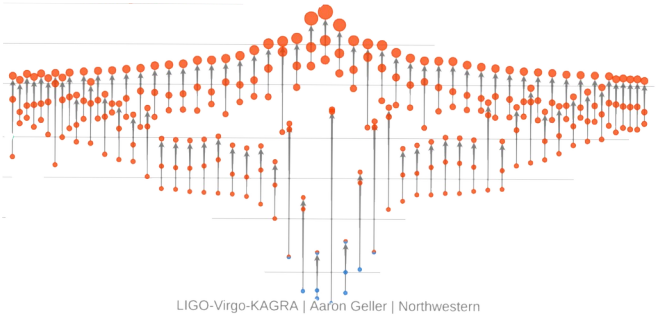
BH merger population



making sense of a jumble of everything

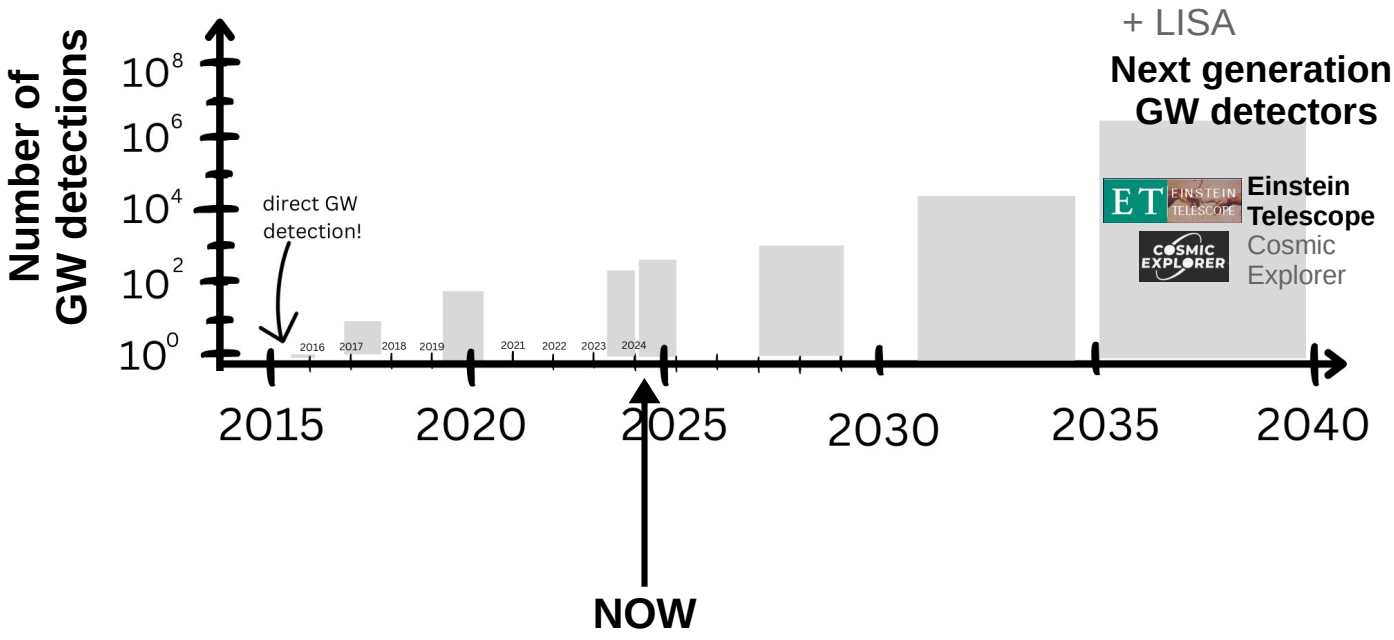
Martyna Chruślińska
(read: Hroo-shlin-ska)

MPA fellow → ESO fellow

Max Planck Institute for Astrophysics

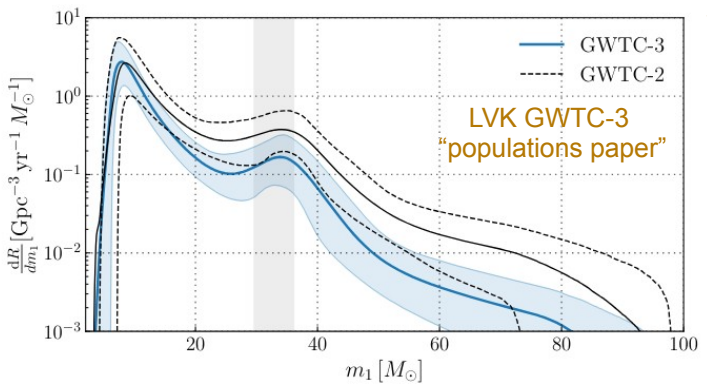
European Southern Observatory

This talk: how do we go about extracting astrophysical information from the **population**



This talk: how do we go about extracting astrophysical information from the **population**

not this: characterising the observed population



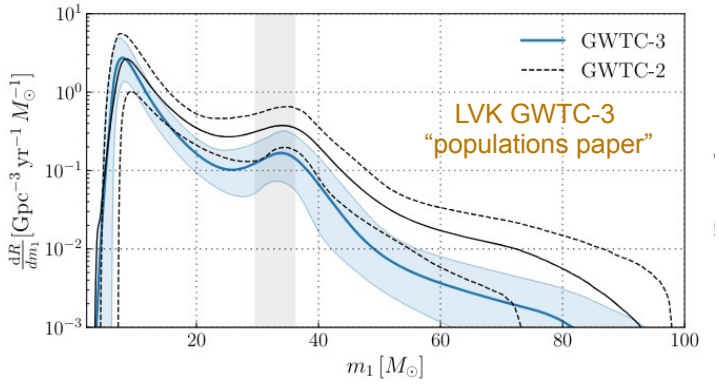
→ *talk by V. De Renzis*

BH merger population properties:

Focus on best constrained**: merger rate & mass distribution** *(+evolution with redshift)*

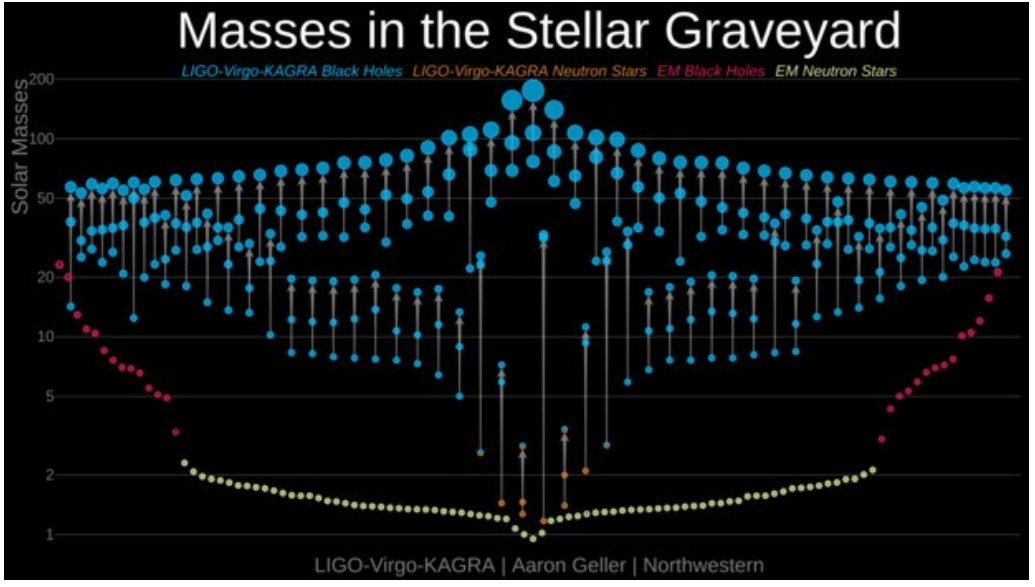
(also: effective spins, mass ratio, correlations between the properties)

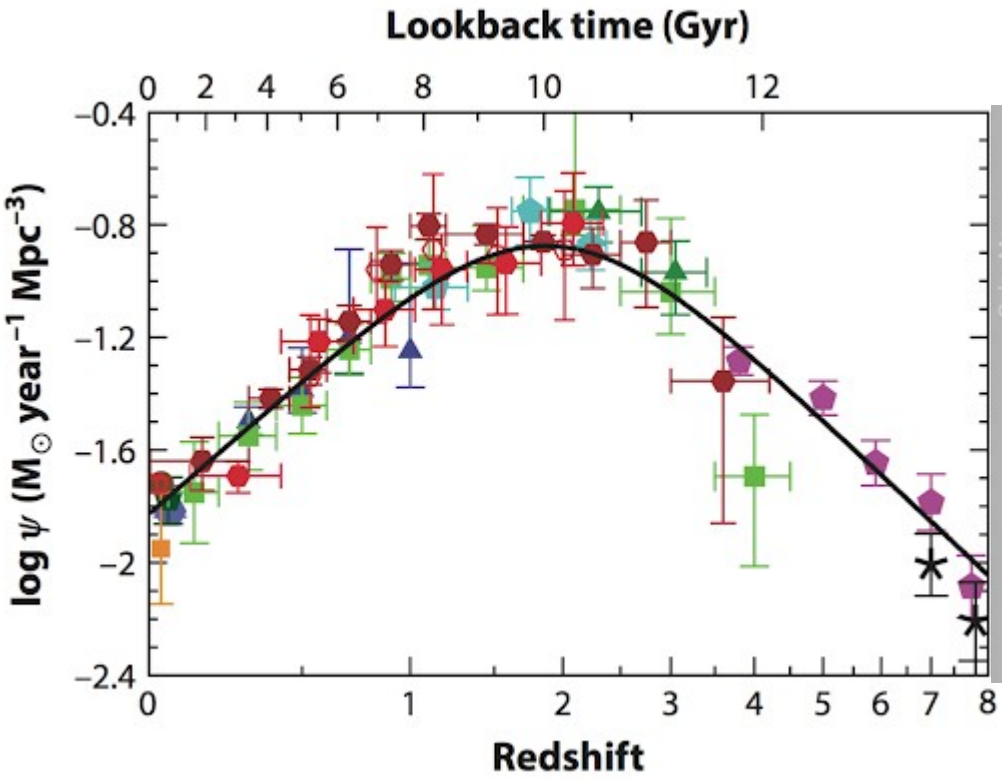
This talk: how do we go about extracting astrophysical information from the **population**

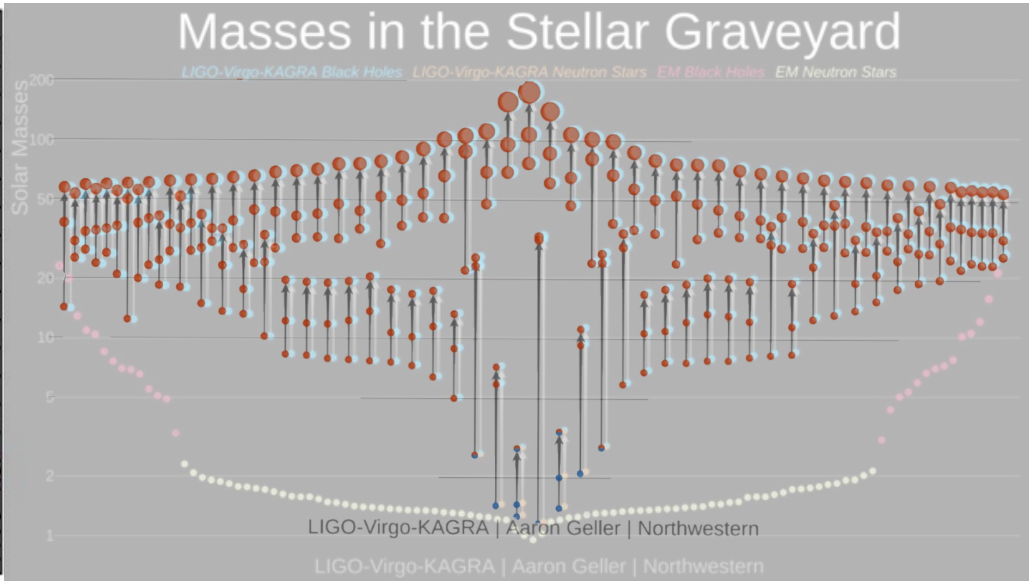


← how did this population come to be?
← what can it tell us about
the astrophysical processes ?

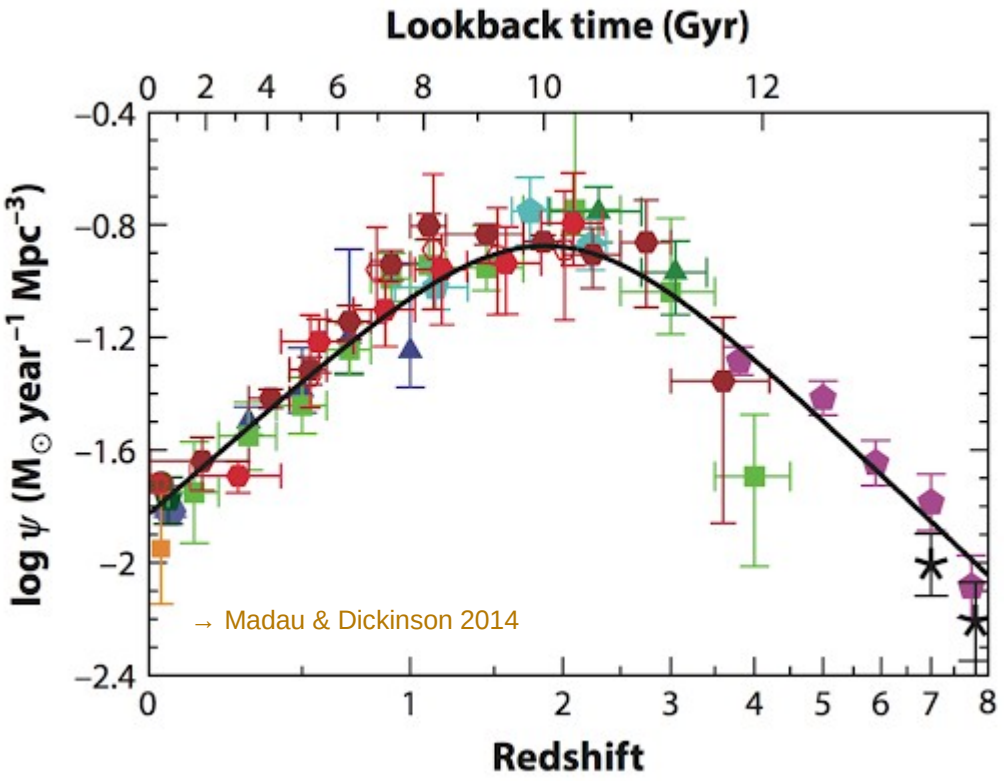
BH merger population properties:
Focus on best constrained**: merger rate & mass distribution** *(+evolution with redshift)*
(also: effective spins, mass ratio, correlations between the properties)


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern



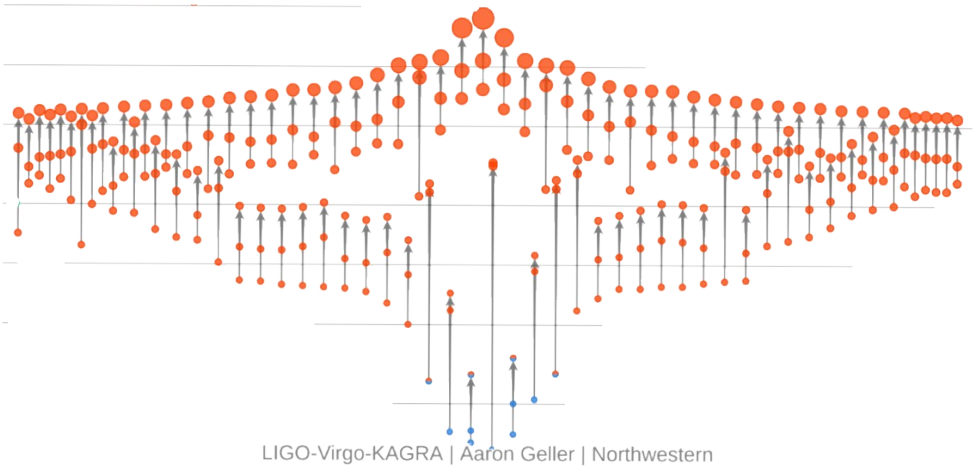


LIGO-Virgo-KAGRA | Aaron Geller | Northwestern



cosmic star formation history

*not the most recent version



LIGO-Virgo-Kagra GWTC-3
BH merger population

This talk is about BHs that used to be stars.

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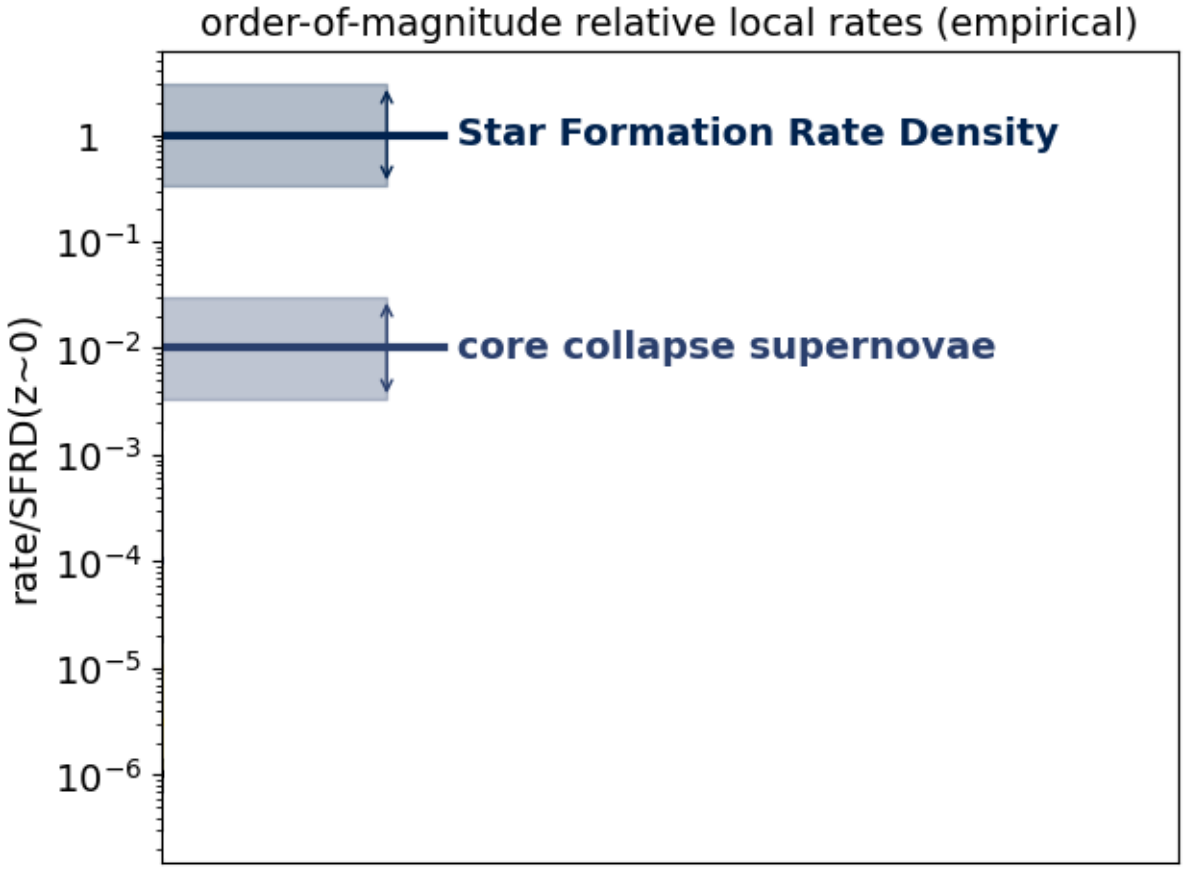

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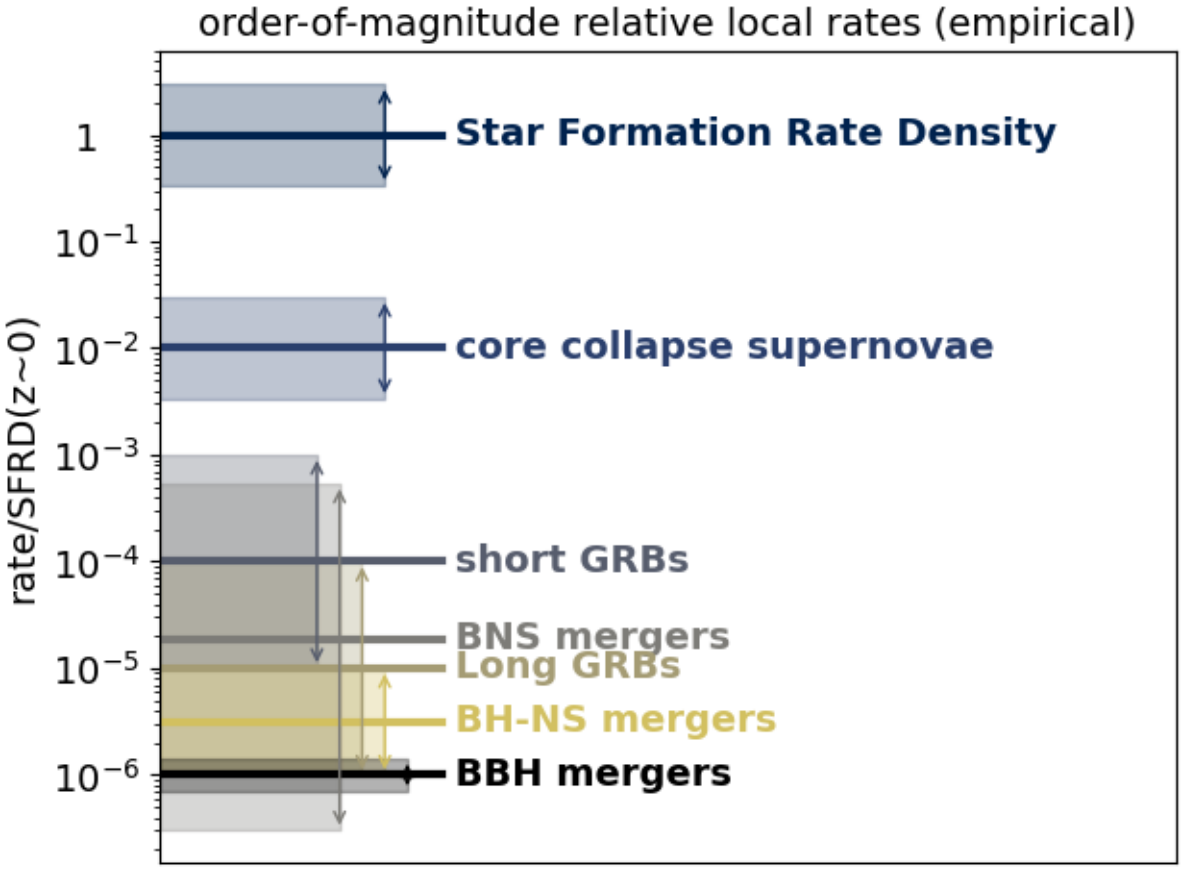

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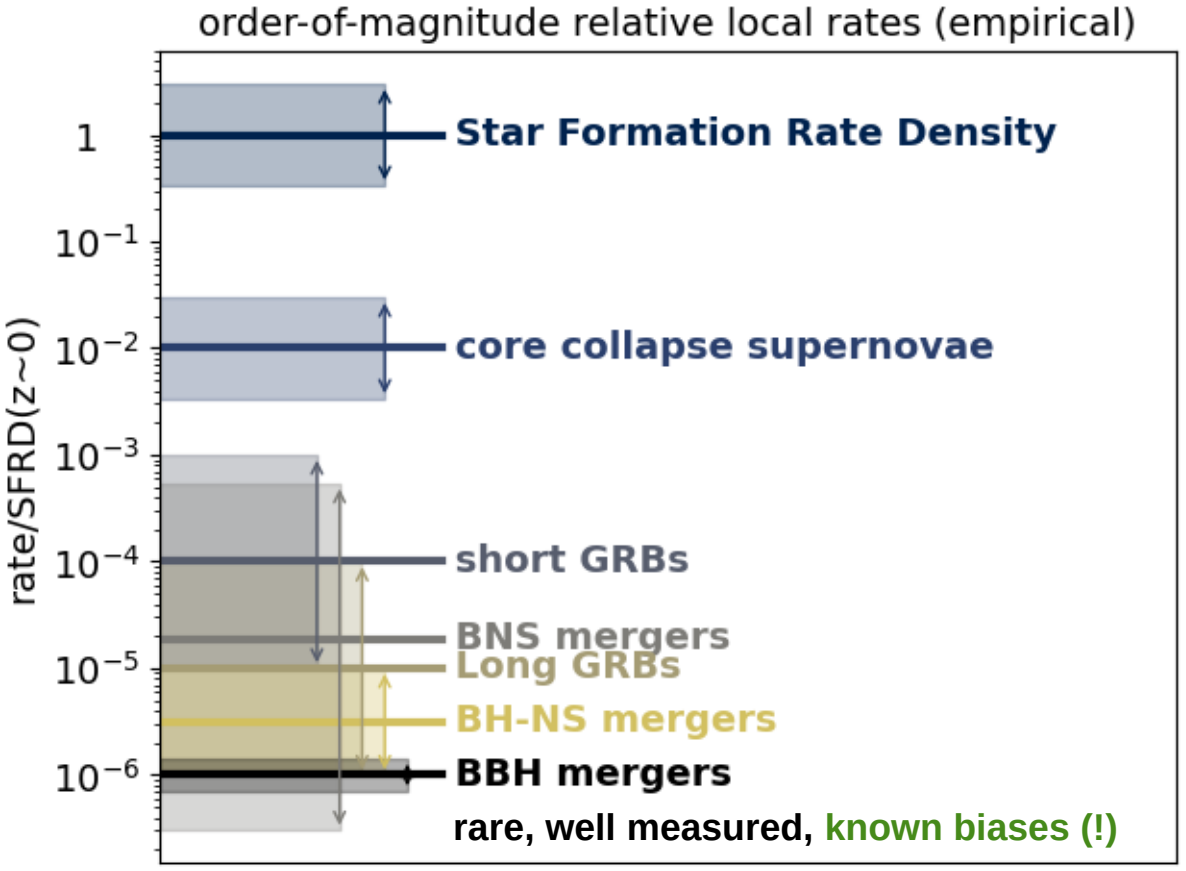
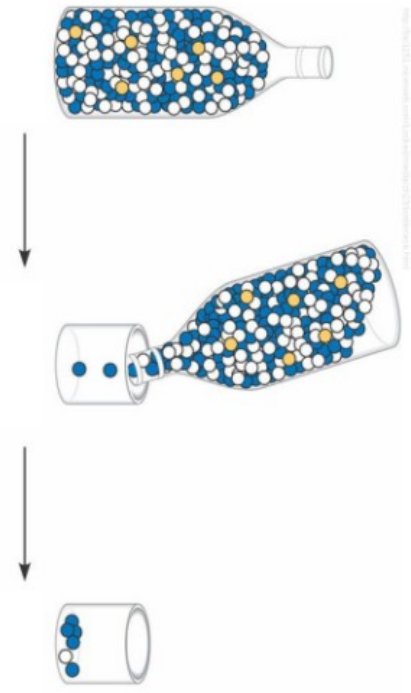
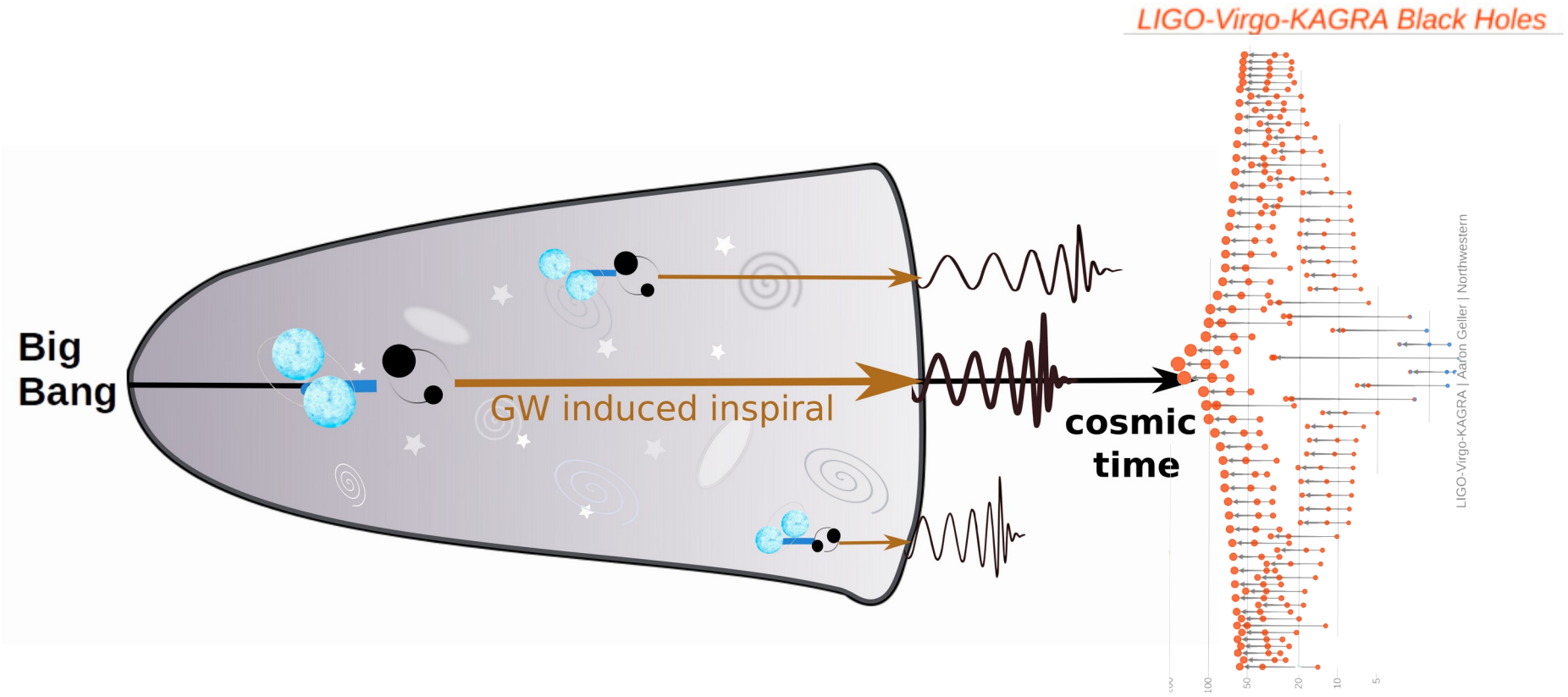
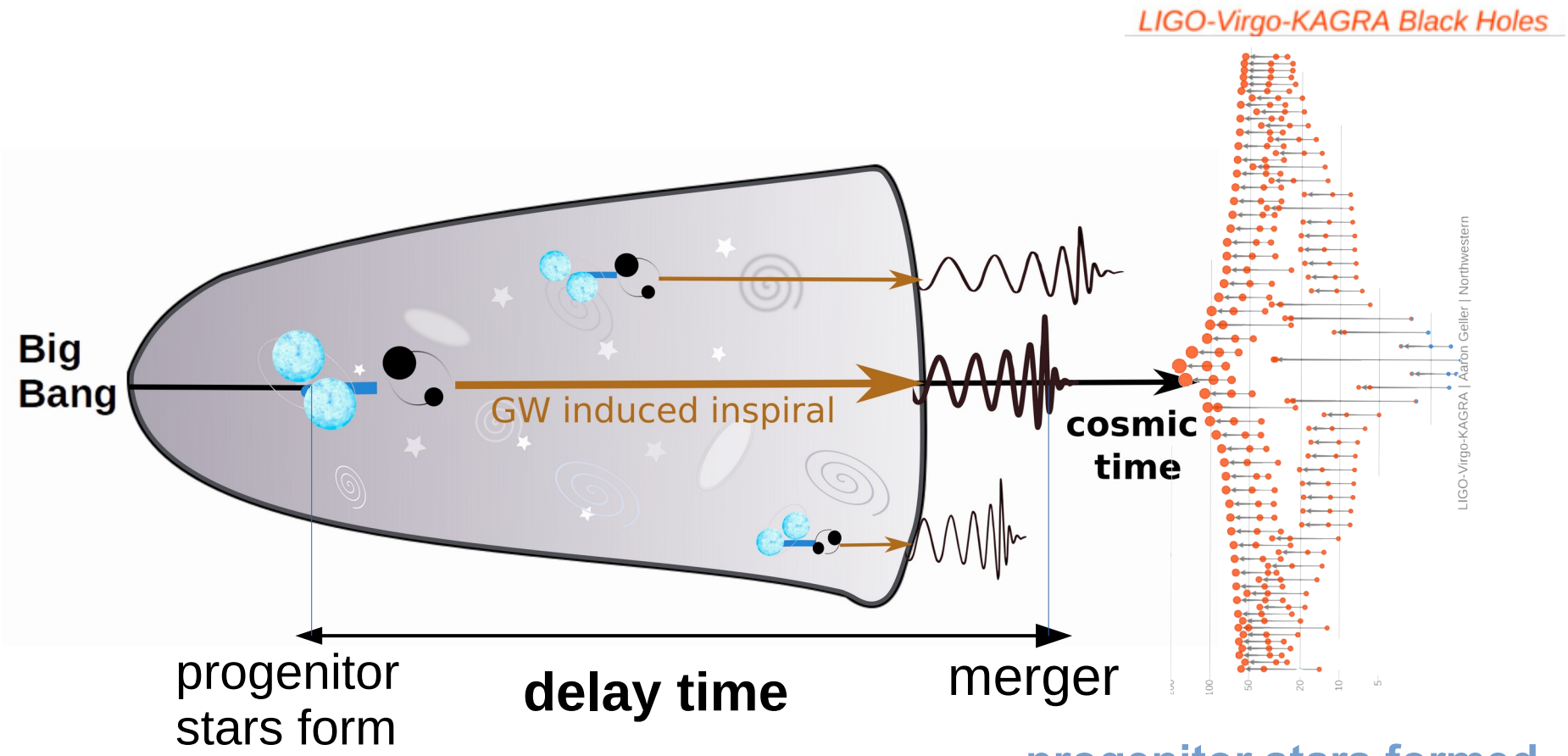






