Astrophysics of LIGO/Virgo sources in O3 era
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# SFR history & chemical evolution of the Universe

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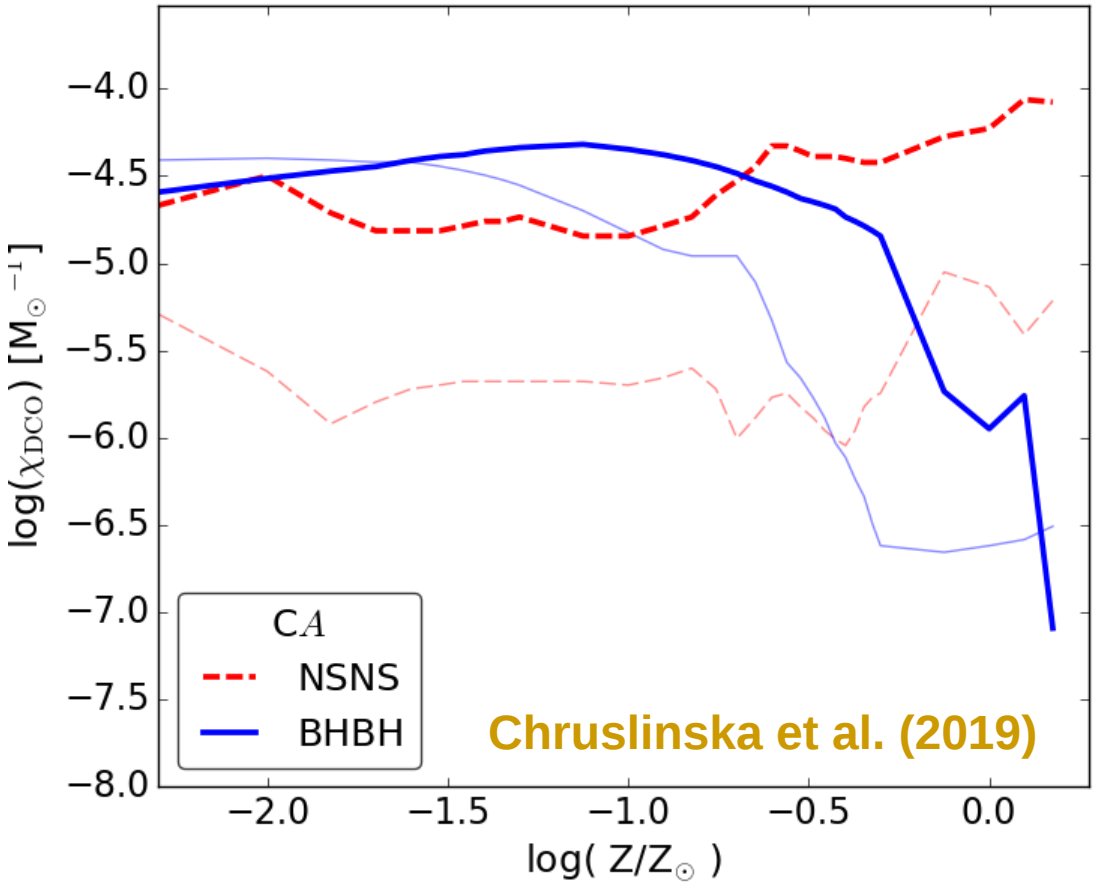
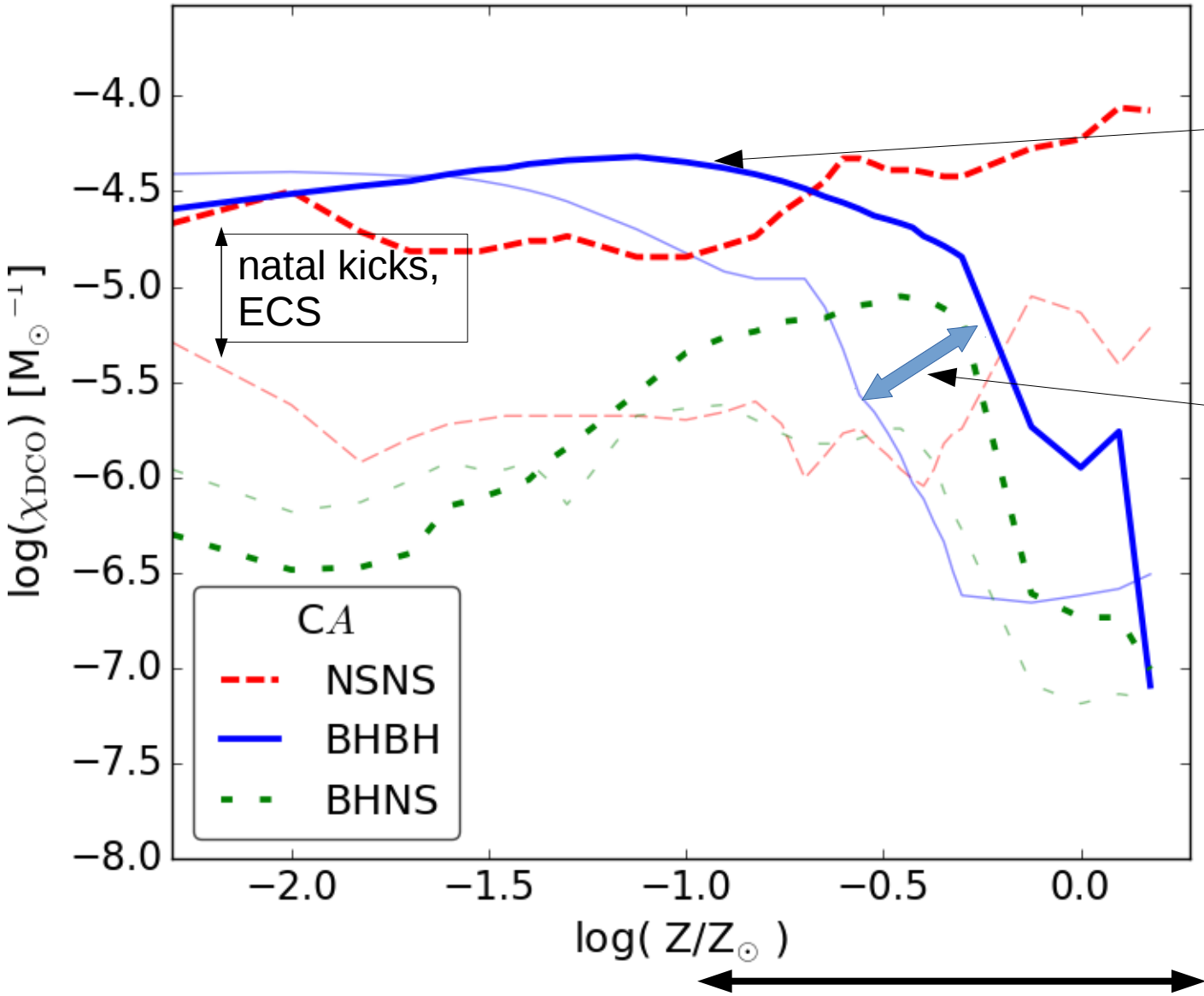
# Number of merging binaries
# *per unit of formed stellar mass* vs metallicity




← example population synthesis simulations result (model dependent!)

# Formation efficiency vs metallicity

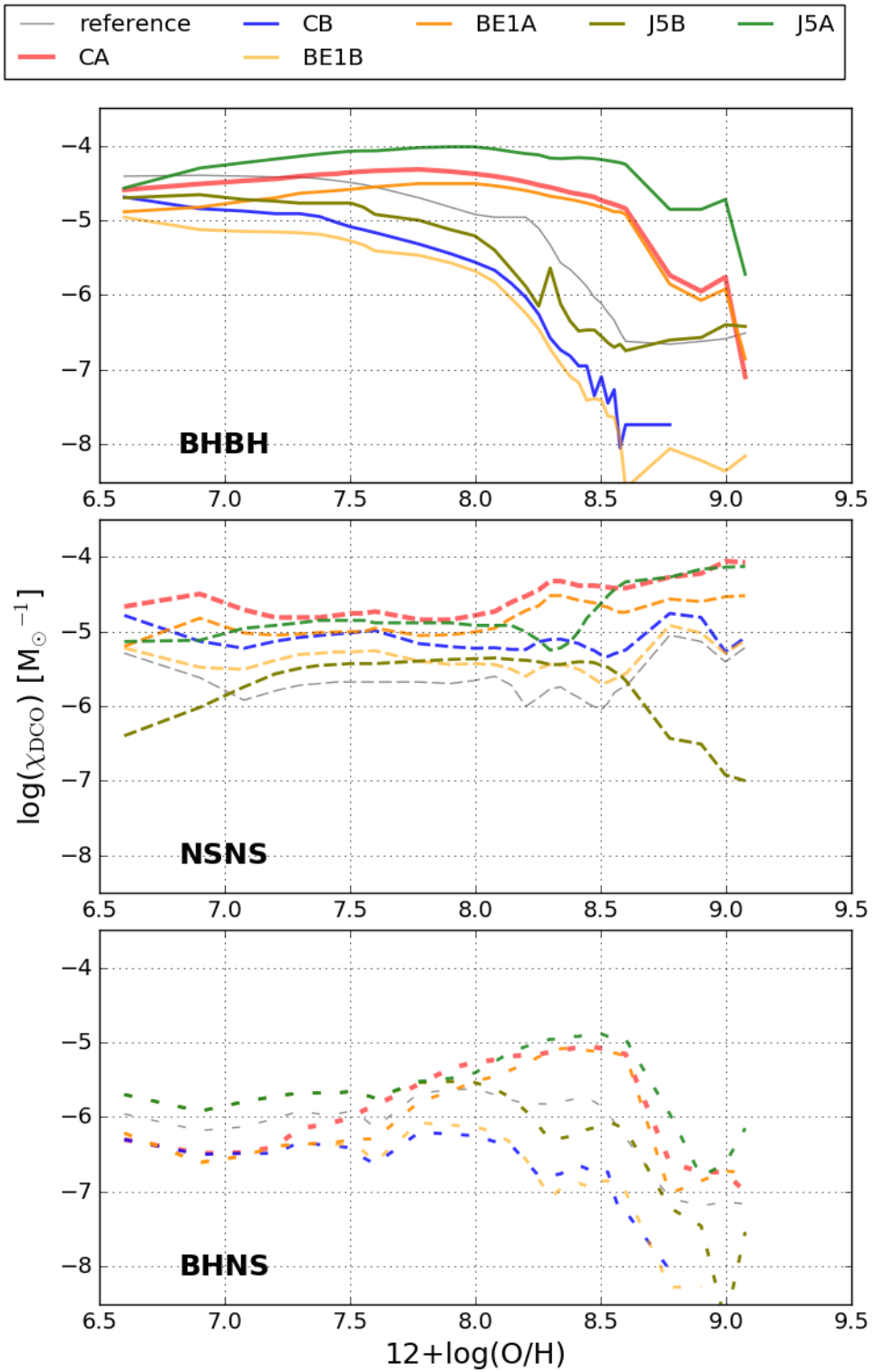
(number of merging binaries per unit star-forming mass vs metallicity)



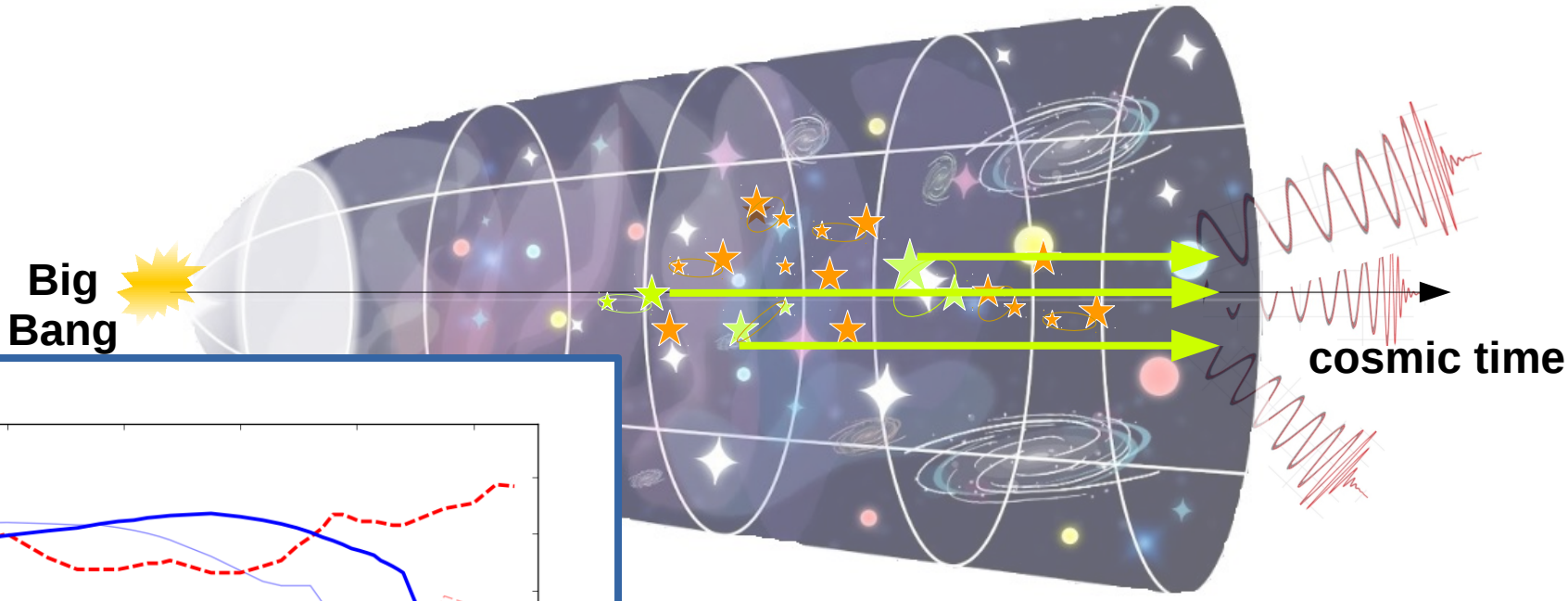

Low-Z → massive BH progenitors → ***direct collapse*** → no kick

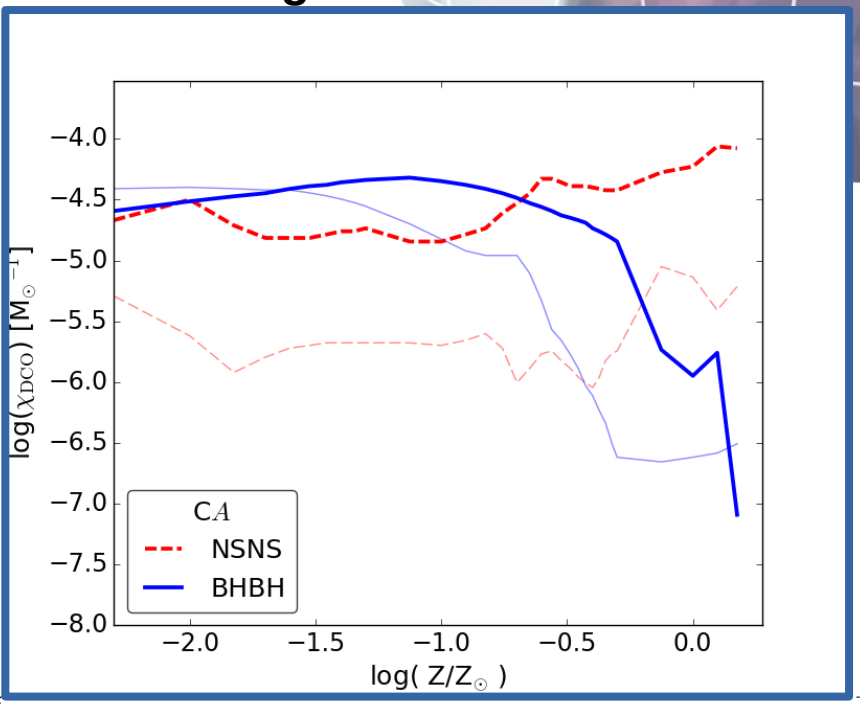
high-Z → likely CE with 'HG donor'

→ **Chruslinska M.**, Nelemans G. & Belczynski K. (2019) ; see also discussion in Klencki+18


reference
CA
CB
BE1B
BE1A
J5B
J5A
BHBH
NSNS
BHNS
log(χDCO) [M⊙−1]
12+log(O/H)
−4
−5
−6
−7
−8
6.5
7.0
7.5
8.0
8.5
9.0
9.5

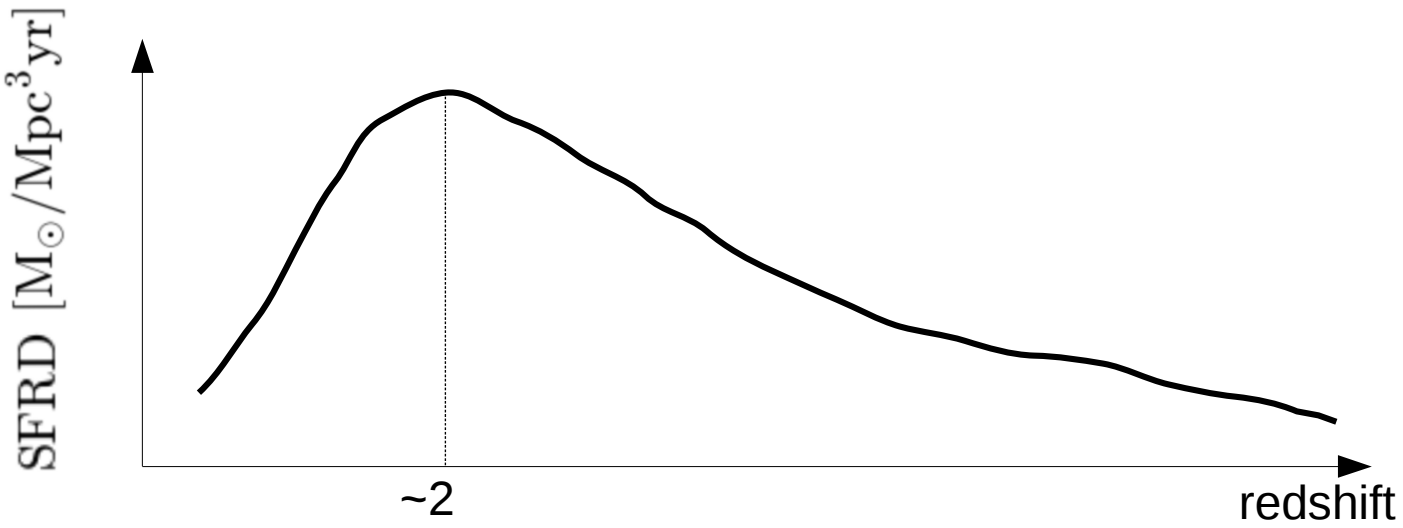
We observe a mixture of objects coming from progenitors formed at different z & **metallicities**



