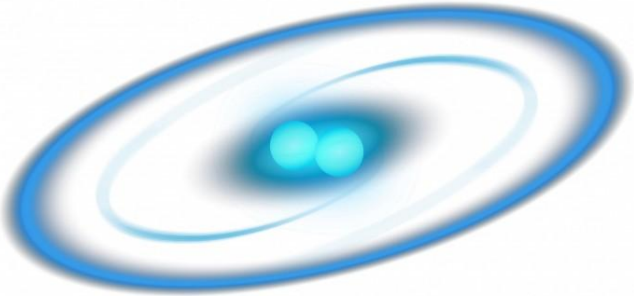
École Doctorale d'Astronomie & Astrophysique
d'île-de-France

The parameter space of binary neutron stars populations



Mathieu VENET
Encadrement par Irina DVORKIN

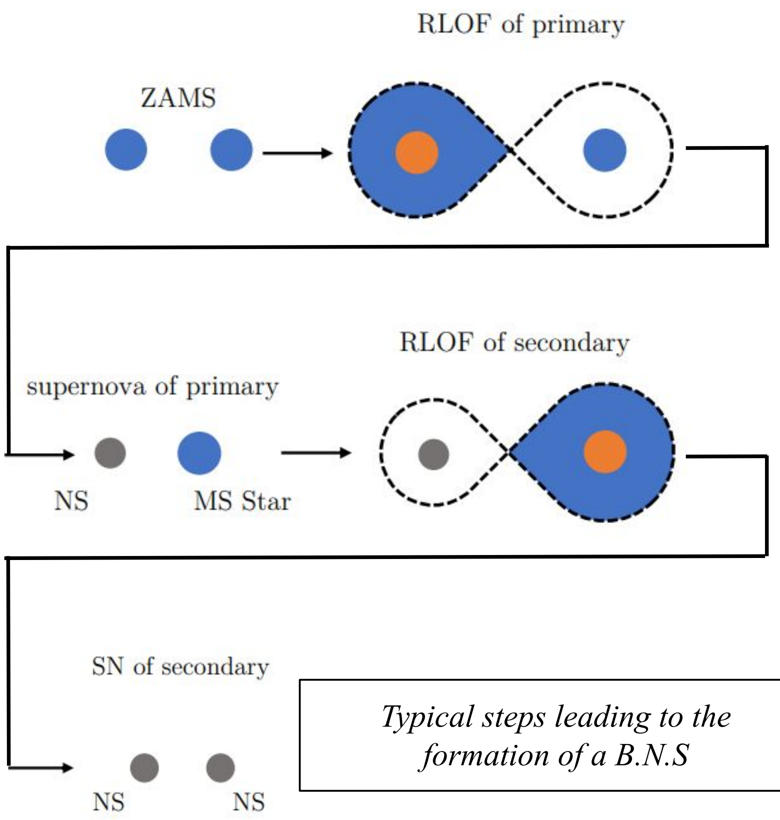
SCIENCES
SORBONNE
UNIVERSITÉ

Binary neutrons stars (B.N.S) formation

- **Rare compact objects systems**
- **Following a typical formation**
  - High-mass stars (~8-20 solar masses) on the main sequence
  - Supernovae and potential binary destruction

An evolution governed by complex physics

- **A high number of parameters**
  - Single Star Evolution (metallicity, winds…)
  - Binary Star Evolution (mass transfers, common enveloppe)
  - With each having its own uncertainties