progenitor stars formed *somewhere* in the Universe



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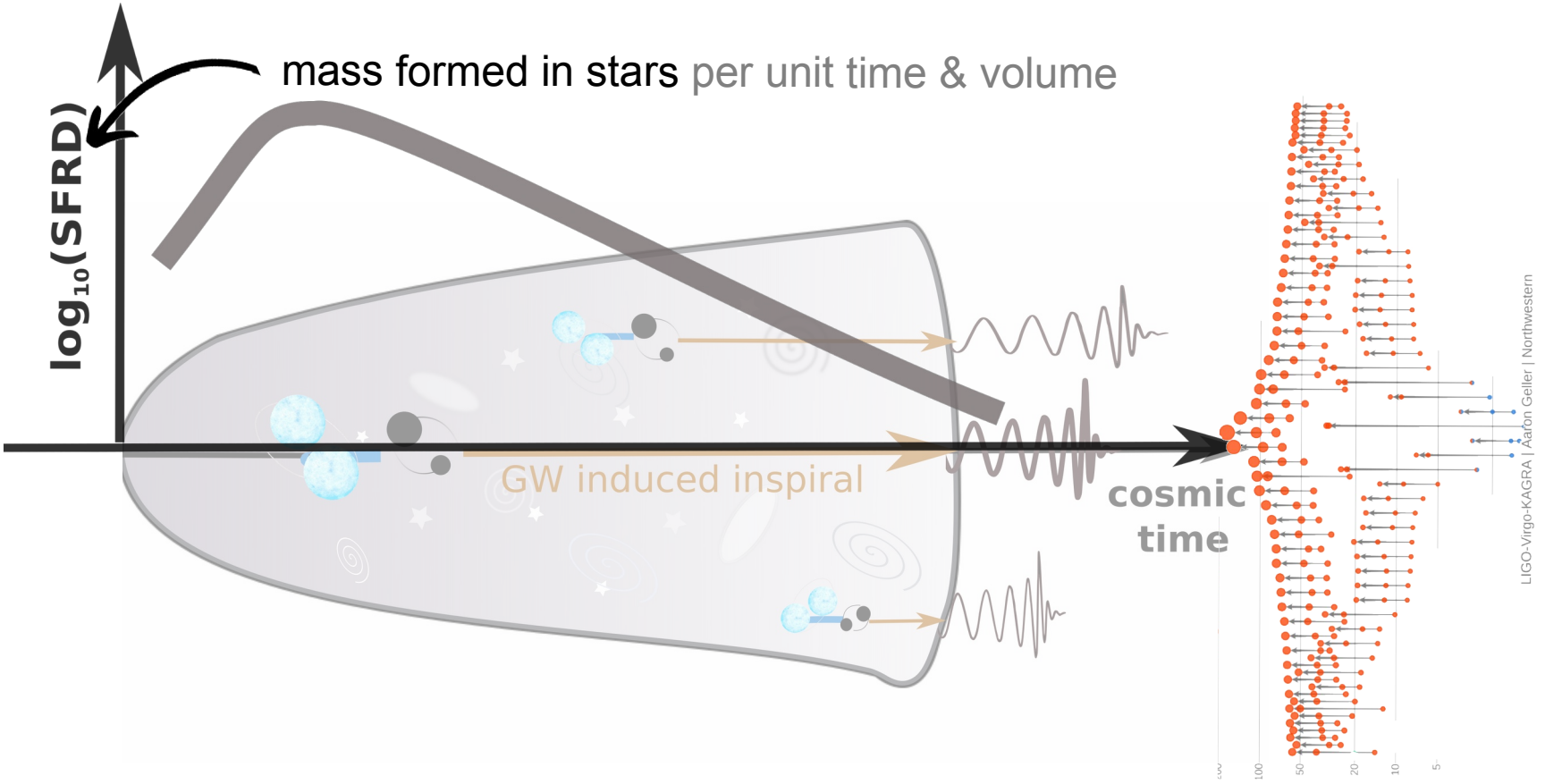
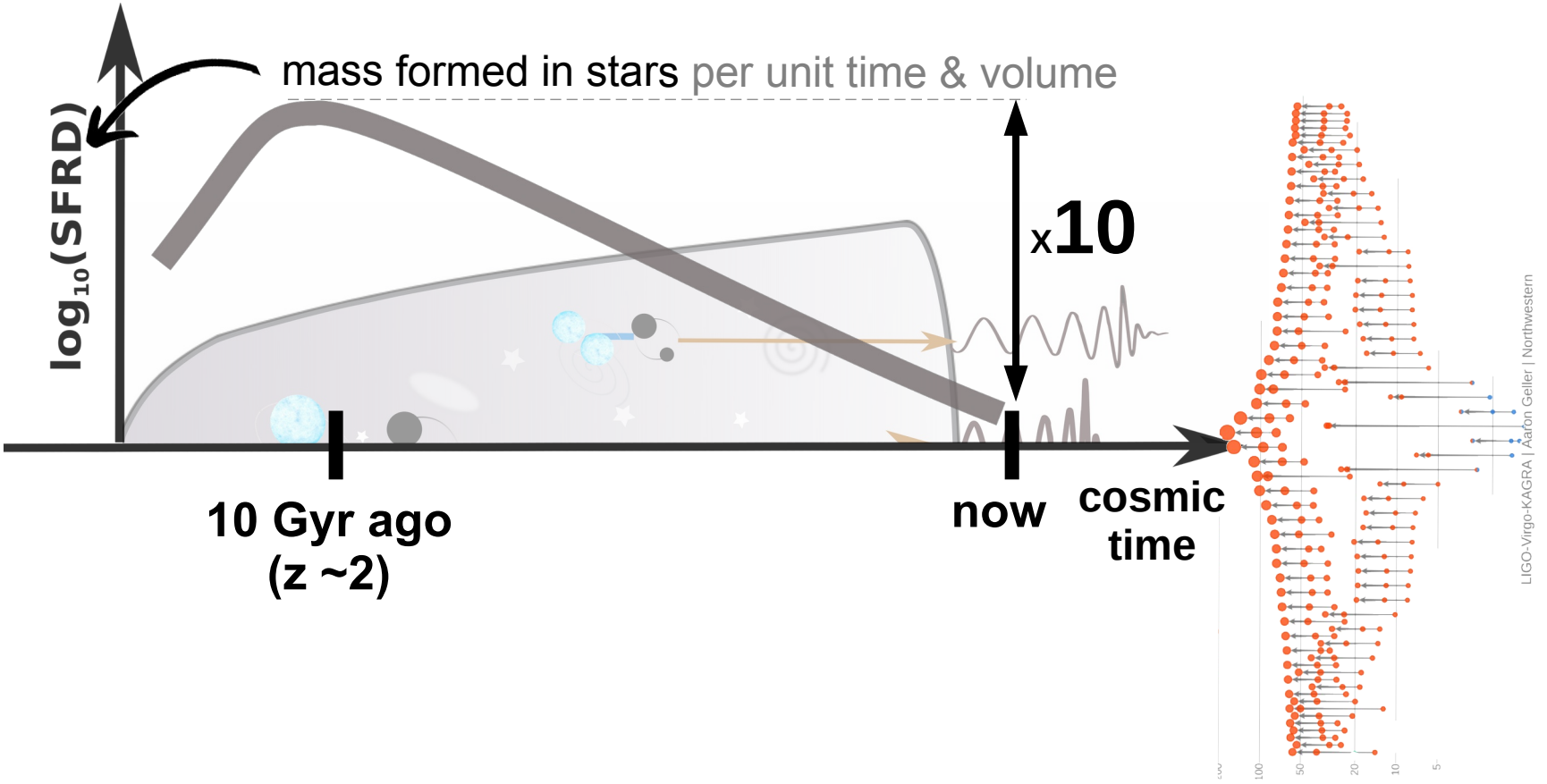
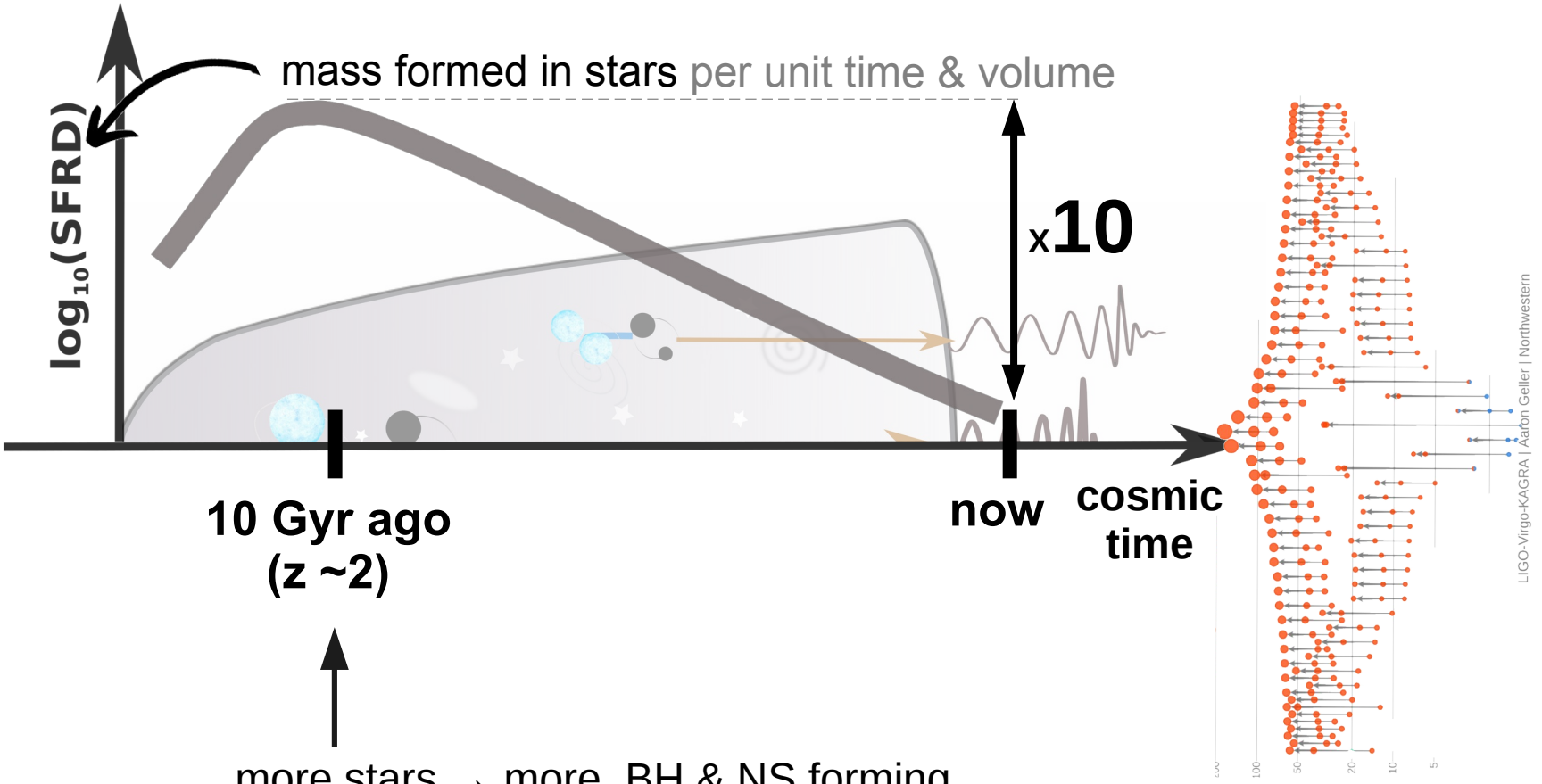
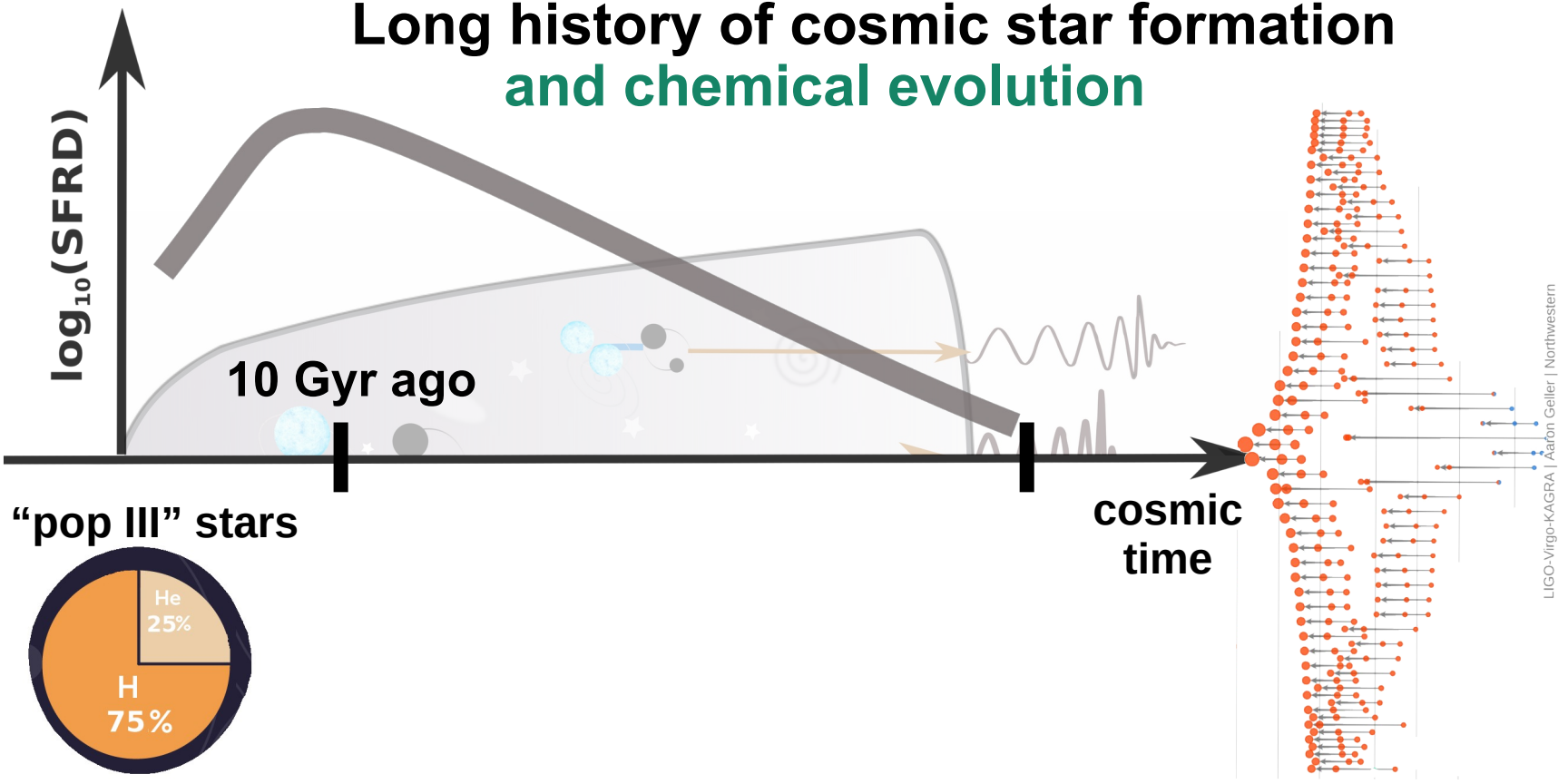

mass formed in stars per unit time & volume
log10(SFRD)
GW induced inspiral
cosmic time
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern


mass formed in stars per unit time & volume
log10(SFRD)
x10
10 Gyr ago
(z ~2)
now
cosmic
time
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern



more stars → more BH & NS forming
(but: will they merge? when?)

Long history of cosmic star formation
and chemical evolution



Long history of cosmic star formation
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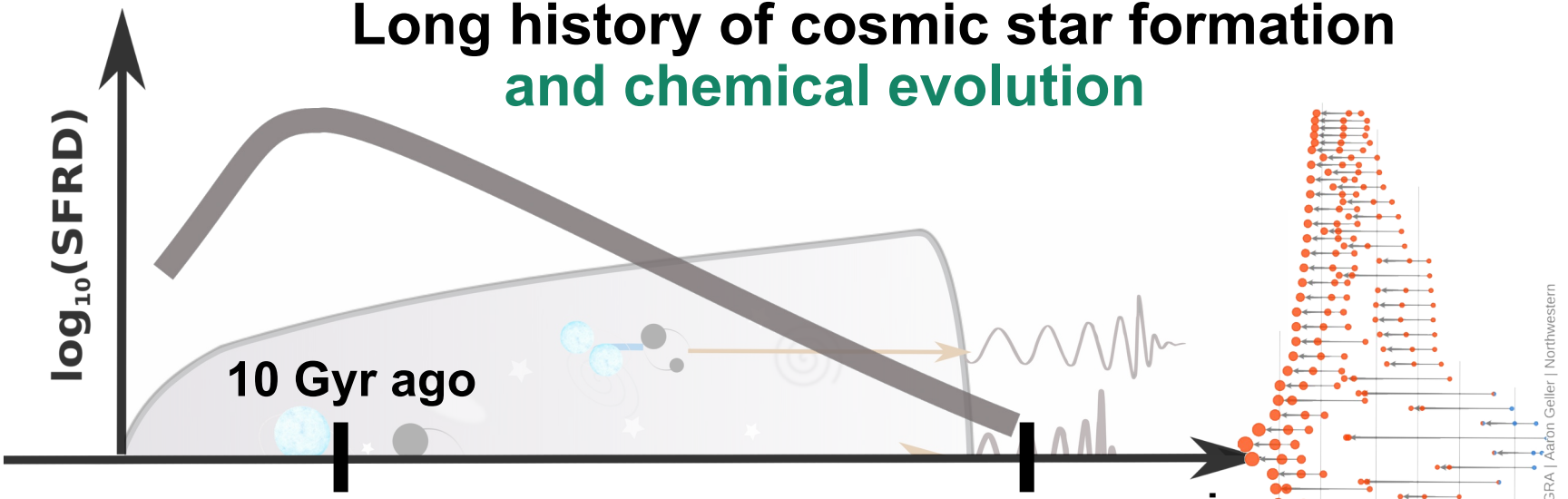
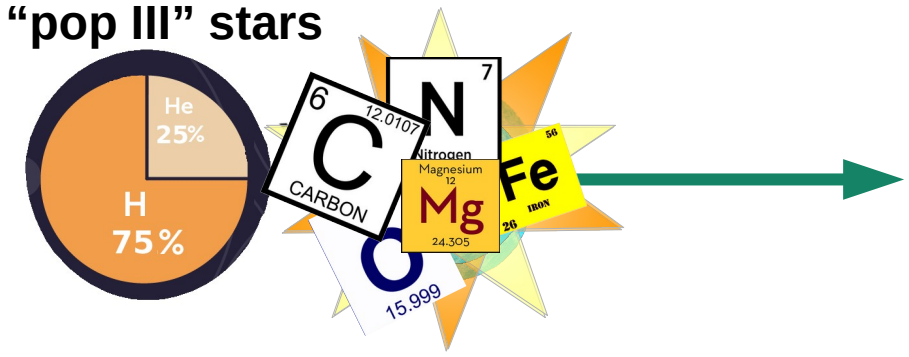
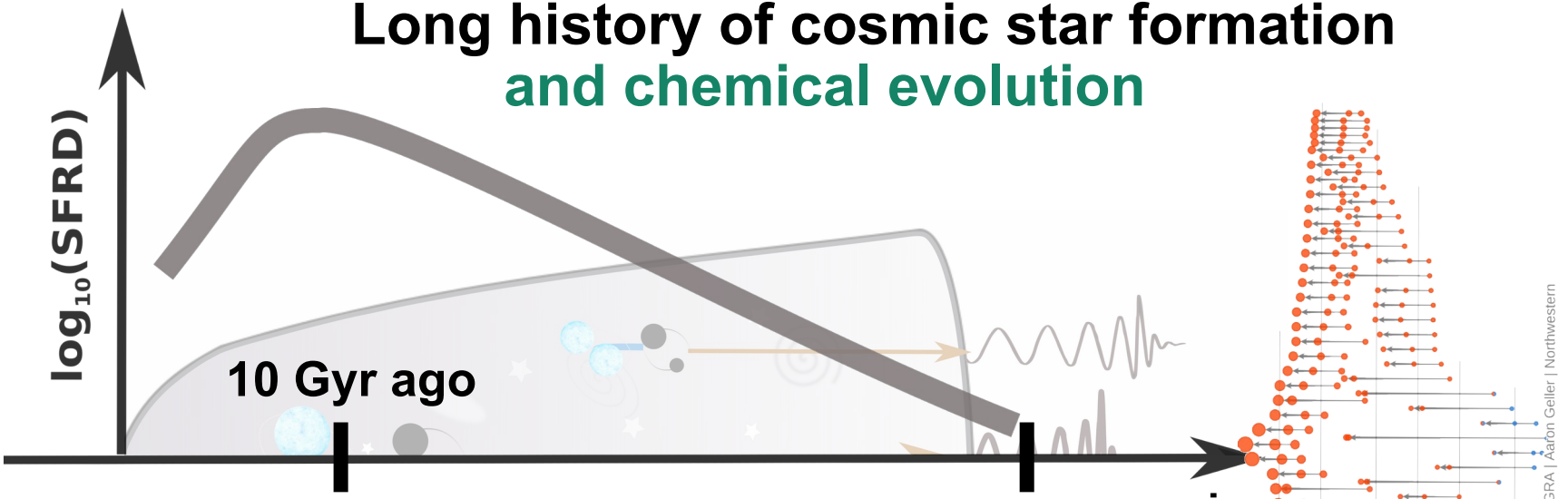
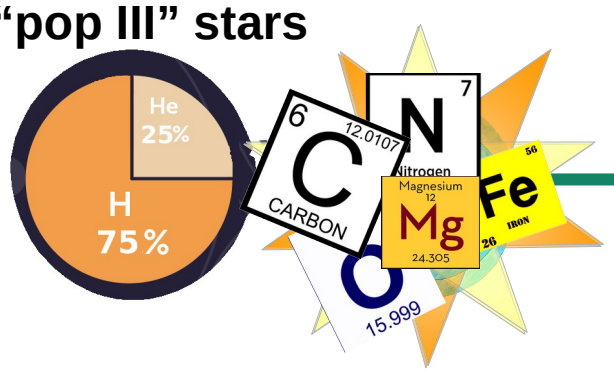


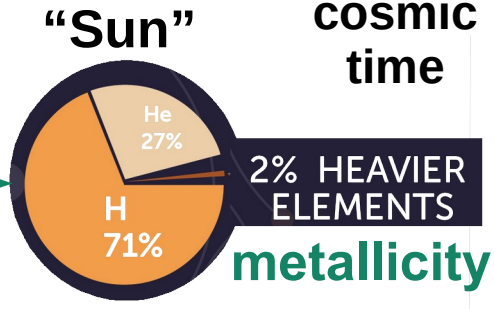


LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Long history of cosmic star formation
and chemical evolution







metallicity

influence astrophysical processes !