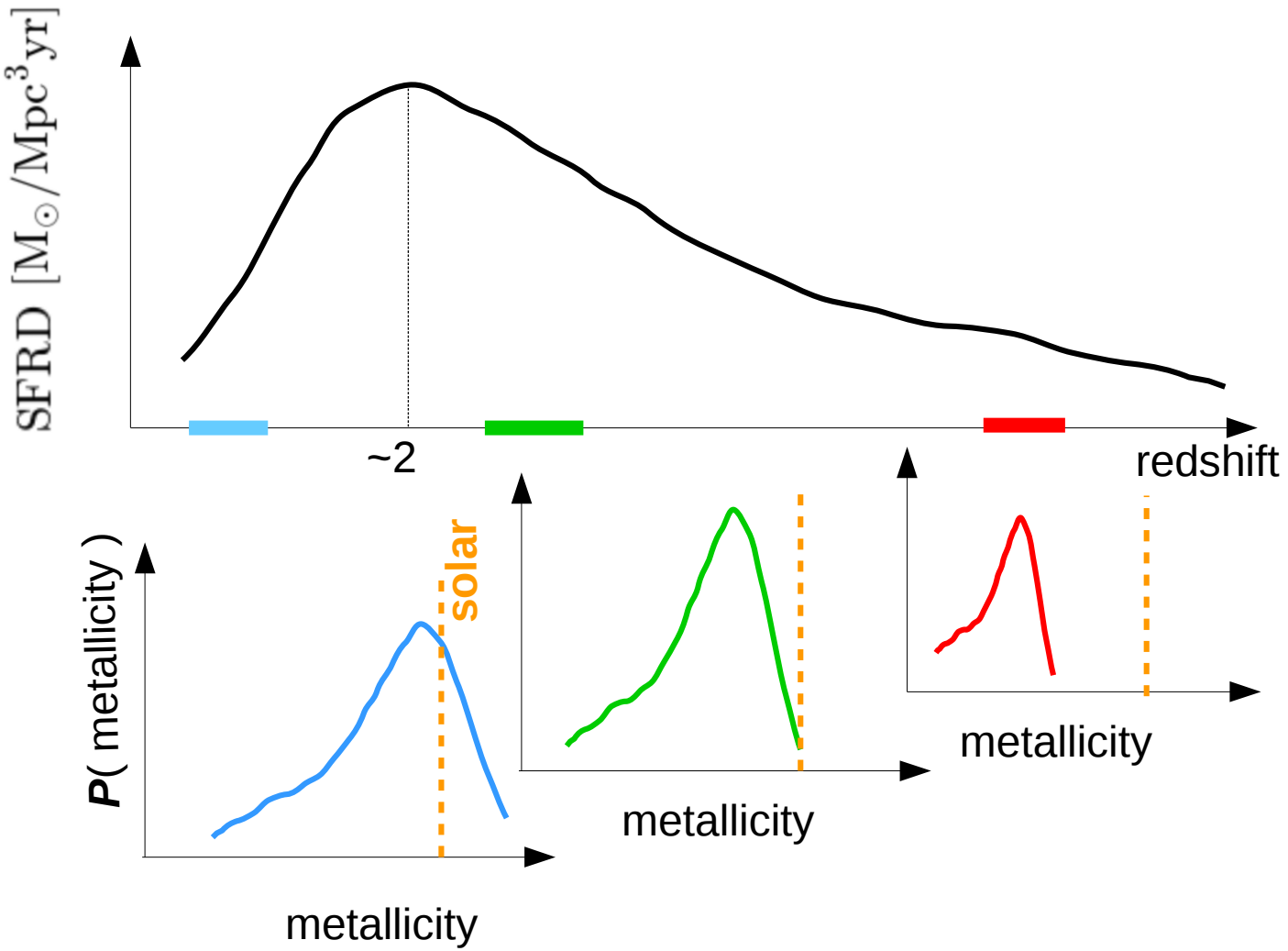




More SFR at low metallicities:
- more BH-BH mergers
- (a bit) less NS-NS

# Star formation history of the Universe



# Birth metallicities of stars across the cosmic history



# SFR(z,Z) - different approaches...

→ MOBSE ( Mapelli+17, Mapelli&Giacobbo ‘18 ):
based on Illustris cosmological simulations

→ BPASS 2.2, COMPASS ( Eldridge+18, Barrett+18 ):
Langer & Norman‘06 model for metallicity distribution +
Madau & Dickinson‘14 cosmic SFR history

→ StarTrack ( Dominik+13, Dominik+15 ):
combining results from Erb+06/Pei+99/Young & Fryer’07
to distribute metallicity in galaxies +
Fontana+06 galaxy mass distribution +
Strolger+04 cosmic SFR history
( Belczynski+16 ):
Madau & Dickinson‘14 mean metallicity of the baryonic
Universe (up-shifted by 0.5 dex, gaussian scatter of 0.5 dex)
+ Madau&Dickinson‘14 cosmic SFR history
(Belczynski>19): Madau & Fragos’17

→ …

**Recent additions:**

→ Boco et al. (2019):
empirical SFR functions + average history of SF and
chemical enrichment of individual galaxies

→ **Chruslinska & Nelemans (2019)**:
combining empirical scaling relations &
other observational properties of star forming galaxies

→ Neijssel et al. (2019), COMPASS:
compare several metallicity distributions & GSMFs + SFRD(z)

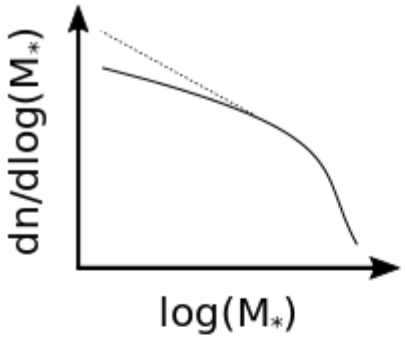
Number of progenitors formed at different z & **metallicities:**
**(very) different assumptions in the literature**

→ even a factor of 10 difference in rates
→ degeneracy with assumptions about the evolution
--- strength of the effect is *model dependent*
→ ratio of rates of different mergers affected
→ also affects e.g. “observed” mass distribution (morning discussion)

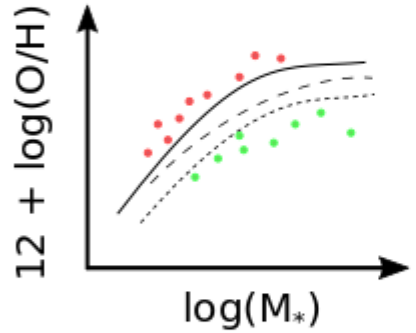
**Chruslinska et al. (2019a)**;
also recently Neijssel et al. (2019), Tang et al. (2019)

# Observation-based SFRD(Z,z)

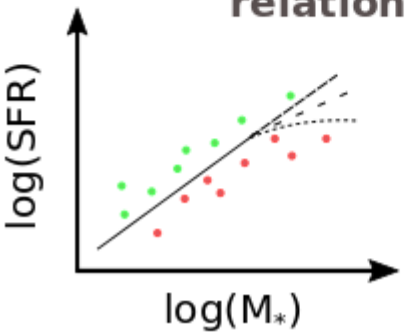
**(active) galaxy mass function**




**mass-metallicity relation**

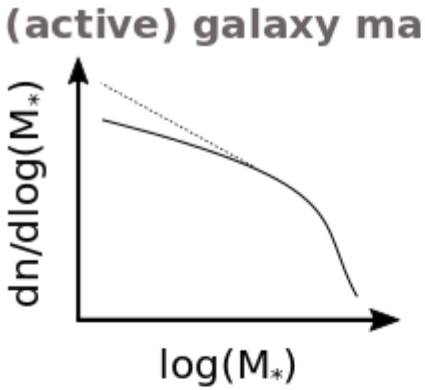


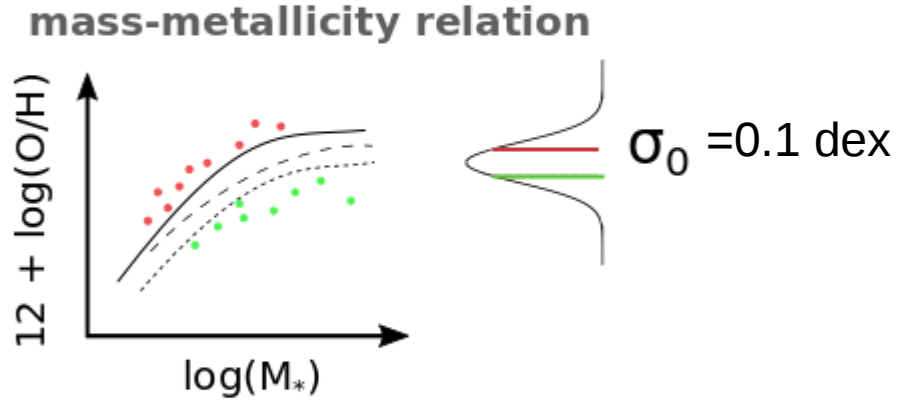

**star formation - mass relation**

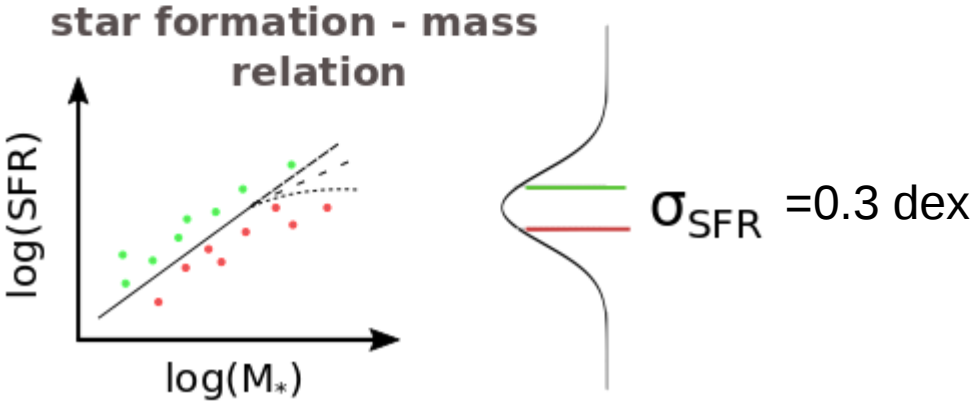



→ Chruslinska M. & Nelemans G. (2019)

# Method: scaling relations



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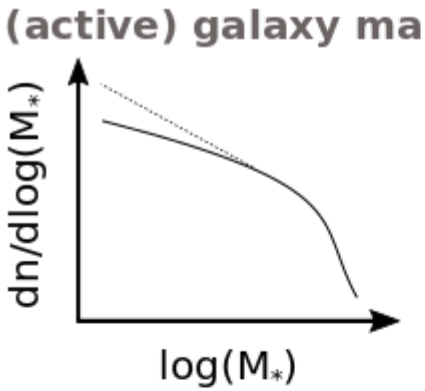
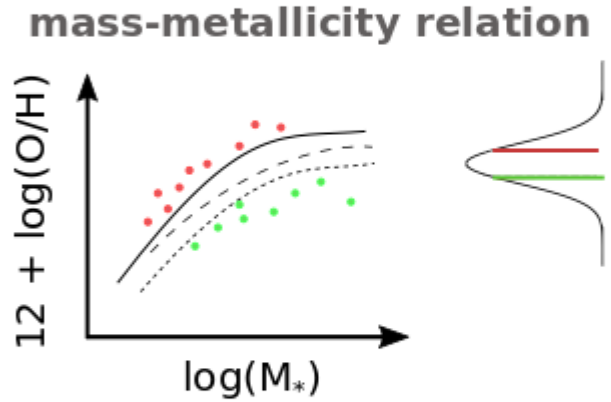
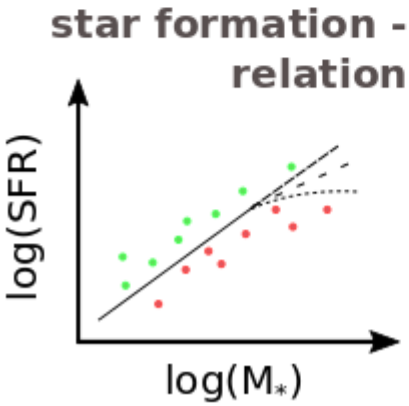


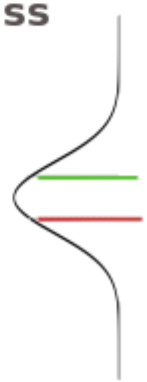

→ **"Fundamental metallicity relation"**
e.g. Ellison et al. (2008), Mannucci et al. (2010), Lara-López et al. (2013), Zahid et al. (2014), Matthee & Schaye (2018) ...