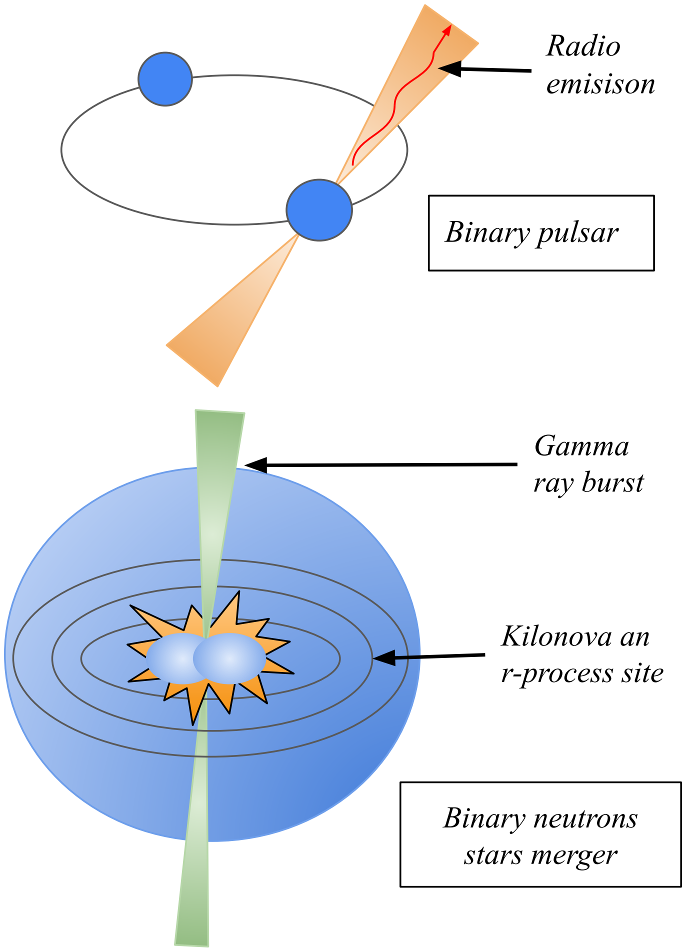


Typical steps leading to the formation of a B.N.S

Pellouin (2023)

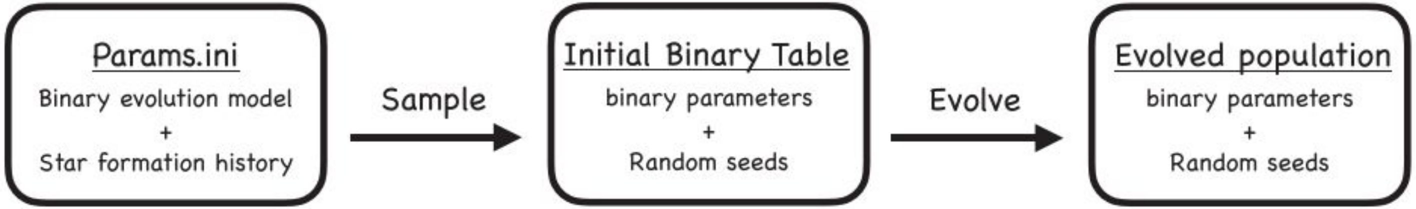
A multi-messenger observation

- **Binary Pulsars (pulsar + N.S)**
  - Emitting in radio
  - About 20 detected to this day
- **Extragalactic observations**
  - B.N.S mergers and gravitational waves emission
  - Associated phenomenon : kilonovae, gamma ray bursts



The key role of population synthesis codes

- **What is a population synthesis code?**
  - Simulates the evolution of binary star populations
  - Description of key physical processes
  - Enables comparison with limited observational data
- **Why COSMIC ?**
  - Optimized for simulating the evolution of a very large number of systems (typically over 1 billion)



Breivik et al. (2020)

Parameters space exploration

- **COSMIC** includes about **50 parameters,** linked to more than **130 different models.**
- **Initial population setup**
  - Chabrier (2003) IMF and top-heavy IMF for lowest metallicities
  - Initial separation and eccentricity sampled from Sana and al (2012)
- **Some key parameters need to be explored for B.N.S formation**
  - Metallicity bins to describe different stellar formation epochs/environnements
  - 4 parameters that affect greatly B.N.S populations
- **Two** allocations of **500k computing hours** on national supercomputers have been granted

GENCI
Le calcul intensif au service de la connaissance

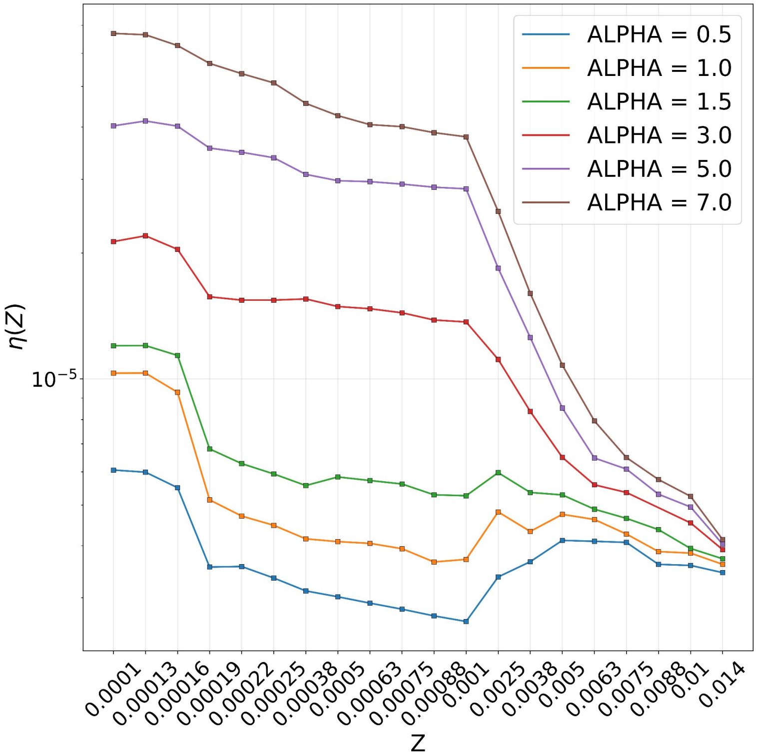
Parameter	Physical impact	Number of values
Metallicity	Single star evolution	20
Alpha	Efficiency of C.E	6
Qcflag	Conditions of C.E	3
Kickflag	Types of kick distribution	2
CE_kickflag	Kick prescription during C.E	2

