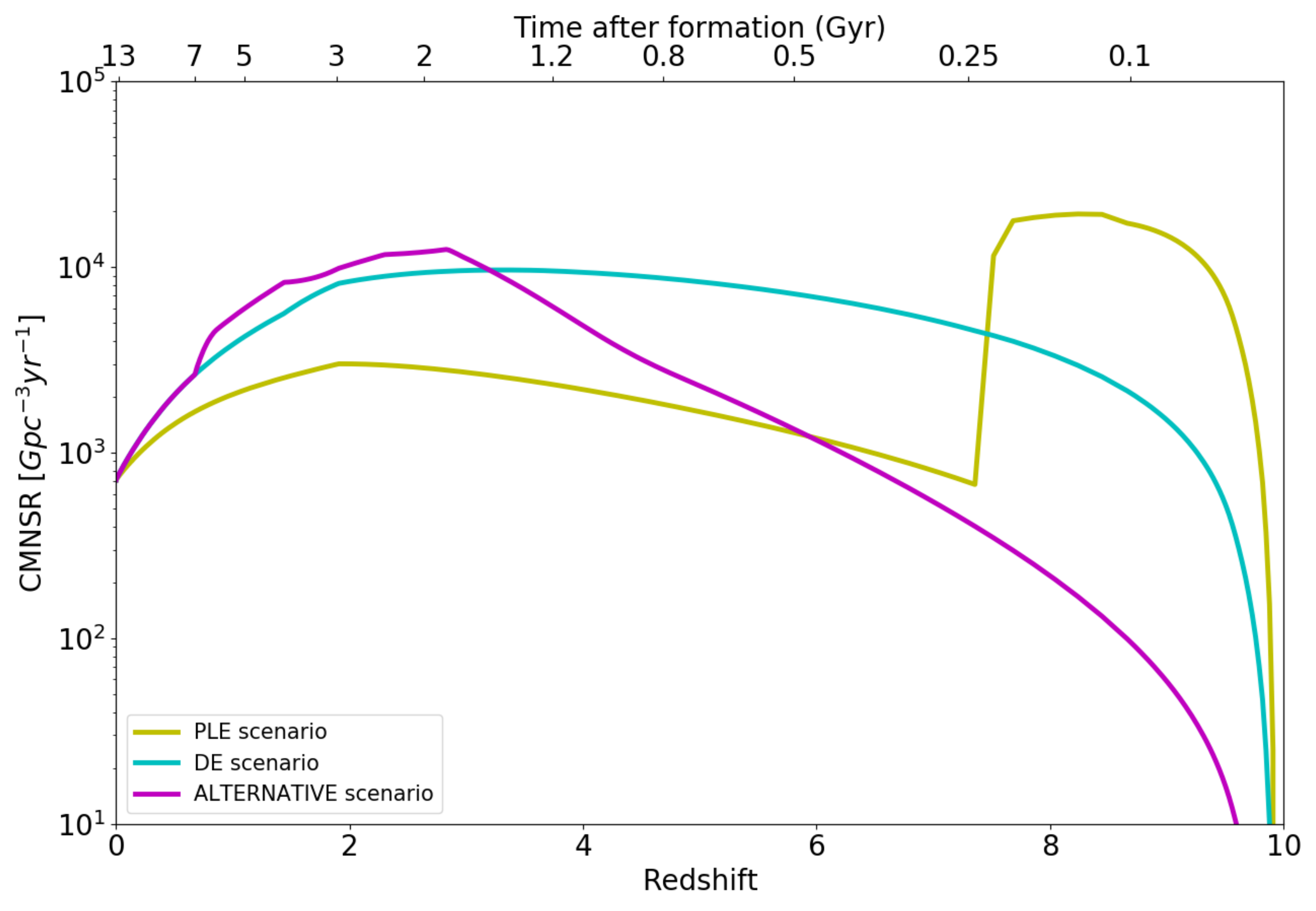
- If a DTD is adopted, the decrease is smoother since MNS will not stop after the quenching of the SF and the ellipticals will contribute to the CMNSR during the whole range of redshift