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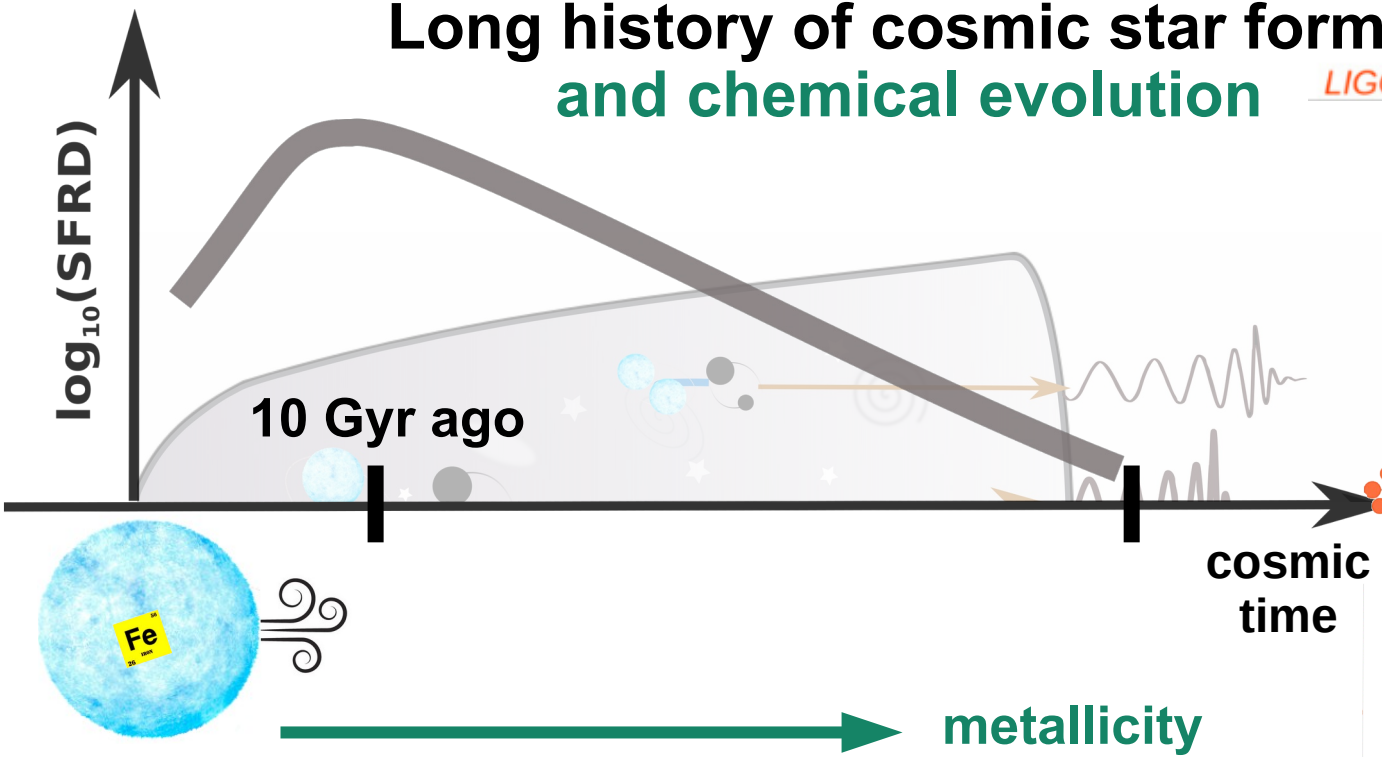
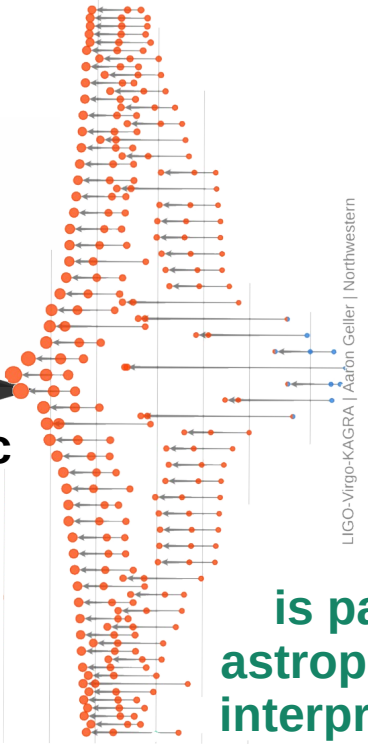
Long history of cosmic star formation
and chemical evolution



metallicity

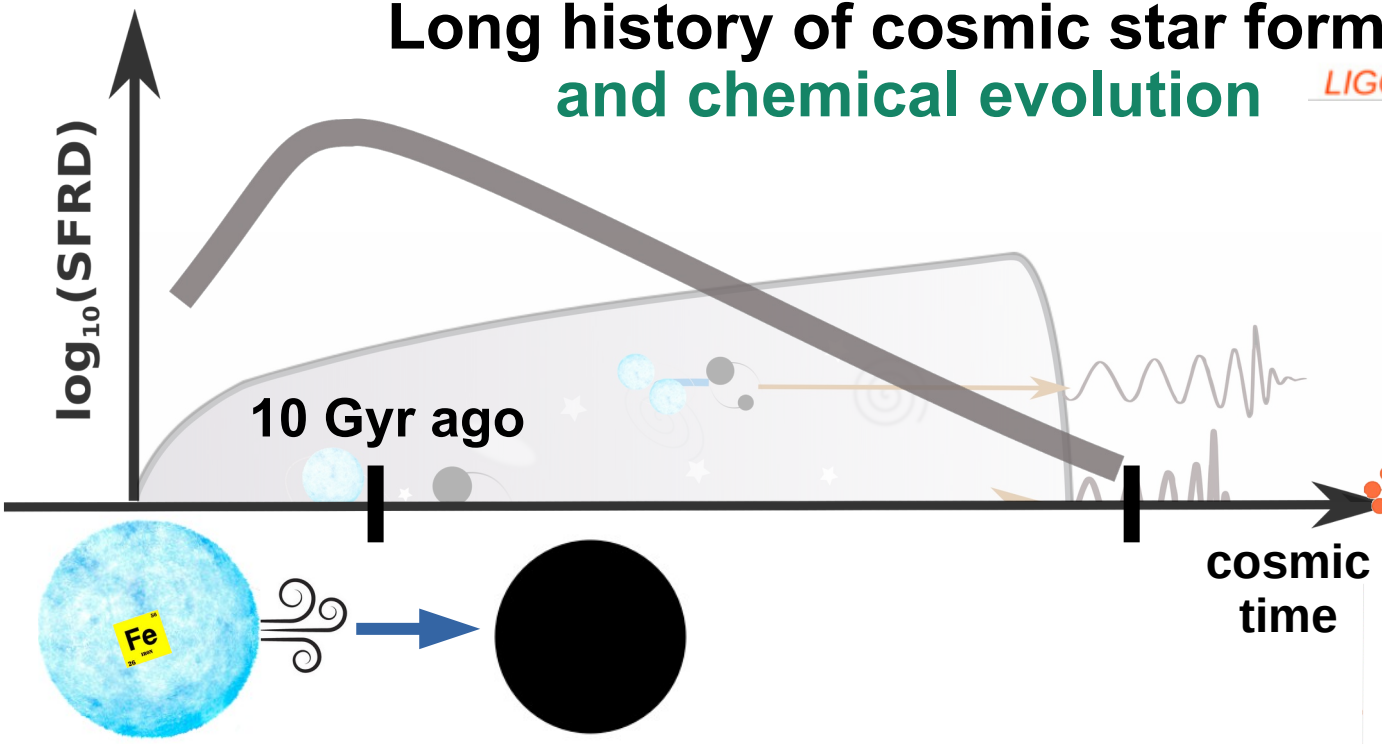
lower metallicity → lower wind mass loss

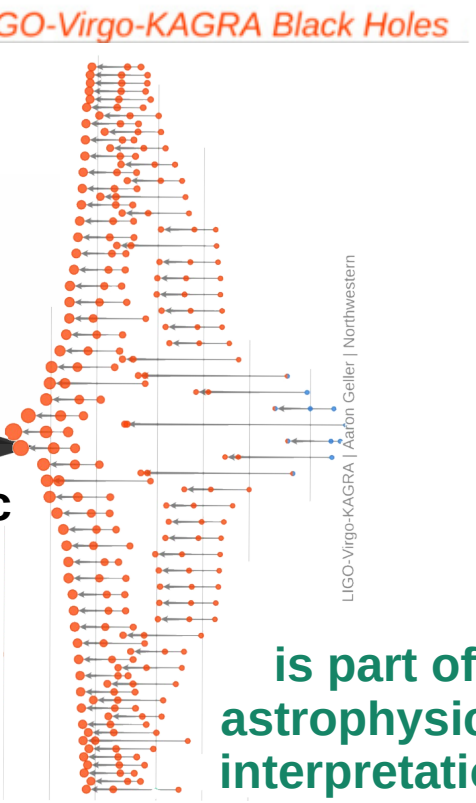
LIGO-Virgo-KAGRA Black Holes



is part of astrophysical interpretation!

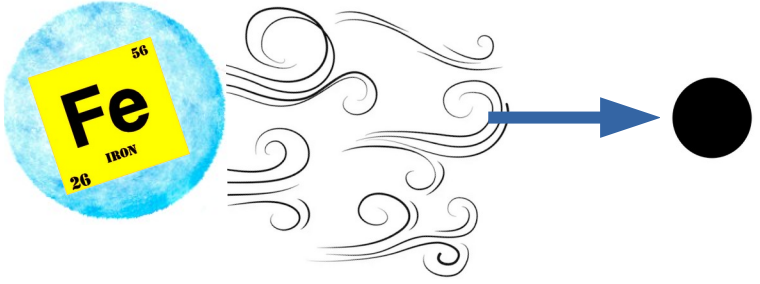
Long history of cosmic star formation
and chemical evolution



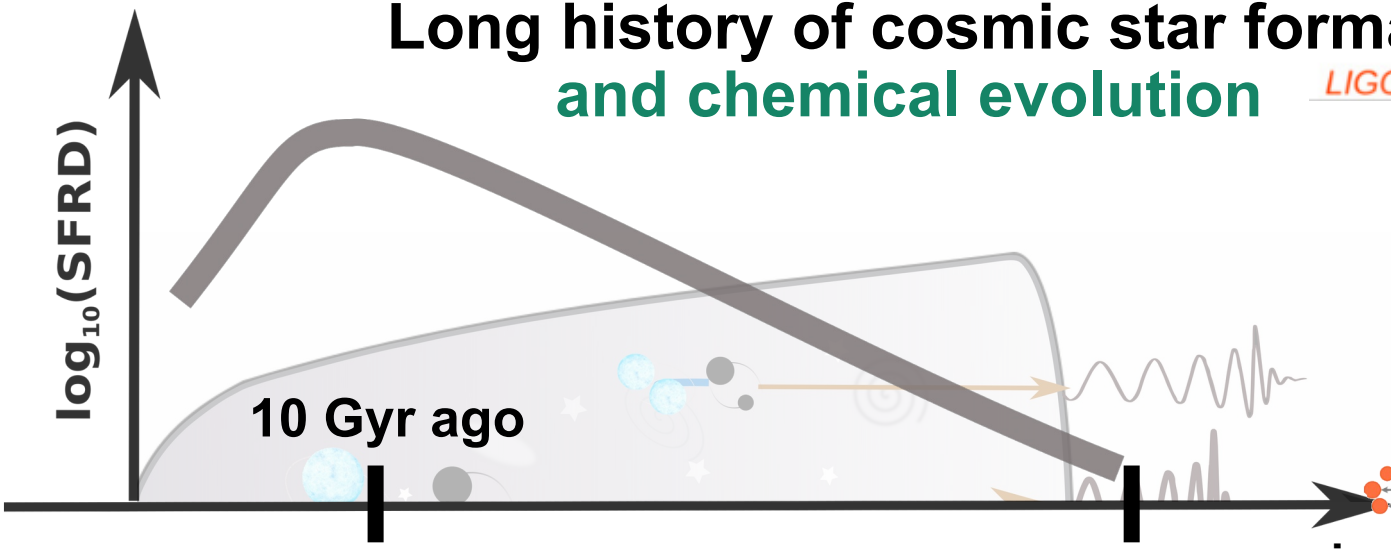


is part of astrophysical interpretation!

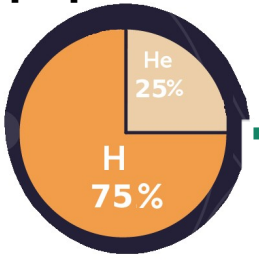
“ lower metallicity → lower wind mass loss → more massive BH ”



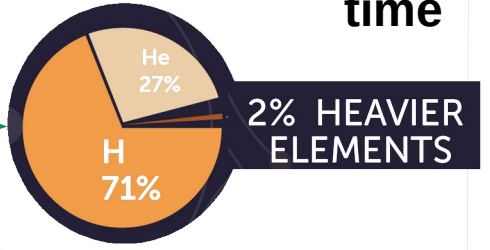
Long history of cosmic star formation
and chemical evolution

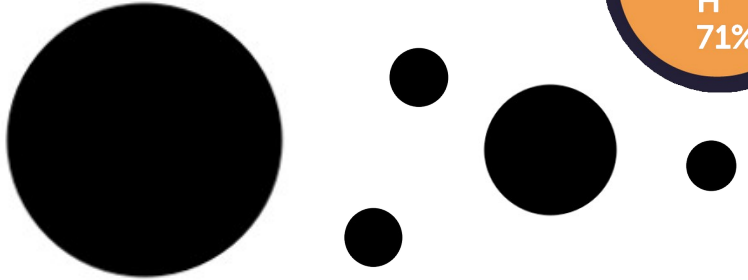


“pop III” stars

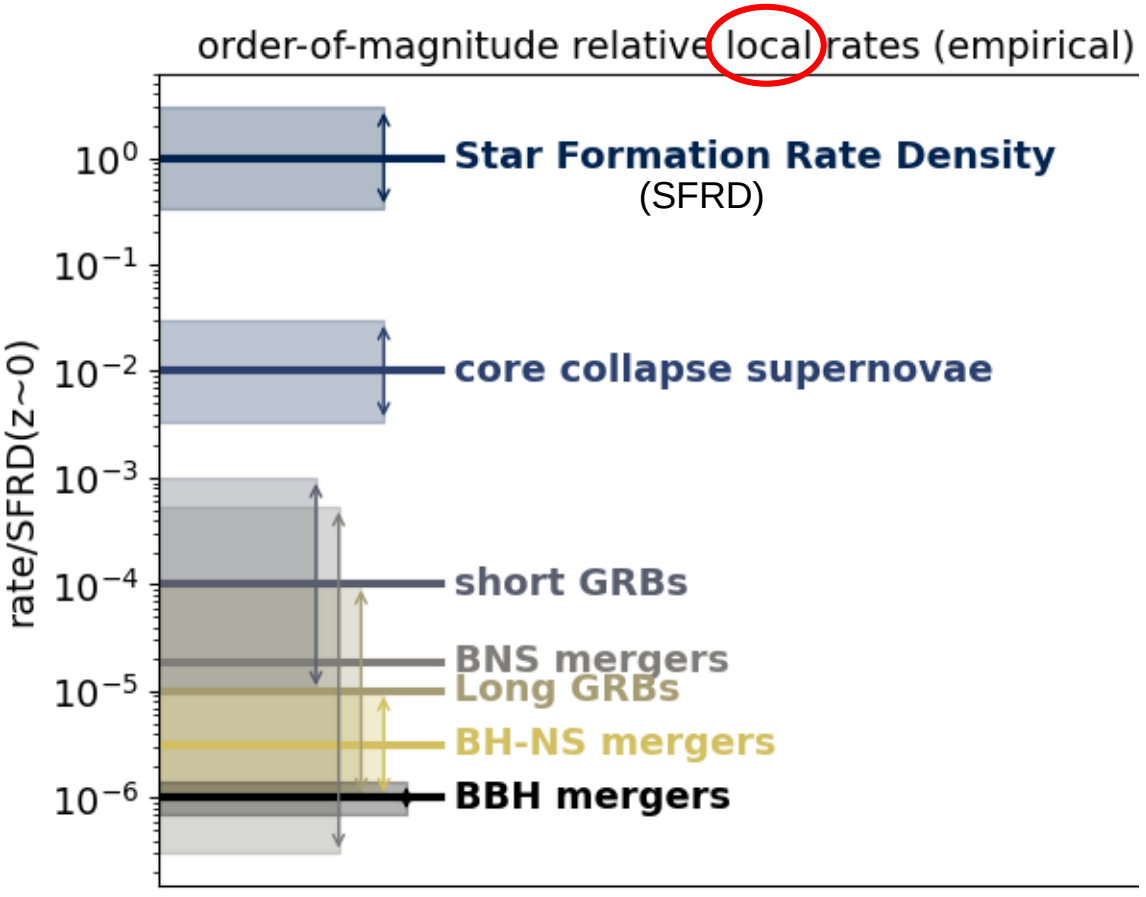


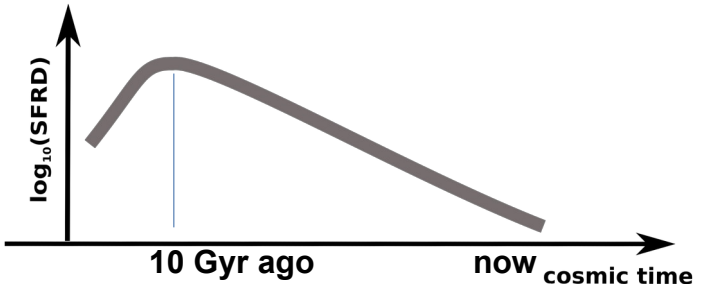
“Sun”

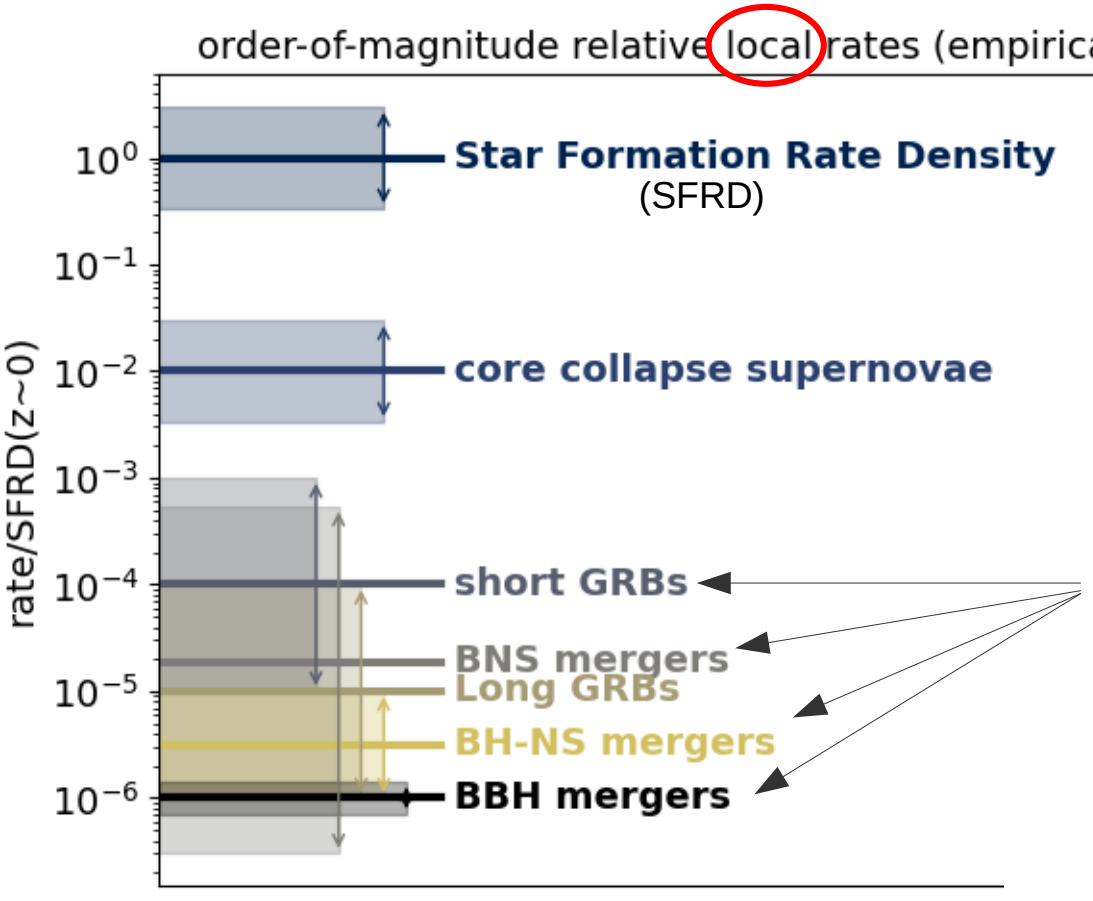


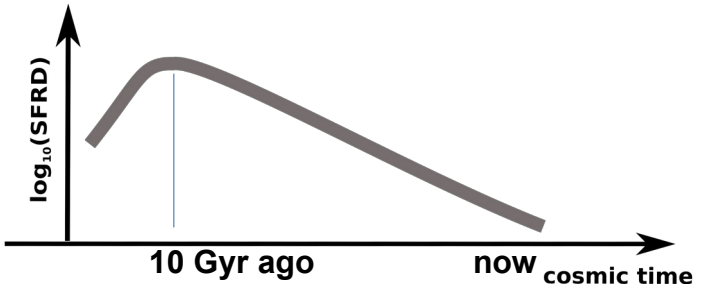


is part of astrophysical interpretation!

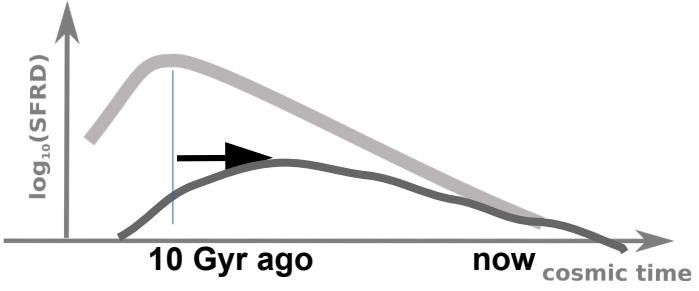

order-of-magnitude relative local rates (empirical)
rate/SFRD(z~0)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Star Formation Rate Density
(SFRD)
core collapse supernovae
short GRBs
BNS mergers
Long GRBs
BH-NS mergers
BBH mergers


$\log_{10}$(SFRD)
10 Gyr ago
now
cosmic time

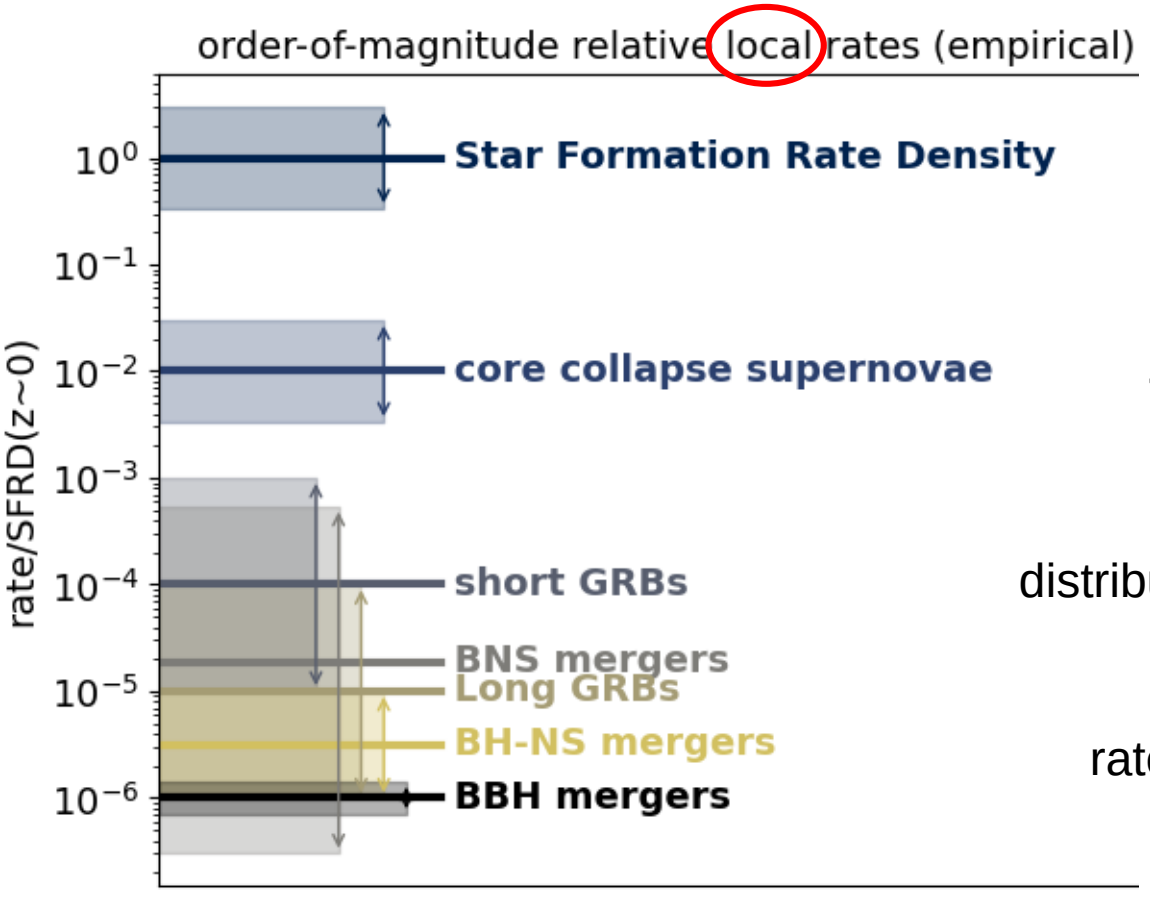


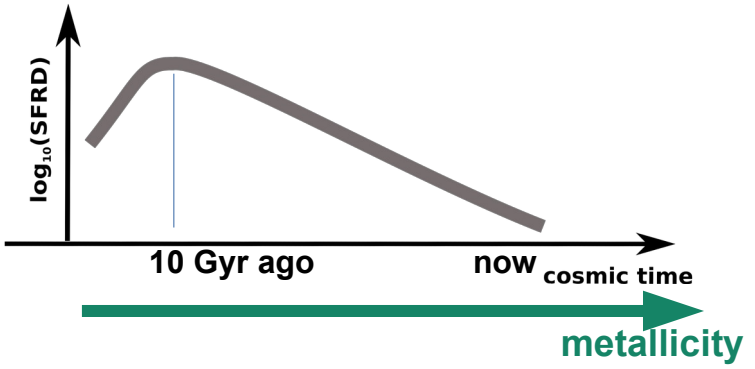


form with a (significant) **delay**



rate/SFRD varies over the cosmic history

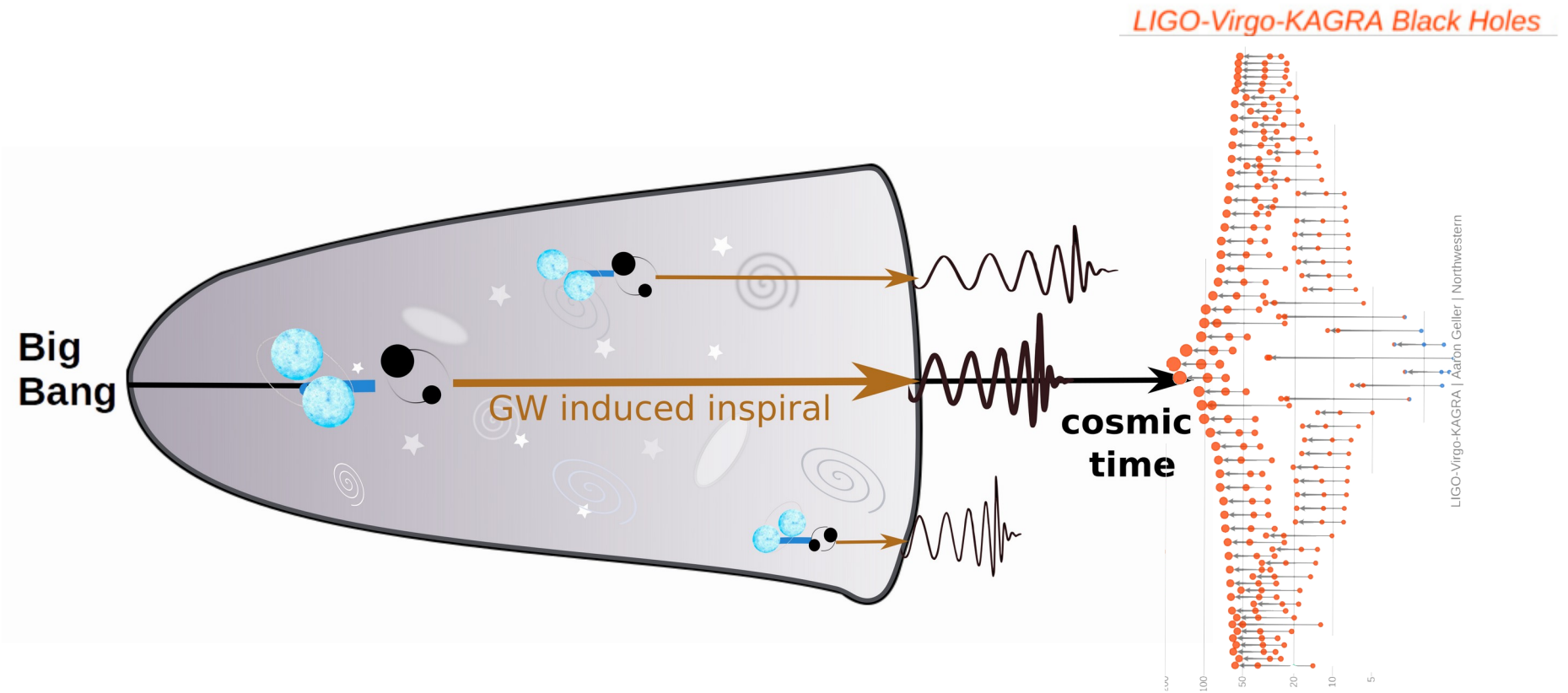




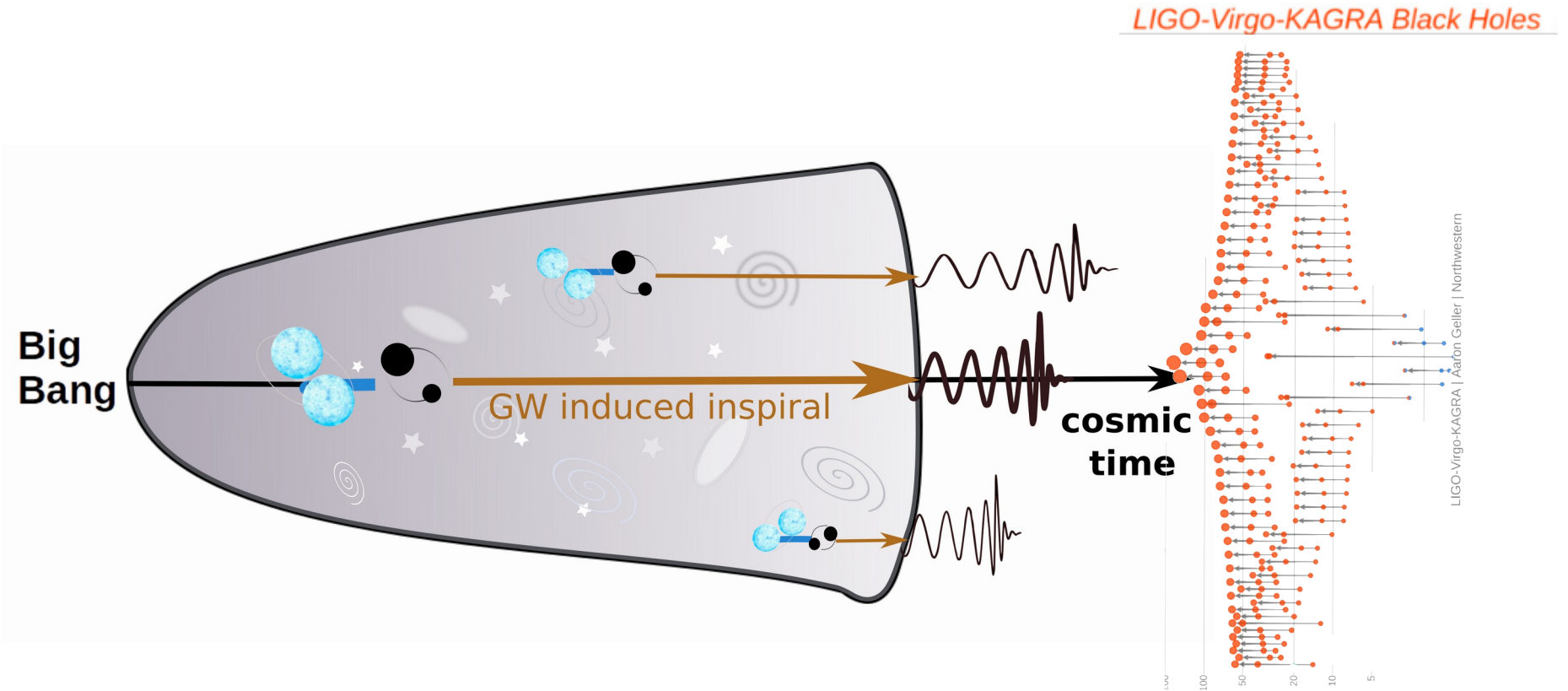
distribution of stellar birth metallicities changes