Parameters comparison

- **Formation efficiency**

$$\eta(Z) = \frac{\mathcal{N}_{\mathrm{TOT}}(Z)}{M\star(Z)}$$

- The **ALPHA** parameter
  - Common envelope (CE) phase: unstable mass transfer where the donor's envelope engulfs the system
  - ALPHA = efficiency of the common envelope ejection ⇒ higher ALPHA means easier envelope ejection
  - **η**(Z) increases with ALPHA ⇒ heavy systems can survive the CE phase to fall into the BNS mass range

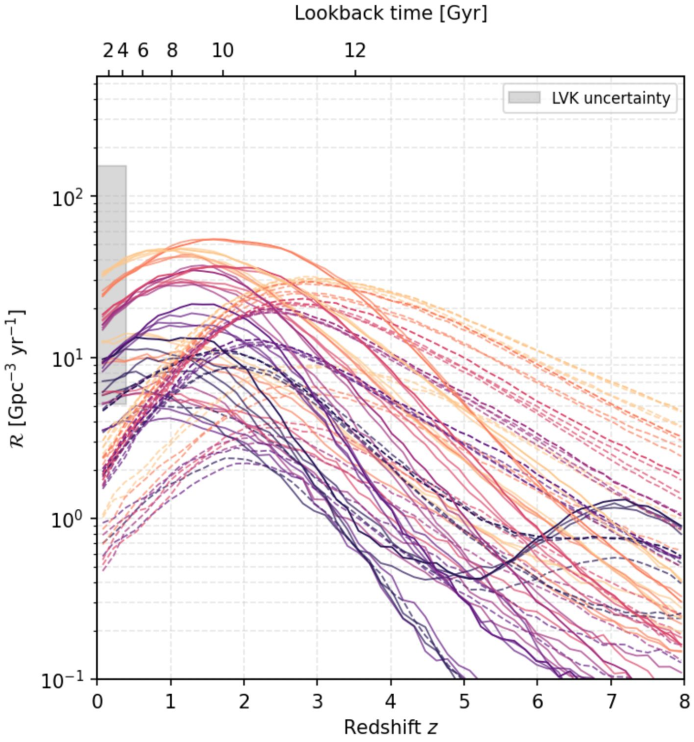


η as a function of metallicity for a selected set of models. Different colors correspond to variations in the ALPHA value.

Comparison between models

- **Cosmological merger rates**
  - **COSMIC** gives us a BNS population for a metallicity bin with its merger time delay
  - We combine this with a cosmological **SFR model** and a **metallicity-redshift relation**

- **Impact of the main parameters on the merger rate**
  - If the **ALPHA** value is hig**h the merger rate** is **greater**
  - **Comparison** with the **LVK** BNS **merger rate** uncertainty

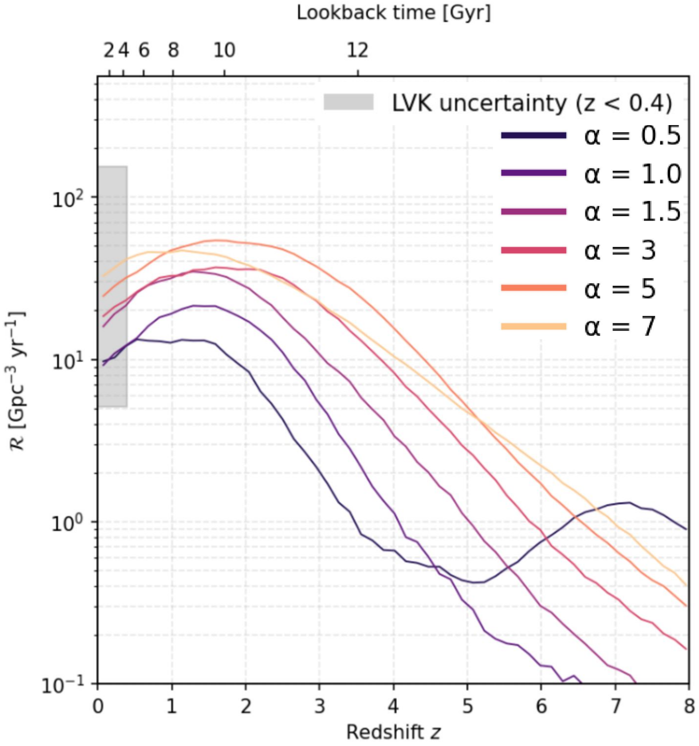


Merger rate as a function of redshift for all models. Different colors linestyles and opacities corresponds to variations in the ALPHA values, KICKLFAG, QCFLAG and CE_KICKFLAG prescriptions