$$CMNSR = \sum_k R_{MNS,k}(t) n_k$$

DTD



No DTD



PLE scenario				
MNS DTD	TOT CMNSR ($yr^{-1}Gpc^{-3}$)	Spirals CMNSR ($yr^{-1}Gpc^{-3}$)	Ellipticals CMNSR ($yr^{-1}Gpc^{-3}$)	Irregulars CMNSR ($yr^{-1}Gpc^{-3}$)
Constant 10 Myr	651	643	0	8
$\beta = -0.9$	647	607	33	7
DE scenario				
MNS DTD	TOT CMNSR ($yr^{-1}Gpc^{-3}$)	Spirals CMNSR ($yr^{-1}Gpc^{-3}$)	Ellipticals CMNSR ($yr^{-1}Gpc^{-3}$)	Irregulars CMNSR ($yr^{-1}Gpc^{-3}$)
Constant 10 Myr	751	706	0	8
$\beta = -0.9$	662	651	3	7
ALTERNATIVE scenario				
MNS DTD	TOT CMNSR ($yr^{-1}Gpc^{-3}$)	Spirals CMNSR ($yr^{-1}Gpc^{-3}$)	Ellipticals CMNSR ($yr^{-1}Gpc^{-3}$)	Irregulars CMNSR ($yr^{-1}Gpc^{-3}$)
Constant 10 Myr	715	706	0	8
$\beta = -0.9$	711	651	52	7

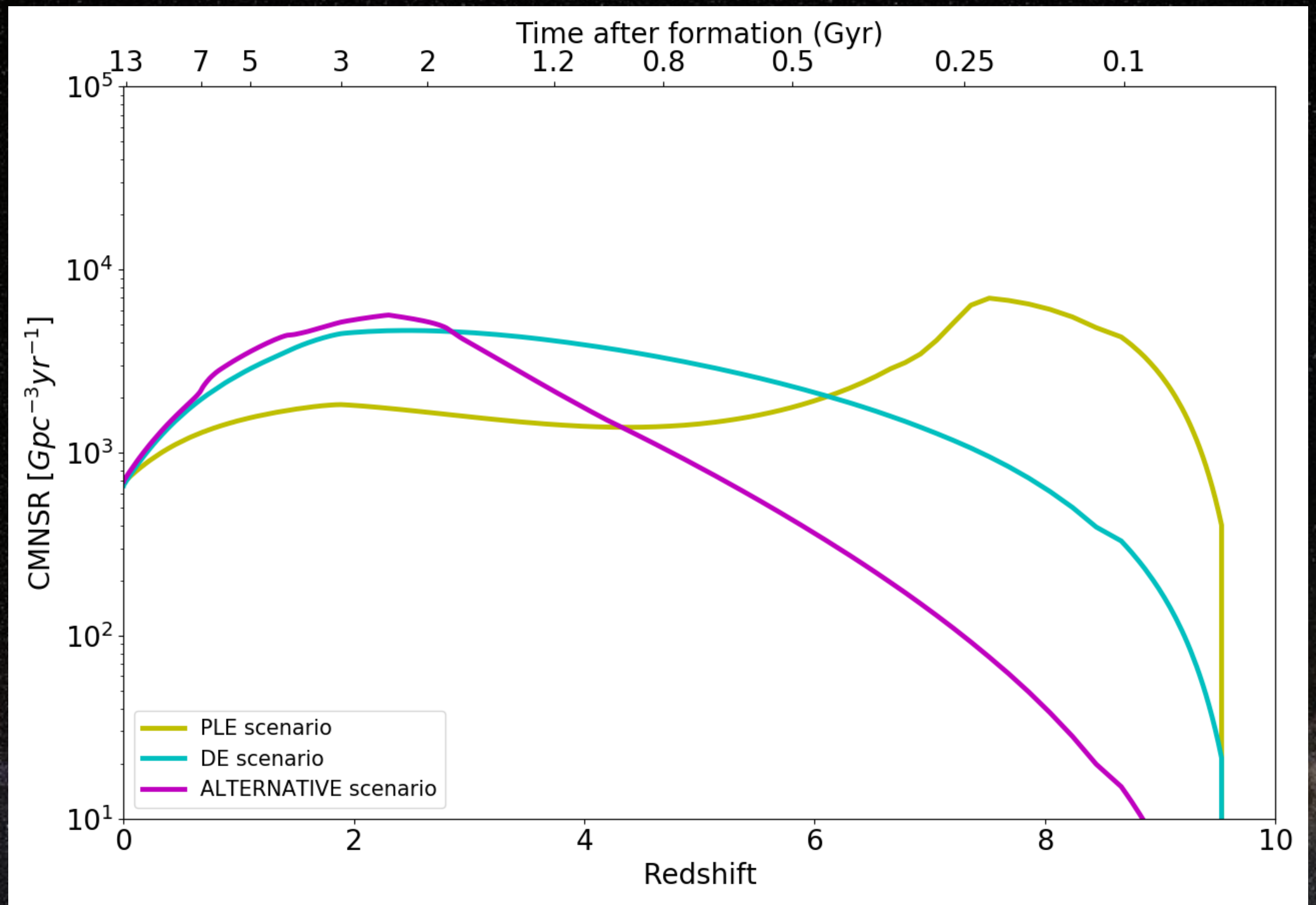
$1540^{+3200}_{-1220} Gpc^{-3} yr^{-1}$ Abbott+17