↓

rate/SFRD varies over the cosmic history

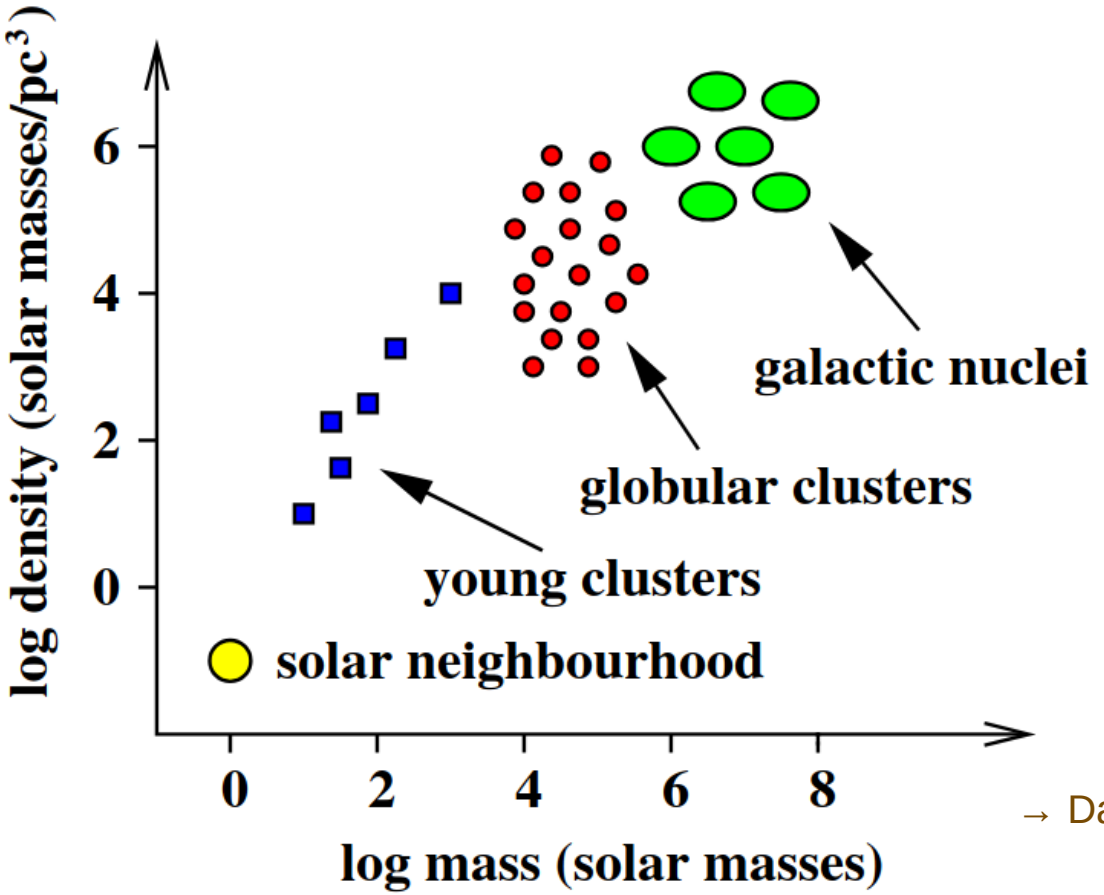


GW-observed population
different formation times,
chemical compositions



GW-observed population
different formation times,
chemical compositions,
environments

Environment → GW source “formation channels”



→ Davies (2002)

*1 pc = 3 ^{x} 10^{13} km

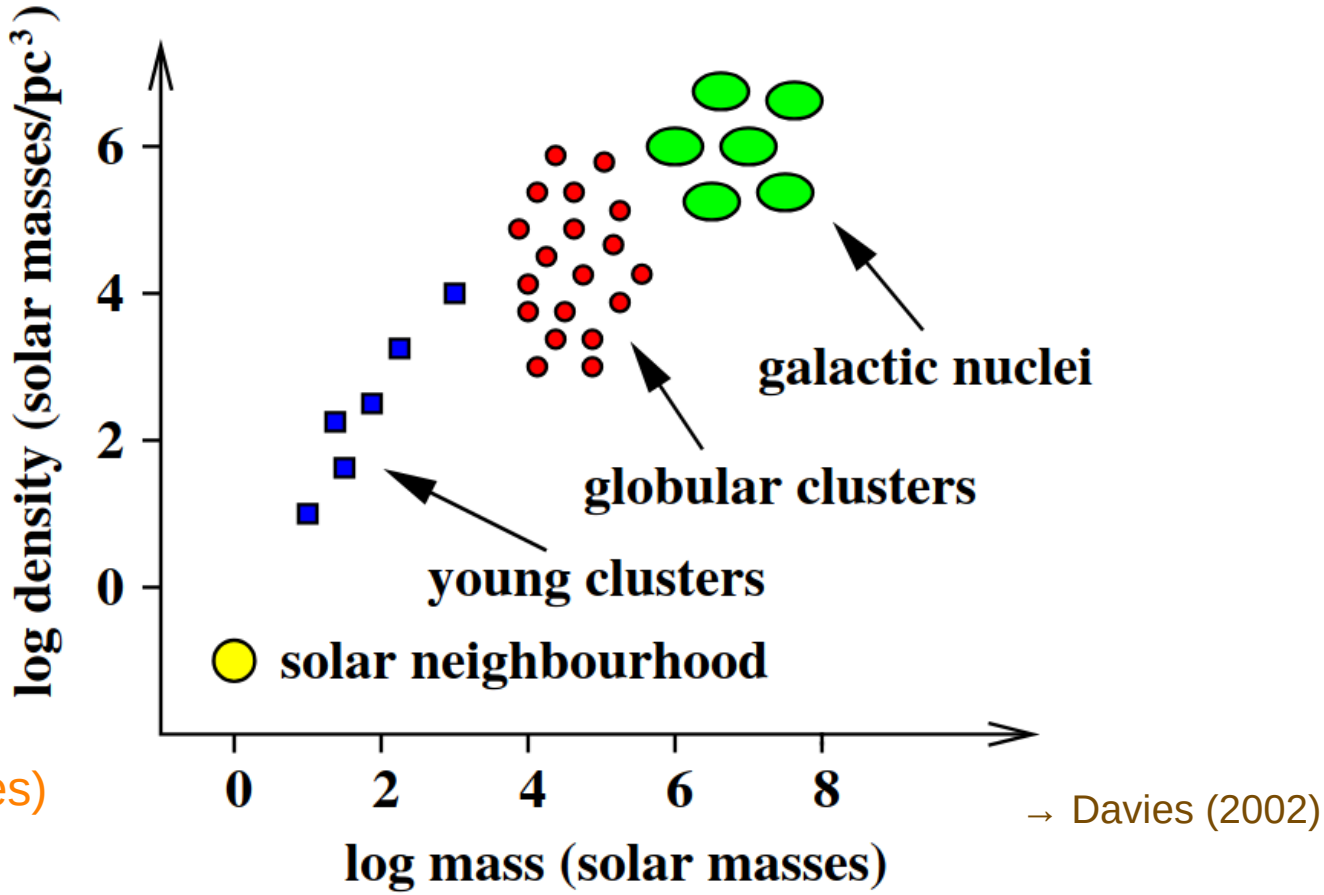
Environment → GW source “formation channels”

dynamical formation

“dense environments”

“galactic field”

isolated (stars, binaries/multiples) **evolution**



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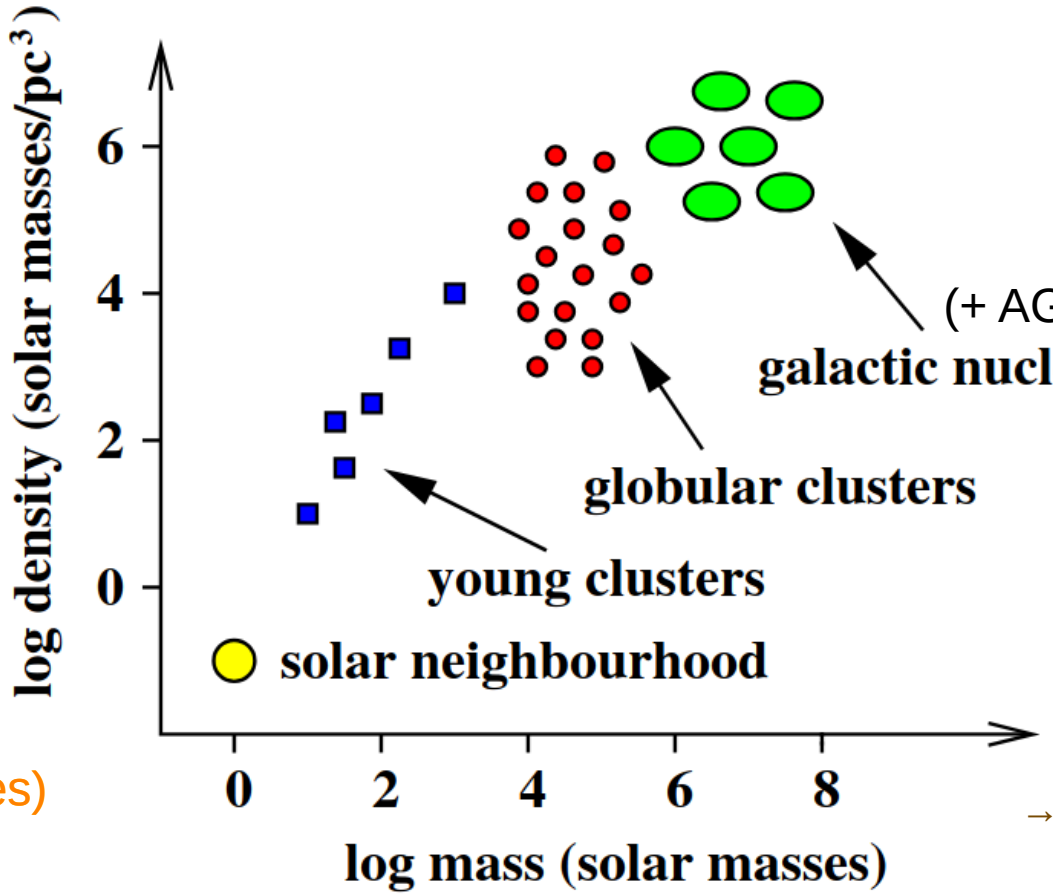


→ talks by A. Trani, B. Liu

→ talk by S. Rastello

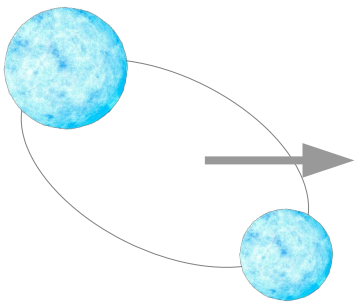
→ Davies (2002)

*1 pc = 3×10^{13} km

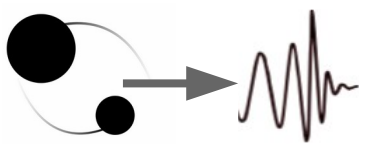
Environment → GW source “formation channels”

“galactic field”

isolated
(stars, binaries/multiples)
evolution

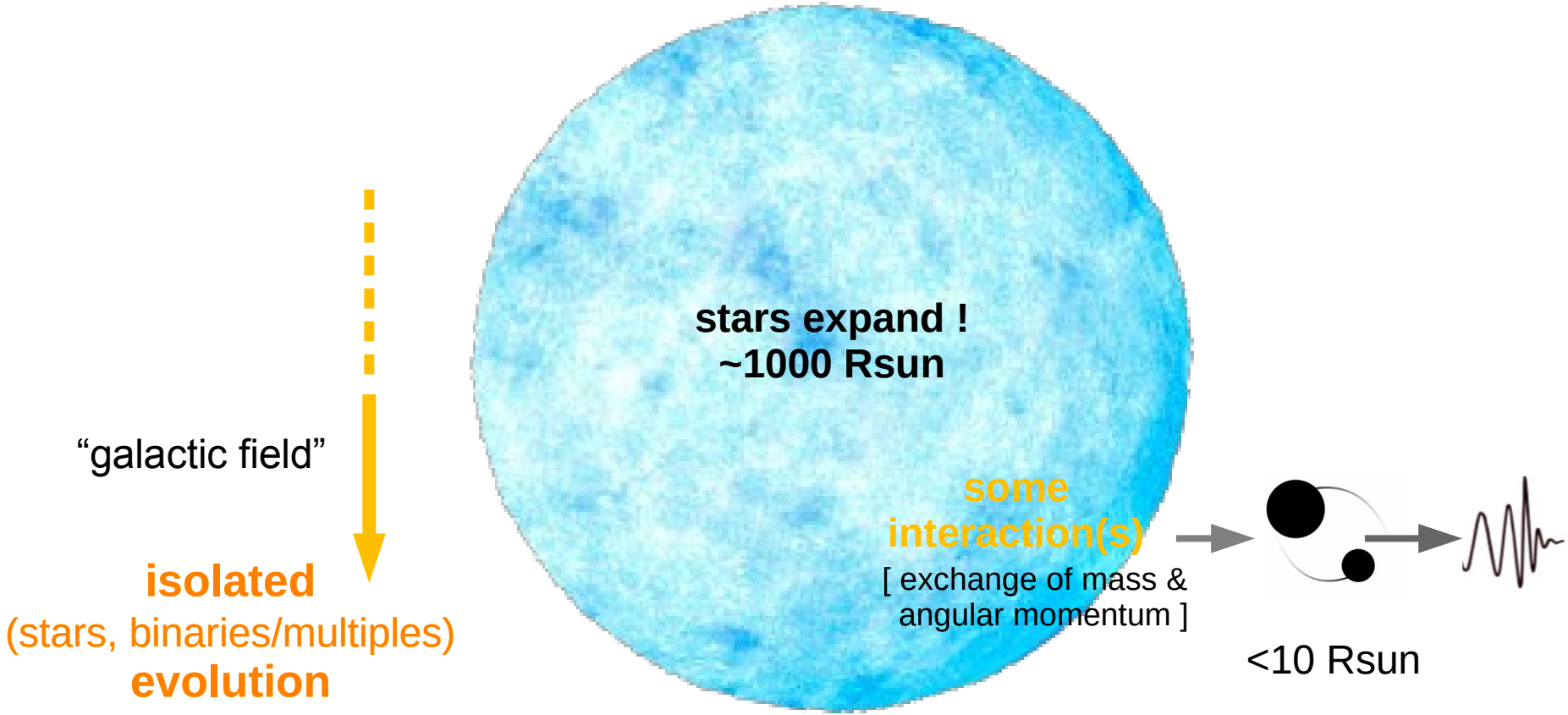


some interaction(s)
[exchange of mass & angular momentum]



<10 Rsun

Environment → GW source “formation channels”



Environment → GW source “formation channels”

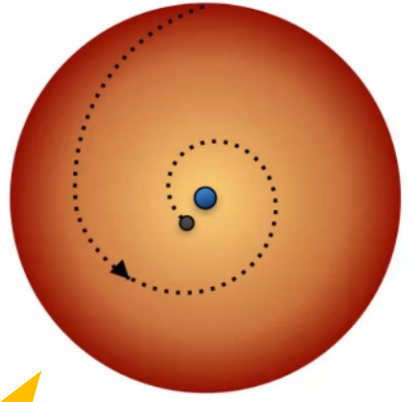
→ start wide and tighten (a lot) through mass transfer phase(s)

Tutukov & Yungelson'93, Belczynski+02, Mennekens & Vanbeveren'14, Eldridge & Stanway 2016, van den Heuvel+17, Stevenson+17, Mapelli+18, Chruslinska+19, Bavera+21, Klencki+21, Marchant+21, Olejak+21, Iorio+23…(+ many !)

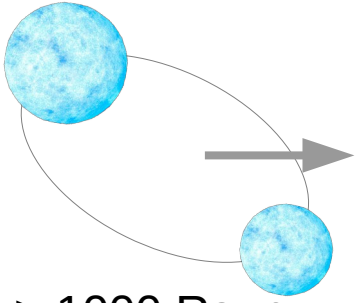
“galactic field”

isolated
(stars, binaries/multiples)
evolution

stable mass transfer



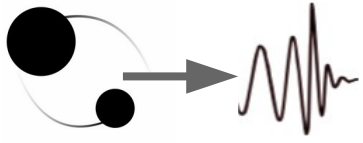
common envelope evolution



> 1000 Rsun

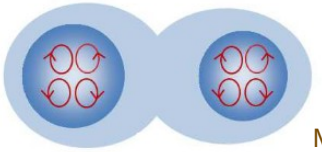
some interaction(s)

[exchange of mass & angular momentum]



<10 Rsun

Environment → GW source “formation channels”

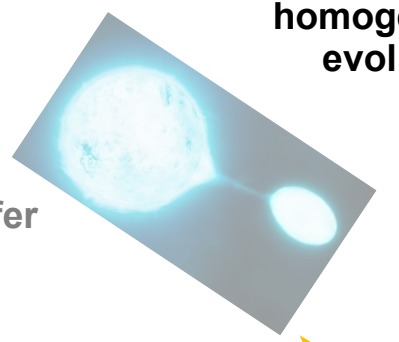


→ Talk by
M. Dall'Amico

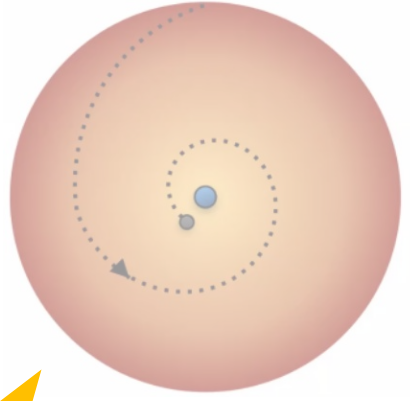
→ start very close and
avoid radial expansion

Mandel & de Mink 2016, de Mink & Mandel 2016, Marchant+16

chemically homogeneous evolution



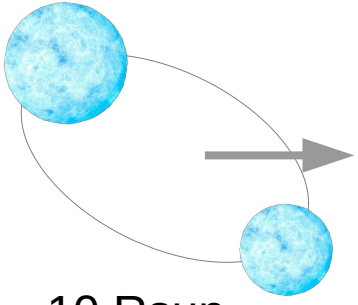
stable mass transfer



common envelope evolution

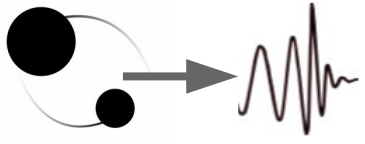
“galactic field”

isolated
(stars, binaries/multiples)
evolution



~10 Rsun

some interaction(s)
[exchange of mass & angular momentum]



<10 Rsun

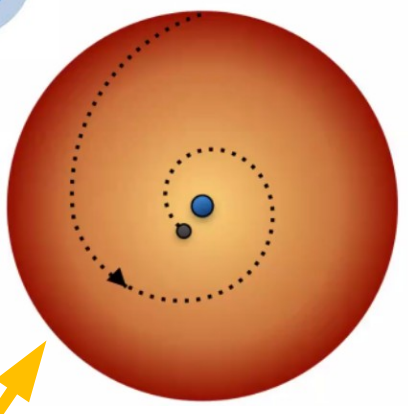
Environment → GW source “formation channels”

Which formation path?

→ sensitive to stellar mass and **metallicity**

→ many layers of uncertainties

(mixing, winds, nuclear & core-collapse & binary physics, what massive stars at low metallicity actually do?)

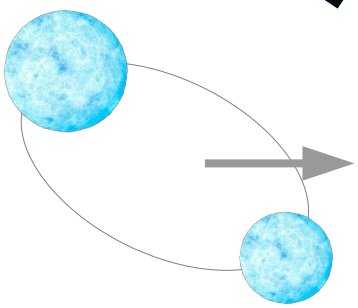


“galactic field”

isolated

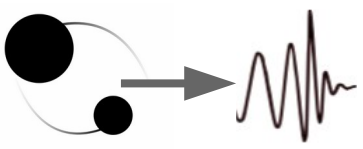
(stars, binaries/multiples)

evolution



some interaction(s)

[exchange of mass & angular momentum]



→ Talks by E. Korb, M. Dall'Amico

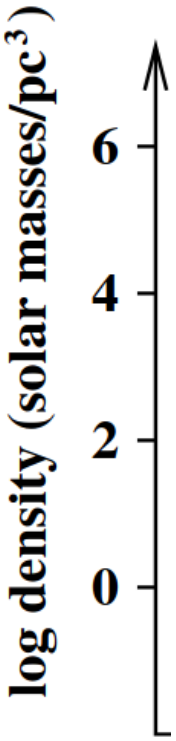
Environment → GW source “formation channels”

dynamical formation

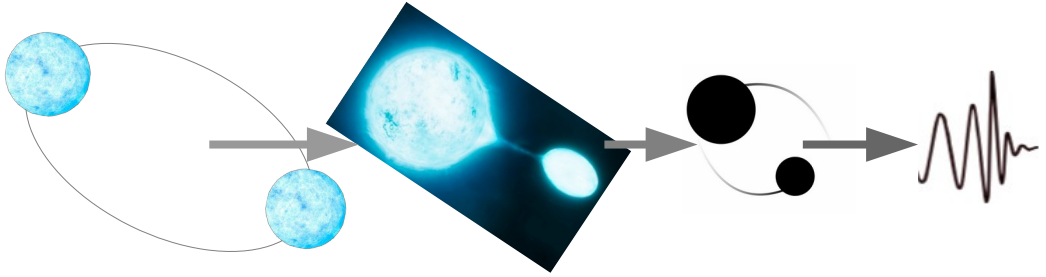
“dense environments”

“galactic field”

isolated
(stars, binaries/multiples)
evolution



BHs from stars that co-evolve & affect each other



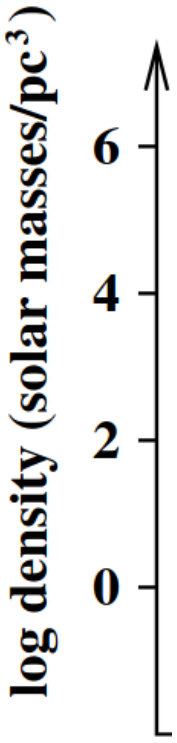
Environment → GW source “formation channels”

dynamical formation

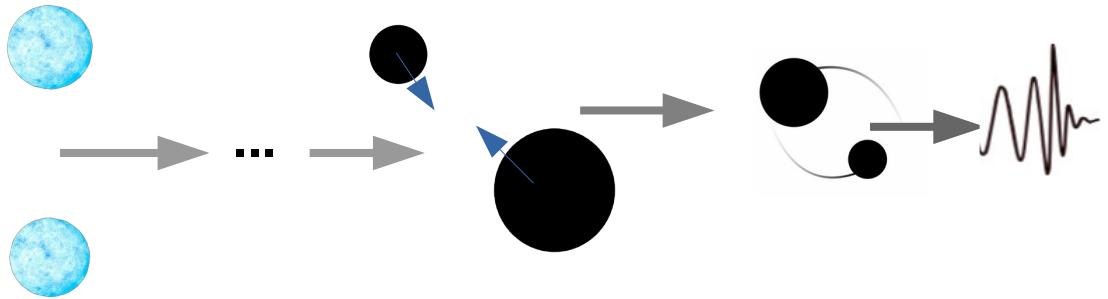
“dense environments”

“galactic field”

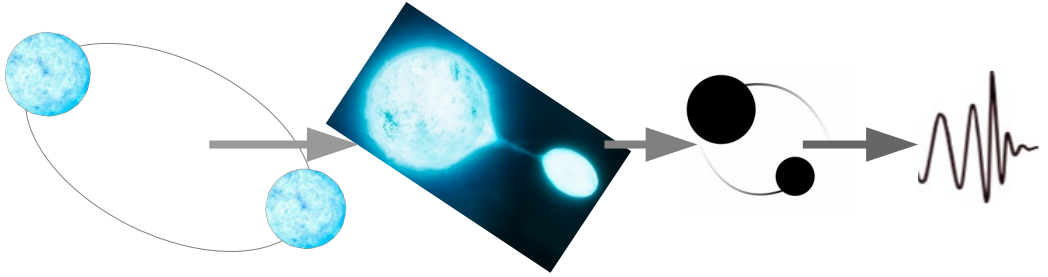
isolated (stars, binaries/multiples) **evolution**



pairing of BHs from “unrelated” stars



BHs from stars that co-evolve & affect each other



Environment → GW source “formation channels”

dynamical formation

“dense environments”

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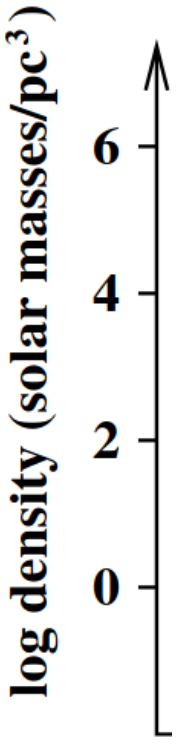
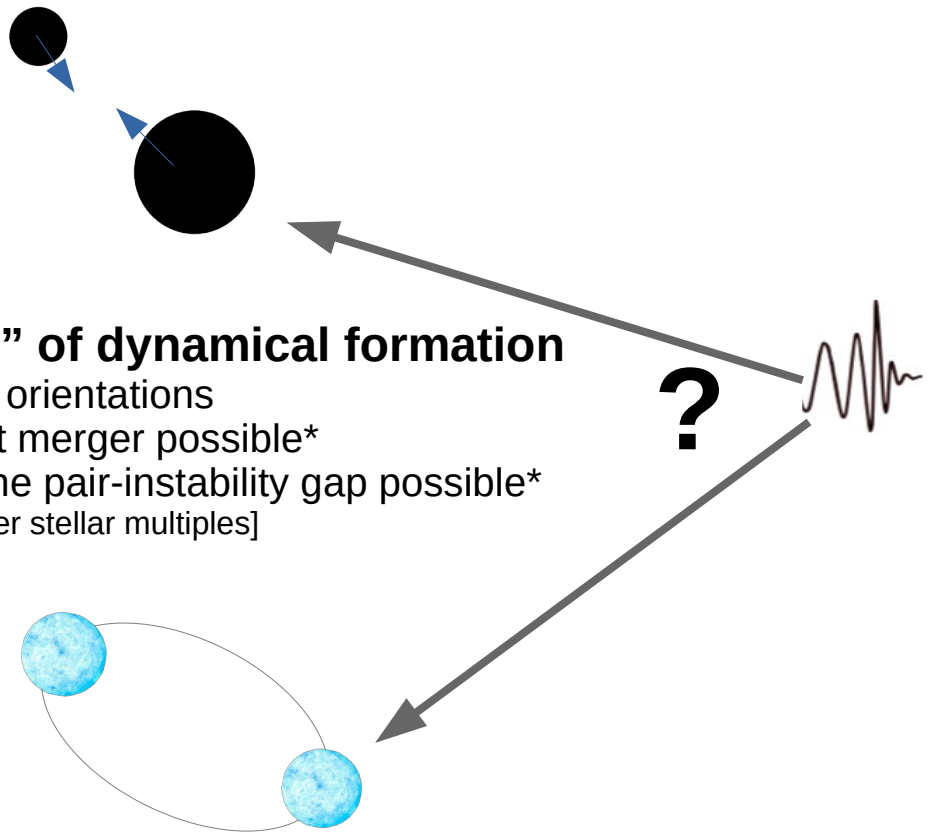
isolated (stars, binaries/multiples) **evolution**