Comparison between models

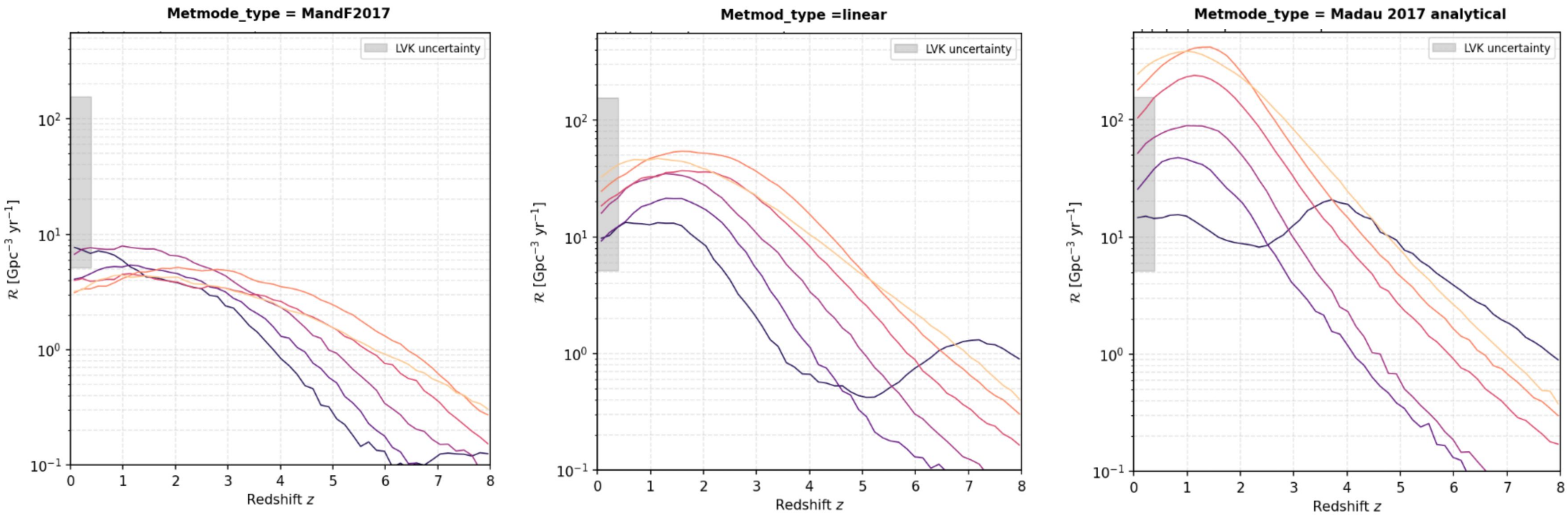
- **Cosmological merger rates**
  - **COSMIC** gives us a BNS population for a metallicity bin with its merger time delay
  - We combine this with a cosmological **SFR model** and a **metallicity-redshift relation**

- **Impact of the main parameters on the merger rate**
  - If the **ALPHA** value is hig**h the merger rate** is **greater**
  - **Comparison** with the **LVK** BNS **merger rate** uncertainty



Merger rate as a function of redshift for a selection of models. Different colors corresponds to variations in the ALPHA values

Metallicity-redshift relation



- **MandF2017** (Madau & Fragos (2017)) and **linear** (Gallazzi et al. (2008), De Cia et al. (2018)) models are based on **observational data** while **Madau 2017 analytical** is an **analytical relation** obtained from the Madau & Fragos (2017) SFR
- This uncertainty makes it **hard to discriminate specific models**

Merger rate as a function of redshift for all models and for different metallicity–redshift relations. From left to right: the MandF2017 relation, the linear relation, and the analytical Madau 2017 relation.

Conclusion

BNS systems formation and observables

- **Rare compact objects** systems that rely on intricate physical processes
- **Limited** observational data

COSMIC and the parameter space exploration

- **Population synthesis codes** provide a means to **explore key physical parameters** and help understand limited **observational data**
- **Parameter space exploration** of around ~**1600** B.N.S populations

Formation efficiency

- We can define **the most important parameters** and their **impact on the formation efficiency**
- We can identify **general trends with metallicity evolution** linked to **key physical parameters**

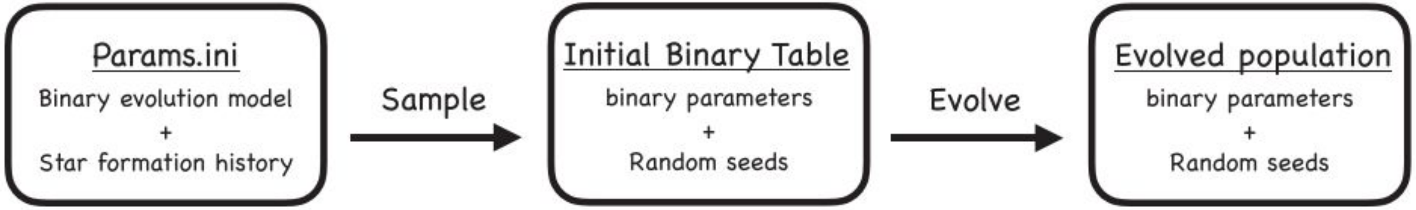
Cosmological merger rates

- A way to **compare** the different **models to a limited observational data set**
- But uncertainties in the **metallicity-redshift relation** makes **discriminating models difficult**