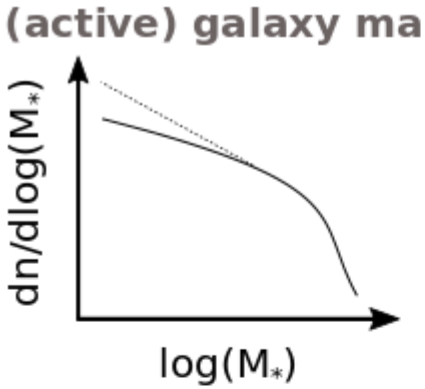

$\sigma_0$ =0.1 dex

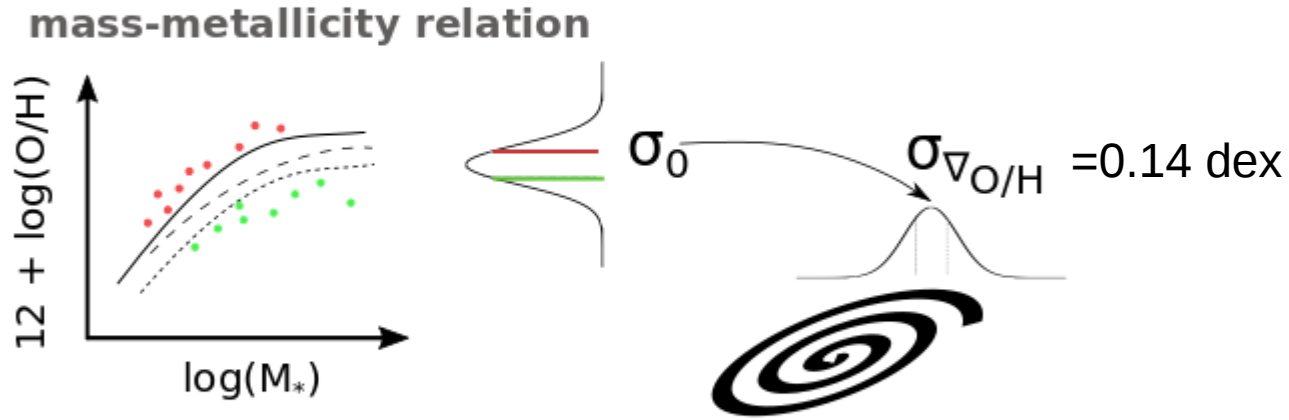


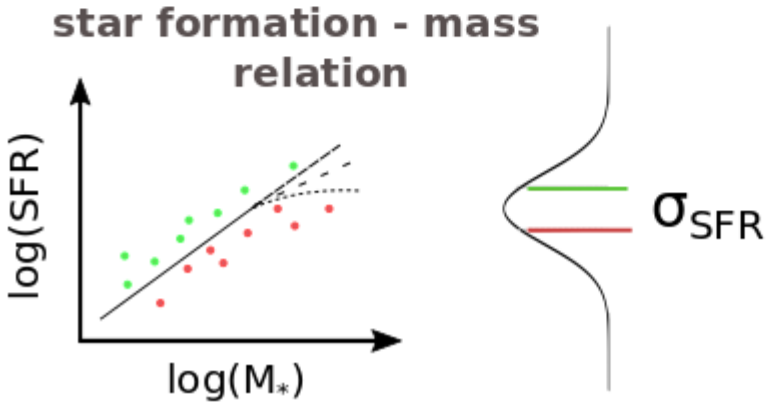



$\sigma_{SFR}$ =0.3 dex

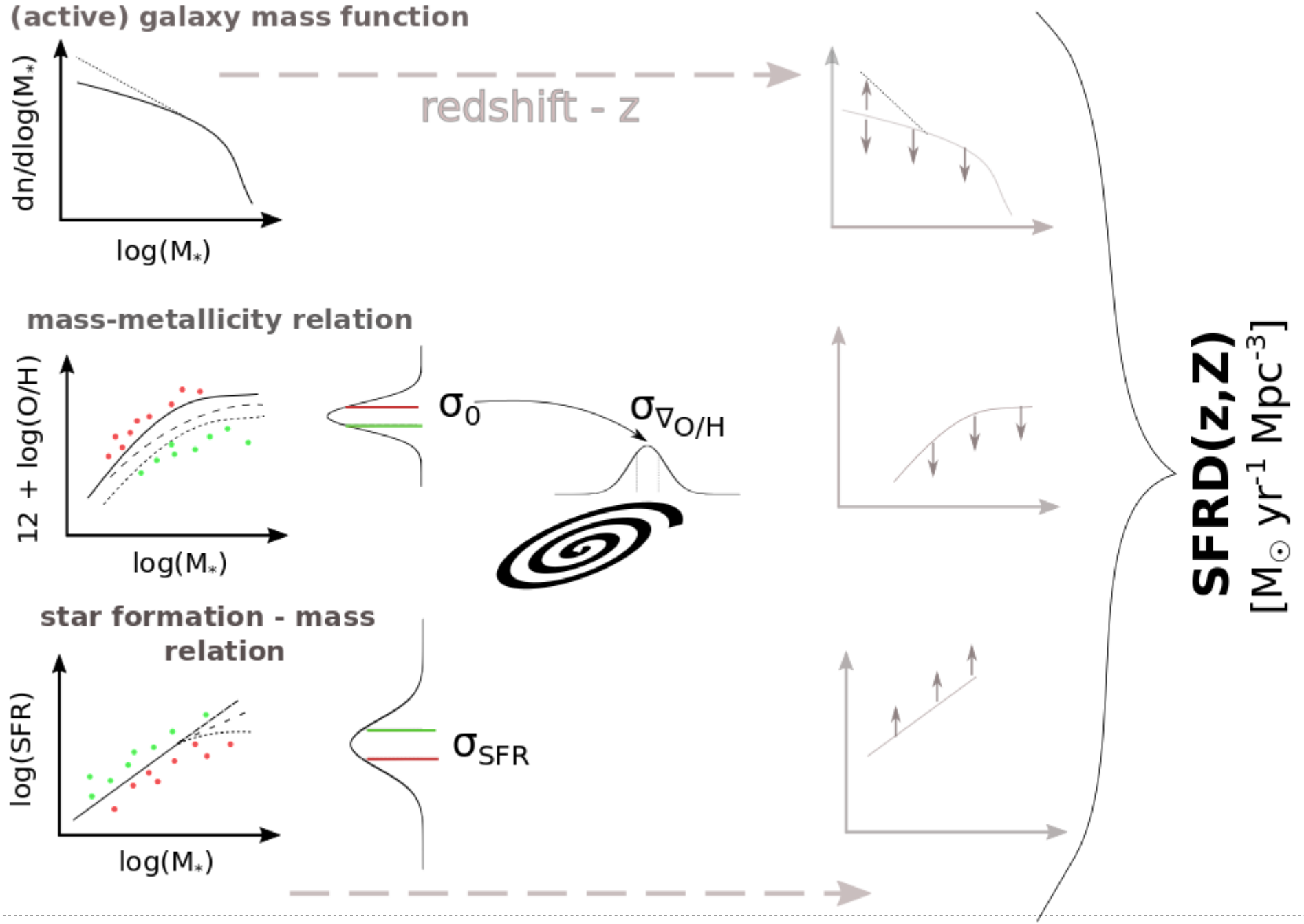
# Method: scaling relations



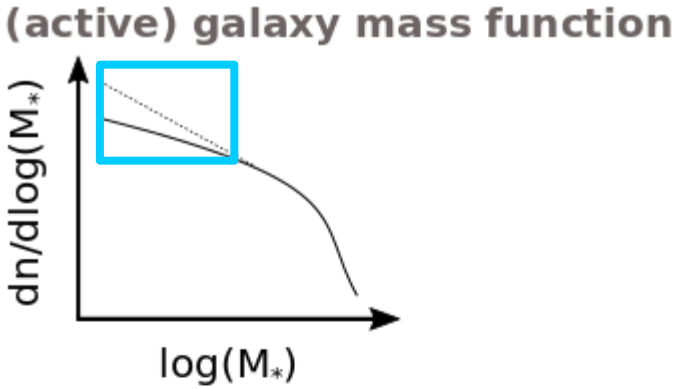



# Method: scaling relations



# Galaxy Stellar Mass Function





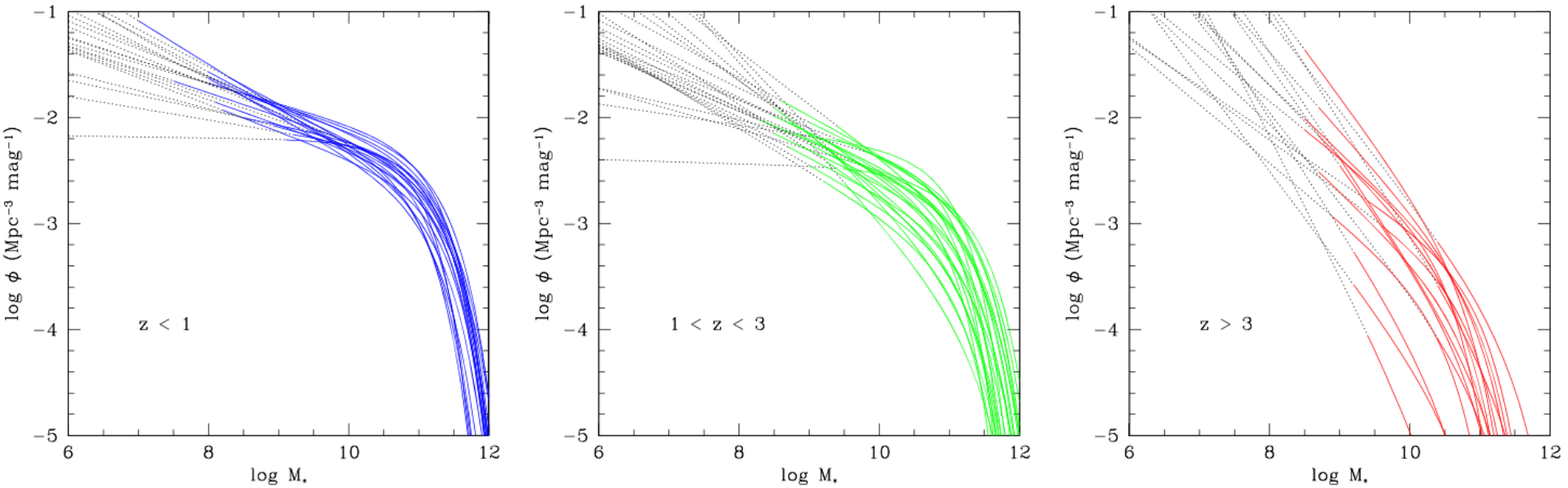
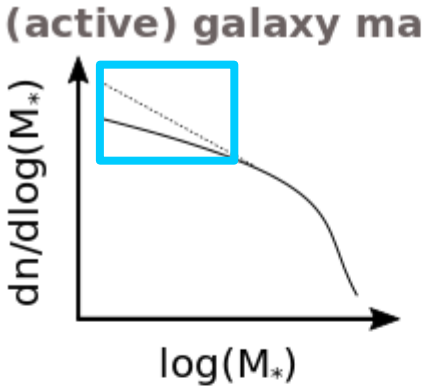
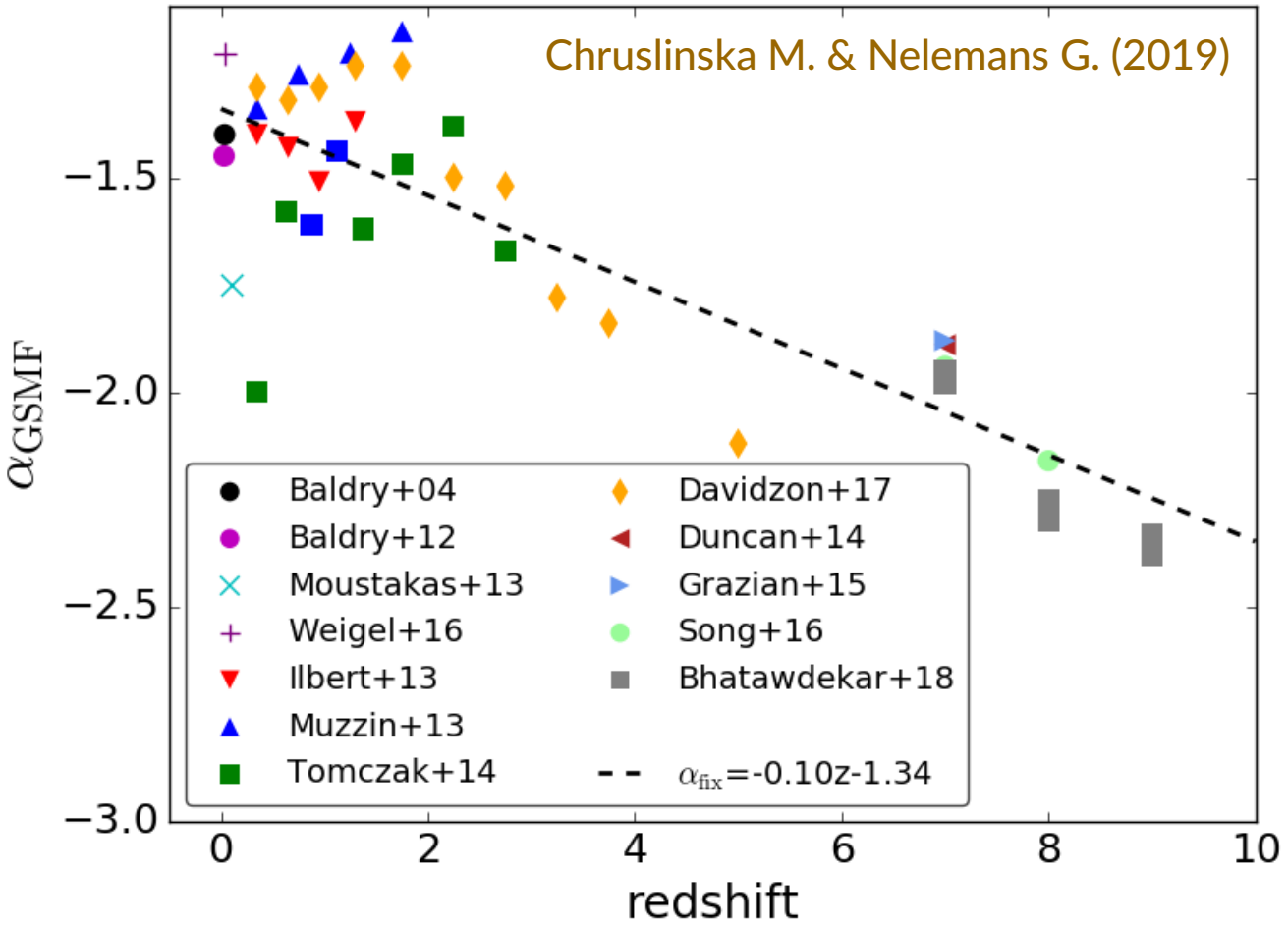




Figure 1 from Conselice et al. (2016): GSMF derived by different authors in three *z* ranges

# Galaxy Stellar Mass Function




→ low mass - end slope
(seepening with z?)



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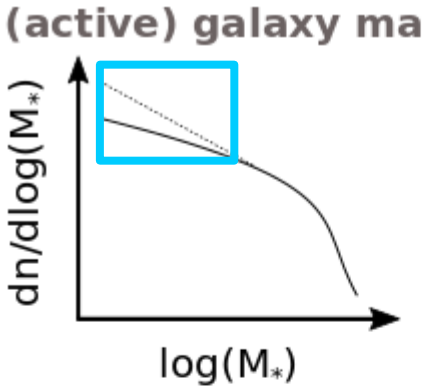


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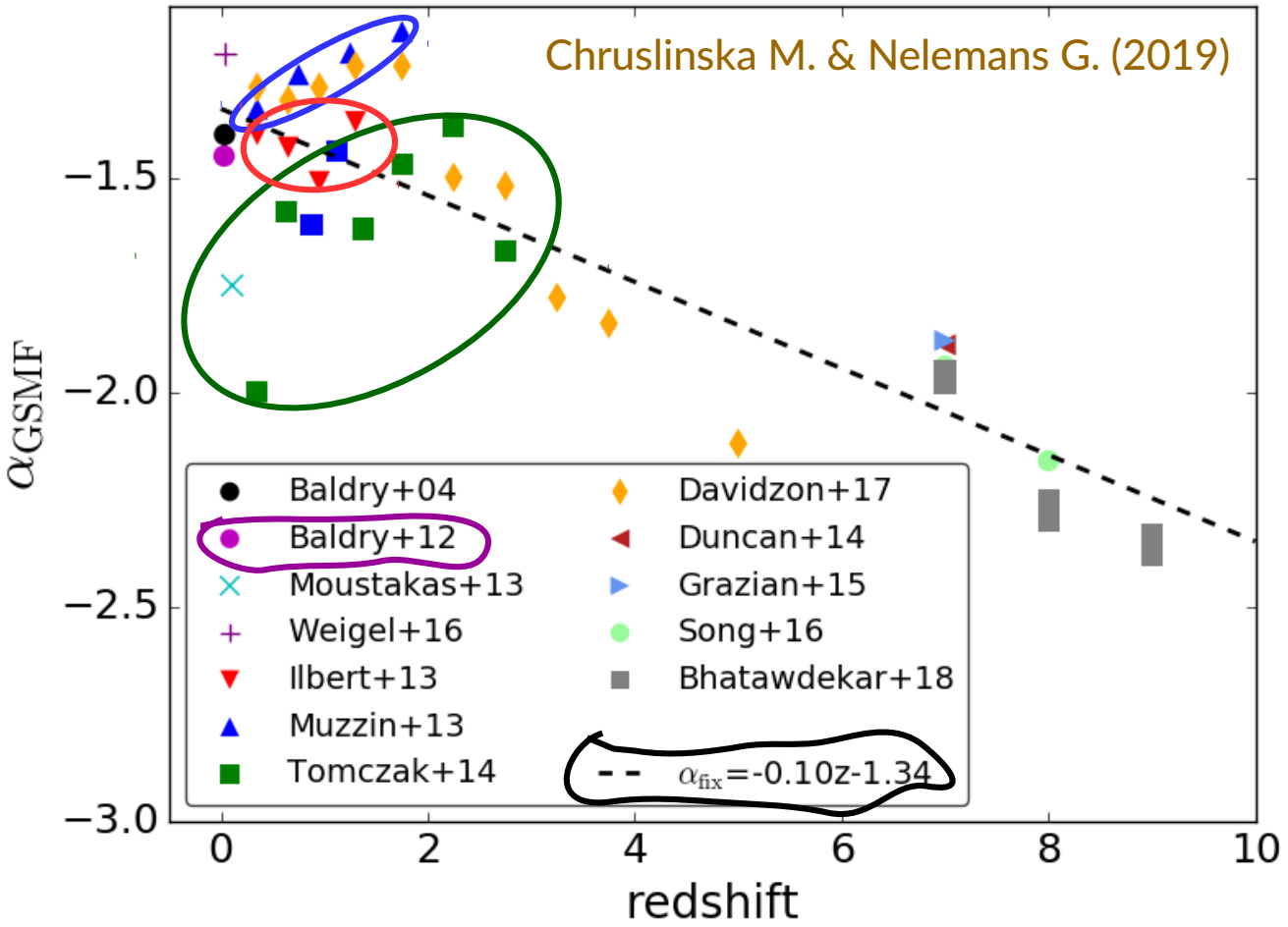
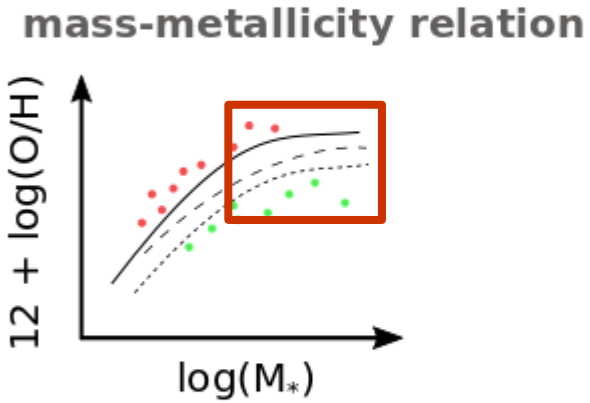
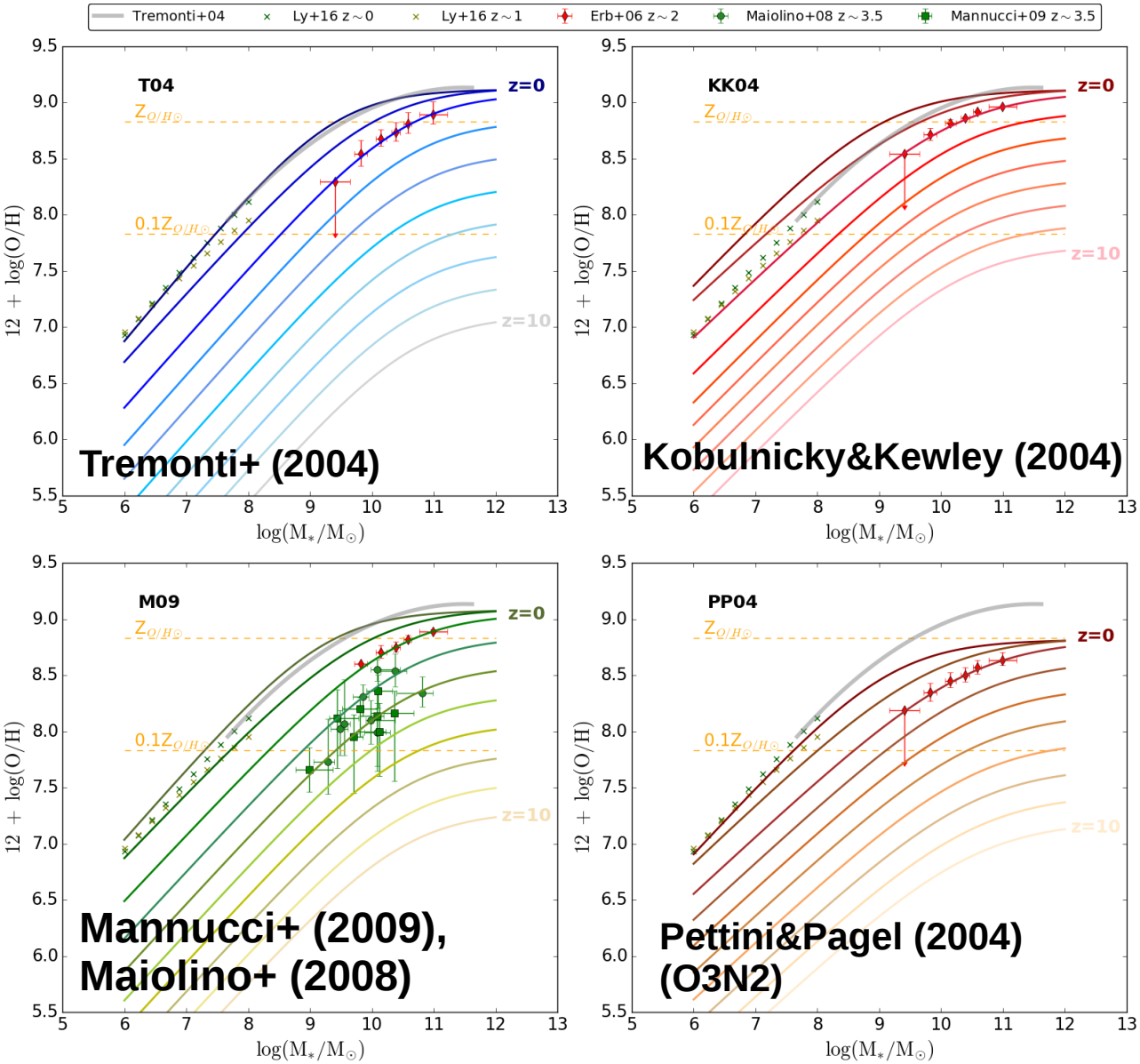