“fingerprints” of dynamical formation

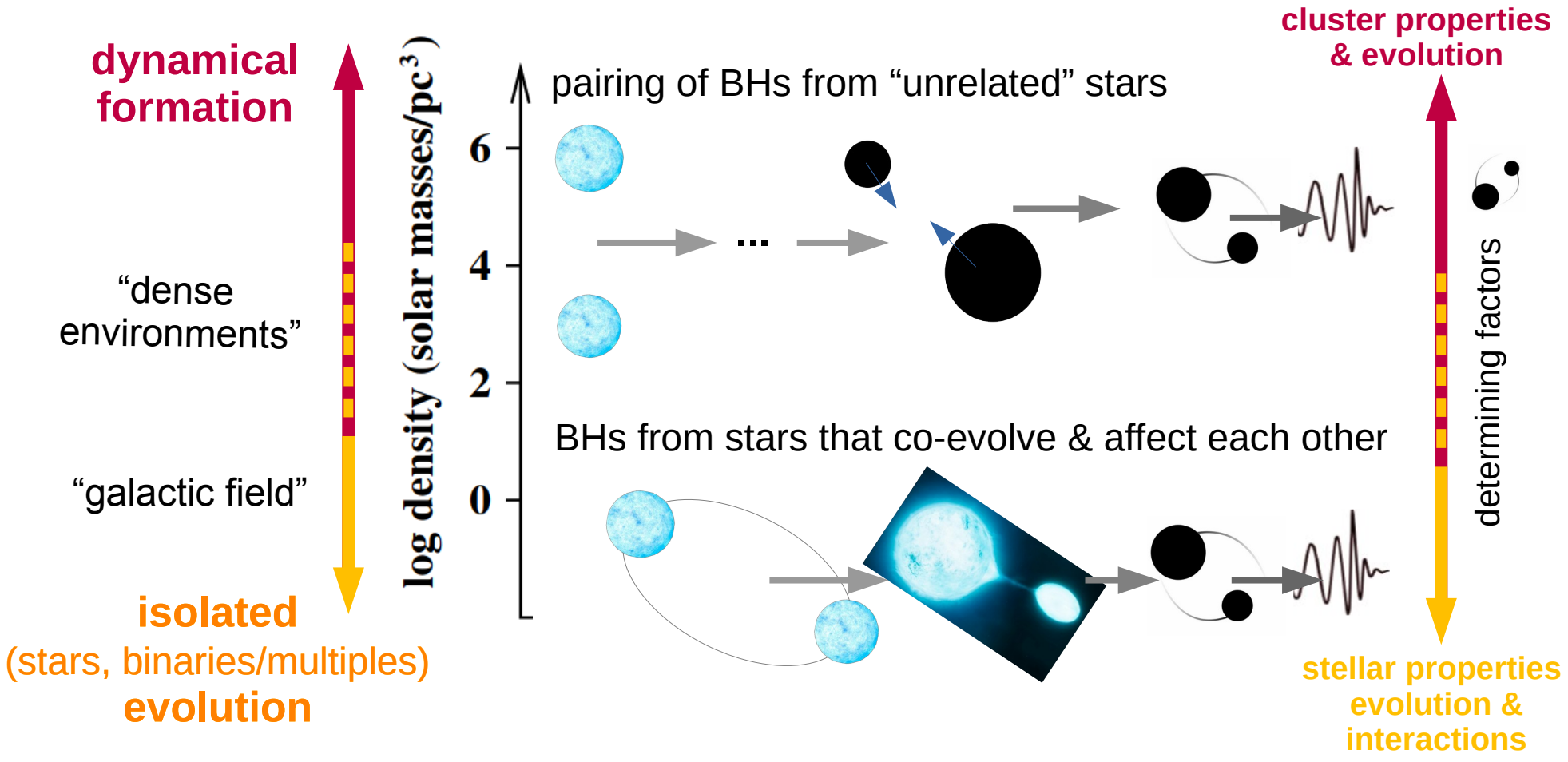
→ isotropic spin orientations

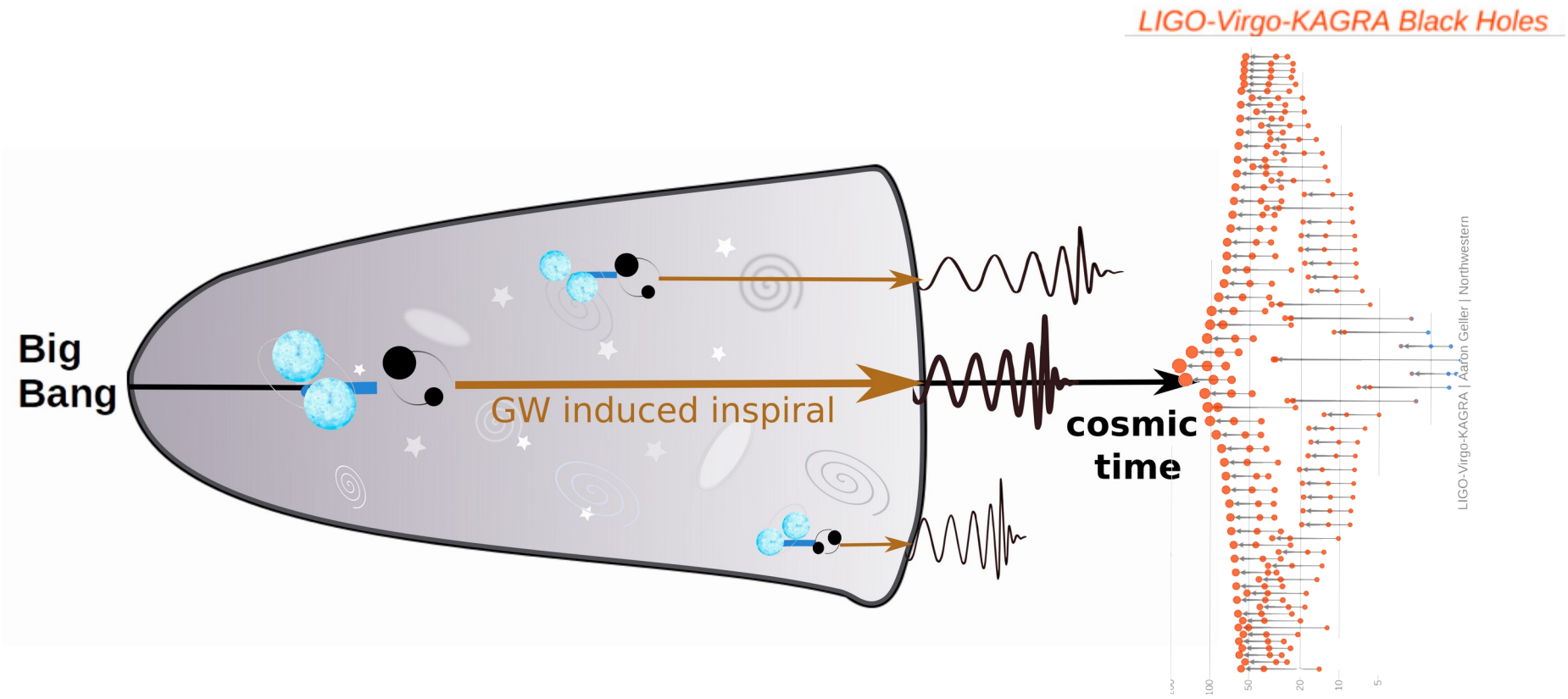
→ eccentricity at merger possible*

→ BH mass in the pair-instability gap possible*

[*but: higher-order stellar multiples]

Environment → GW source “formation channels”





Dense environments over the cosmic history?

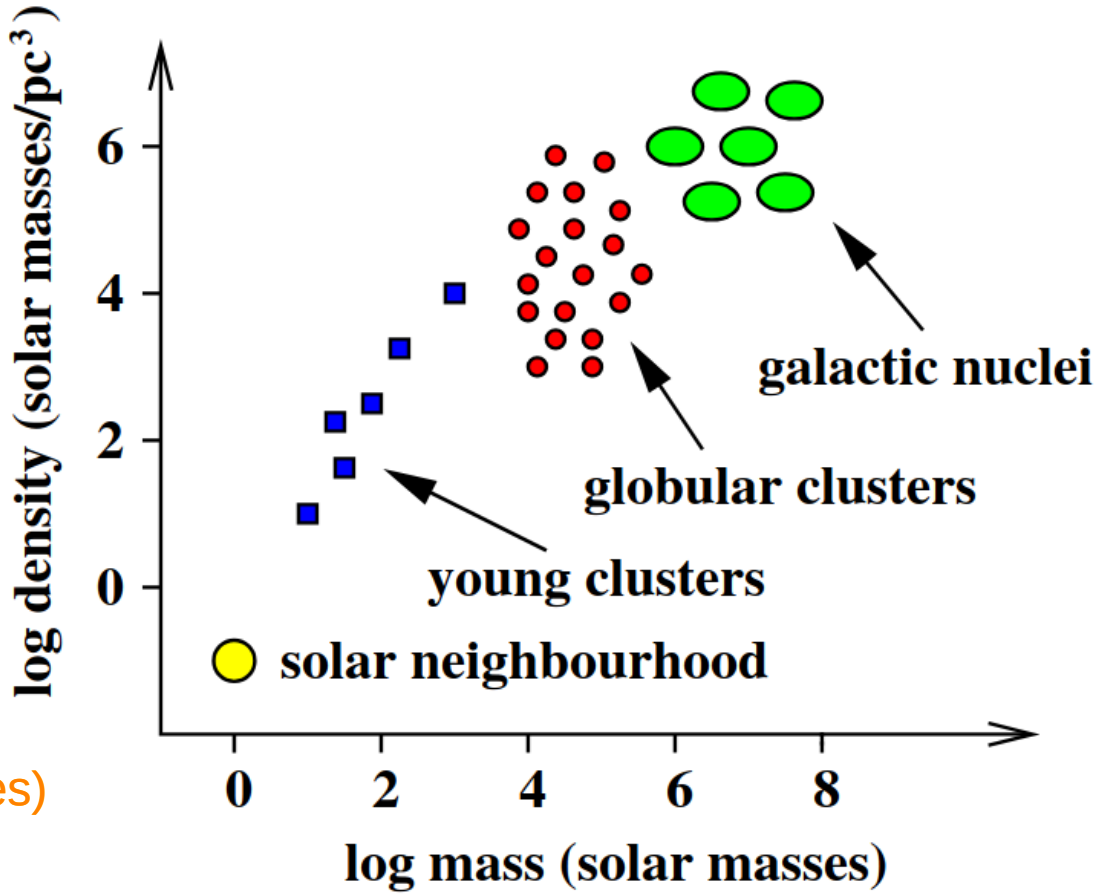
Dense environments → when and how they are formed?

dynamical formation

"dense environments"

"galactic field"

isolated
(stars, binaries/multiples)
evolution



Dense environments → when and how they are formed?

dynamical formation

"dense environments"

"galactic field"

isolated
(stars, binaries/multiples)
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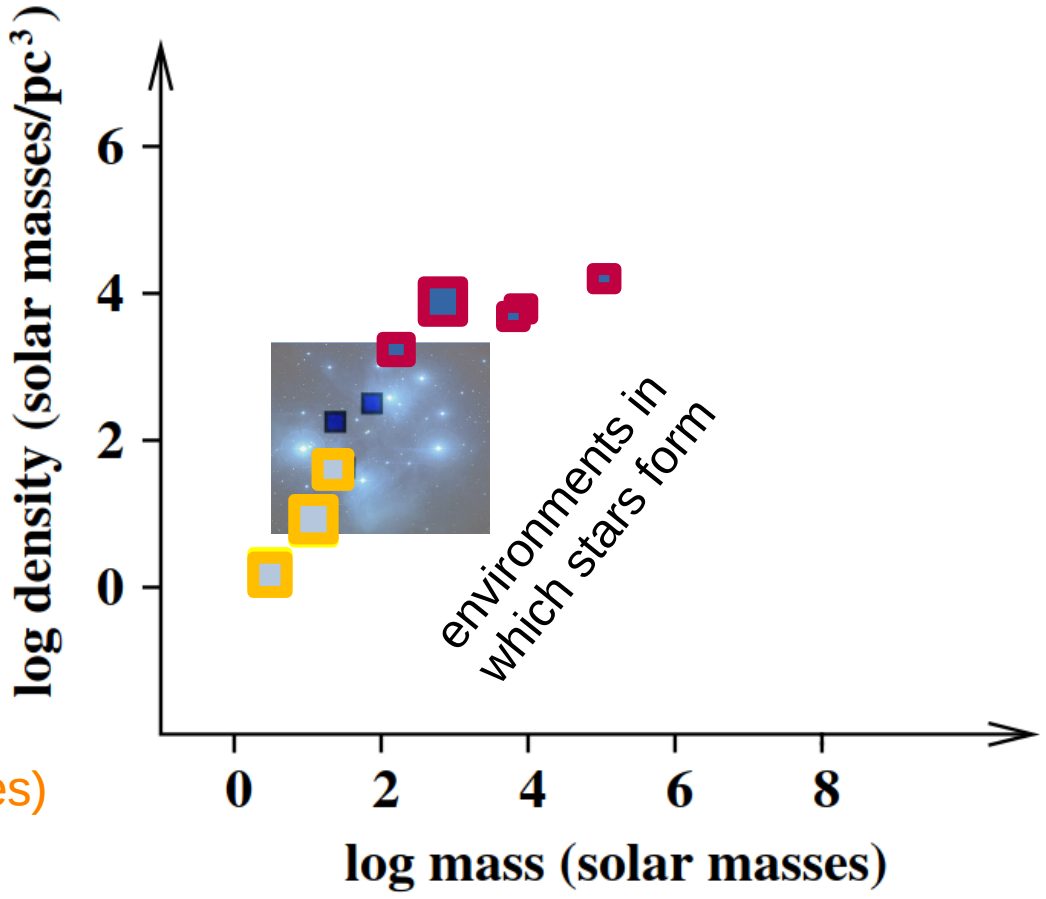

Dense environments → when and how they are formed?

dynamical formation

“dense environments”

“galactic field”

isolated
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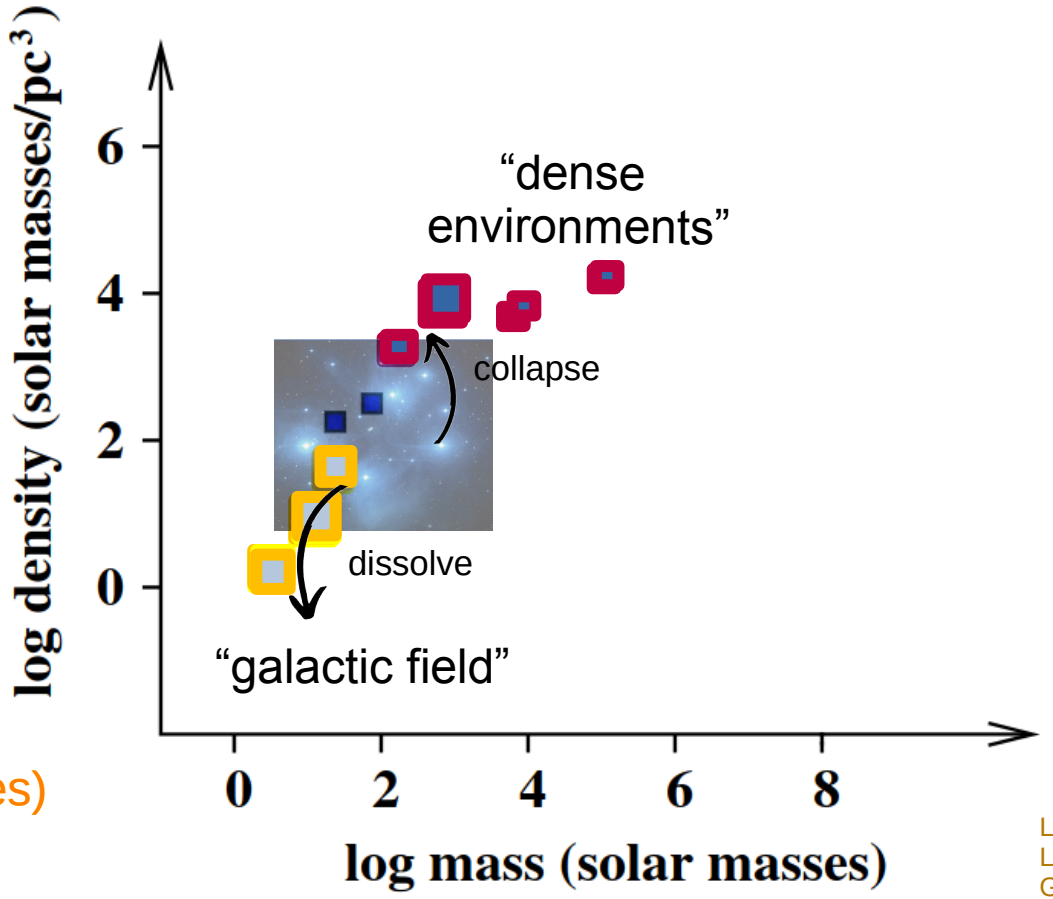
evolution



Lada & Lada 2003, Baumgardt+03, Lamers+05, El-Badry+13, Kruijssen+15, Guszejnov+17, Reina-Campos+17..

dynamical formation

"dense environments"

"galactic field"

isolated (stars, binaries/multiples) **evolution**

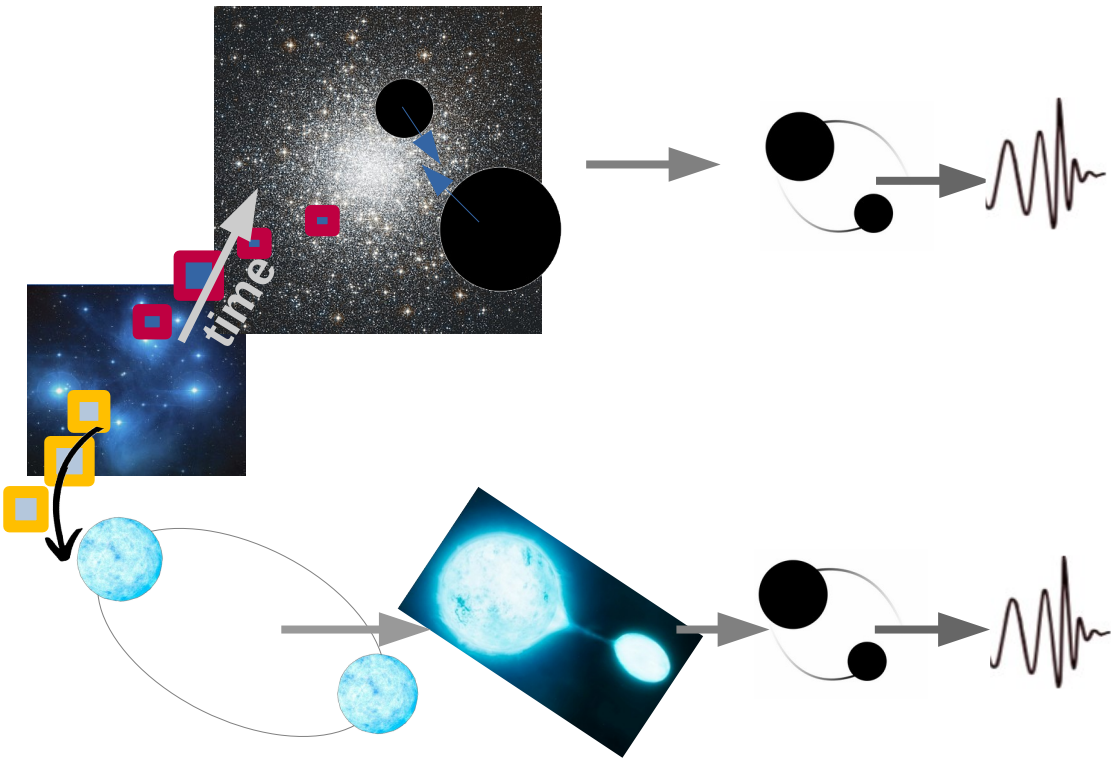
log density (solar masses/pc^3)

6

4

2

0



dynamical formation

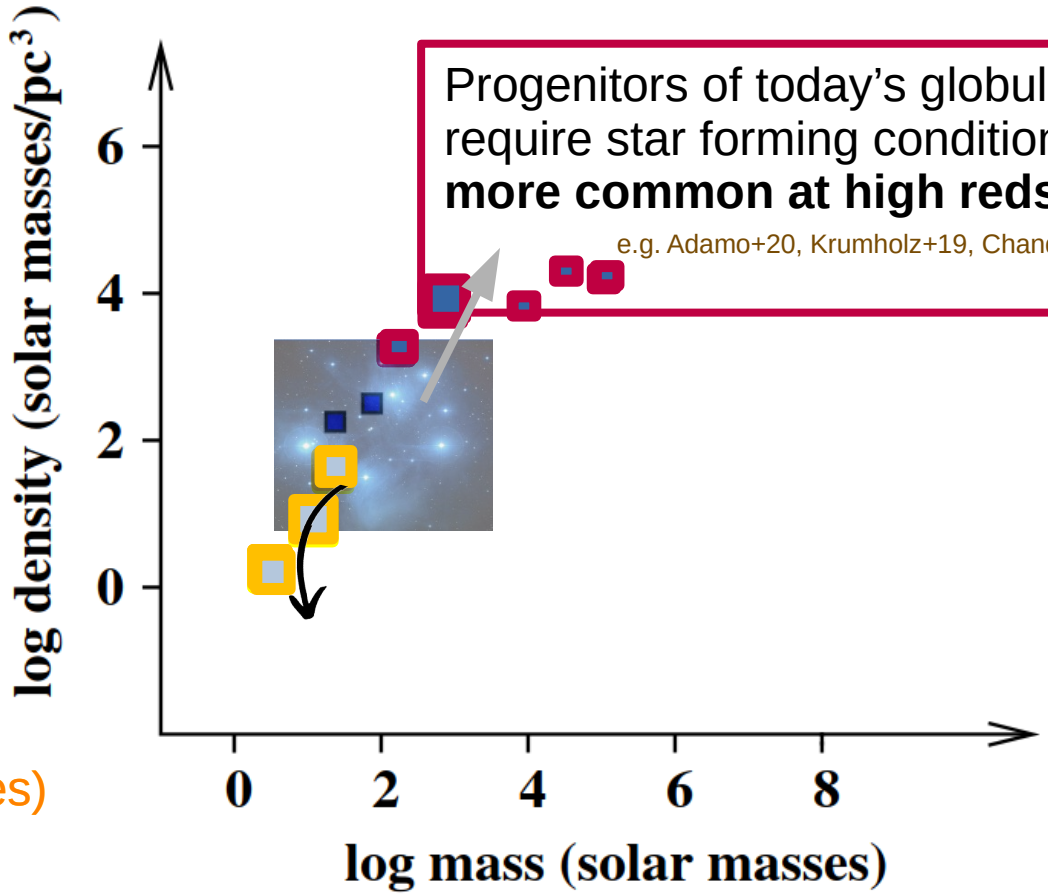
"dense environments"

"galactic field"

isolated

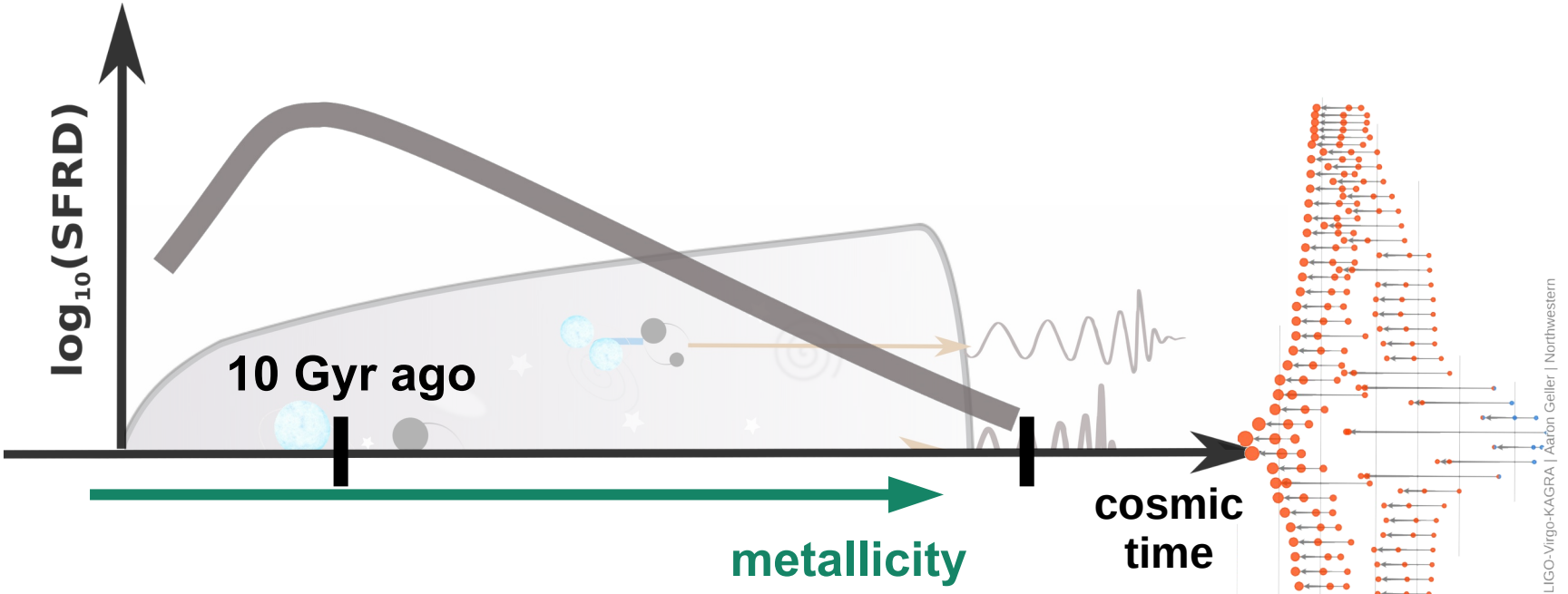
(stars, binaries/multiples)

evolution



Progenitors of today's globular clusters require star forming conditions that are **more common at high redshifts**

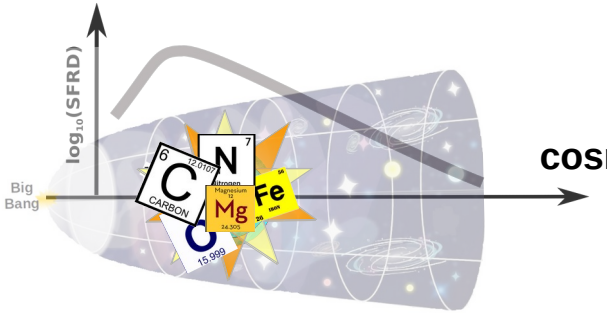
e.g. Adamo+20, Krumholz+19, Chandar+23, Grudic+23



relative rate of BH mergers from different formation channels varies over cosmic time !

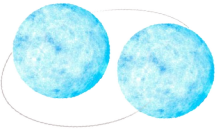
→ **another “fingerprint” of formation channel**

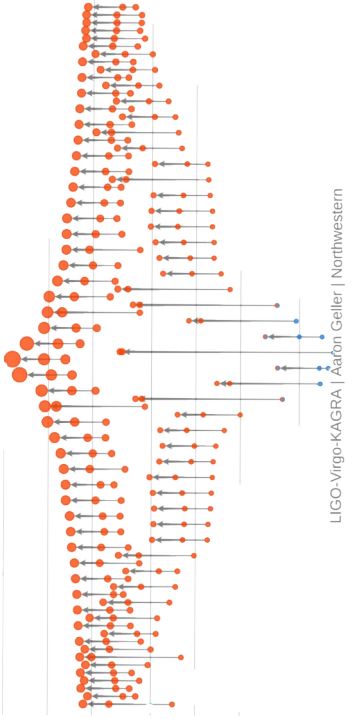
From star formation to BH/NS merger population



cosmic time

+



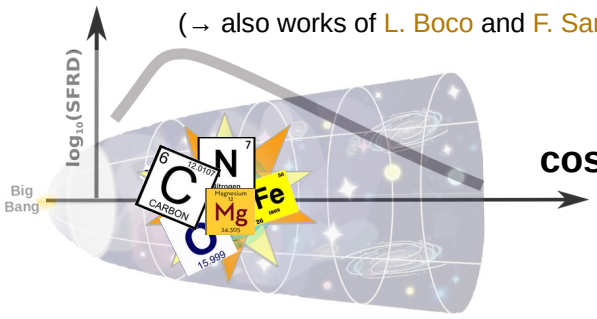


From star formation to BH/NS merger population

number & birth chemical composition of stars?

overview for GW→ Chruslinska 2024

(→ also works of L. Boco and F. Santoliquido)



cosmic time

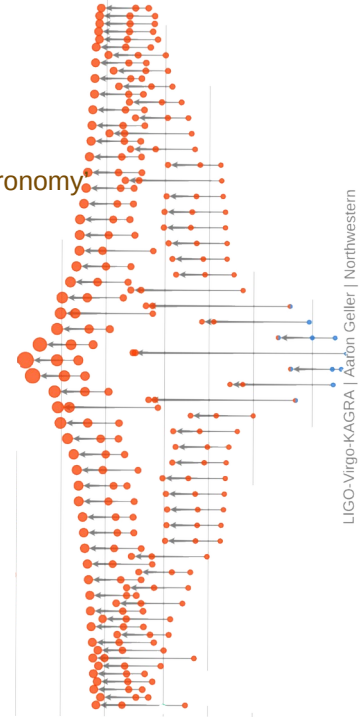
+

evolution

stars, binaries, multiples

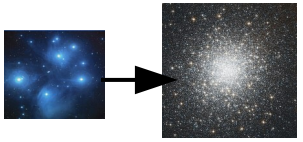
overview for GW:→ Chapter 1 'BHs in the Era of GW Astronomy' ed. Arca Sedda, Bortolas, Spera *(arXiv:2311.15778)*,
→ Iorio+23

recent review on binaries:
Marchant & Bodensteiner 23



IMF? (systematic variations: Jerabkova+18, Chruslinska+21)
binary/multiple initial parameters?
Klencki+18 (in GW context)

birth environment?