Annexe

Advantages and principle of COSMIC

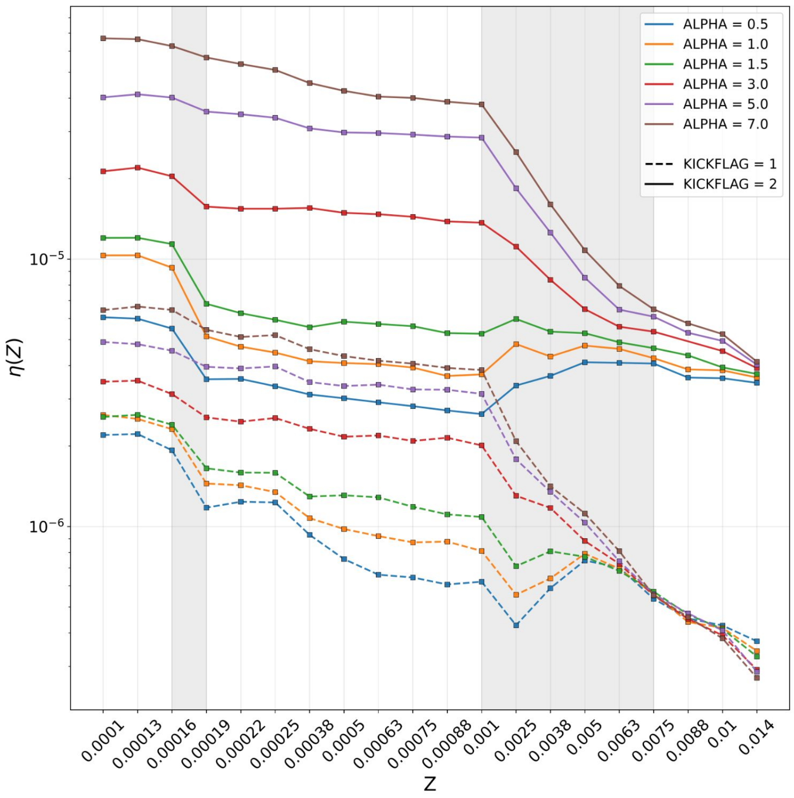
- **The principle of COSMIC**
  - Initializes Zero-Age Main Sequence (ZAMS) stars based on distributions from scientific literature
  - Simulates system evolution
    - Single-star evolution using a one-zone model.
    - Binary system evolution using analytical models (GW, RLOF, CE…)
- **Why COSMIC ?**
  - Optimized for simulating the evolution of a very large number of systems (typically over 1 billion).
  - Incorporates the latest astrophysical models
  - Supports accretion-induced collapse.

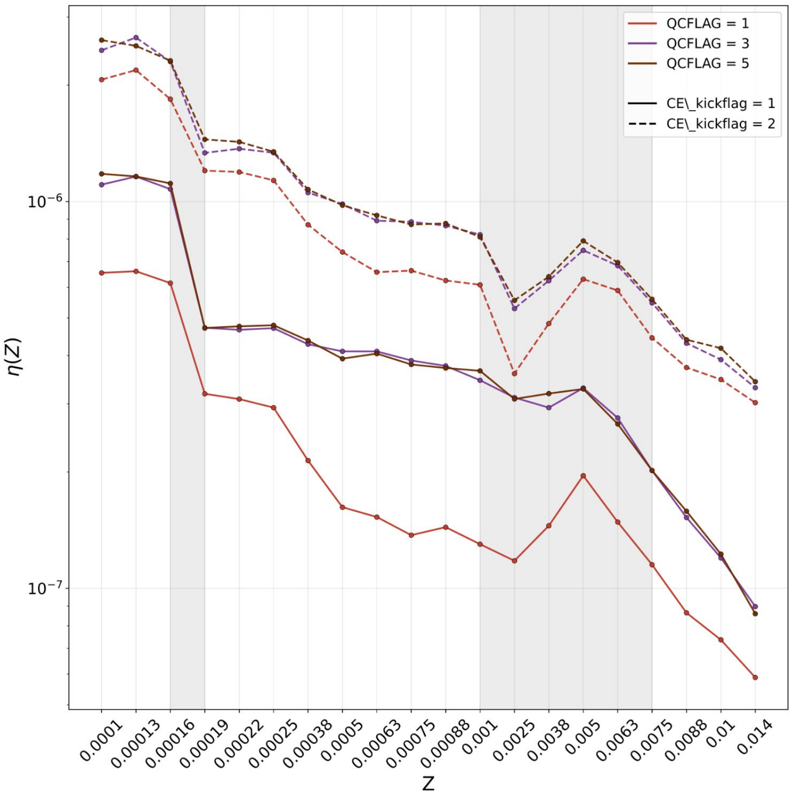


Breivik et al. (2020)