# Mass – metallicity relation

Chruslinska M. & Nelemans G. (2019)



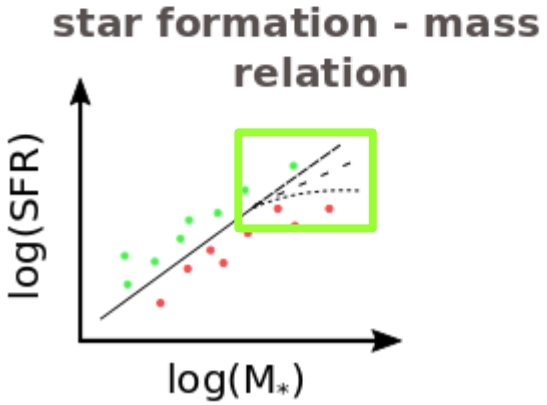

→ metallicity calibration; different methods
- → normalization
- → slope
- → evolution with z – extrapolation above z=3.5

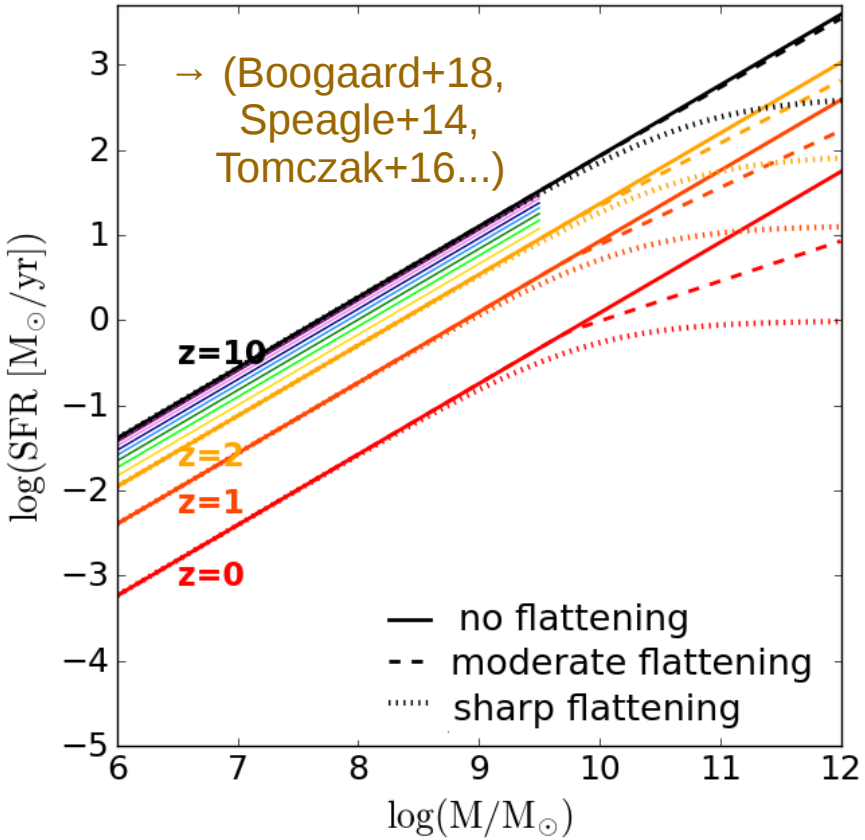


# Star formation – mass relation

→ high mass - end slope:

- no flattening — e.g. Speagle et al. (2014), Pearson et al. (2018)
- (some) flattening — e.g. Whitaker et al. (2014), Lee et al. (2015), Renzini & Peng (2015), Schreiber et al. (2015), Tomczak et al. (2016)



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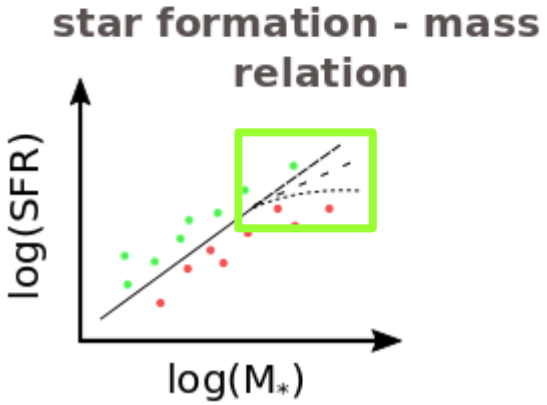
- (some) flattening — e.g. Whitaker et al. (2014), Lee et al. (2015), Renzini & Peng (2015), Schreiber et al. (2015), Tomczak et al. (2016)

→ evolution with redshift

steeper at z<~2, slower above

e.g. Weinmann et al. (2011), Gonzalez et al. (2014), Tasca et al. (2015), Santini et al. (2017), Pearson et al. (2018)



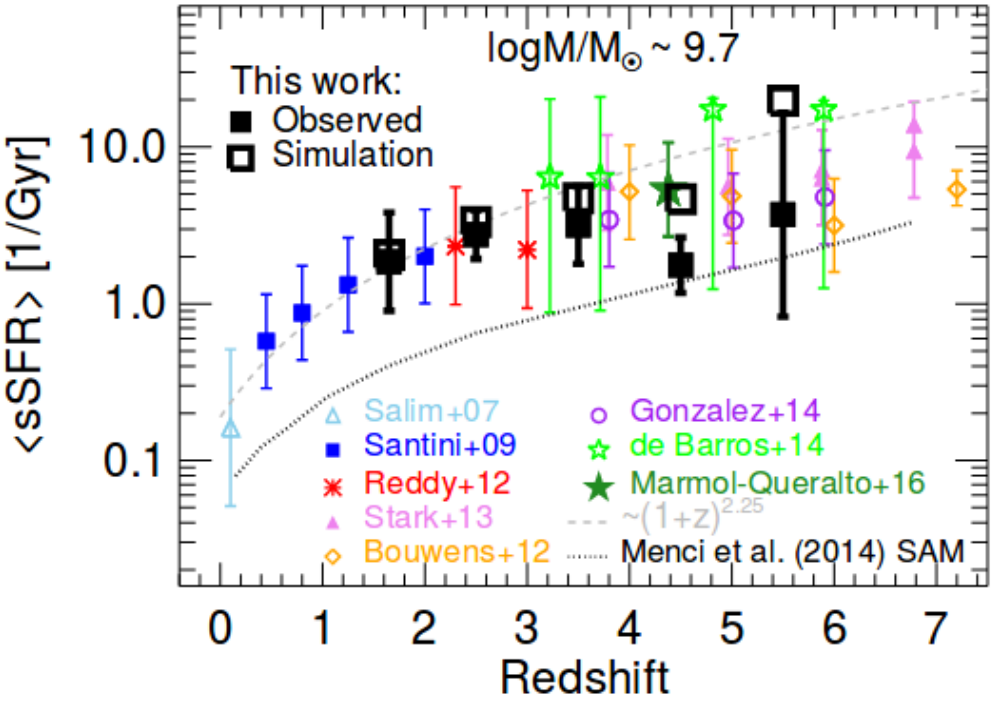
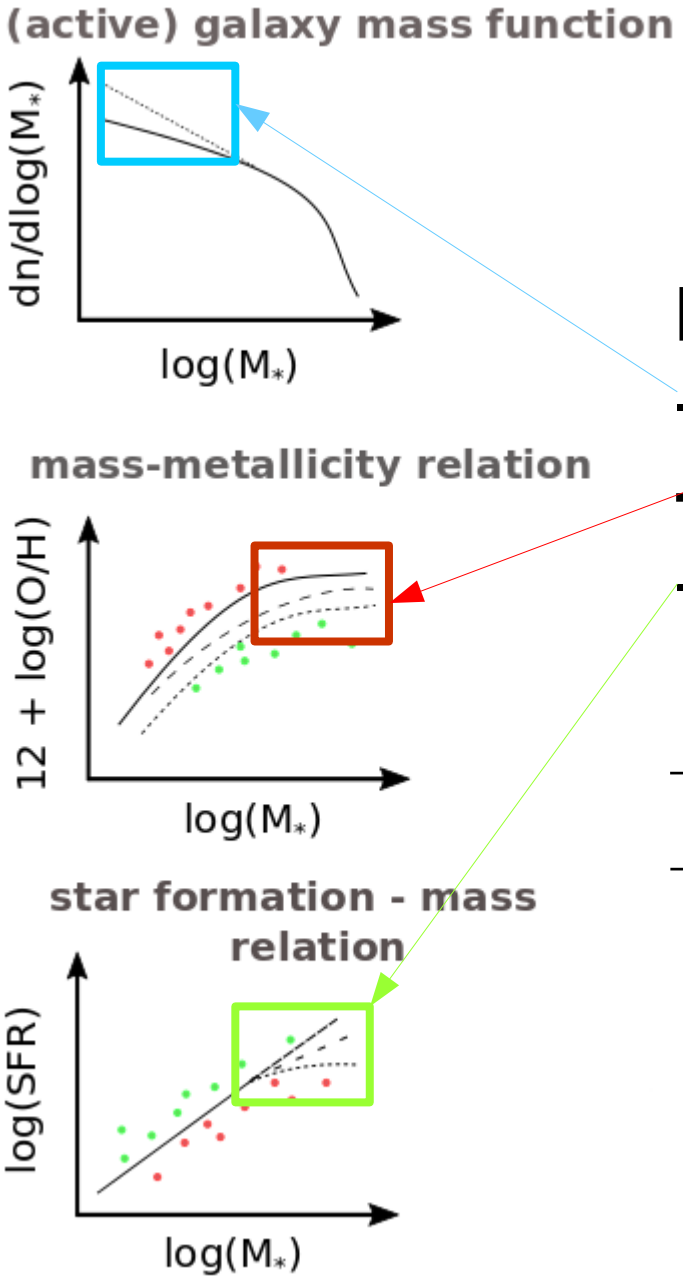




Fig. 5 from Santini et al. (2017) mean sSFR vs z



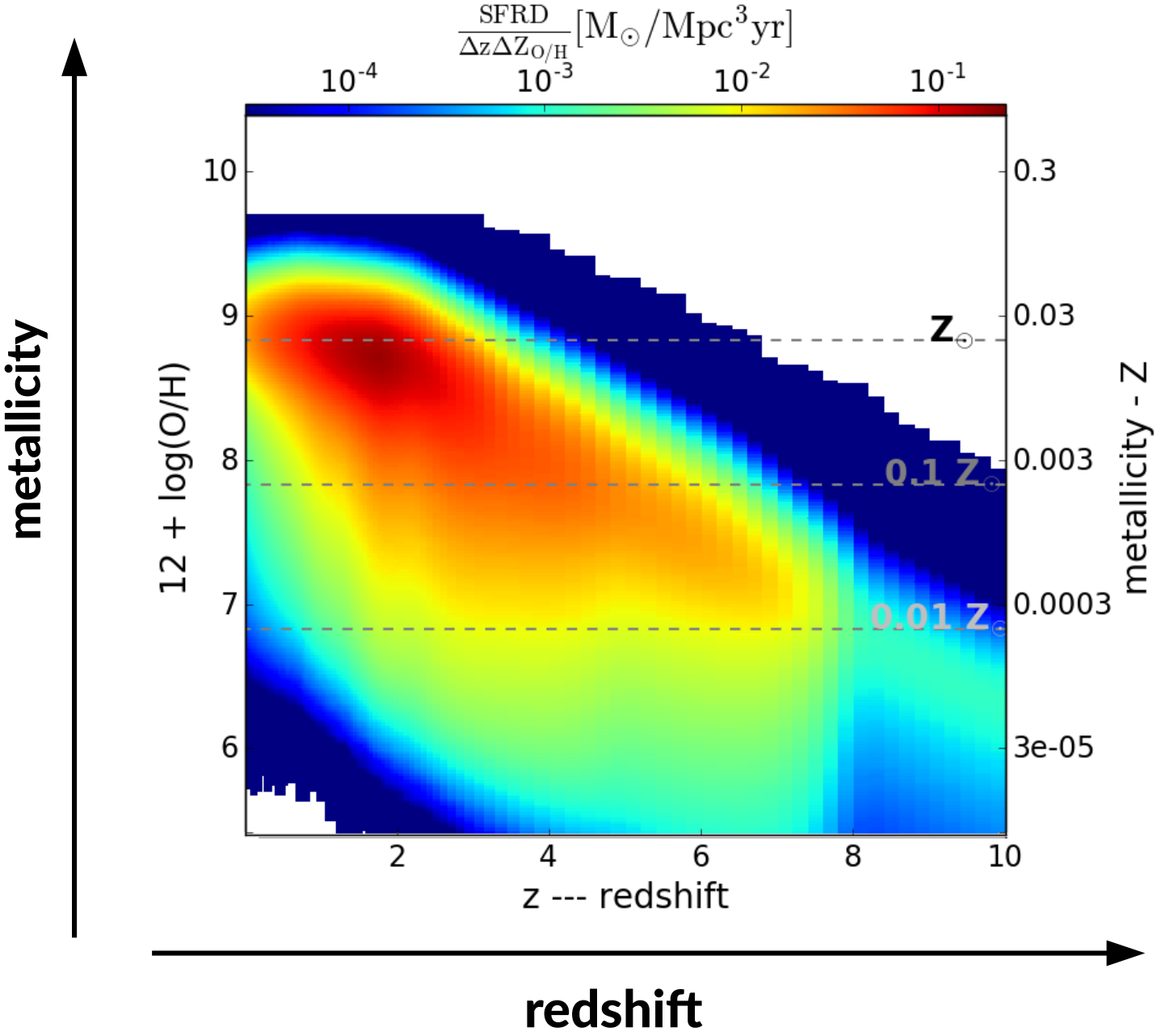

Main sources of uncertainty:
-low mass end of the GSMF
-**MZR: normalization** & shape
-SFMR: flattening (?) at high masses

→ extrapolation needed at high z

→ (what if the *IMF is not universal*
*Chruslinska et al. in prep.*)

→ Chruslinska M. & Nelemans G. (2019)

# (you are going to see a lot of this kind of figures)



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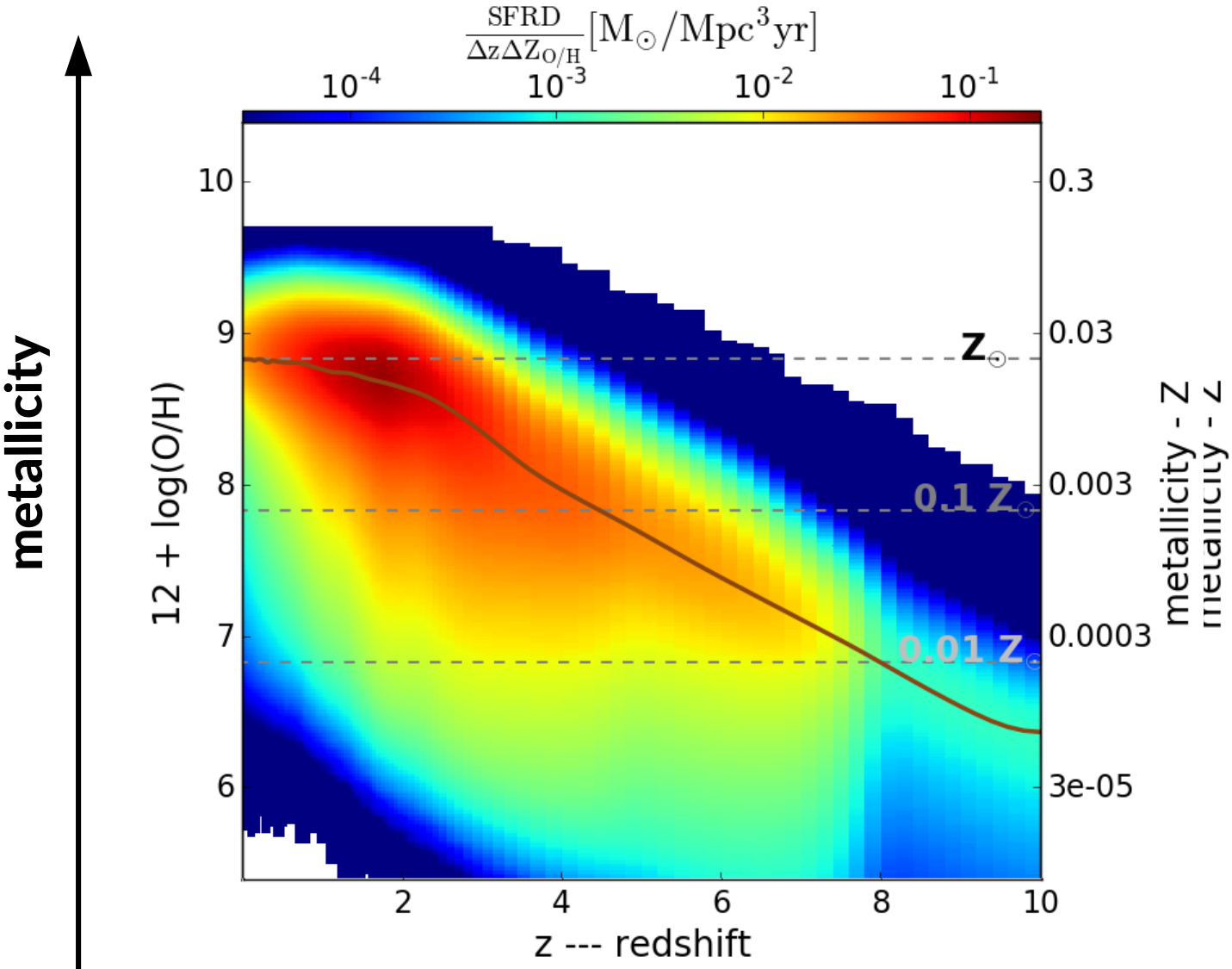