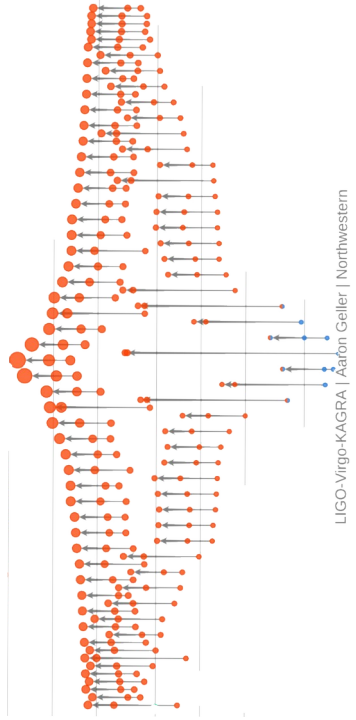


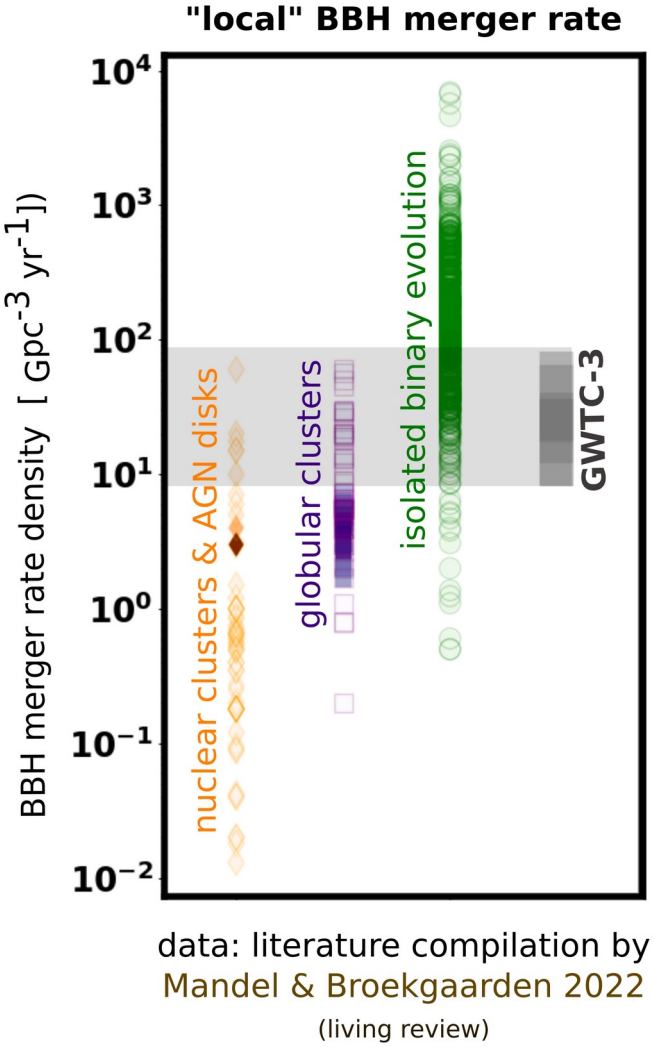
clusters

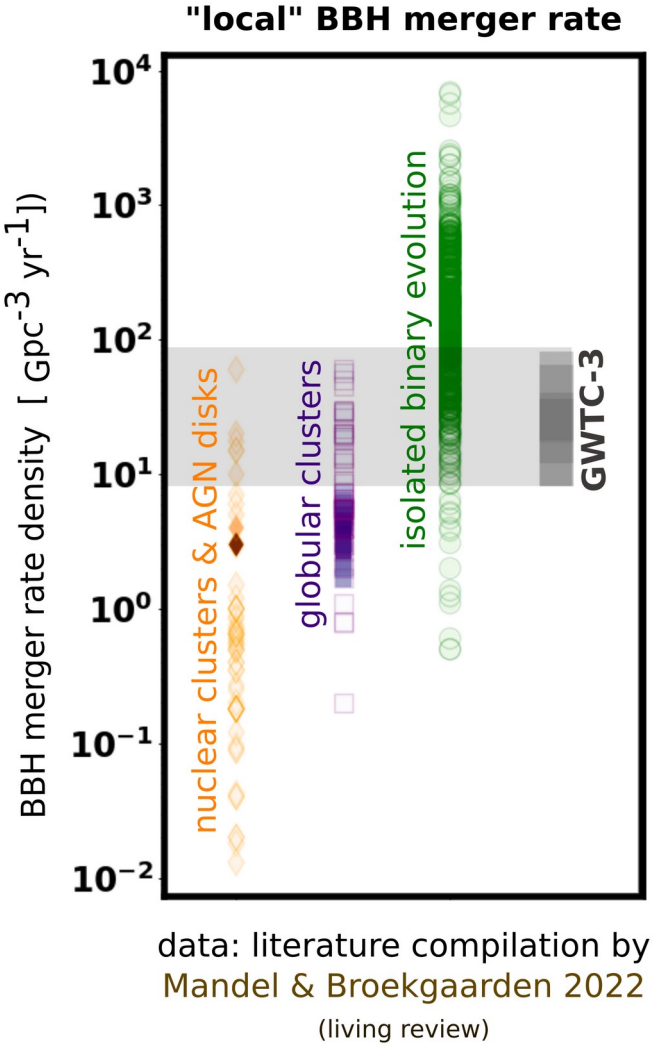
star forming conditions and initial cluster properties:
Adamo+20, Krumholz+19, Grudic+23 (obs./theory)
Antonini & Gieles'20, Fishbach & Fragione'23, Bruel+24 (initial cluster properties & GW)

BH/NS merger formation channels overview:
e.g. Barack+19, Mandel & Broekgaarden 2022

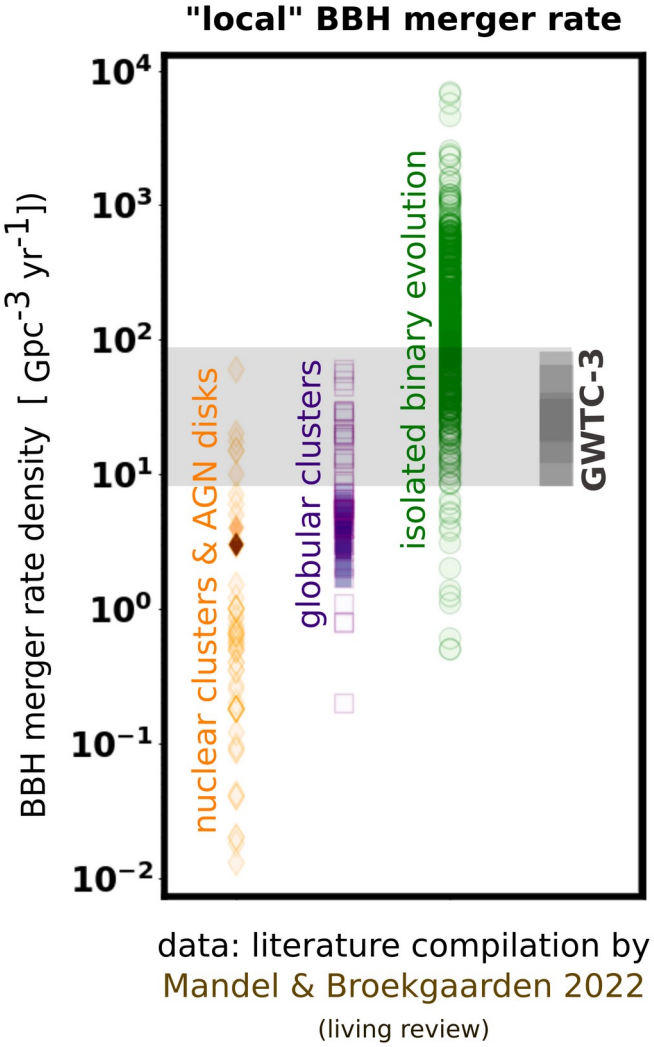
Astrophysical interpretation




"local" BBH merger rate
BBH merger rate density [Gpc-3 yr-1])
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
nuclear clusters & AGN disks
globular clusters
isolated binary evolution
GWTC-3
data: literature compilation by
Mandel & Broekgaarden 2022
(living review)

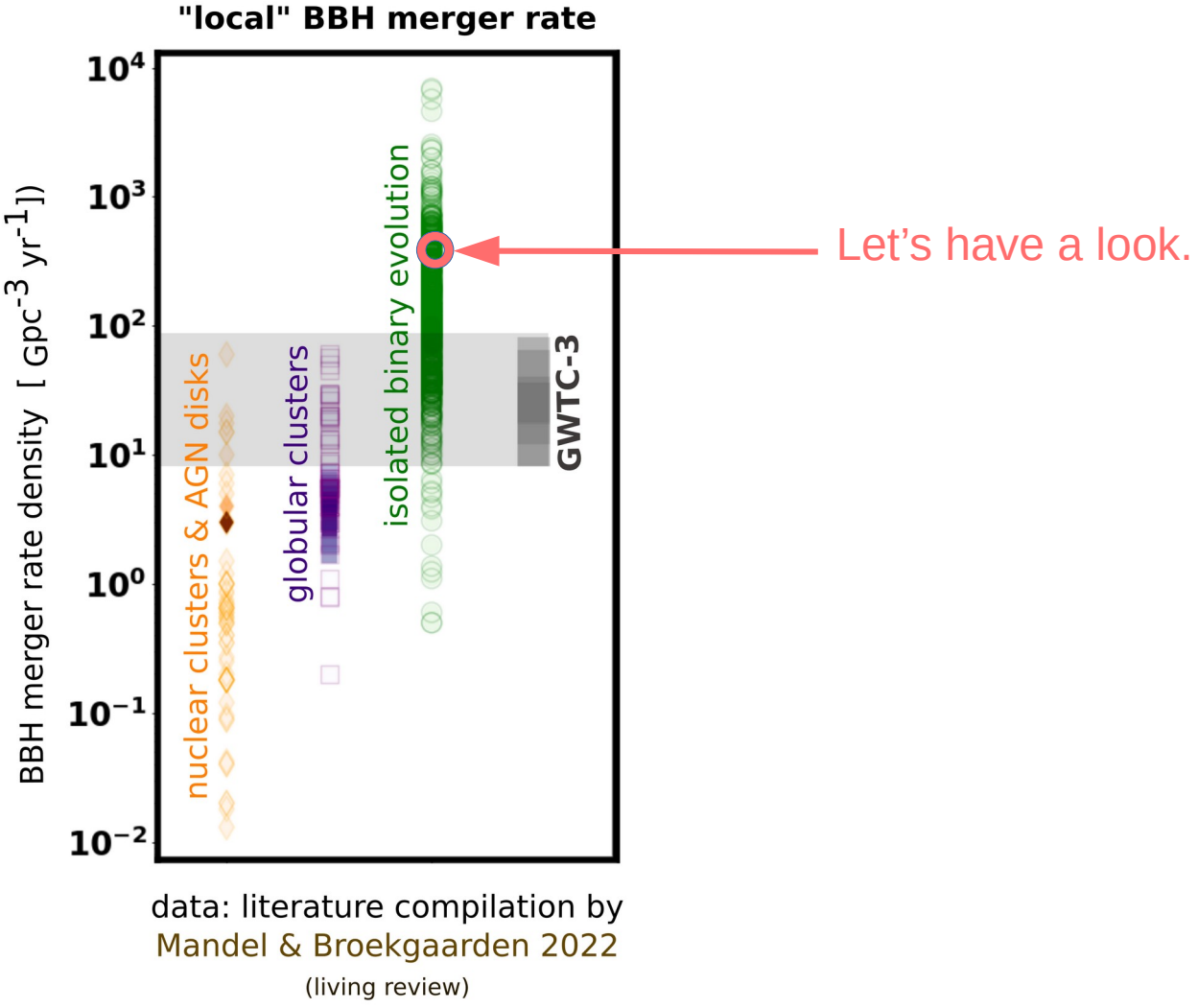


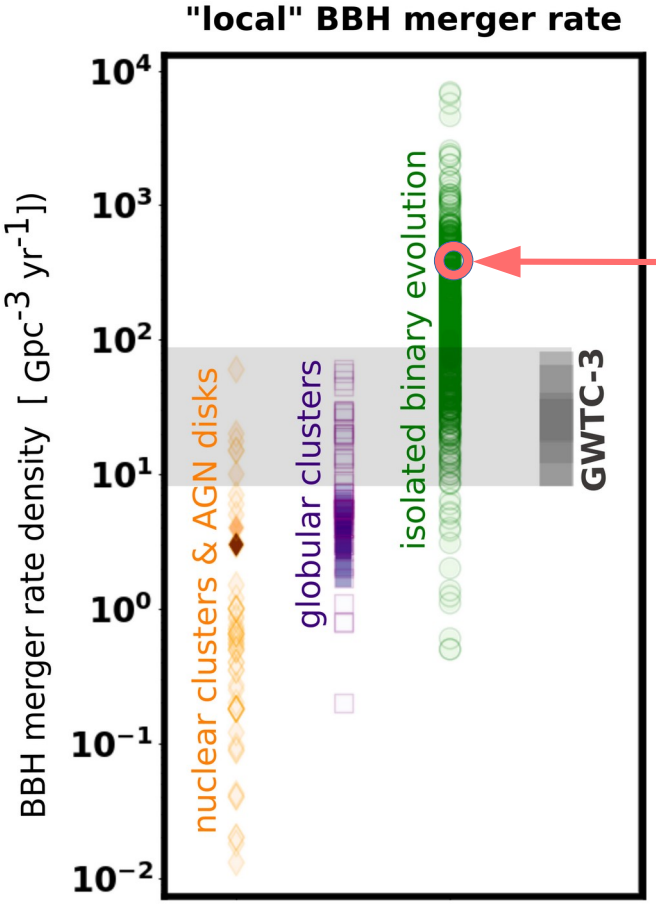
Constraints are tight compared to predictions.



Constraints are tight compared to predictions.

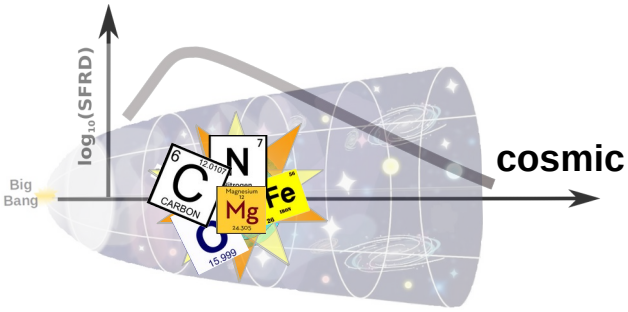
Interpretation is unclear: degeneracies


"local" BBH merger rate
BBH merger rate density [Gpc^{-3} yr^{-1}])
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
nuclear clusters & AGN disks
globular clusters
isolated binary evolution
GWTC-3
Let's have a look.
data: literature compilation by
Mandel & Broekgaarden 2022
(living review)



data: literature compilation by
Mandel & Broekgaarden 2022
(living review)

Let's have a look.



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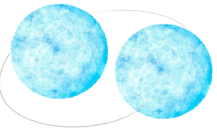
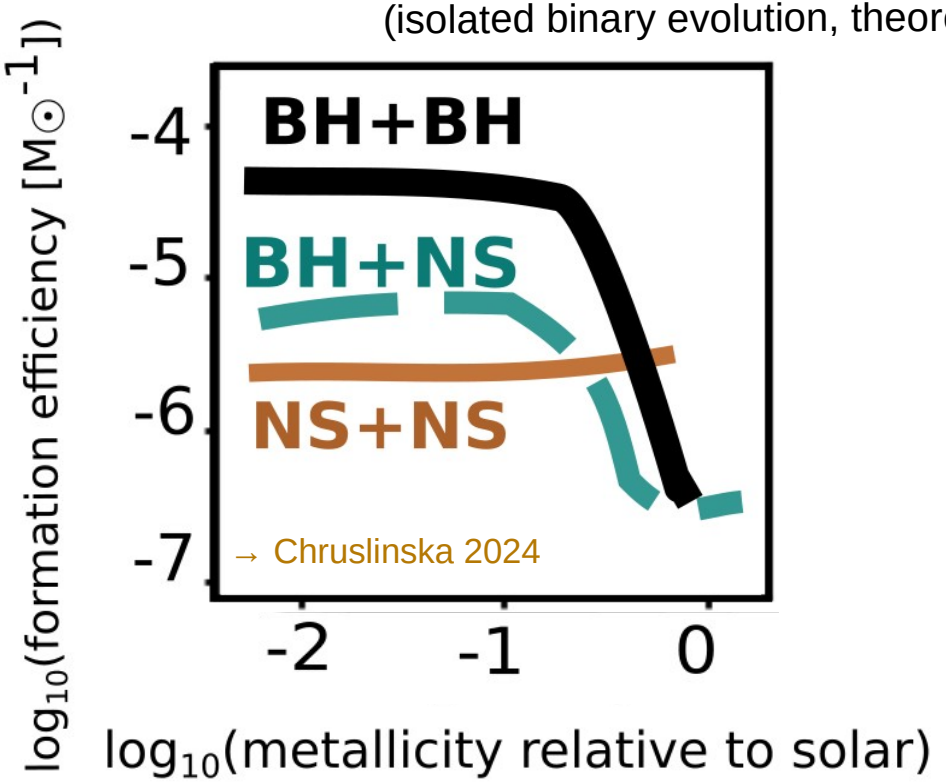


"typical" model

(isolated binary evolution, theoretical)



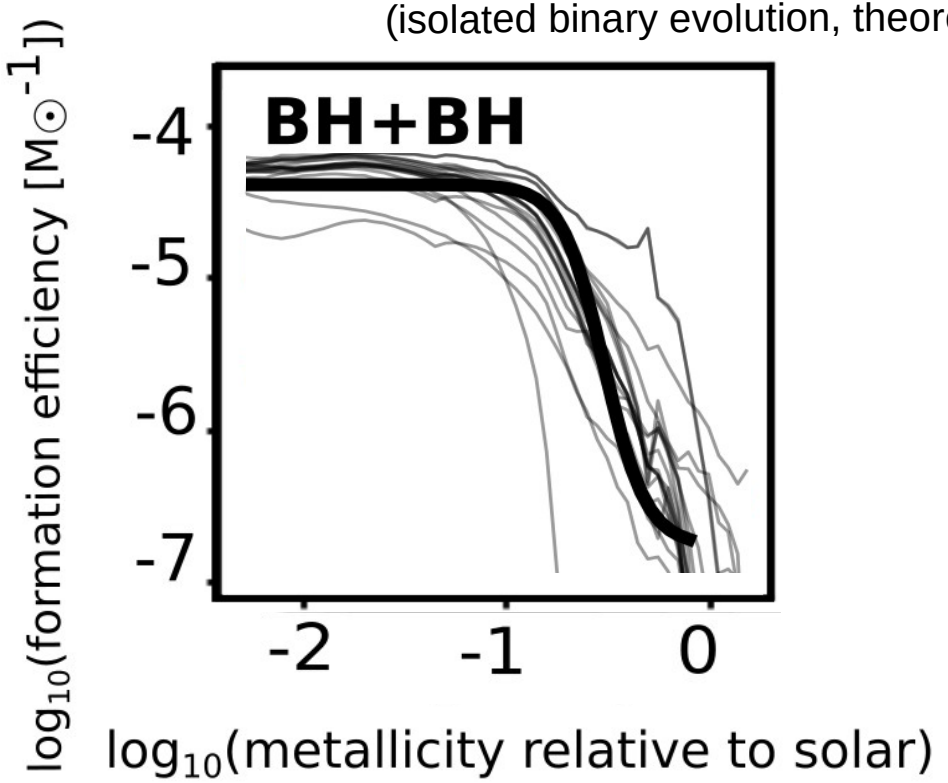
e.g. Belczynski et al. 2010, Dominik et al. 2012, Eldridge & Stanway 2016, Stevenson et al. 2017, Klencki et al. 2018, Giacobbo et al. 2018, Neijssel+19, Chruslinska+19, Santoliquido+21 Broekgaarden+22, Iorio+23 ...

▬ "typical" model

(!) low metallicity preference (!)

* “low” but not *extremely* low, definitely not “pop III” low

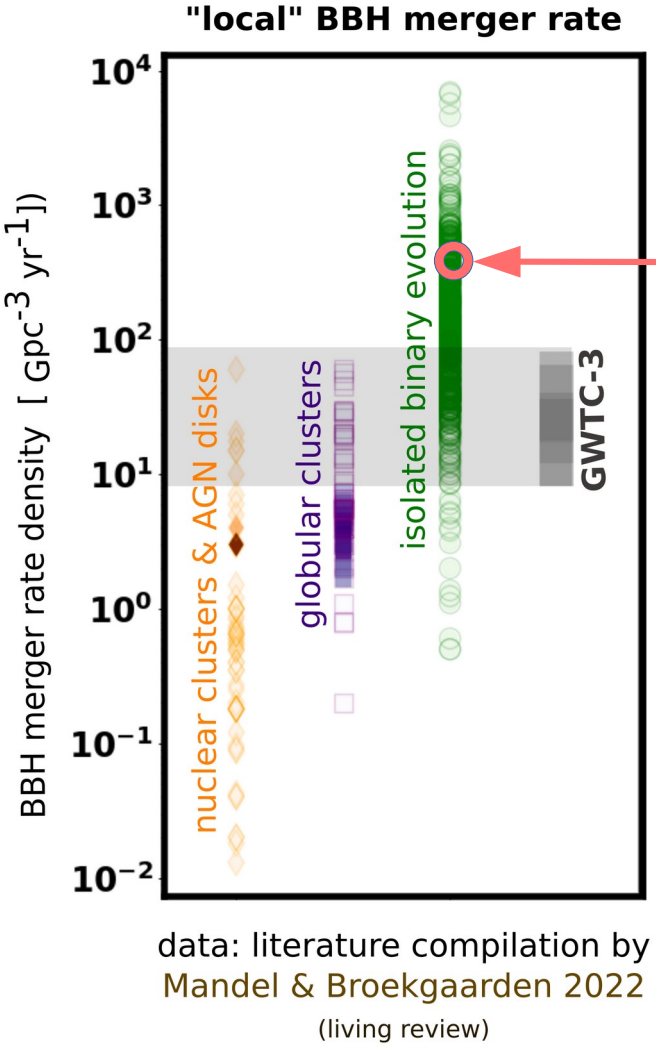
(isolated binary evolution, theoretical)



“typical” model

binary population synthesis models from Broekgaarden+22

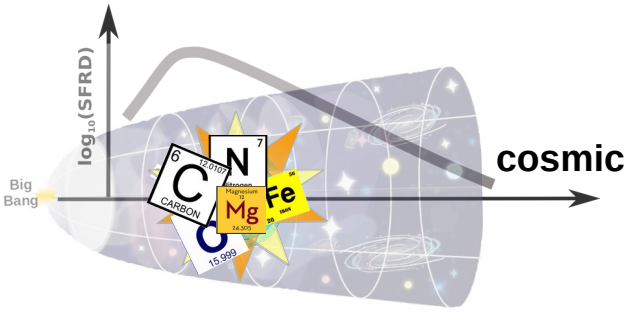
e.g. Belczynski et al. 2010, Dominik et al. 2012, Eldridge & Stanway 2016, Stevenson et al. 2017, Klencki et al. 2018, Giacobbo et al. 2018, Neijssel+19, Chruslinska+19, Santoliquido+21 Broekgaarden+22, Iorio+23 ...



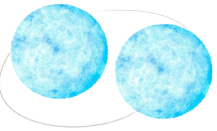
data: literature compilation by
Mandel & Broekgaarden 2022
(living review)

(!) low metallicity (!)

Let's have a look.

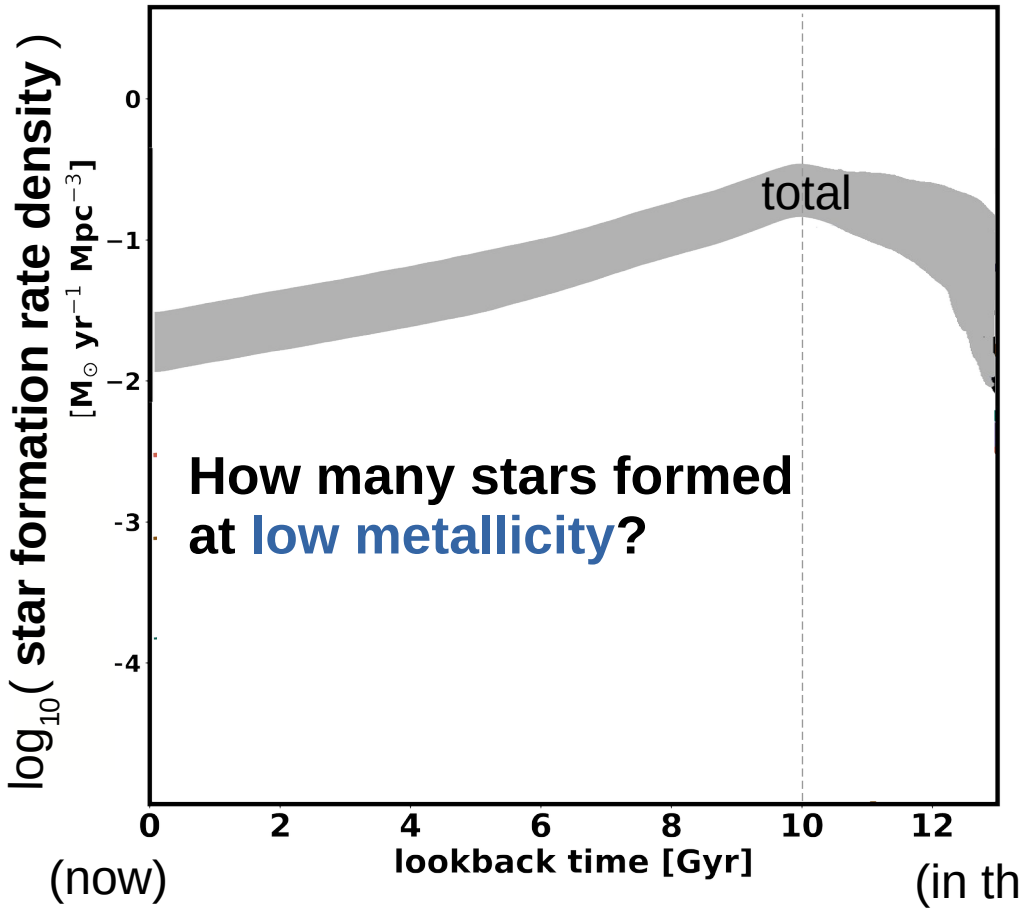


+



"typical" model

Rate of star formation in the history of the Universe

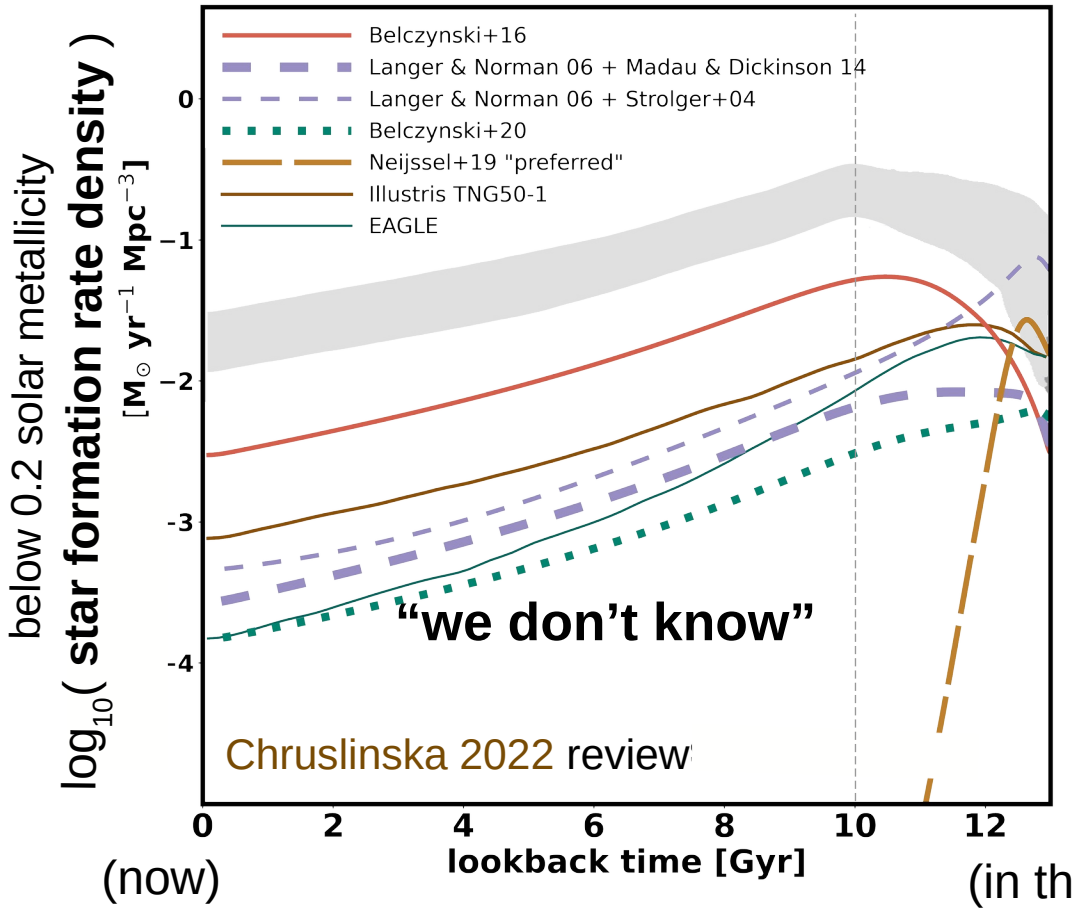


(now)

(in the early Universe)