Annexe

Formation efficiency





Annexe

Cosmological merger rate

$$\mathcal{R}(z) = \frac{d}{dt_{\mathrm{lb}}(z)} \int_{z_{\max}}^{z} \psi(z') \frac{dt_{\mathrm{lb}}(z')}{dz'} \times \int_{Z_{\min}(z')}^{Z_{\max}(z')} \eta_{merge}(Z)\, \mathcal{F}(z', z, Z)\, dZ\, dz'$$

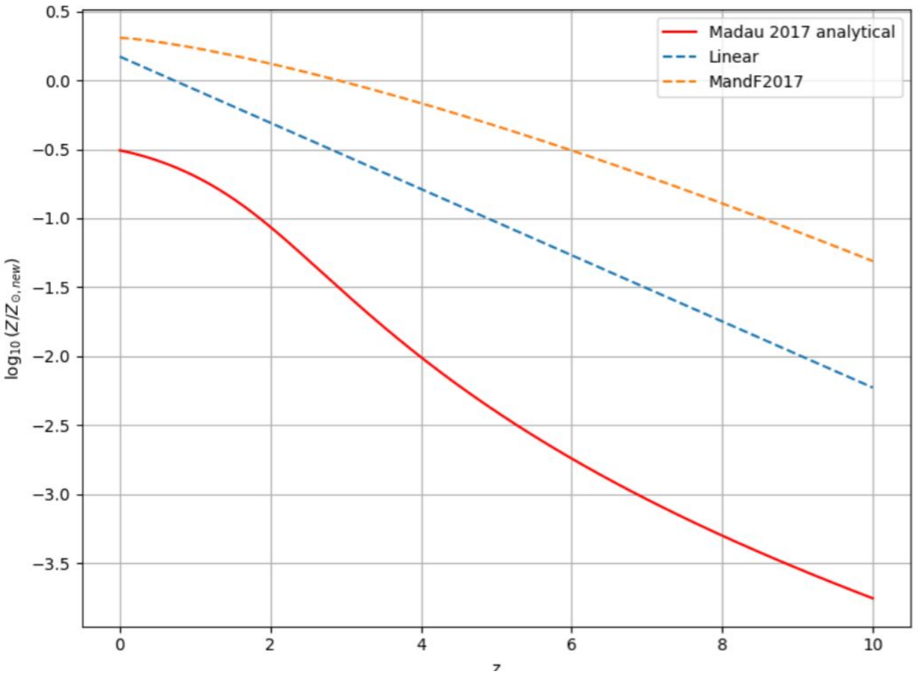
Here, $t_{lb}(z)$ is the look-back time at redshift z, $\psi(z')$ is the cosmic star formation rate density, and $Z_{min}(z')$ and $Z_{max}(z')$ define the metallicity range of stars formed at redshift z'. The term $\eta(Z)$ is the merger efficiency at metallicity Z, while $F(z', z, Z)$ describes the fraction of compact binaries formed at redshift z' and metallicity Z that merge at redshift z, normalized over all systems formed at that metallicity.

$$\bar{Z}(z) = \frac{y(1-R)}{\rho_b} \int_{z}^{z_{\max}} \frac{10^{0.5}\, \psi(z')}{H_0(1+z')\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}}\, dz'$$

$\psi(z')$ is the SFR model, here taken from Madau & Fragos (2017), $H_0 = 68$ km s−1 Mpc−1 is the Hubble constant, $\Omega_\Lambda = 0.69$ is the dark energy density parameter, $\Omega_m = 0.31$, $R = 0.27$ is the fraction of stellar mass returned to the interstellar medium, $y = 0.019$ is the net metal yield, and $\varrho_b = 2.77 \times 1011\ \Omega_b\, h^2\, M_\odot$ Mpc−3 is the present-day baryon density

Annexe

Metallicity-redshift relation



Mean metallicity as a function of redshift for our three models.The red curve represents our integration method using the SFR from Madau & Fragos (2017). The blue and yellow dashed curves represent observational fits from Gallazzi et al. (2008), De Cia et al. (2018), and Madau & Fragos (2017), respectively.