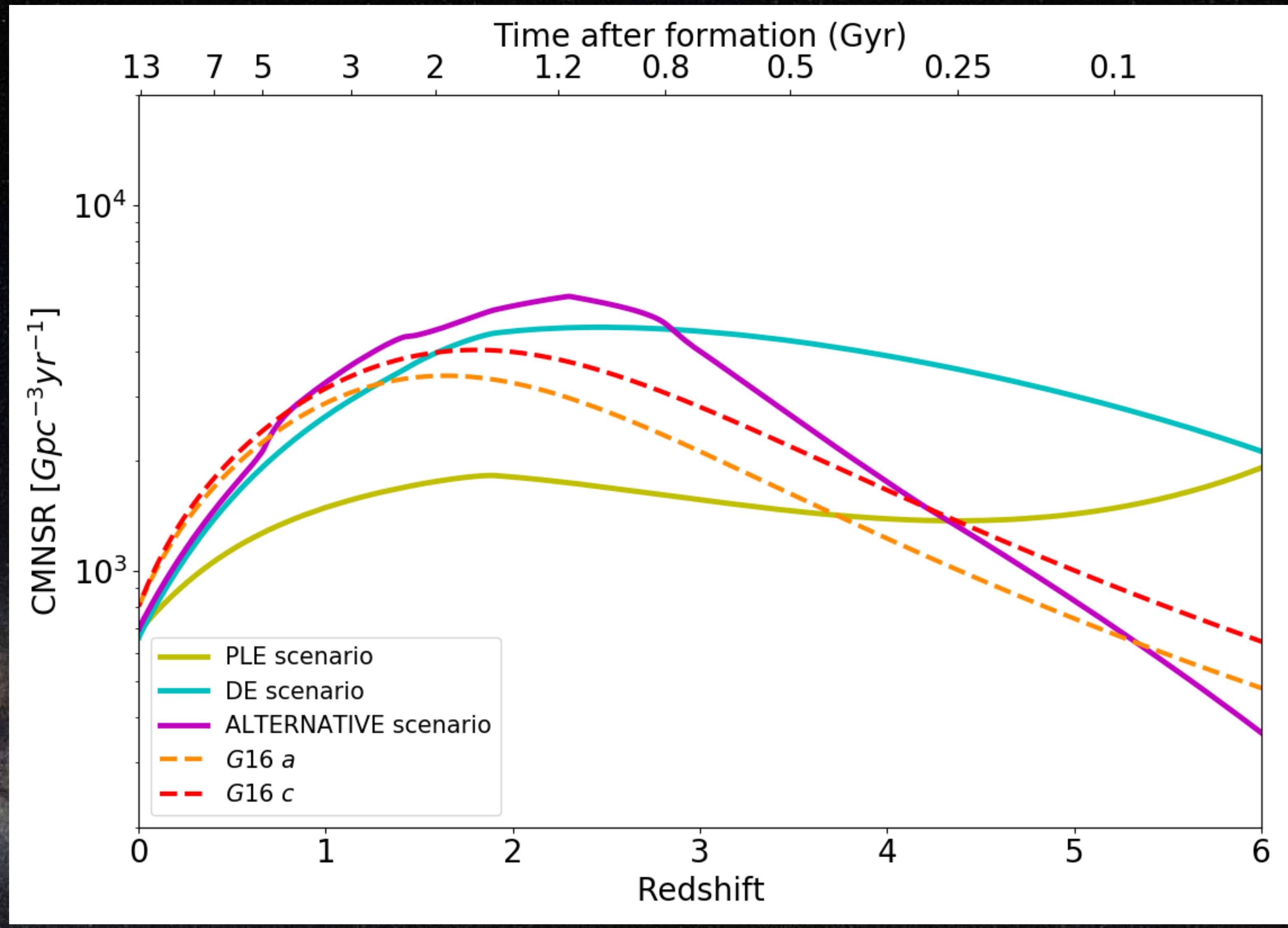
$800^{+2000}_{-600} Gpc^{-3} yr^{-1}$ DellaValle+18