Literature assumptions

Rate of star formation at low metallicity in the history of the Universe

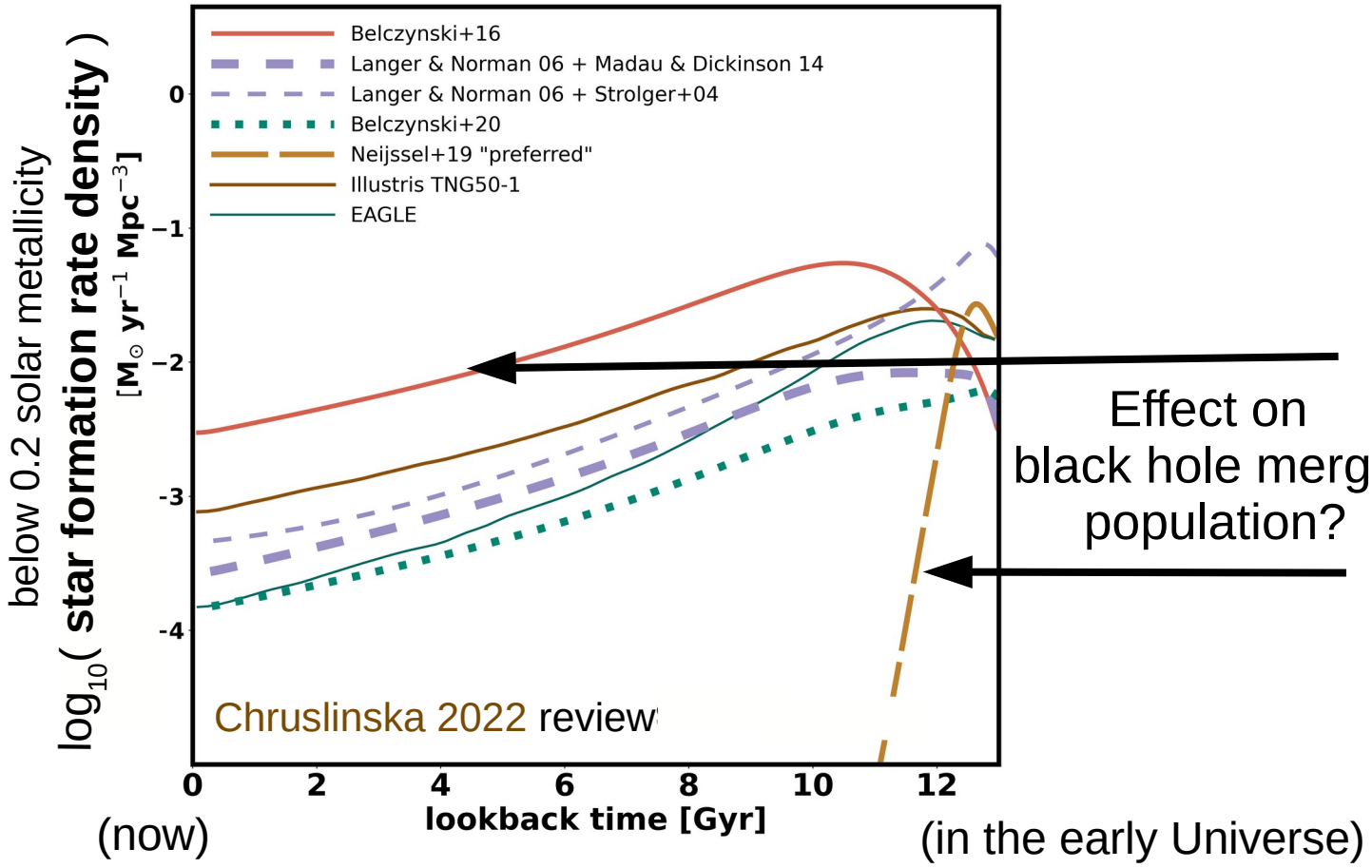


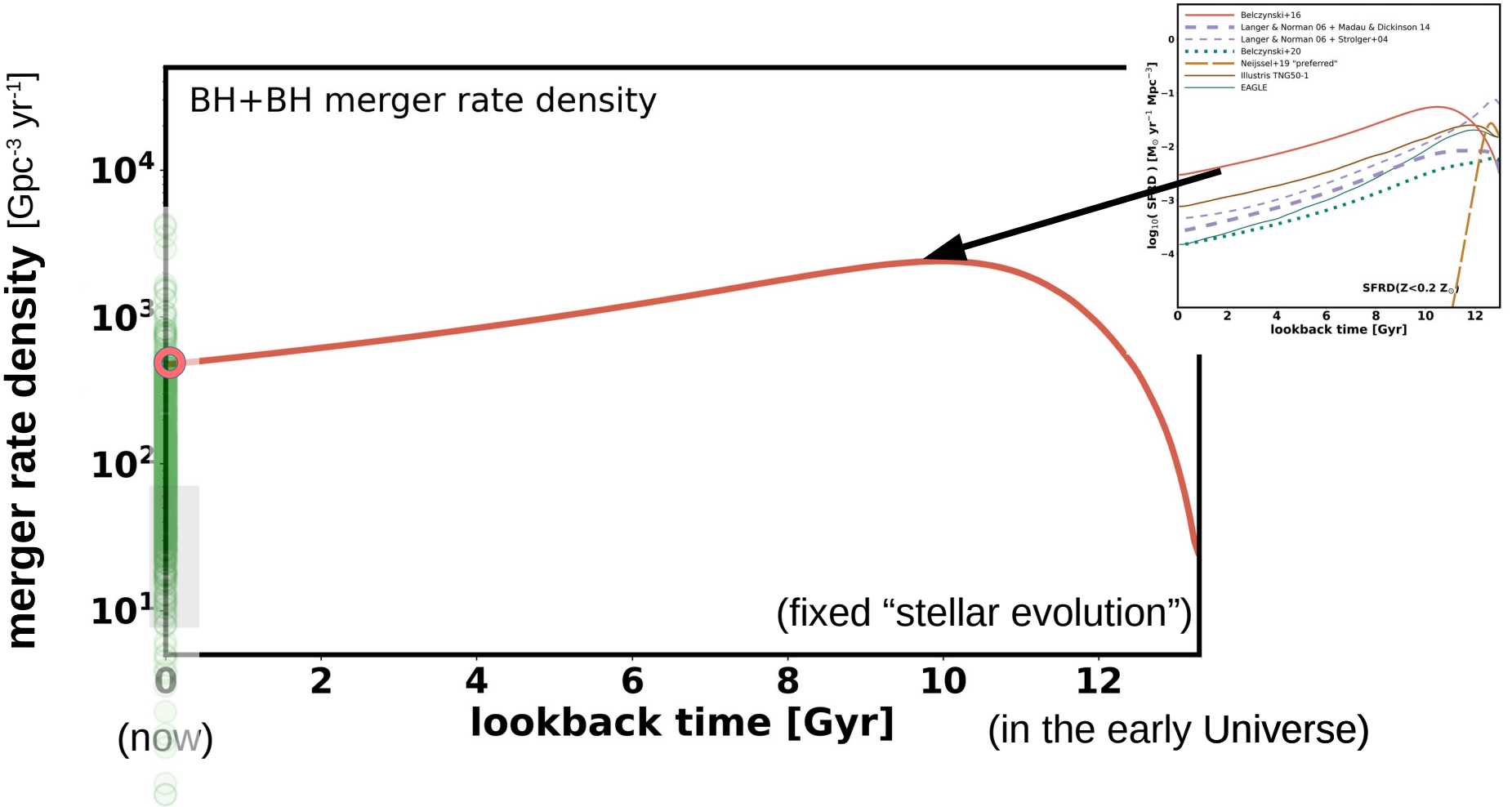
(now)

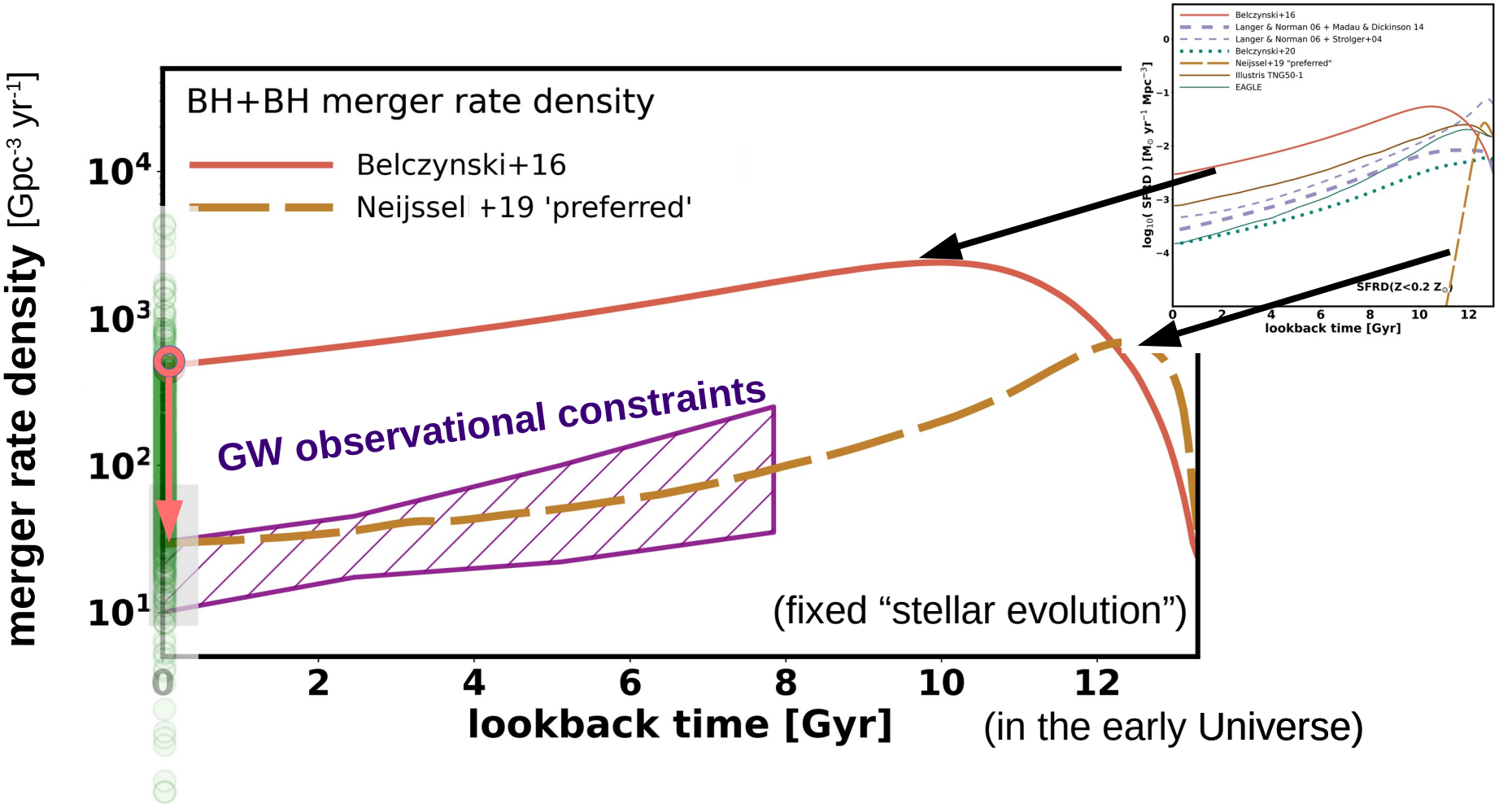
(in the early Universe)

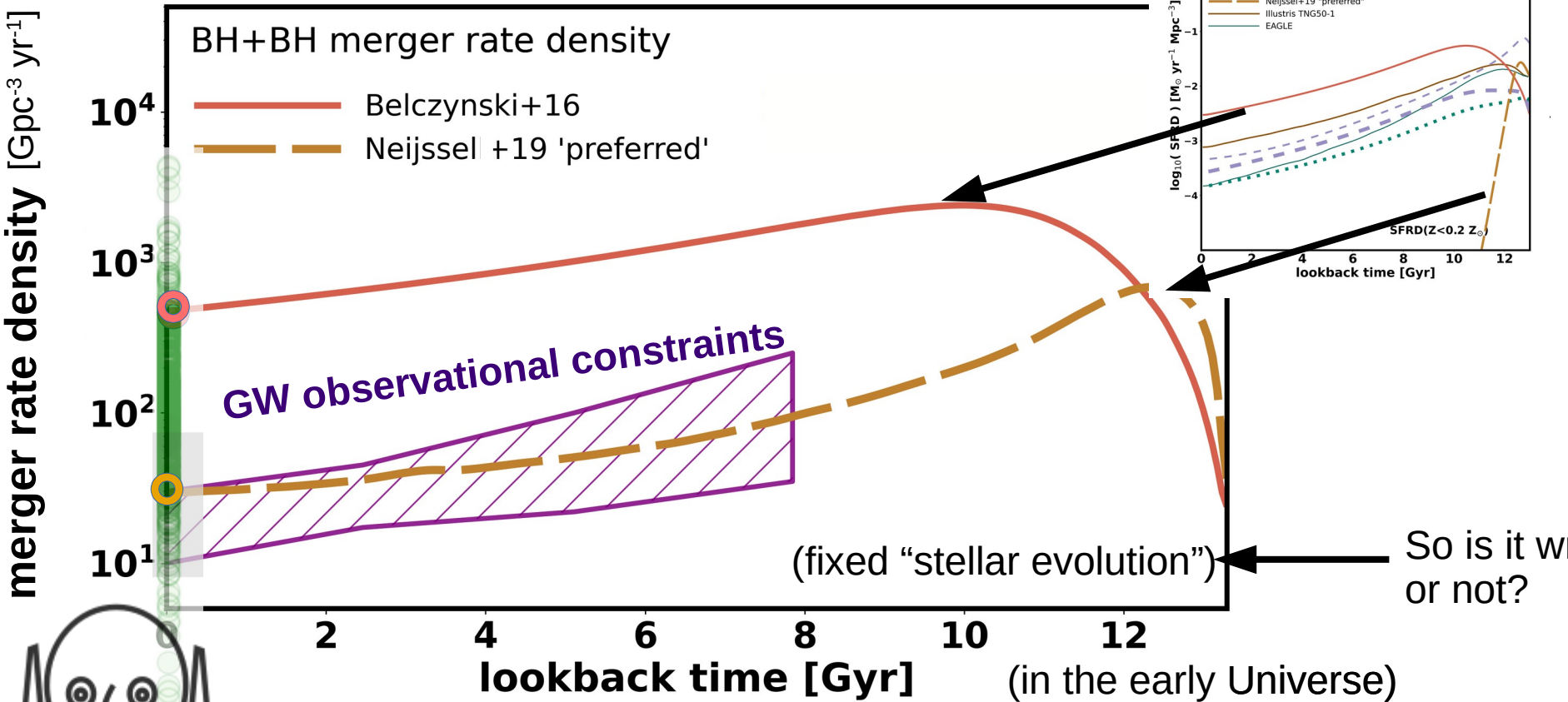
Literature assumptions

Rate of star formation at low metallicity in the history of the Universe




BH+BH merger rate density
merger rate density [Gpc^{-3} yr^{-1}]
10^4
10^3
10^2
10^1
0
2
4
6
8
10
12
lookback time [Gyr]
(now)
(in the early Universe)
(fixed “stellar evolution”)
Belczynski+16
Langer & Norman 06 + Madau & Dickinson 14
Langer & Norman 06 + Strolger+04
Belczynski+20
Neijssel+19 "preferred"
Illustris TNG50-1
EAGLE
$\log_{10}$(SFRD) [$M_\odot$ yr^{-1} Mpc^{-3}]
SFRD(Z<0.2 $Z_\odot$)
lookback time [Gyr]

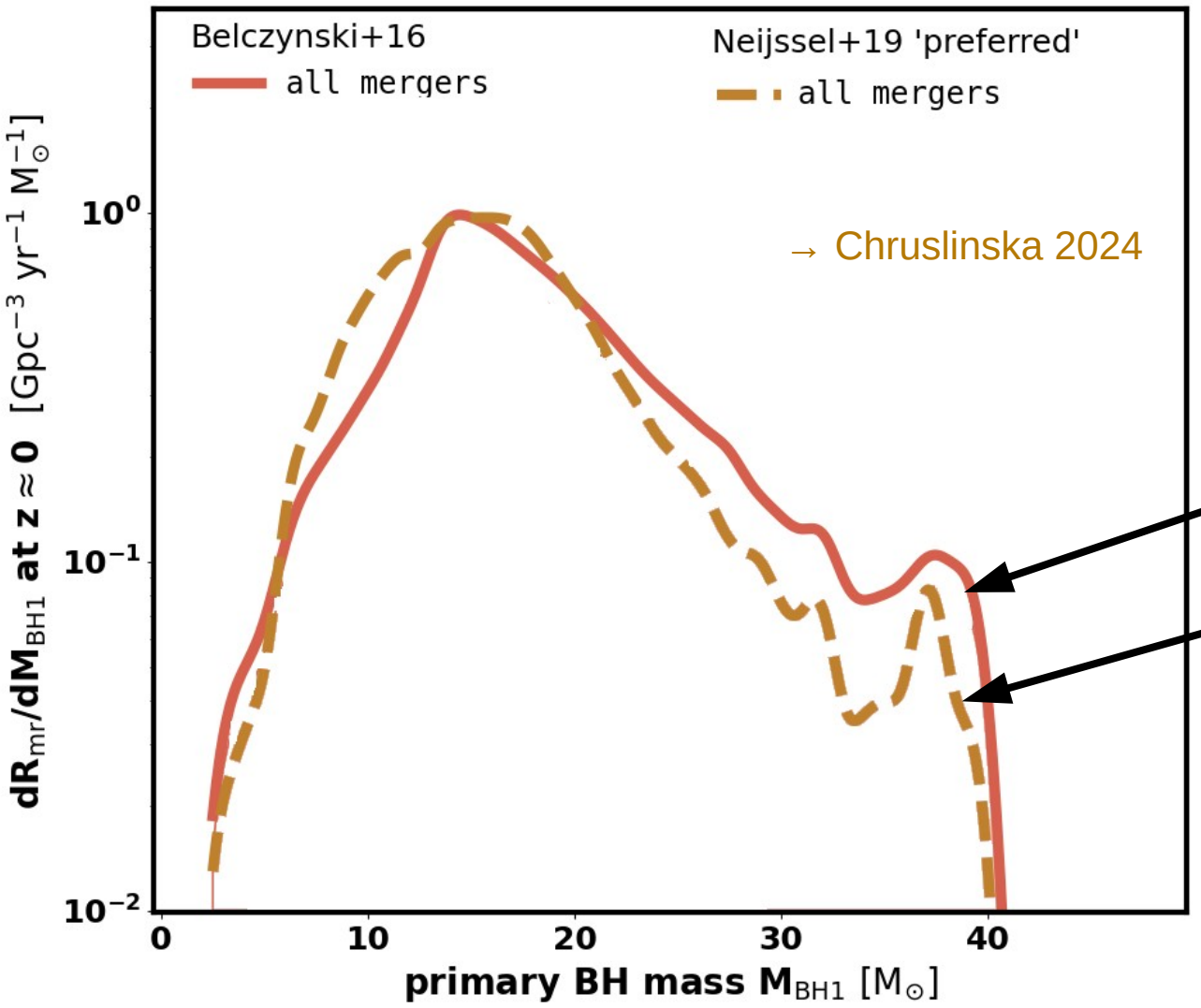

BH+BH merger rate density
Belczynski+16
Neijssel +19 'preferred'
GW observational constraints
(fixed “stellar evolution”)
merger rate density [Gpc-3 yr-1]
lookback time [Gyr]
(in the early Universe)
Belczynski+16
Langer & Norman 06 + Madau & Dickinson 14
Langer & Norman 06 + Strolger+04
Belczynski+20
Neijssel+19 "preferred"
Illustris TNG50-1
EAGLE
SFRD(Z<0.2 Z⊙)
lookback time [Gyr]

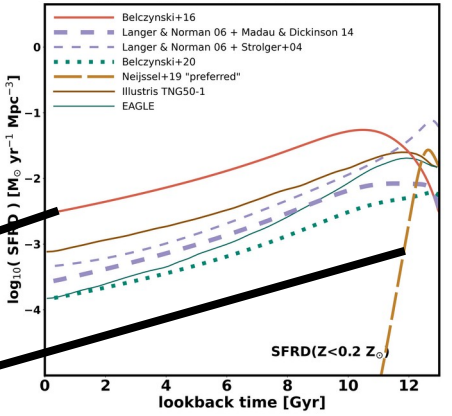


Interpretation problem!

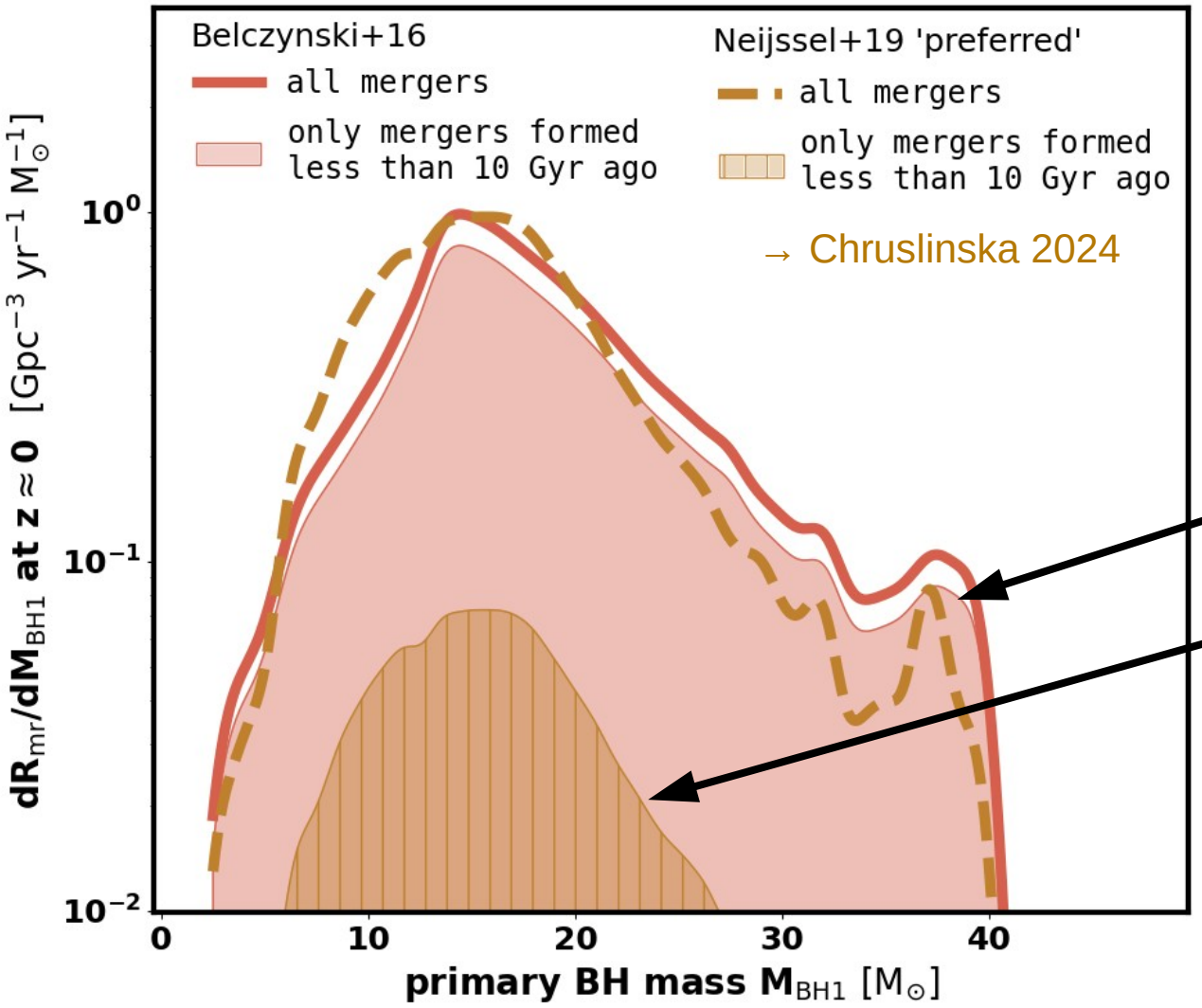
Chruslinska+19a, Neijssel+19,Tang+20, Santoliquido+21, Briel+22, Broekgaarden+22, Chruslinska 2024 ...

Primary BH mass distribution of z~0 BH+BH mergers

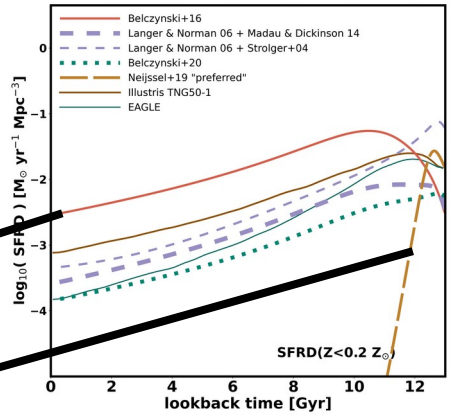




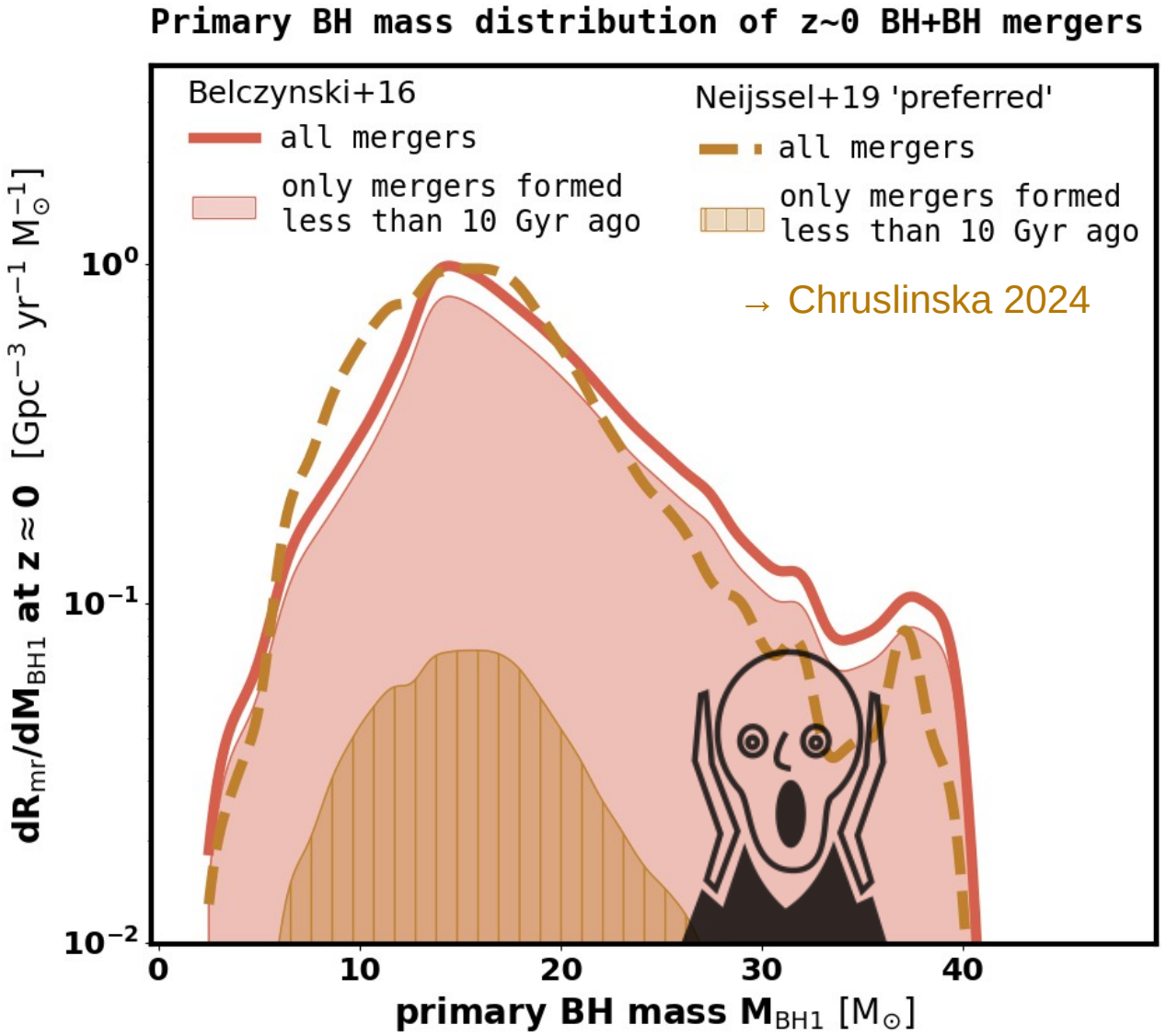
Primary BH mass distribution of z~0 BH+BH mergers



...very different origin of the observed BH mergers!



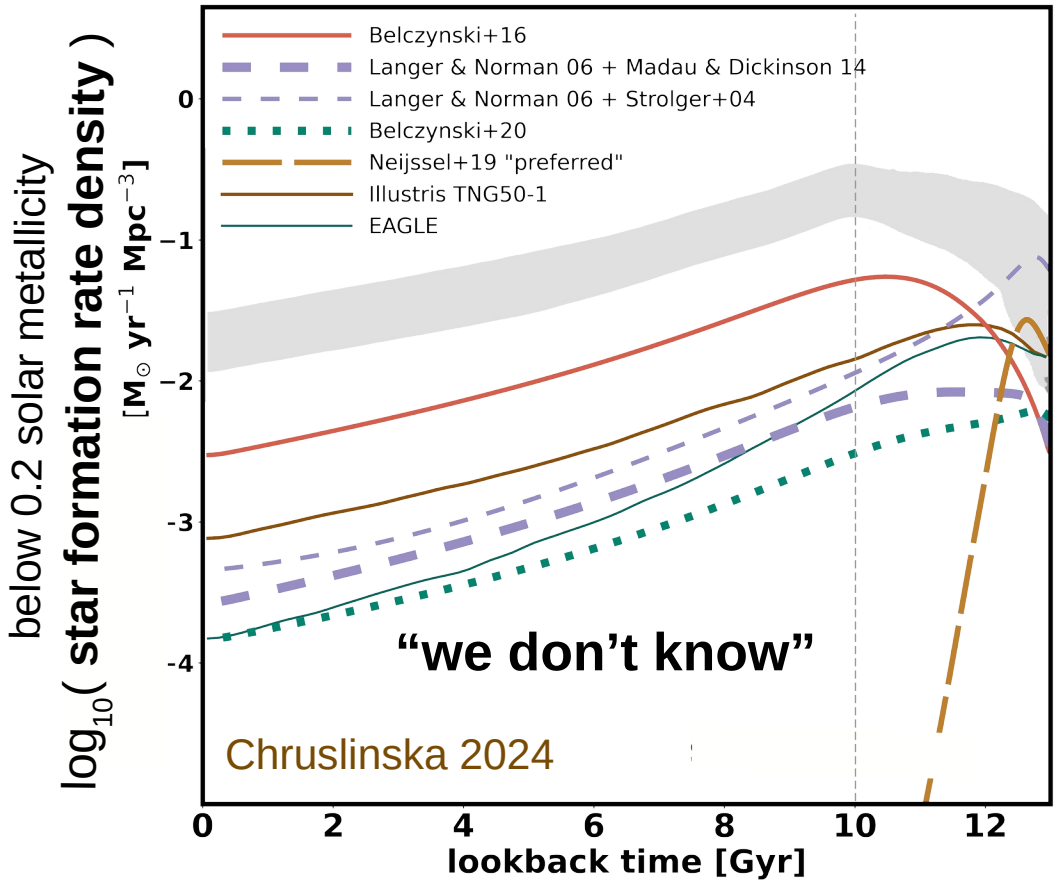
Properties of the most likely merger host galaxies may be different!



...very different origin of the observed BH mergers!