Annexe

Linear metallicity-redshift relation

$$\log\left(\frac{\bar{Z}(z)}{Z_\odot}\right) = a + bz$$

a **= log(1.04) as from Gallazzi et al. (2008)**

"stellar metallicity and stellar mass estimates for a large sample of galaxies drawn from the Sloan Digital Sky Survey Data Release

$\langle Z* \rangle = 1.04 \pm 0.14\ Z_\odot$"

b **= −0.25 as from De Cia et al. (2018)**

"Interpreting abundances of damped Ly-α absorbers (DLAs) from absorption-line spectroscopy has typically been a challenge because of the presence of dust. Nevertheless, because DLAs trace distant gas-rich galaxies regardless of their luminosity, they provide an attractive way of measuring the evolution of the metallicity of the neutral gas with cosmic time.

In this case, we find a slope of the metallicity vs redshift relation of -0.24 ± 0.14 dex"

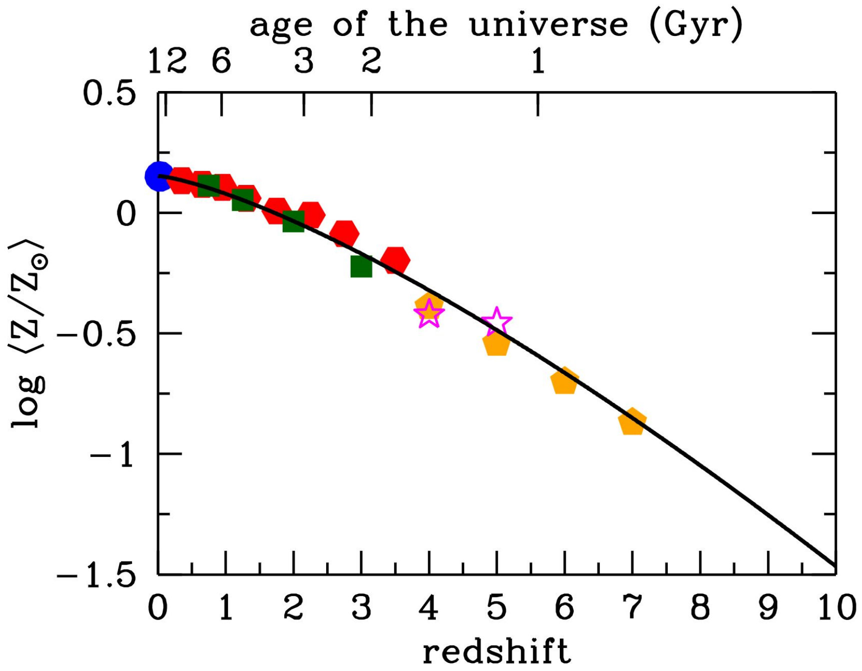
Annexe

MandF2017 metallicity-redshift relation

$$\log\left(\frac{\bar{Z}(z)}{Z_{\odot}}\right) = a - b\ z^{c}$$

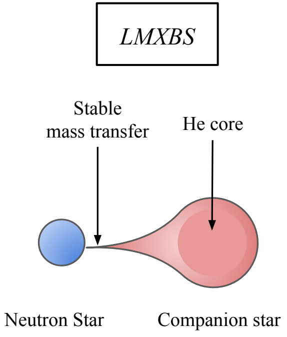
with *a* = 0.153, *b* = −0.074, and *c* = 1.34 as from Madau & Fragos (2017).

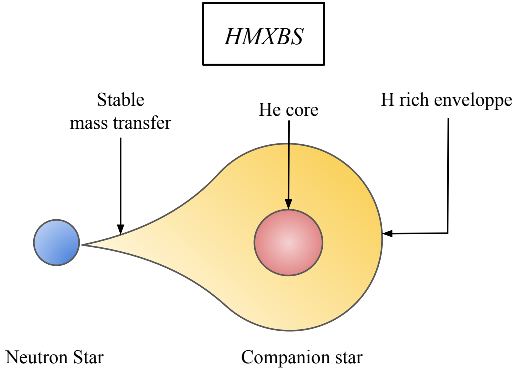
“Figure : Gas-phase metallicity history of the galaxy population as a whole. [...] The data points are from Baldry et al. (2012; blue dot), Ilbert et al. (2013; red hexagons), Kajisawa et al. (2009; green squares), Lee et al. (2012; magenta stars), and Grazian et al. (2015; orange pentagons). Oxygen metallicities are expressed in units of solar (Anders & Grevesse 1989). All estimates of stellar mass have been adjusted to the same IMF. The dashed line shows the best-fitting function á ñ = –Z Z zlog 0.153 0.074 1.34.”