$320^{+490}_{-240} Gpc^{-3} yr^{-1}$ Abbott+21

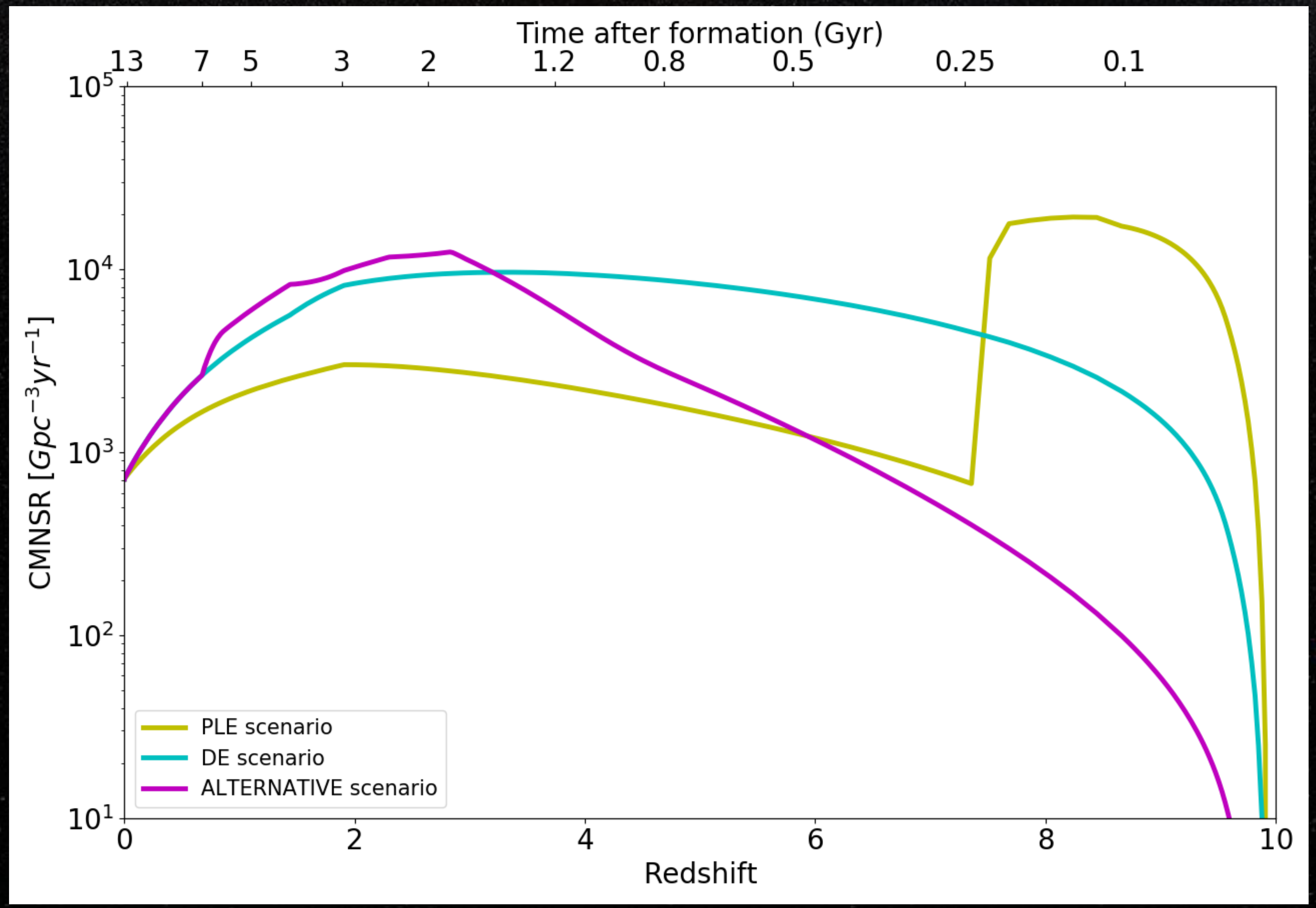
$$CMNSR = \sum_k R_{MNS,k}(t)n_k$$

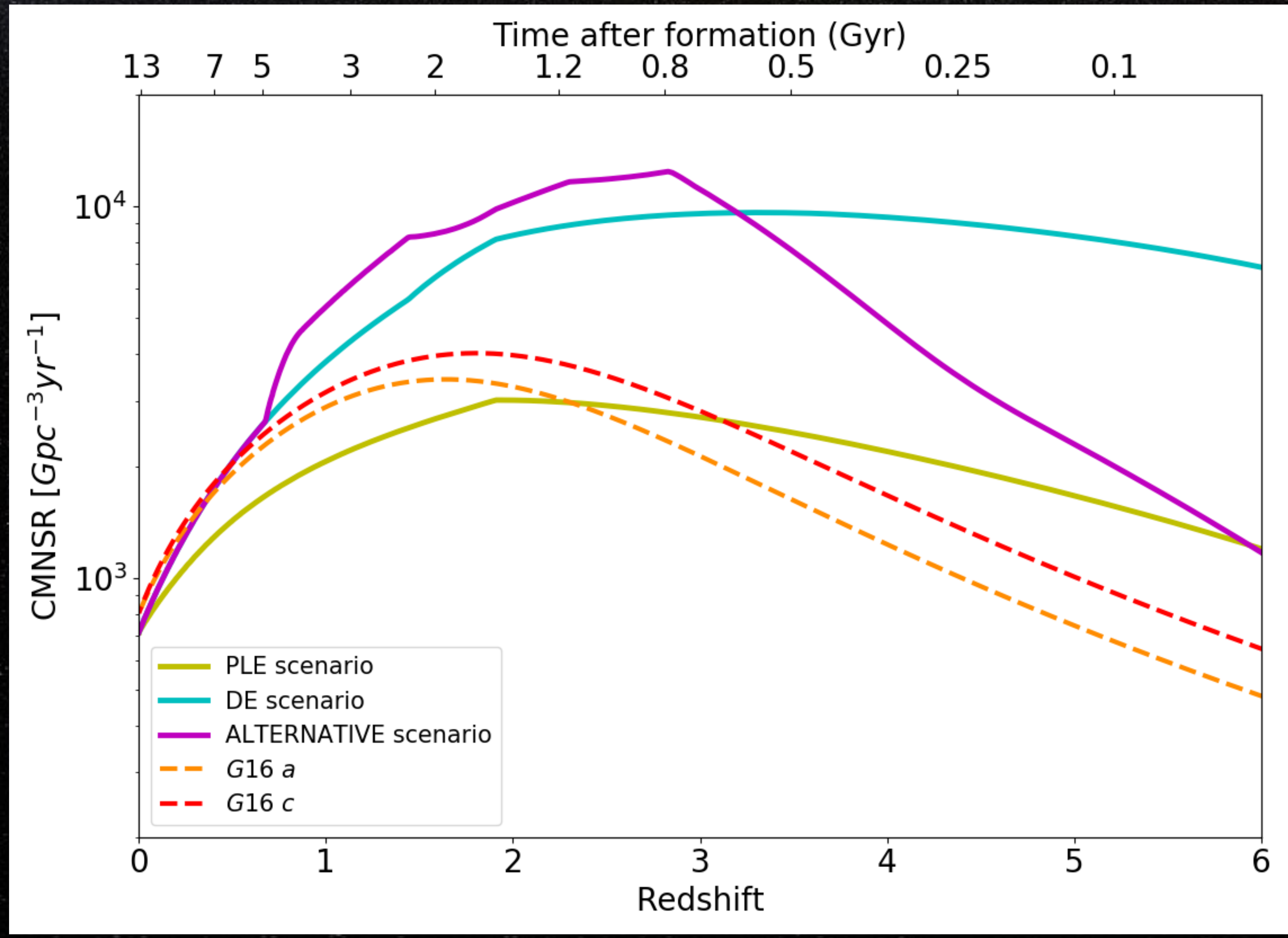
DTD





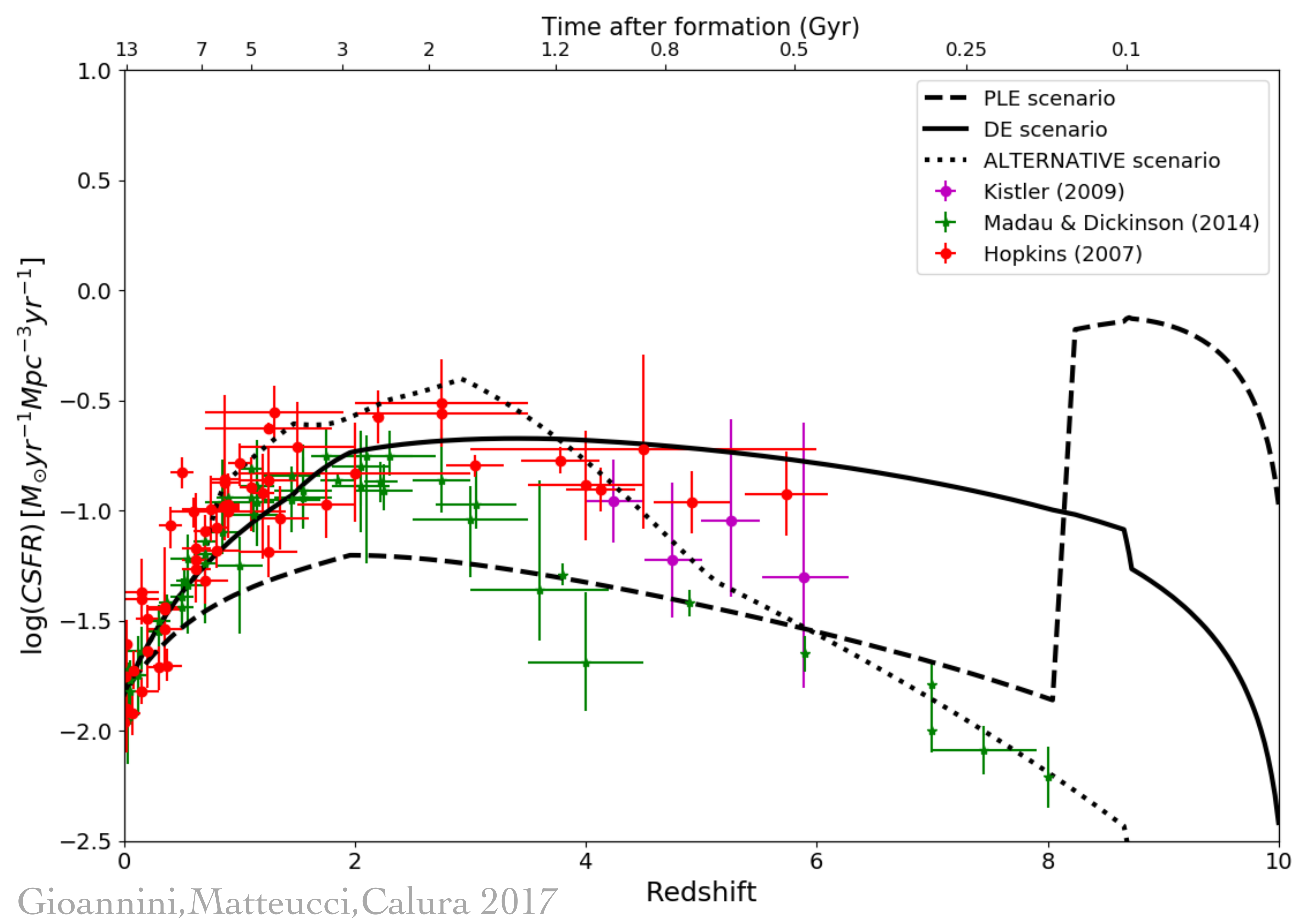
No DTD



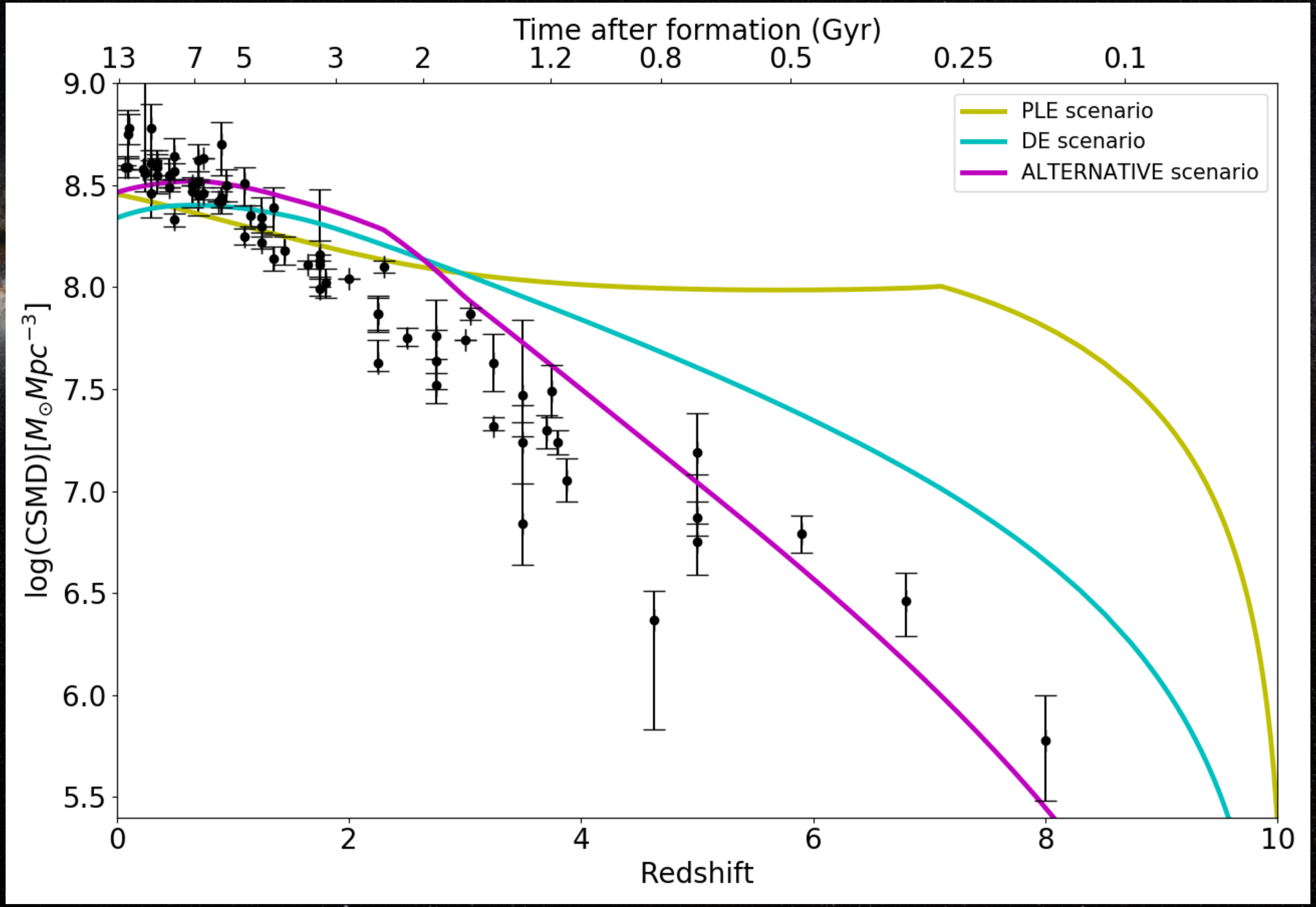


$$CSFR = \sum_{k} \Psi_k(t) n_k$$

$$CSMD = \sum_{k} \rho_{*,k}(t) n_k$$



Gioannini,Matteucci,Calura 2017



Conclusions

- We computed the rate of MNS in galaxies of different morphological type (ellipticals, spirals and irregulars) with different histories of SF
- The present time rate of MNS in the MW is well reproduced either by assuming a DTD with $\beta = -0.9$ or a constant and short (10 Myr) delay time for merging
- The evolution of the [Eu/Fe] vs [Fe/H] has also been studied and it can be reproduced by assuming only MNS as Eu producers only if a constant total delay time of 10 Myr is assumed.
- If more realistic DTDs are assumed also massive stars must produce r-process material with MNS

Conclusions

- We computed the cosmic evolution of the MNS rate in the three cosmological scenario: PLE, DE and alternative
- Our predictions for the present time CMNSR in all three cosmological scenario are consistent with the rate of MNS observed by LIGO/Virgo and the one estimated by Della Valle+18
- Assuming the alternative scenario as the best one, the sGRBs redshift distribution proposed by Ghirlanda+16 is best represented by our CMNSR with a DTD ($\beta = -0.9$). In the case of a constant delay time too many event at high redshift are produced.
- At least in principle, the observations of the number of MNS can be used to discriminate the different scenarios at play. In particular, each scenario is capable of predicting significantly different kilonovae rates in elliptical even at very low redshift.