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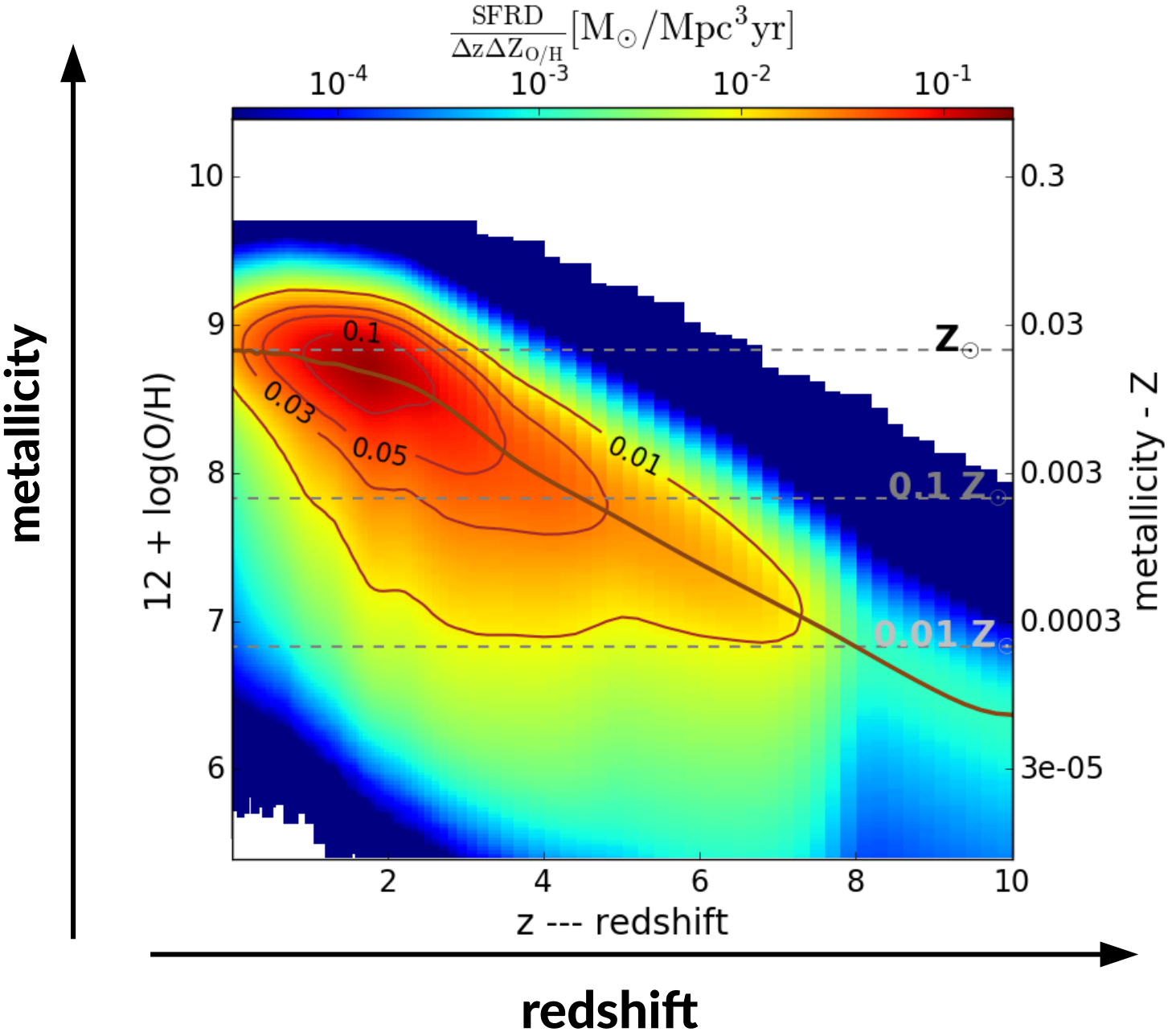
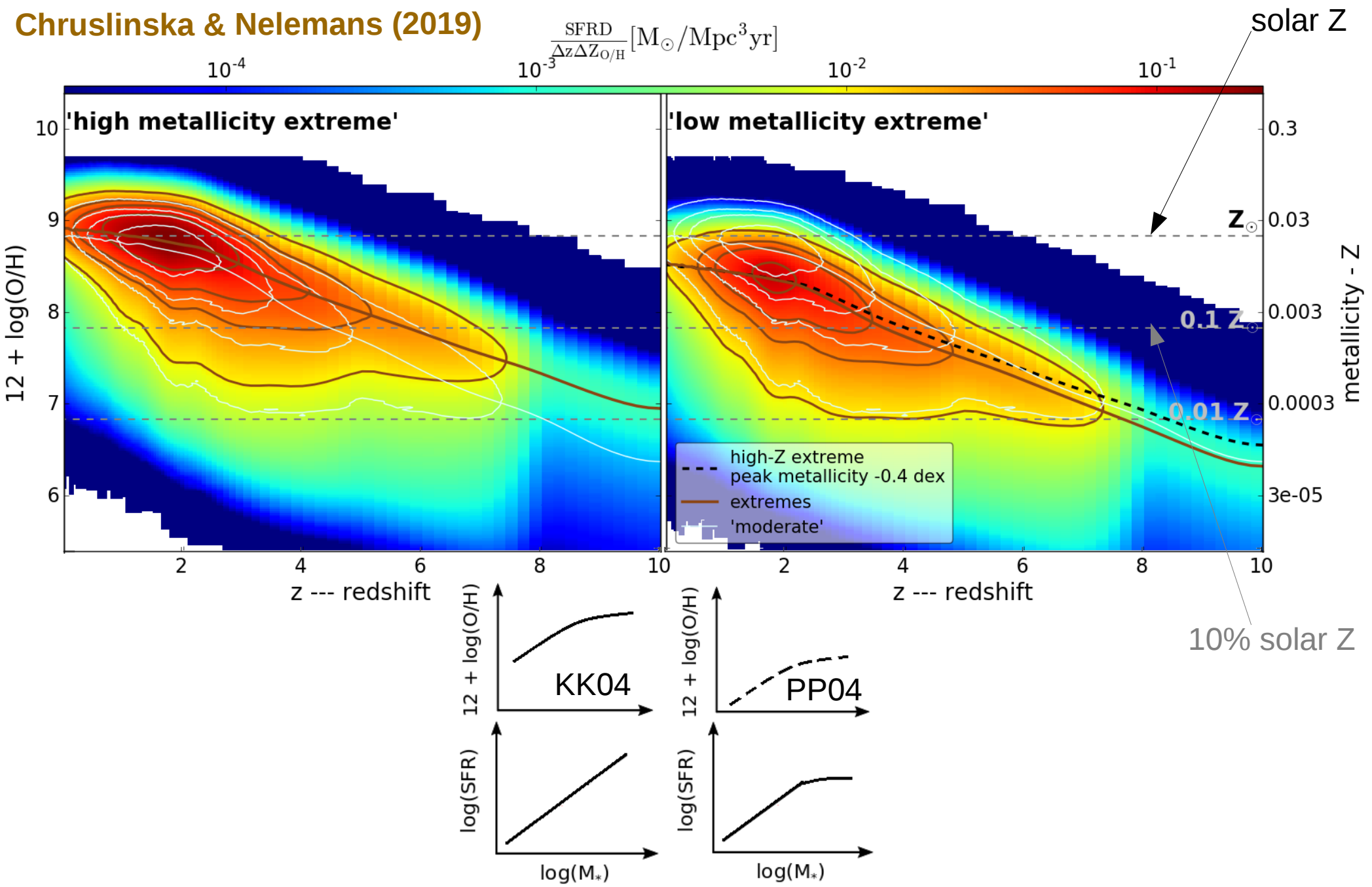


# Results: the extremes

**Chruslinska & Nelemans (2019)**



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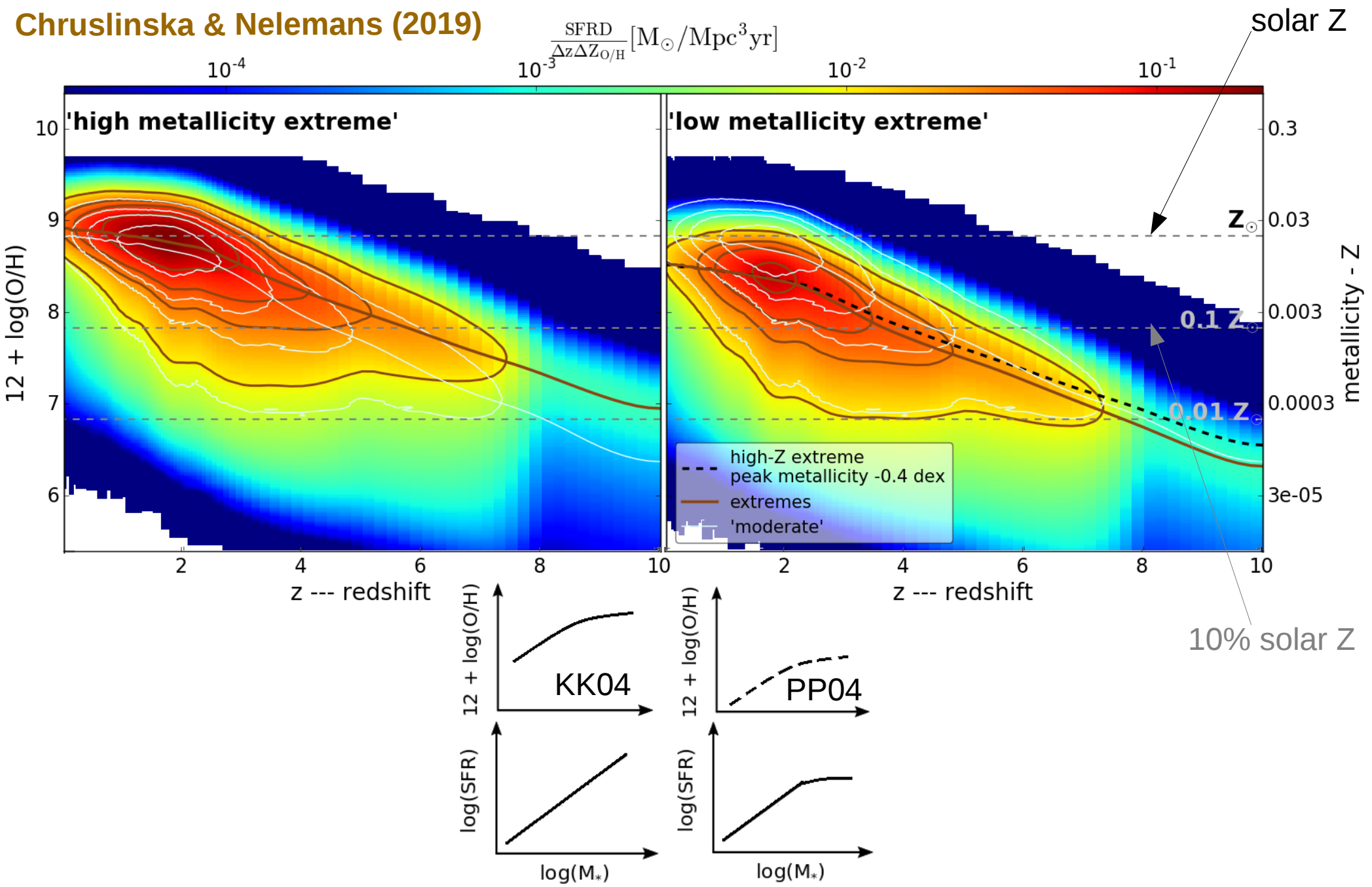

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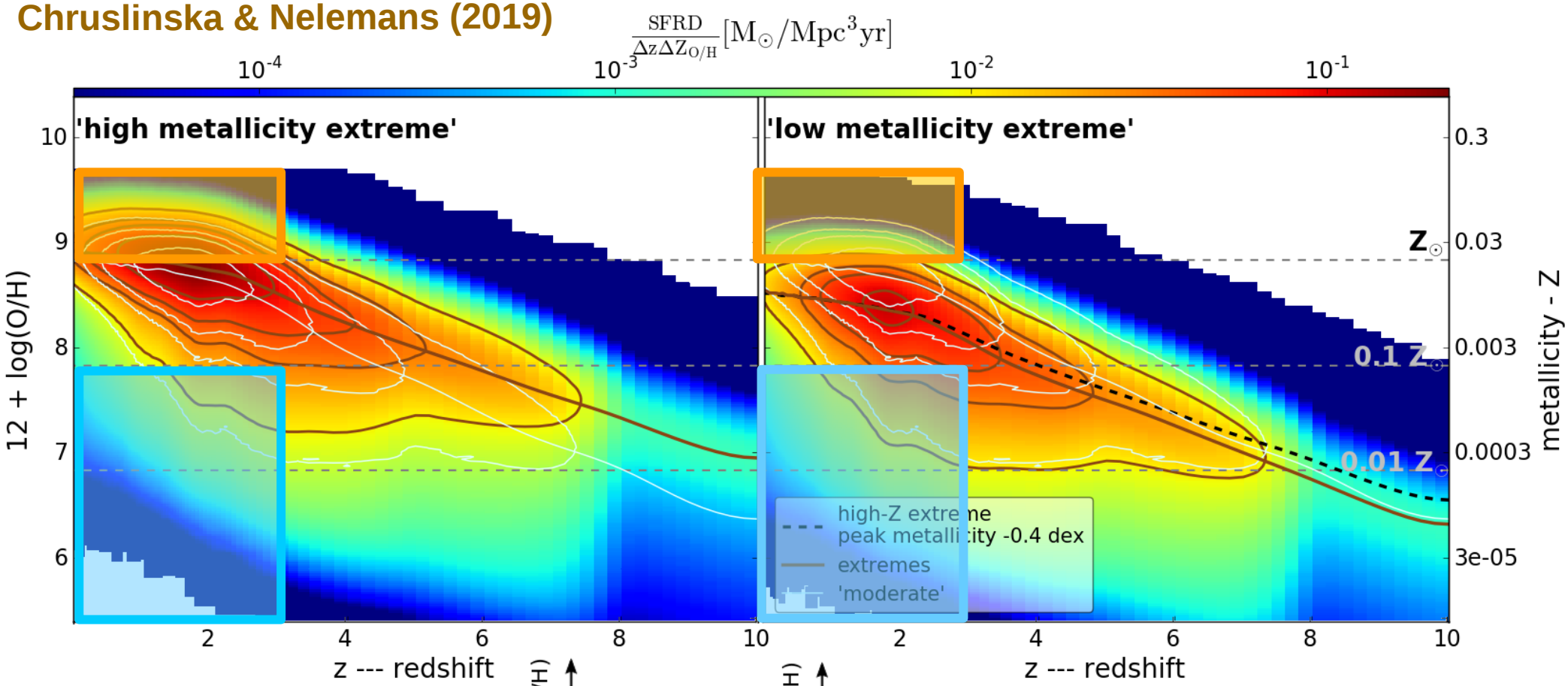
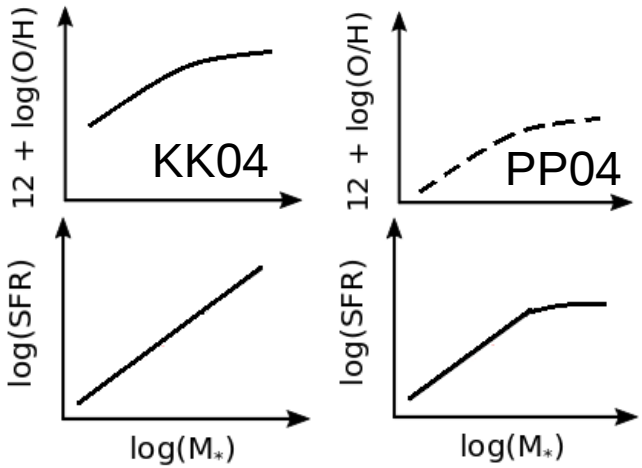



since z=3:

**~9% of $M_*$ at Z<0.1 $Z_O$**

**~27% of $M_*$ at Z>$Z_O$**



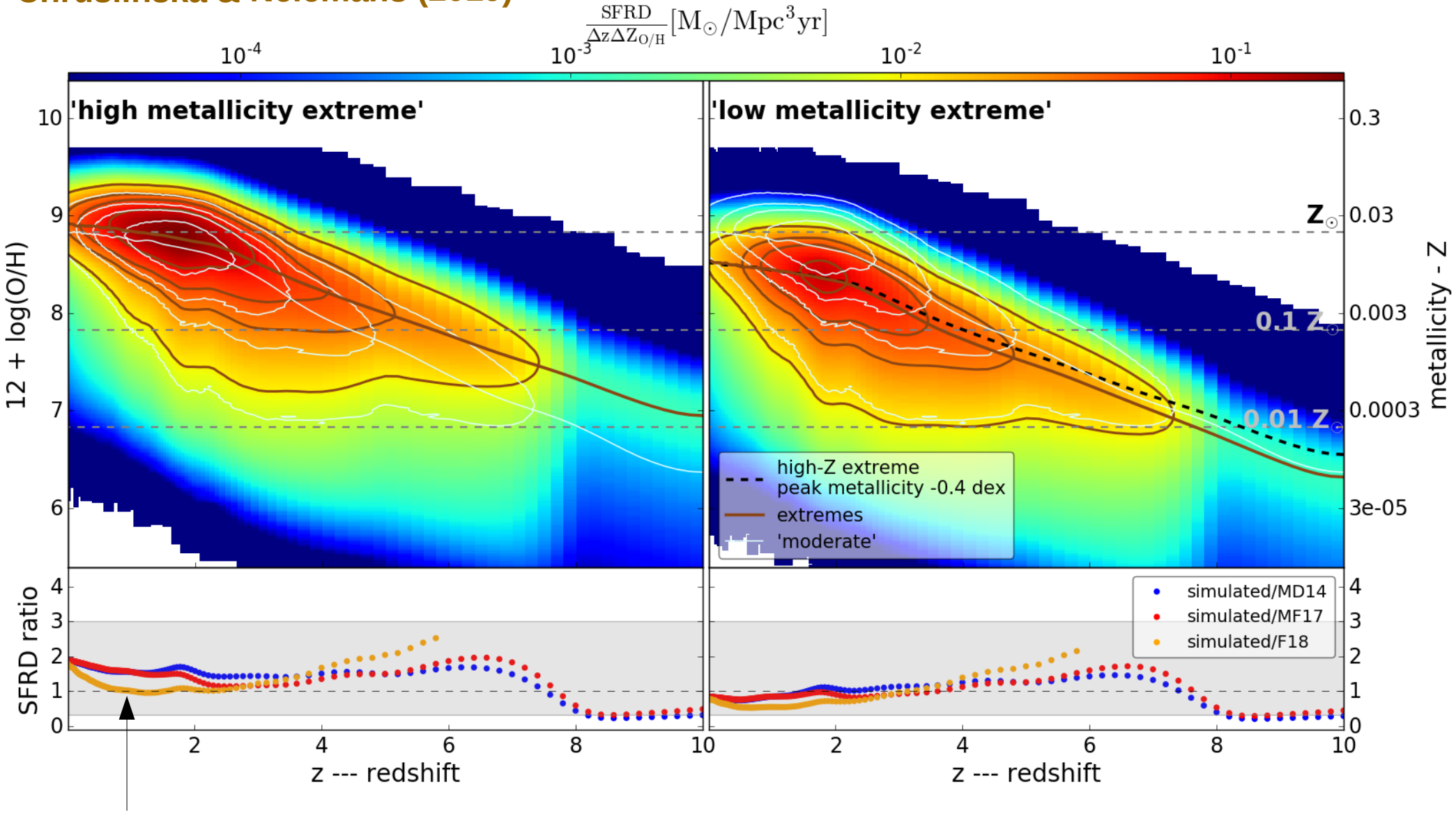

since z=3:

**~27% of $M_*$ at Z<0.1 $Z_O$**

**~1% of $M_*$ at Z>$Z_O$**

# Results: the extremes

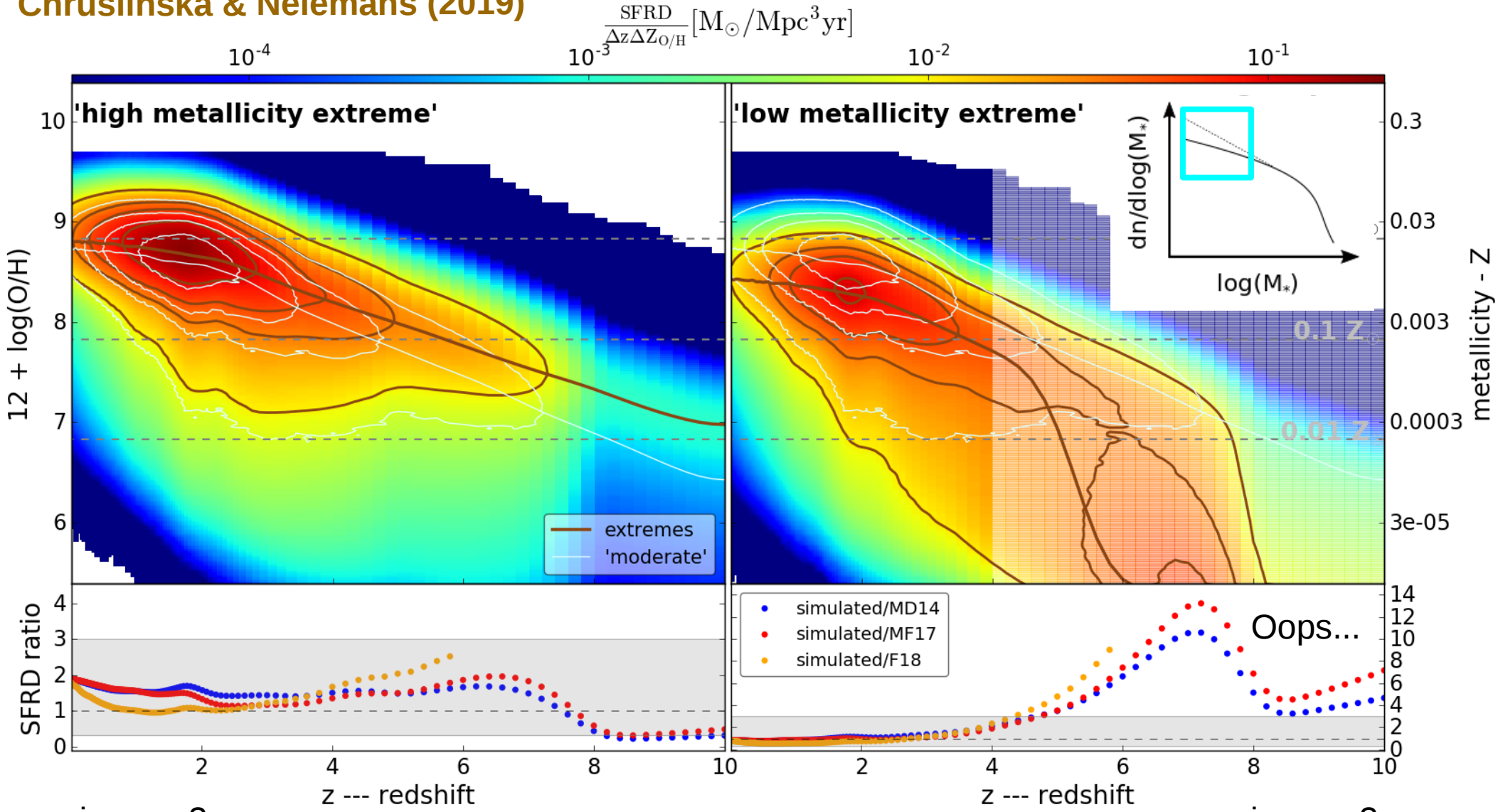
**Chruslinska & Nelemans (2019)**




model/obs. (Madau & Dickinson'14, Madau & Fragos'17, Fermi-LAT Collaboration'18)

# Results: the extremes

**Chruslinska & Nelemans (2019)**




since z=3:

**~9% of $M_*$ at Z<0.1 $Z_O$**

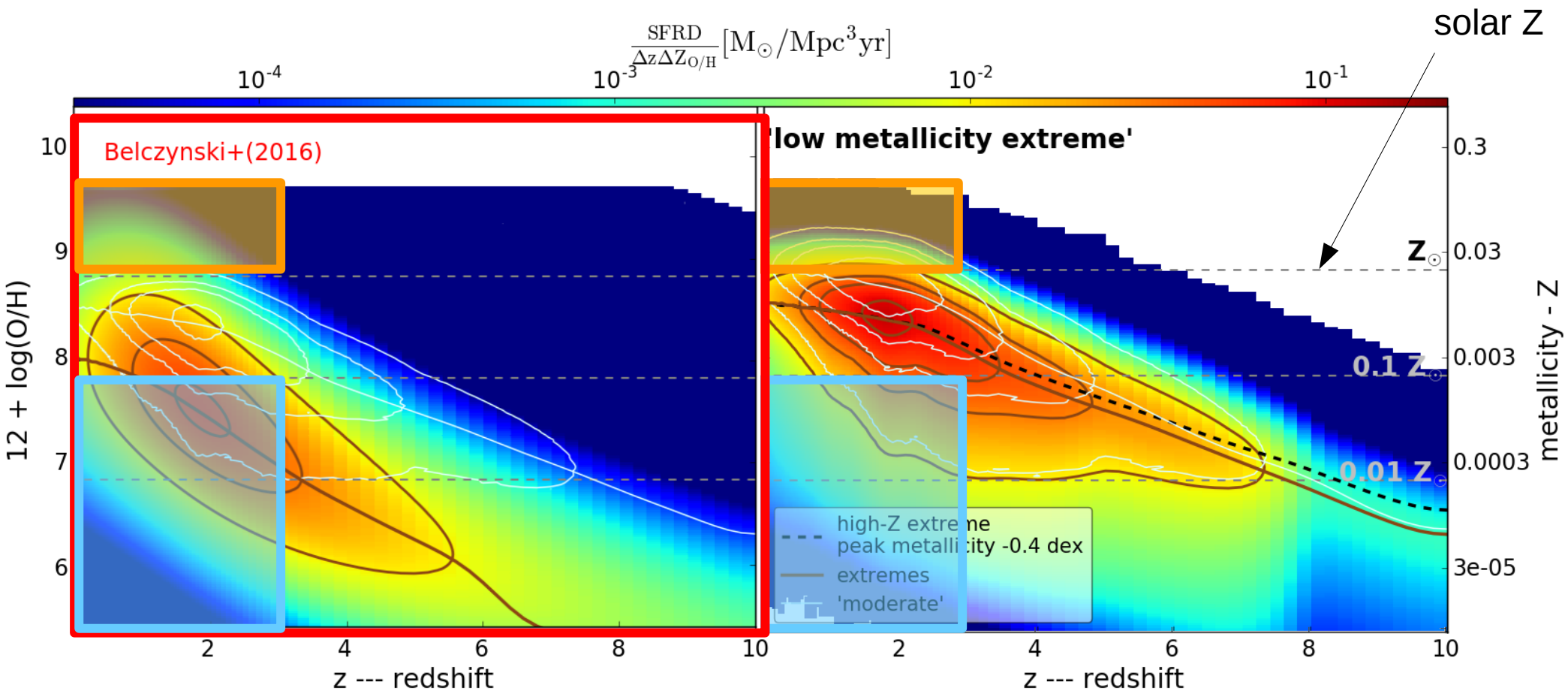
**~27% of $M_*$ at Z>$Z_O$**

since z=3:

**~31% of $M_*$ at Z<0.1 $Z_O$**

**~1% of $M_*$ at Z>$Z_O$**

# Results: the extremes




since z=3:
**~9% of $M_*$ at Z<0.1 $Z_O$**
**~27% of $M_*$ at Z>$Z_O$**

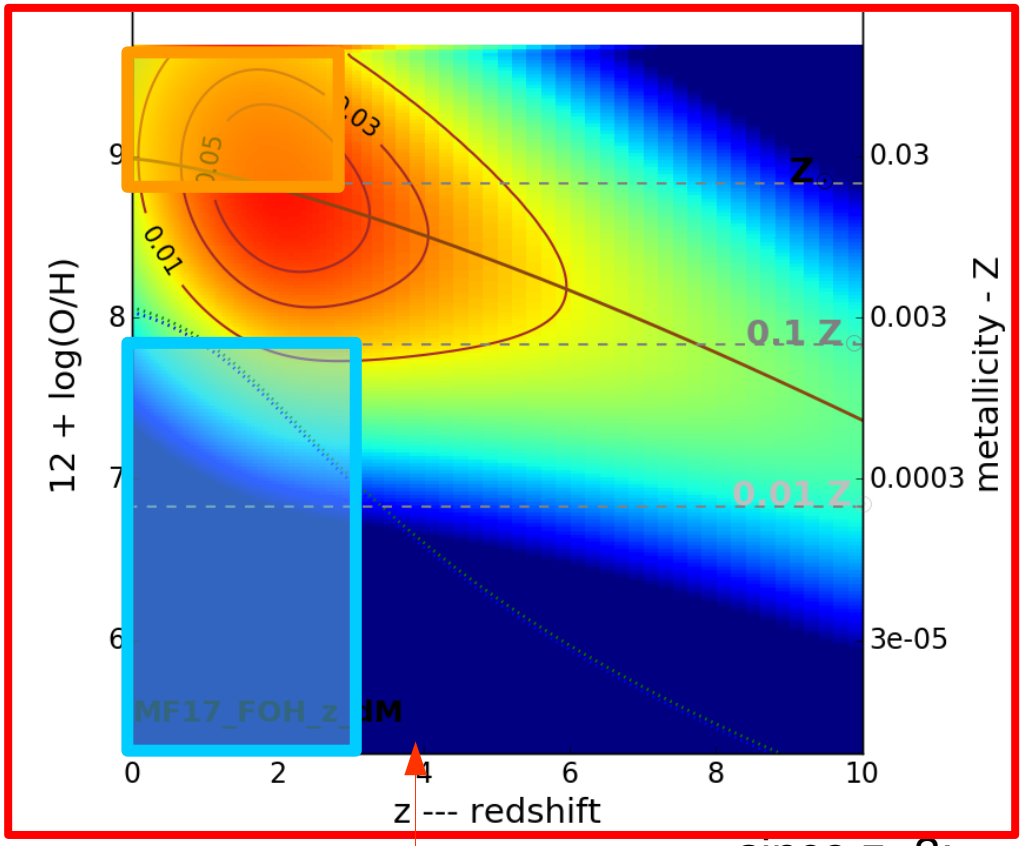
**'Belczynski+16'**
**~75%**
**<1%**

since z=3:
**~27% of $M_*$ at Z<0.1 $Z_O$**
**~1% of $M_*$ at Z>$Z_O$**

(but also different *shape* of the distribution and *normalization* – SFRD(z) !)

# Results: the extremes

(also different *shape* of the distribution and *total* – SFRD(z) !
Observations tell the distribution is not symmetric with respect to the peak - low metallicity tail)

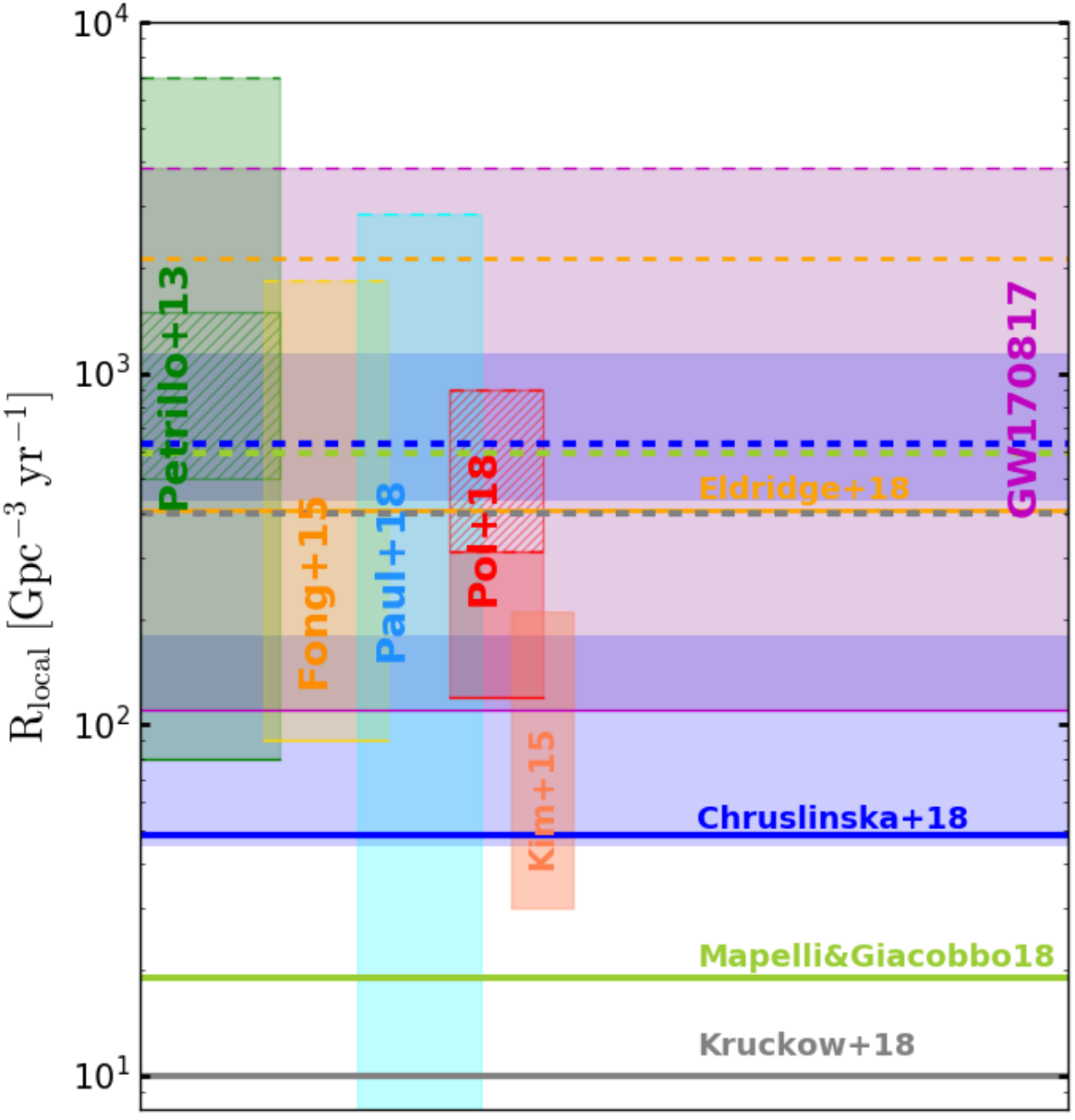



since z=3:
**~9% of $M_*$ at Z<0.1 $Z_O$**
**~27% of $M_*$ at Z>$Z_O$**

since z=3:
**'Belczynski+16'**
**~75%**
**<1%**
**~27% of $M_*$ at Z<0.1 $Z_O$**
**~1% of $M_*$ at Z>$Z_O$**