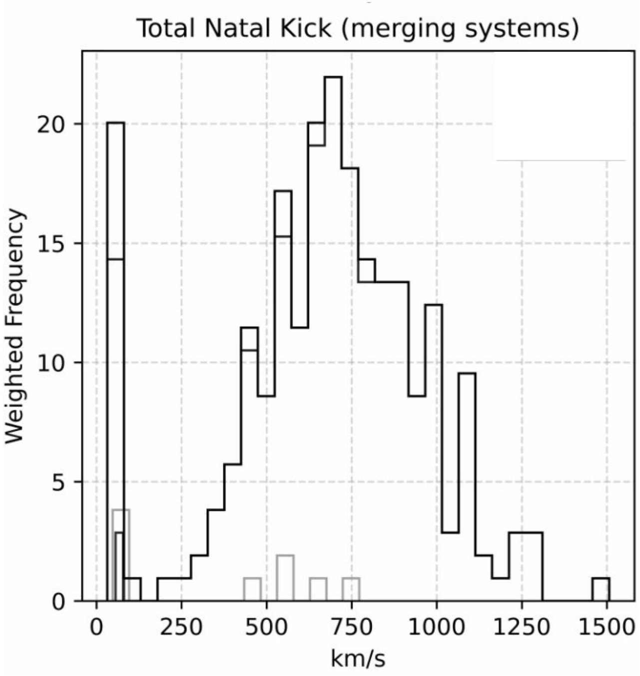


Indirect observations

- **X-ray binaries** are **transient sources** emitting primarily in X-rays
    - They are thought to host an accreting neutron star in a binary system
    - Companion stars can be massive (HMXBs) or stripped/low-mass (LMXBs)
    - New formation channels trace their frequency and key properties as a function of binary evolution parameters (ex : metallicity)
- **B.N.S merger offset** from the star formation site depends on the **supernovae types** and their **respective kicks**





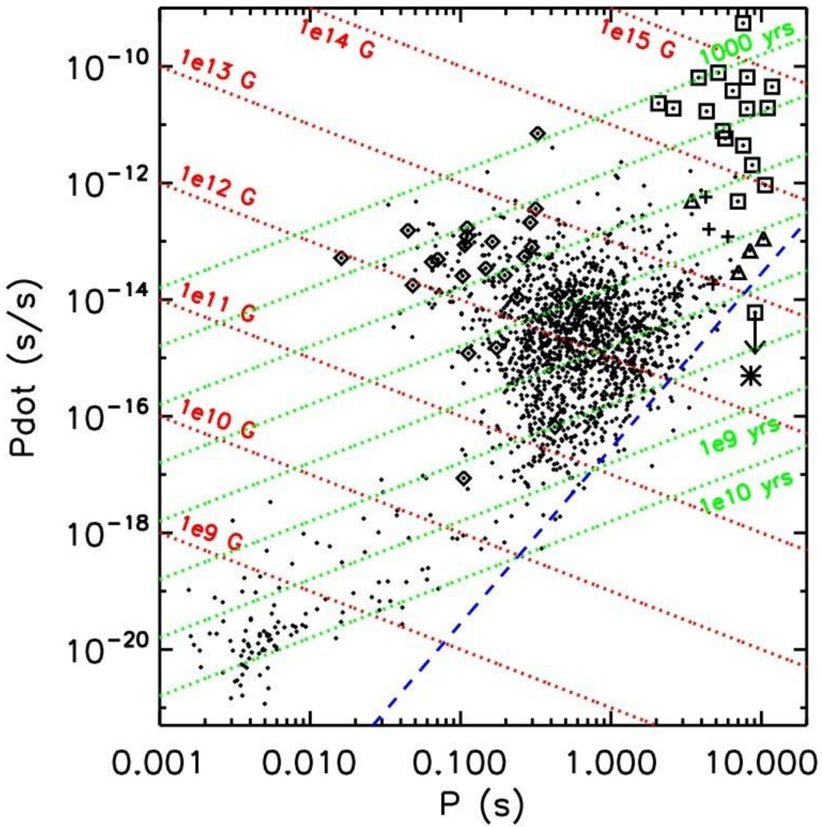


Top histogram: Total natal kick distribution (km s^{-1}) for the merging population.
The low-velocity and high-velocity components of the bimodal distribution correspond to ECSN and CCSN supernovae, respectively.

Annexe : Modélisation du signal radio des pulsars binaires

- Pulsars observables :
  - La death line comme limite de détection
  - La prise en compte d'arguments géométriques
- La modélisation du signal :
  - Modèles analytique (P, dP et B)
  - Utilisation des valeurs de P et dP de COSMIC

Gotthelf et al. (2013)



Bibliographie

[1] Page de garde : Capital International. “In the Spotlight: Marcus Collier-Wright of Neutron Star Systems”. 21 Mai 2024. https://www.capital-staff.com/spotlight-marcus-collier-wright-neutron-star-systems/

[2] : Clément Pellouin. Binary neutron star mergers in the multi-messenger era : very high energy afterglows and progenitor evolutionary tracks. Astrophysics [astro-ph]. Sorbonne Université, 2023.

[3] : Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2020, The Astrophysical Journal Letters, 892, L3

[4] : Deng, Z.-L., Li, X.-D., Shao, Y., & Xu, K. 2024, , 963, 80

[5] : Dvorkin, I., Daigne, F., Goriely, S., Vangioni, E., & Silk, J. 2021, , 506, 437