**using Madau & Fragos (2017):**
**<3.5%**
**~46%**

# Local DNS merger rate density, different methods

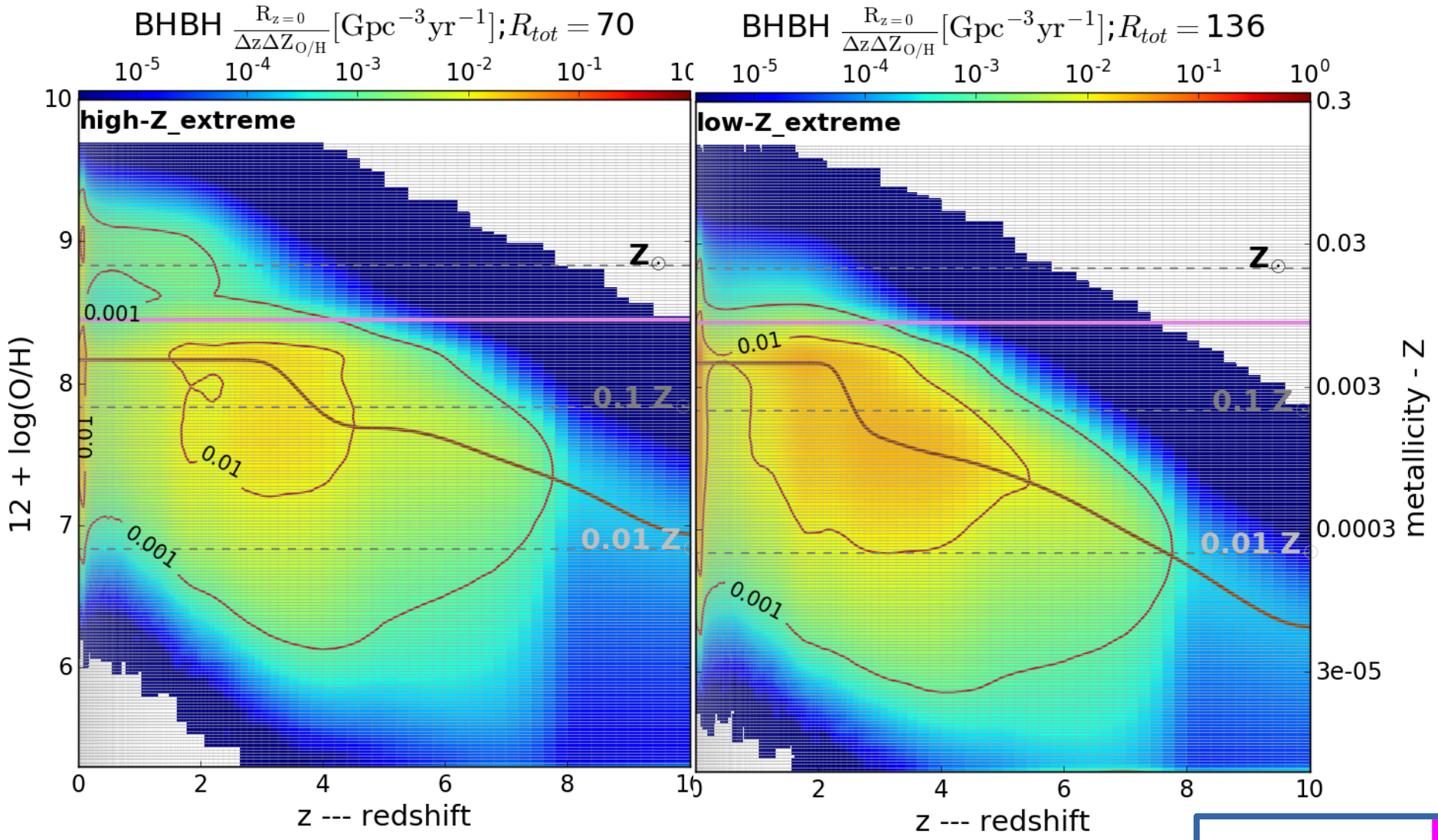



Uncertainty in the star formation history and chemical evolution of the Universe adds uncertainty to our estimates
Chruslinska et al. (2019a,b)

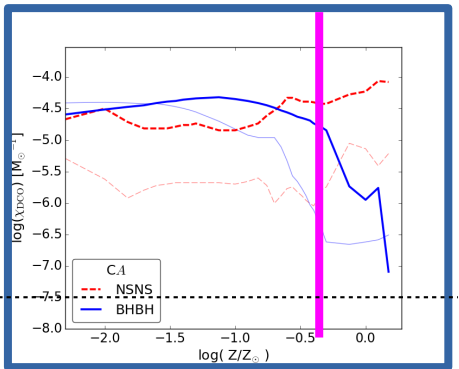
→ **degeneracies**
very limited gain from this kind of comparison…

→ different pop. syn results use different SFR&metallicity assumptions – keep that in mind when you compare them

# Where do they come from..?

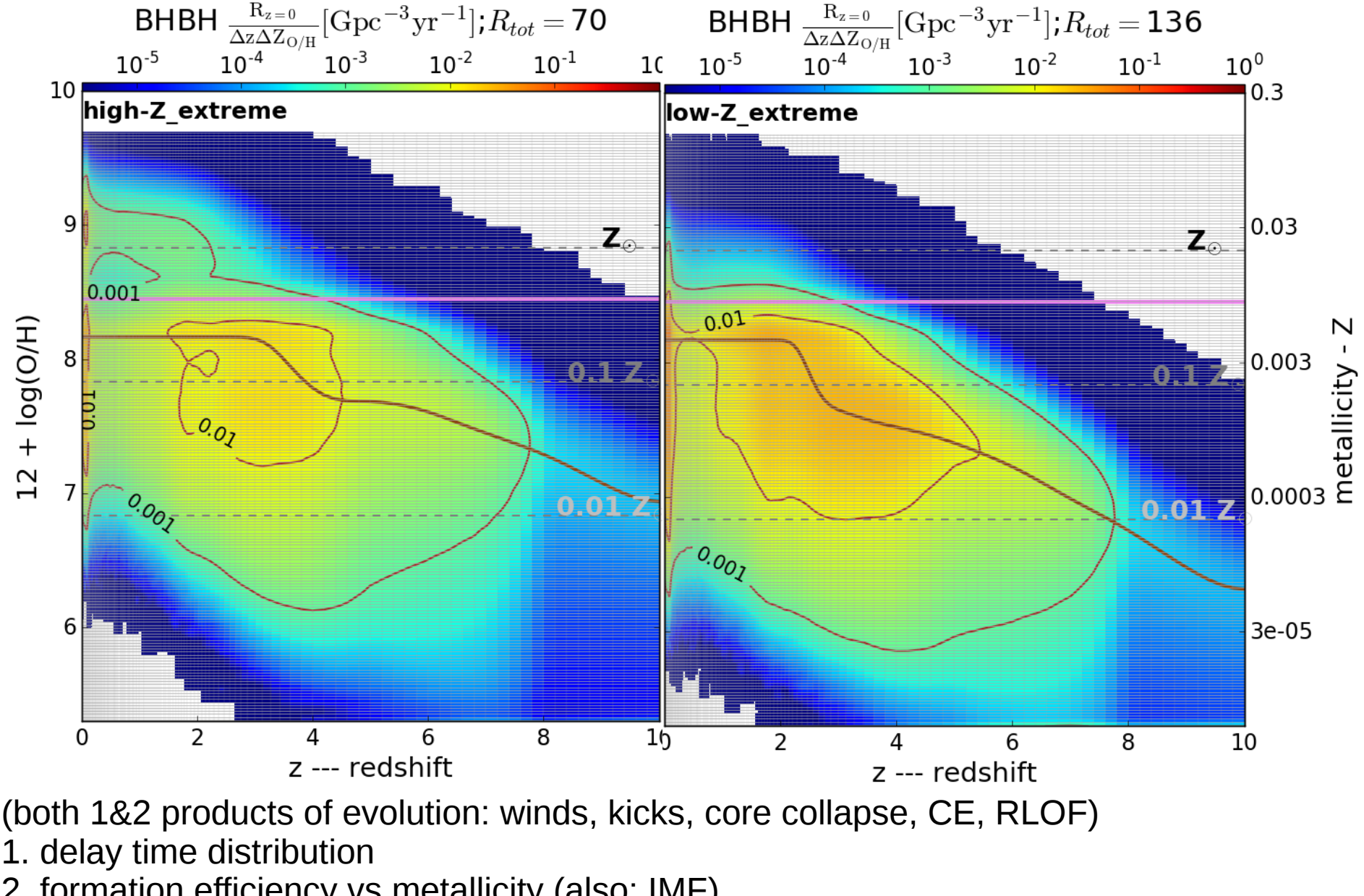



Contribution of different metallicity-redshift bins to the local merger rate density
(sum of all pixels = local merger rate density)
*(sketchy example for a particular model)*




– Martyna Chruslinska

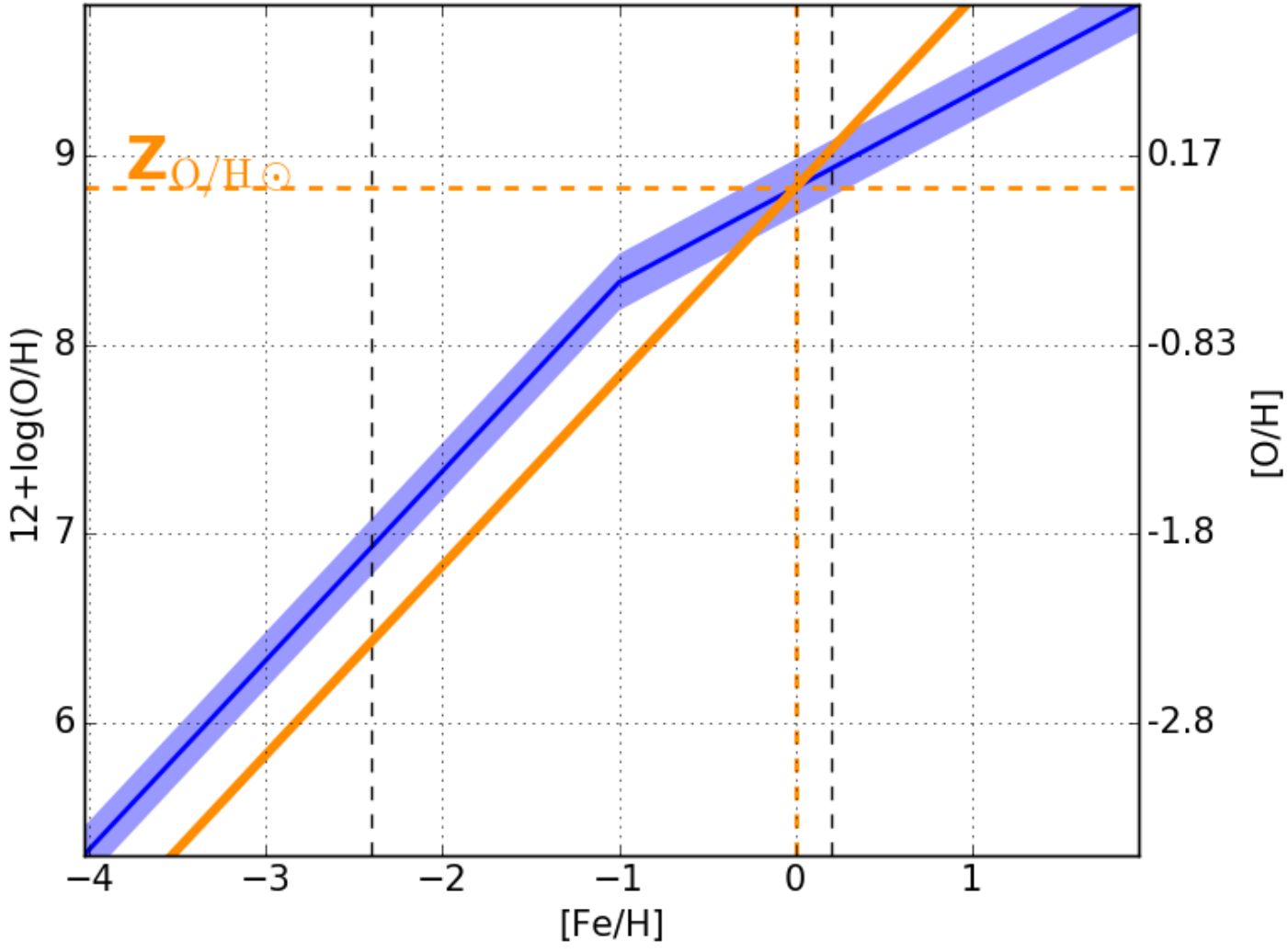
# Where do they come from..?




(both 1&2 products of evolution: winds, kicks, core collapse, CE, RLOF)

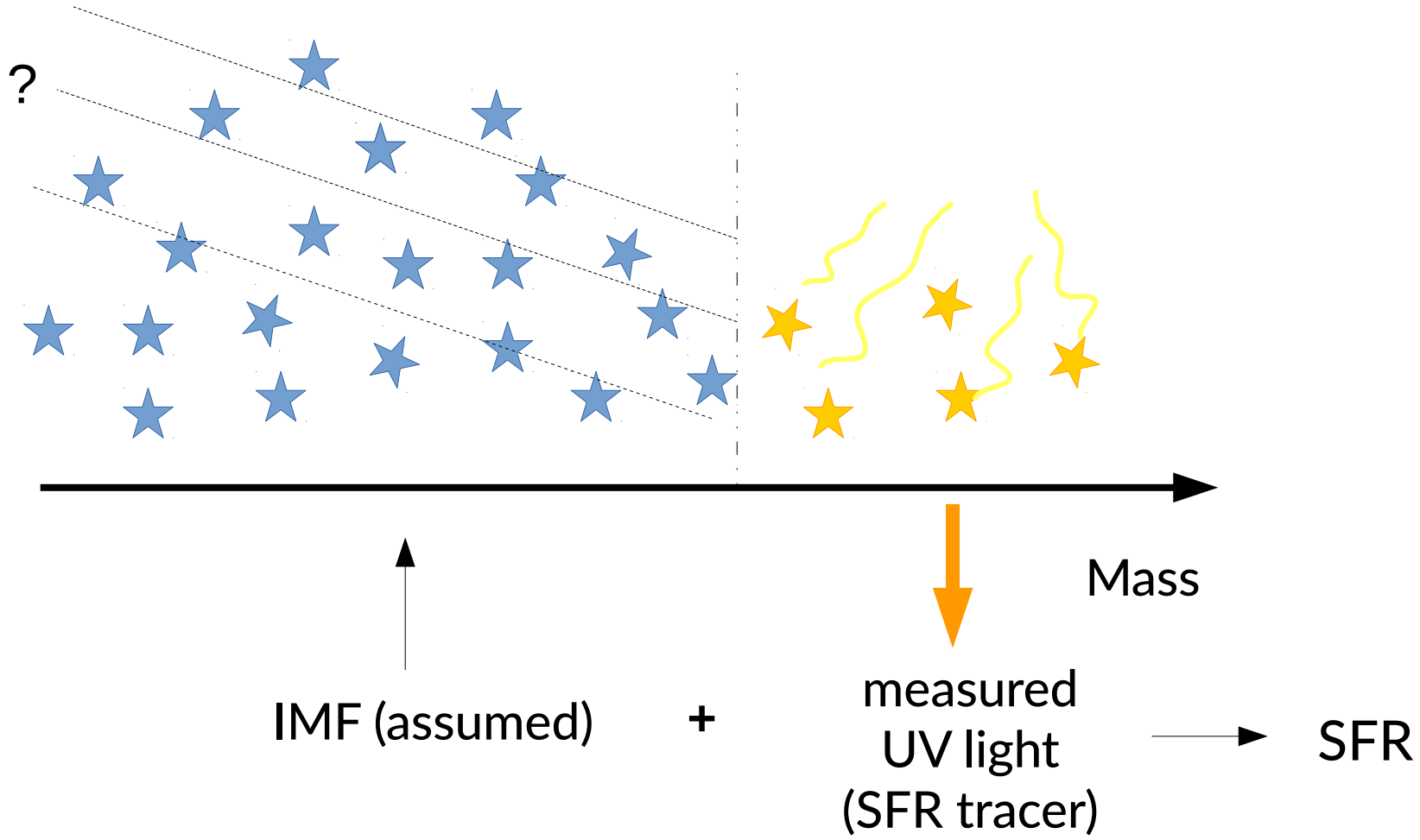
1. delay time distribution
2. formation efficiency vs metallicity (also: IMF)
3. SFR history & chemical evolution of the Universe
   (metallicity calibration, IMF, SFR in galaxies, galaxy M/SFR distribution...)

# “metallicity”, oxygen vs iron



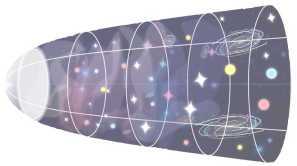

(Milky Way -like relation e.g. Bensby+2004; Reddy+2006; Bensby+2014; Steidel+2016).
→stars with non-solar abundance ratios ?

# What if... the IMF



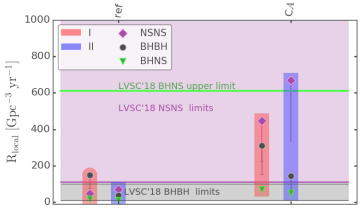
# Concluding remarks

## what & why



→ the observed GW events carry information about the properties of **binaries & the Universe together**

→ we need to know SFRD(Z,z)

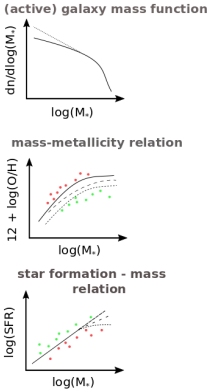



→ **assumptions about the SFRD(Z,z)** affect our estimates (model dependent, DCO type dependent)

→ no simple error bar to add: differs between the models

→ adds to degeneracies

## SFRD(Z,z) – obs. & uncertainties

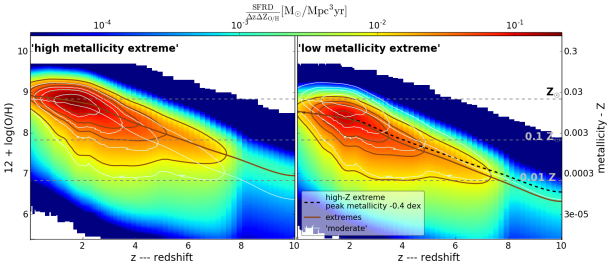



→ **SFRD(Z,z) from observations & uncertainties** (metallicity calibrations, GSMF at low M, SFMR flattening, ***IMF***)

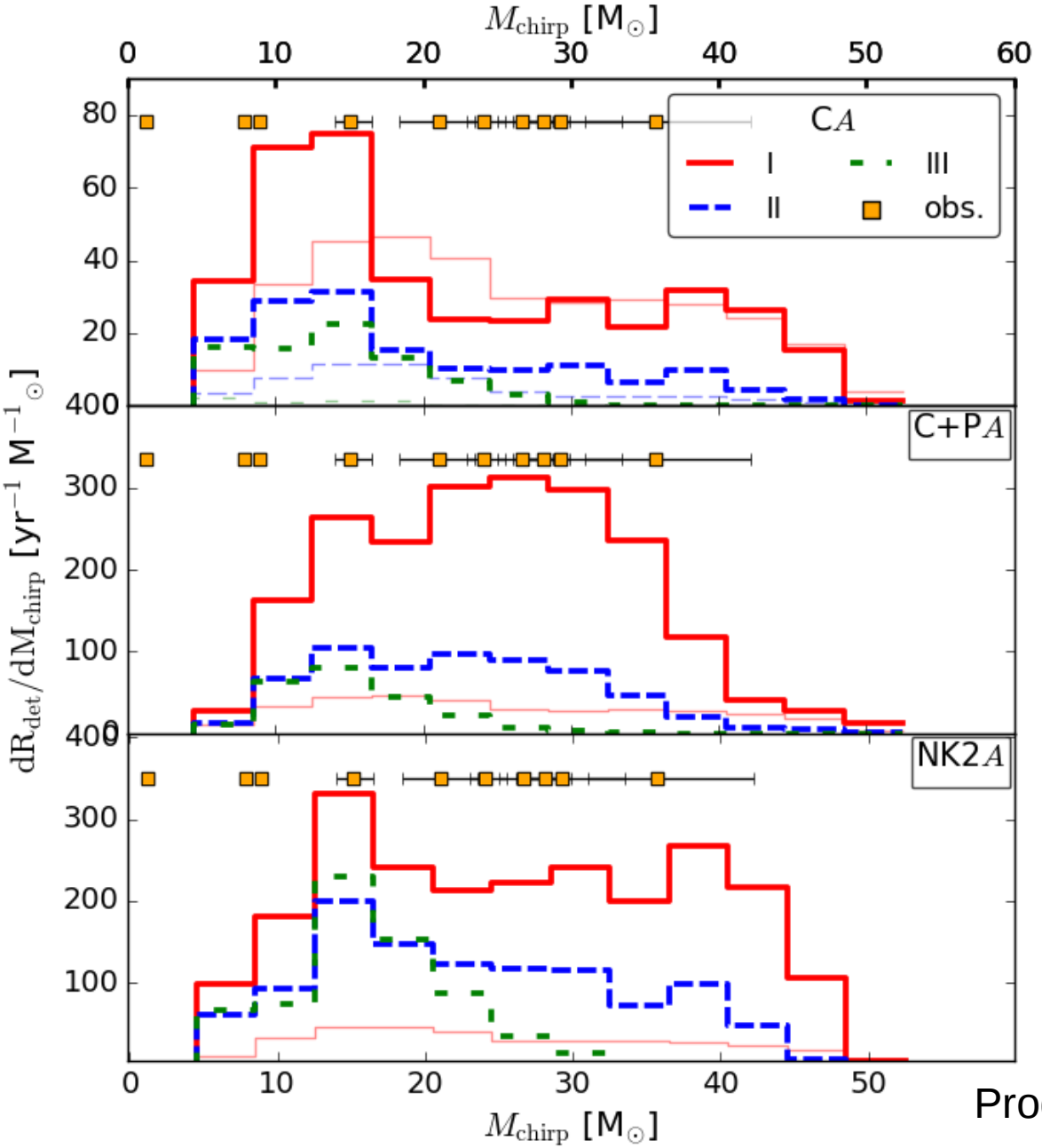
→ **less extreme** than some SFRD(Z,z) used in the literature

→ can be used to **evaluate the uncertainty** due to assumed SFRD(Z,z) e.g. for the rates;
as a **reference for cosmological simulations**

https://ftp.science.ru.nl/astro/mchruslinska/



# SFR(t,Z) and the masses -"detection rate" weighted chirp mass



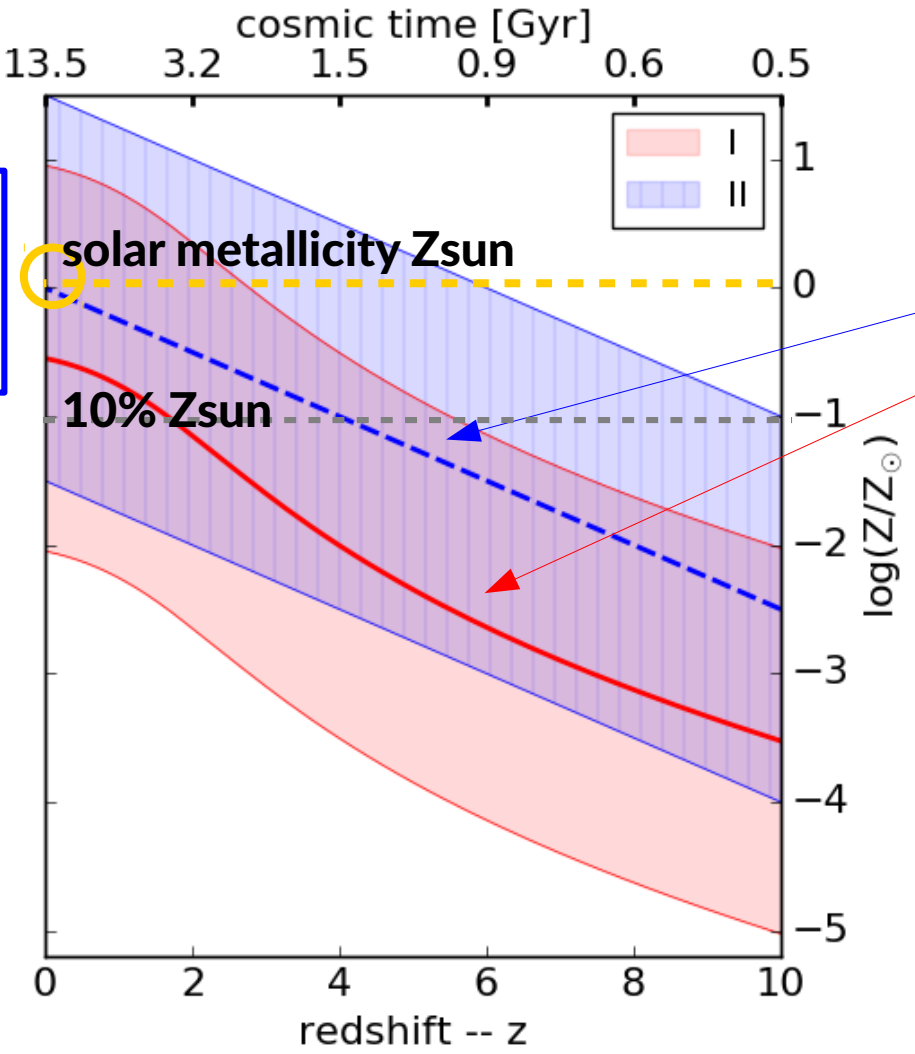

Product of evolution + SFR(t,Z) (+Tdel)

→ **Chruslinska M.**, Nelemans G. & Belczynski K. (2019)

# SFRD(Z,z): different approaches...

"average metallicity of galaxies"

"average metallicity of the Universe + 0.5 dex"

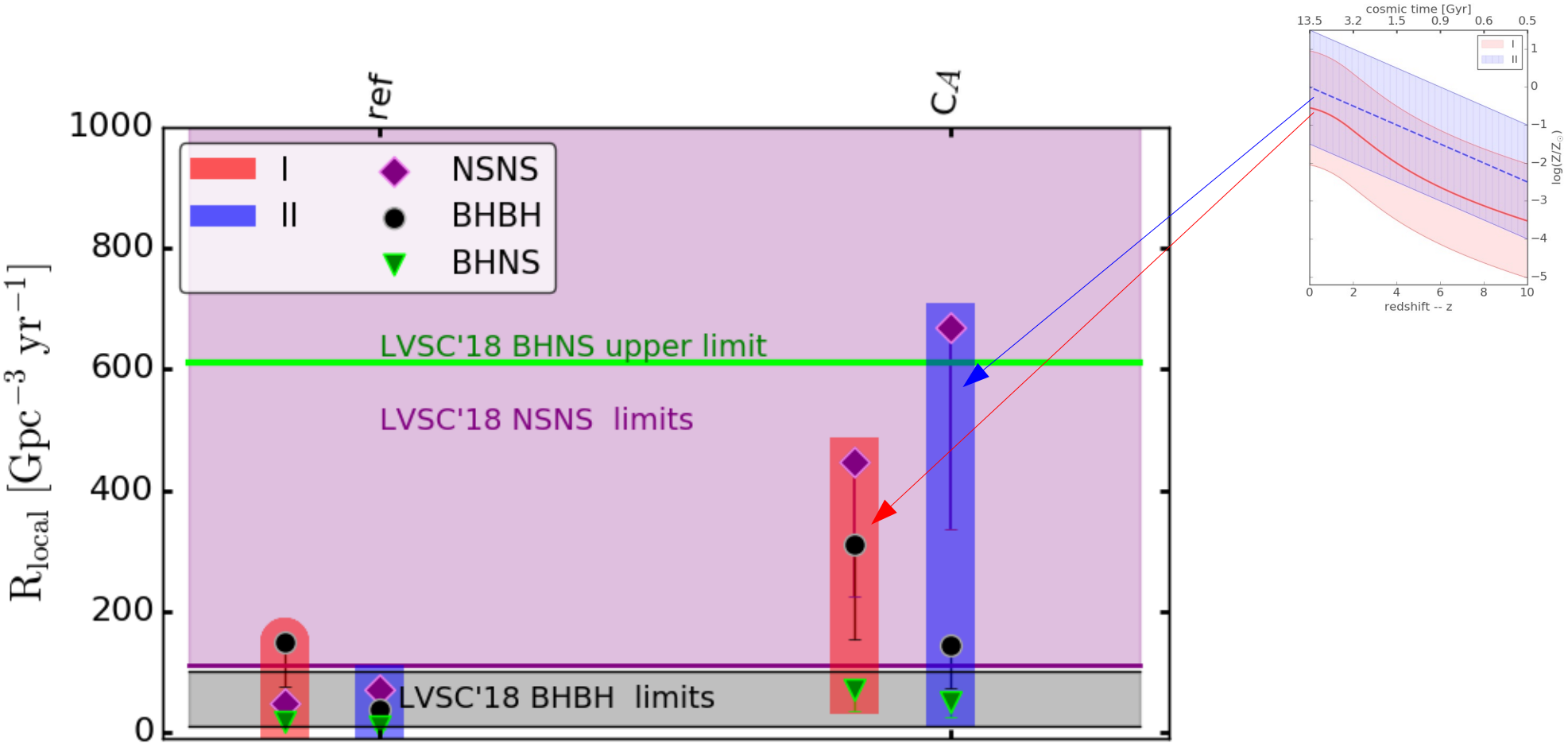



**Mean metallicity evolution** assumed by Dominik+13 and Belczynski+16

(shaded region – 3σ around the mean; σ=0.5 dex scatter in both cases)

→ **Chruslinska M.**, Nelemans G. & Belczynski K. (2019)

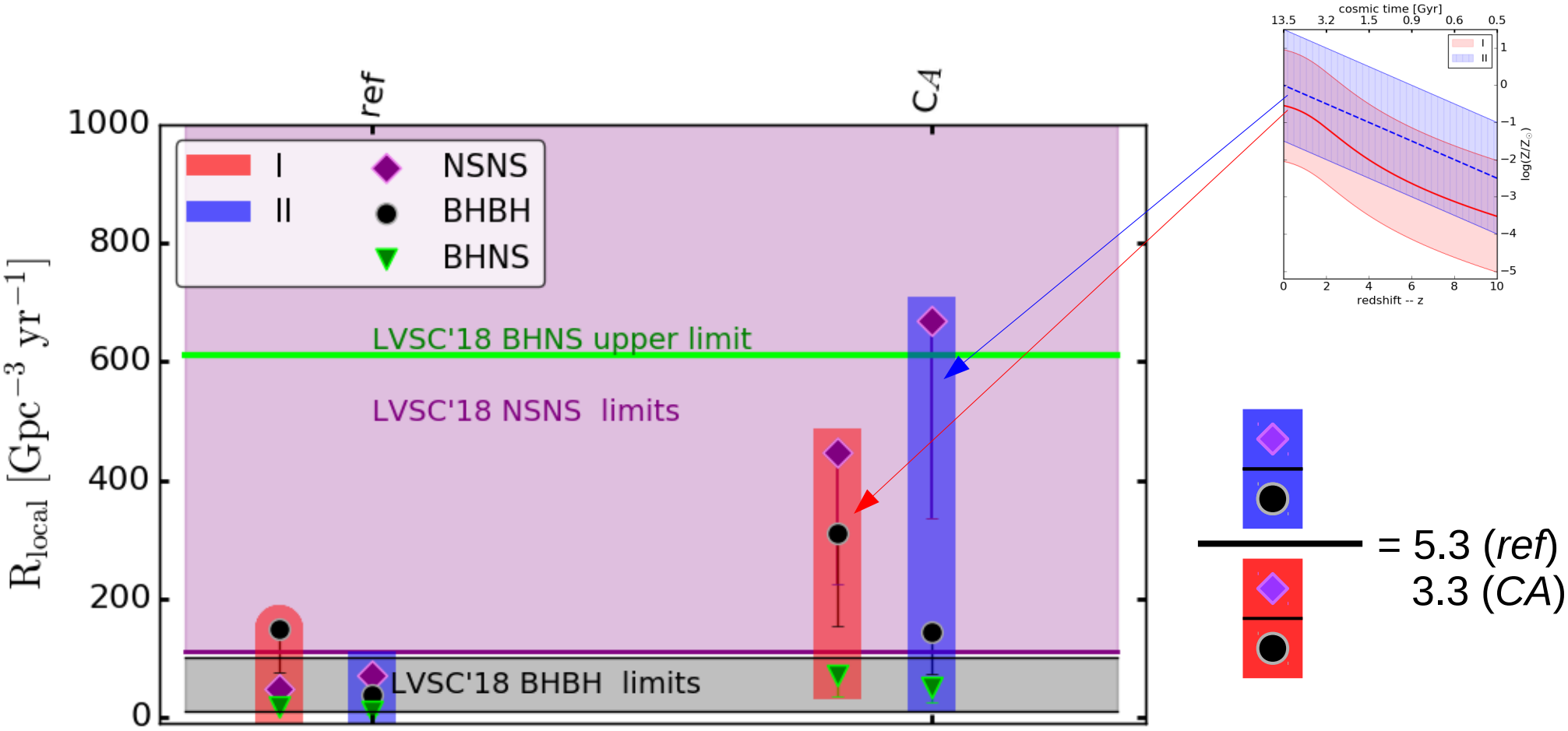
# How important is it for the final result?




SFRD(Z,z) can significantly affect the rate estimates!

→ **Chruslinska M.**, Nelemans G. & Belczynski K. (2019)
(→ recently Neijssel+19 reached similar conclusions)

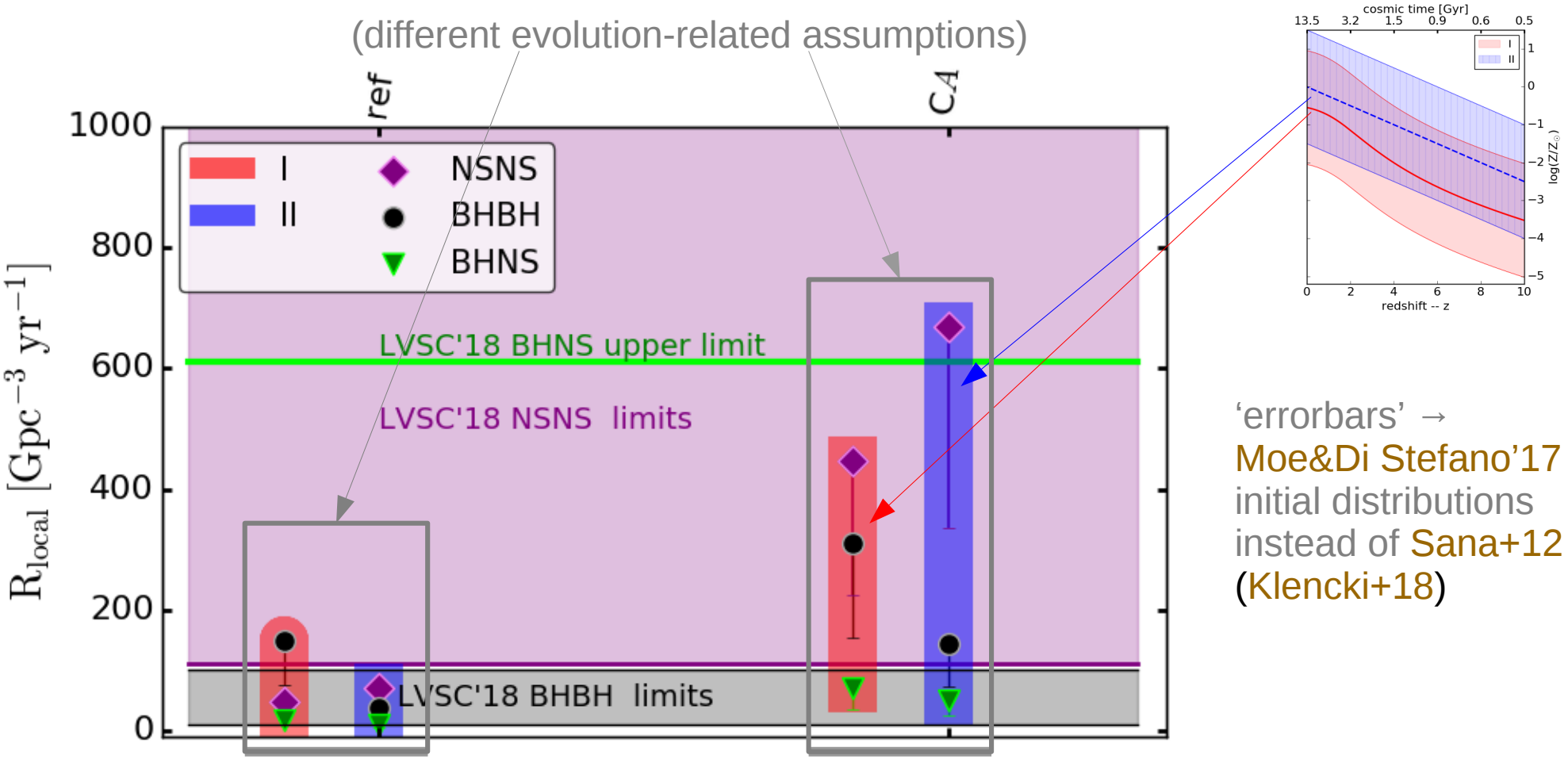
# How important is it for the final result?




**The effect depends on the binary type (BHBH/NSNS/BHNS)**
**→ affects the ratios of rates**

→ **Chruslinska M.**, Nelemans G. & Belczynski K. (2019)

# How important is it for the final result?




'errorbars' → Moe&Di Stefano'17 initial distributions instead of Sana+12 (Klencki+18)

**The effect depends on the model (binary evolution)**
**→ ...no simple universal 'errorbar' to add**

→ **Chruslinska M.**, Nelemans G. & Belczynski K. (2019)