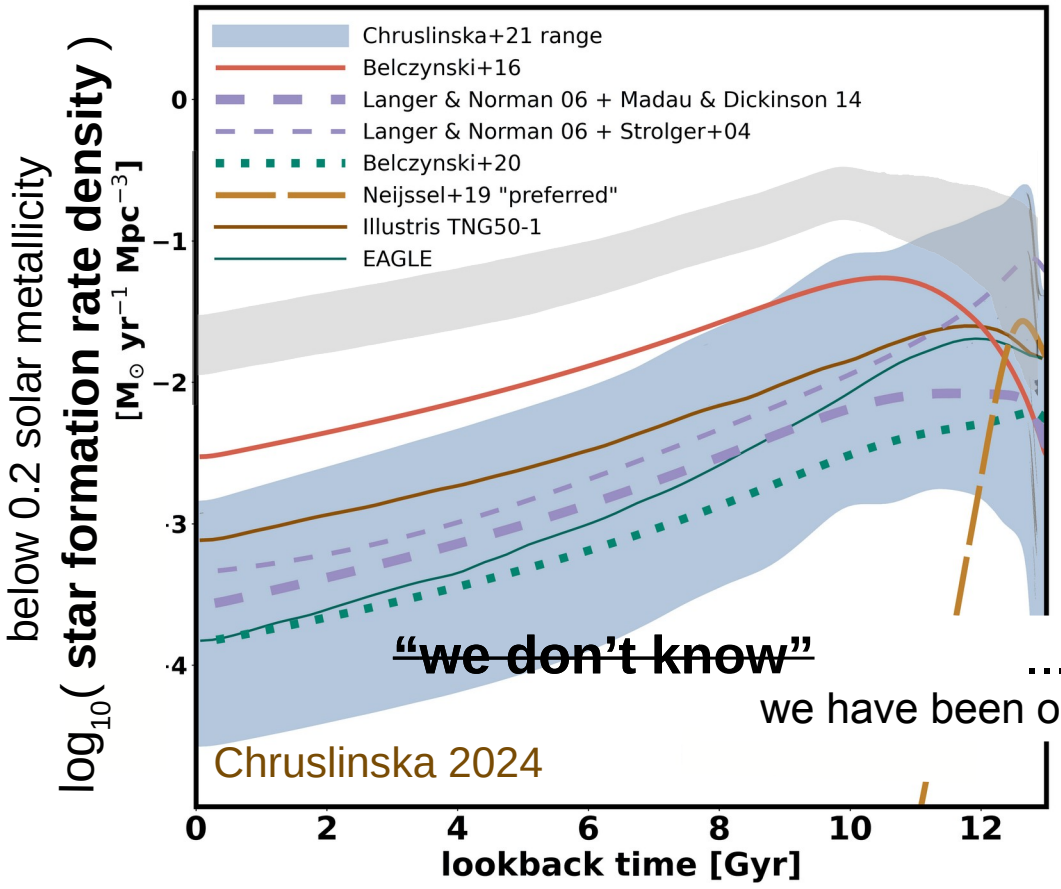
Literature assumptions

“low metallicity” cosmic star formation history



Constraints

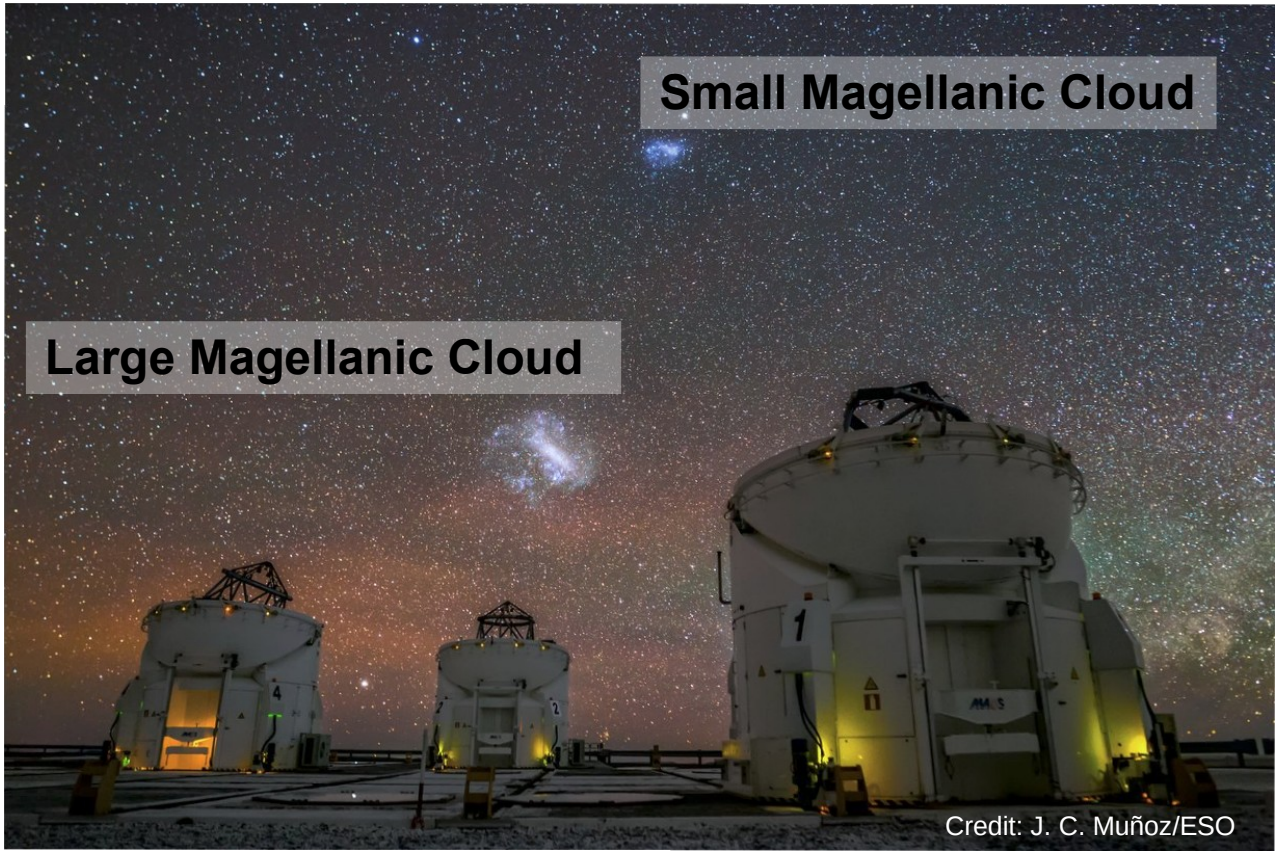
“low metallicity” cosmic star formation history

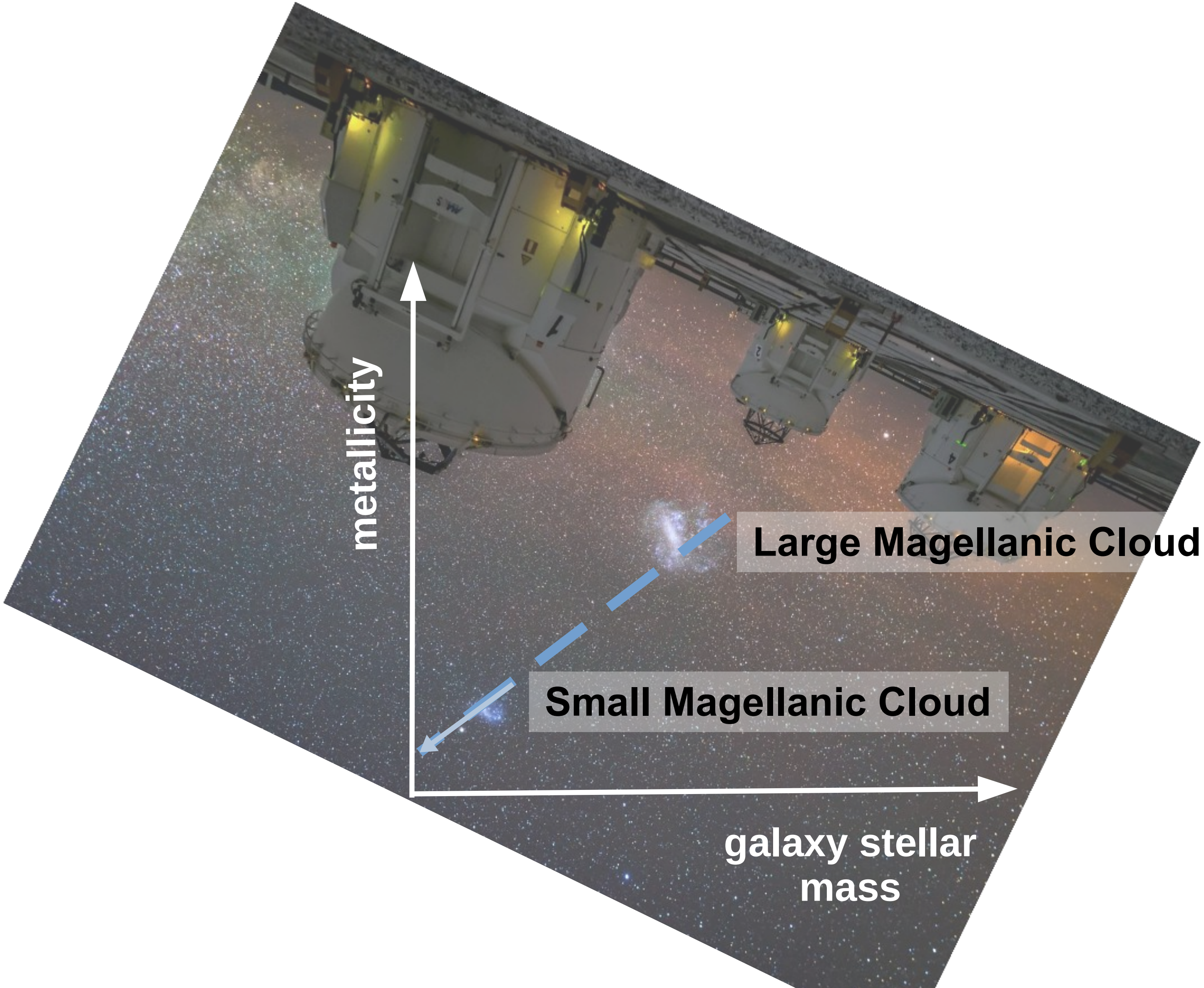


~~**“we don’t know”**~~

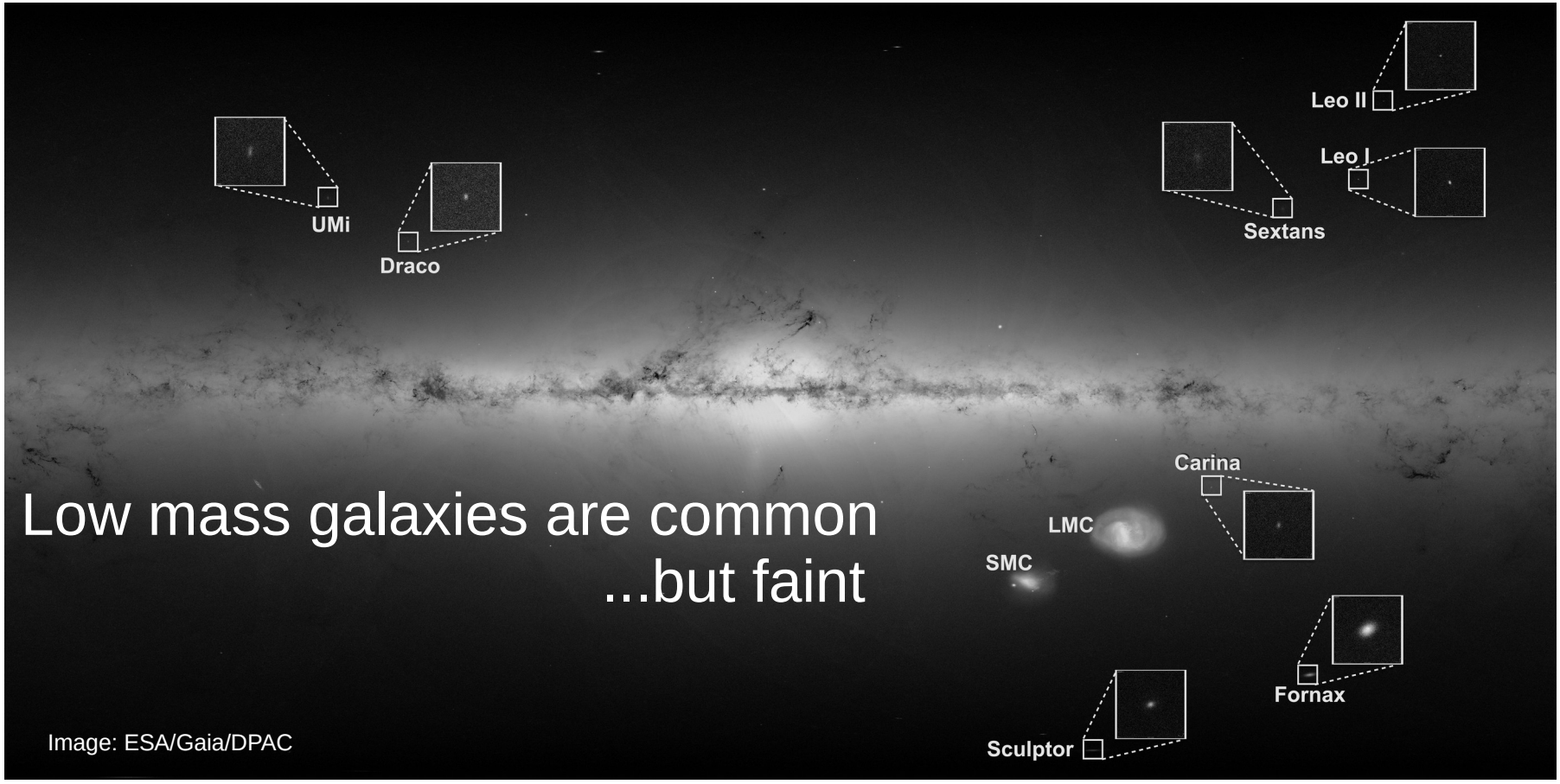
...we **know *something***

we have been observing galaxies for years!

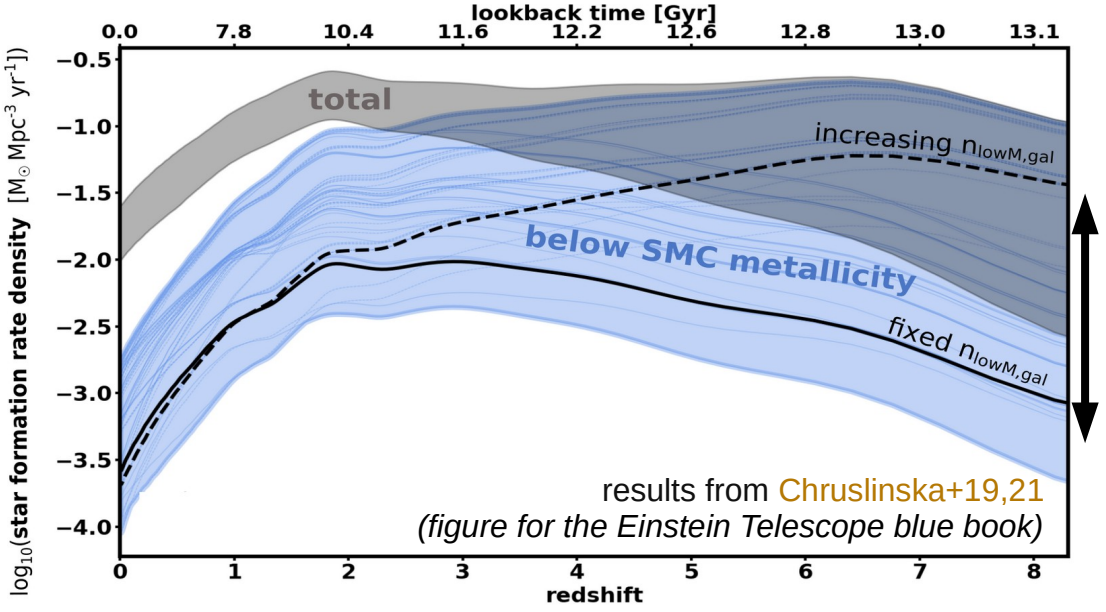

Small Magellanic Cloud
Large Magellanic Cloud
Credit: J. C. Muñoz/ESO


metallicity
Large Magellanic Cloud
Small Magellanic Cloud
galaxy stellar mass

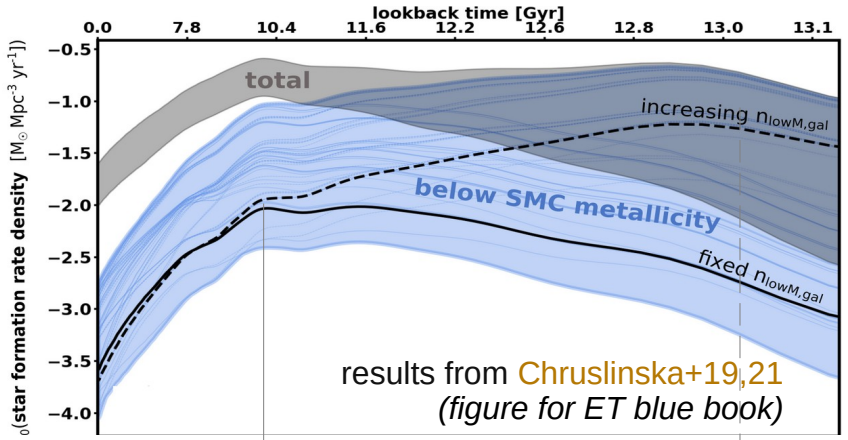
Star formation history at low metallicity:

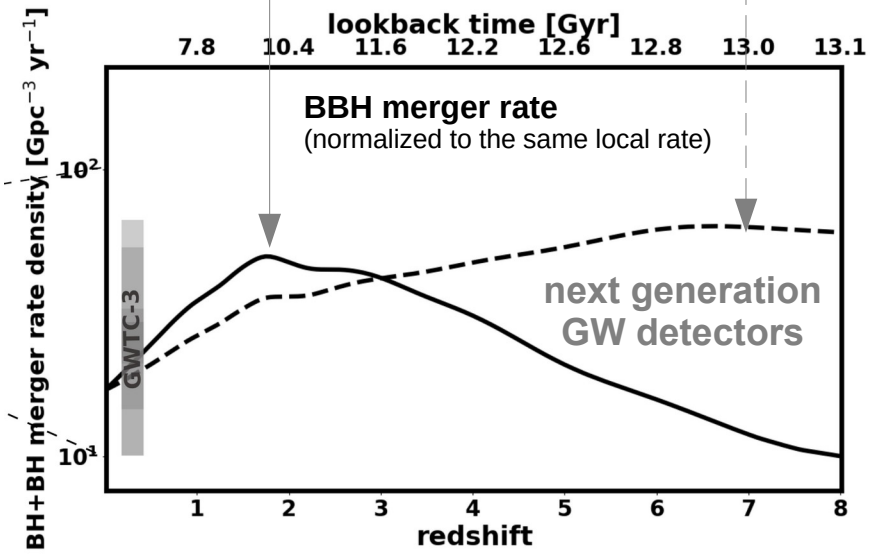


Star formation history at low metallicity & high redshift

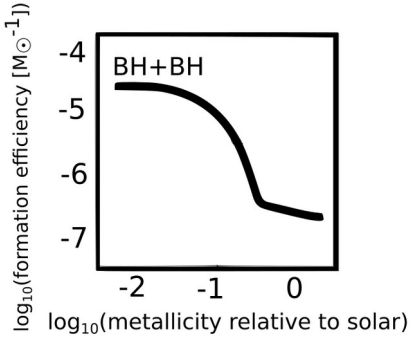


“low mass galaxies
are common but faint”



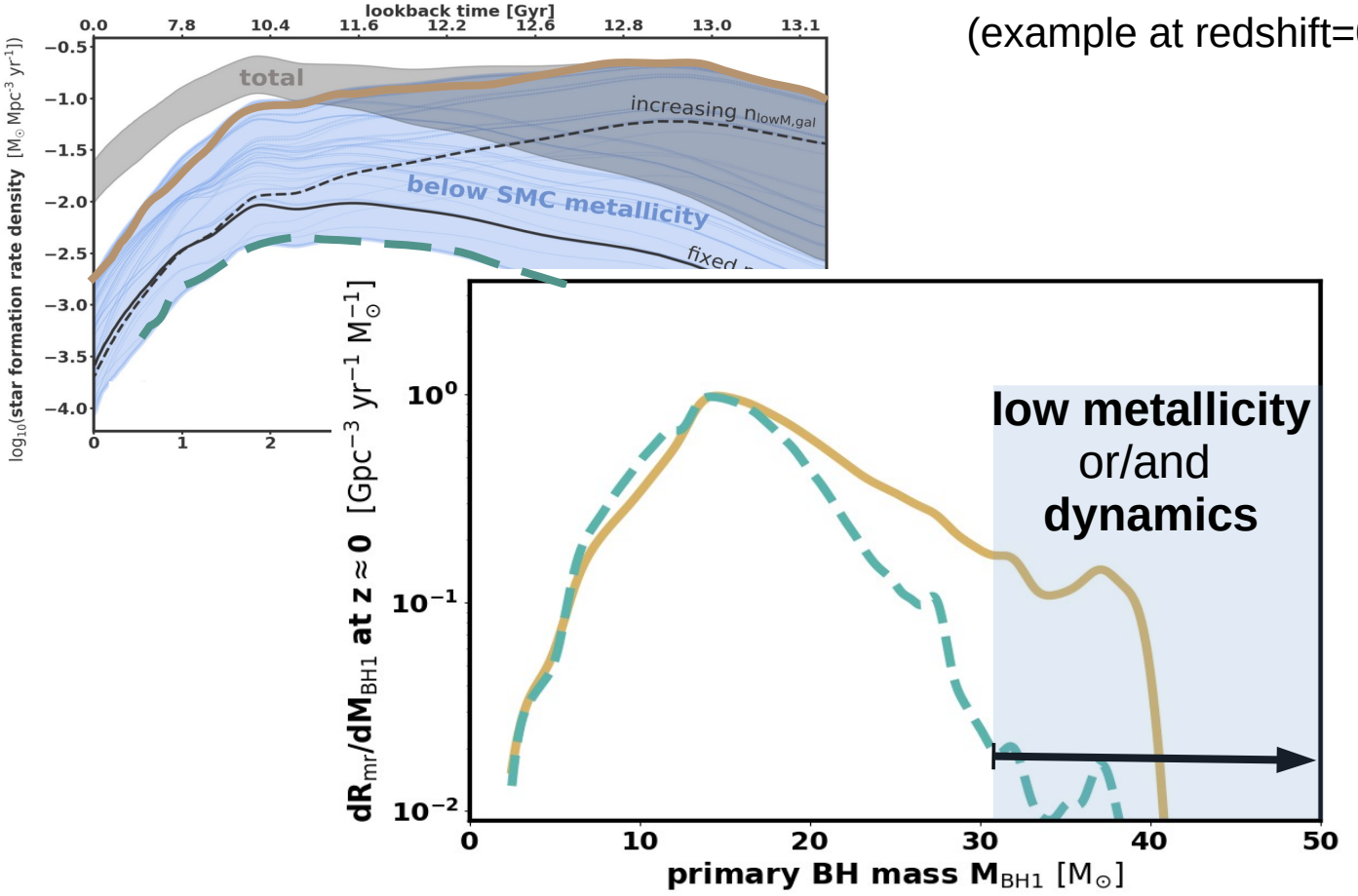


“low mass galaxies
are common but **faint**”
(for electromagnetic studies, not for GW!)



Side note: effect on **BH mass distribution**

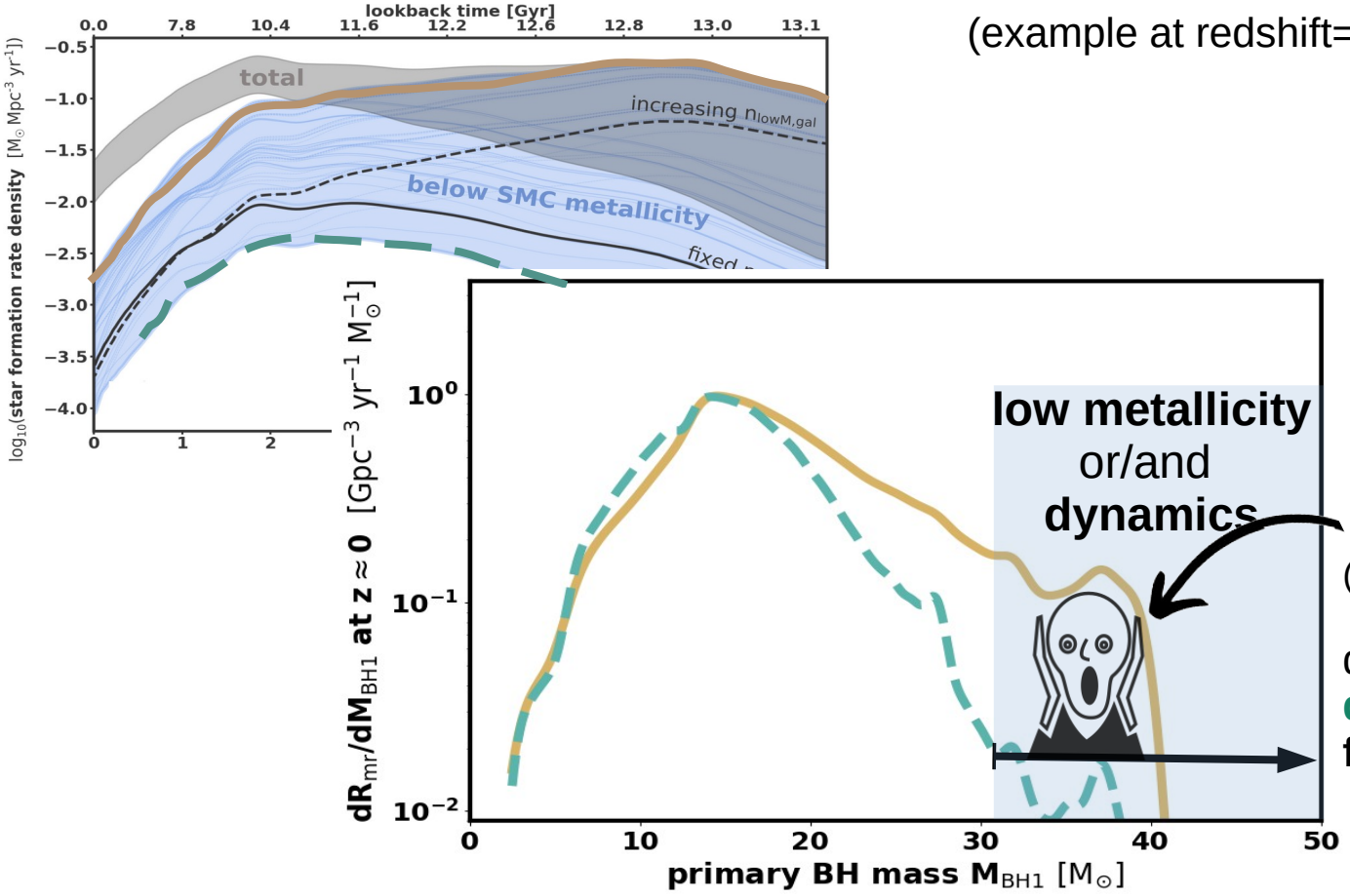
(example at redshift=0, pop.synth. model from van Son+23)



→ see also Van Son et al.+MCh (2022)

Side note: effect on **BH mass distribution**

(example at redshift=0, pop.synth. model from van Son+23)

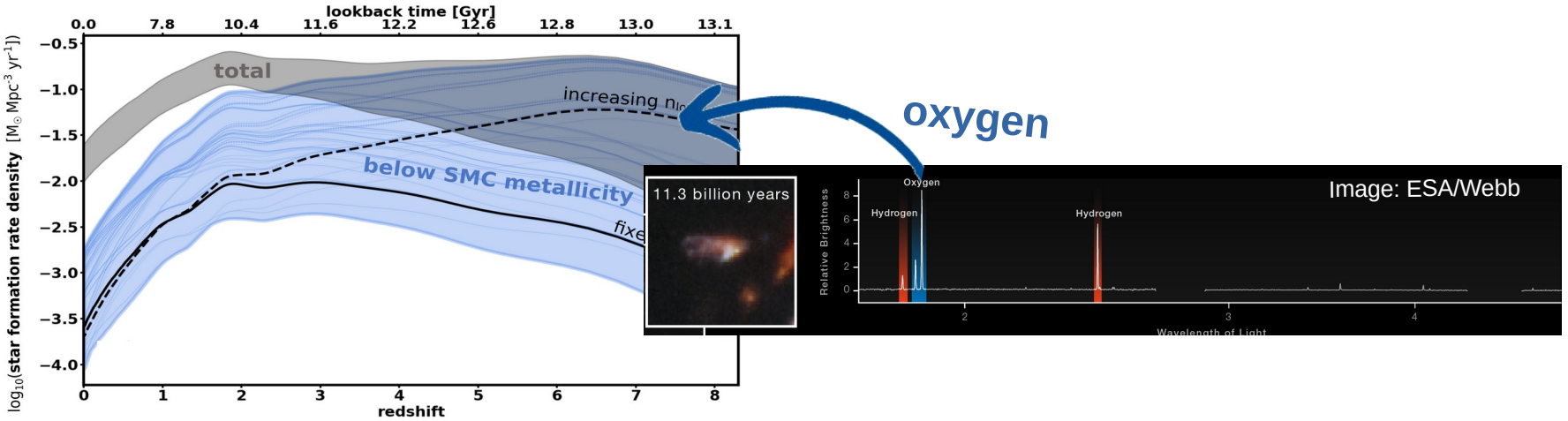


whether we see a feature
(and at what redshift! → next generation GW detectors)
depends on **metallicity-dependent cosmic star formation history**

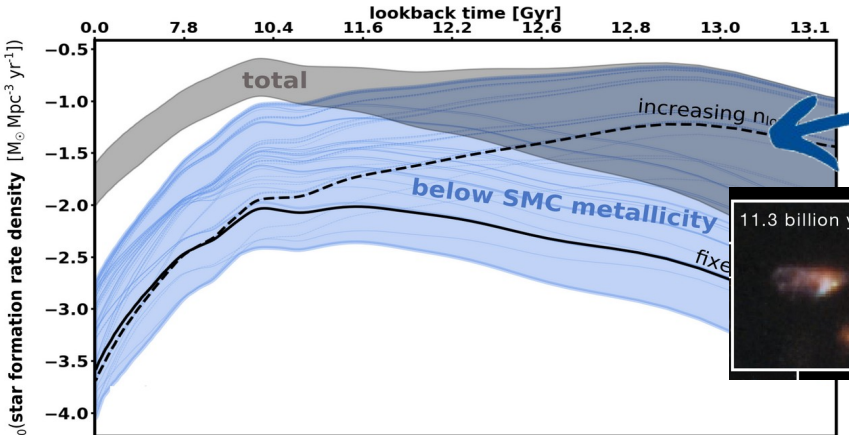
→ (also “pop III”) talk by F. Santoliquido

→ see also Van Son et al.+MCh (2022)

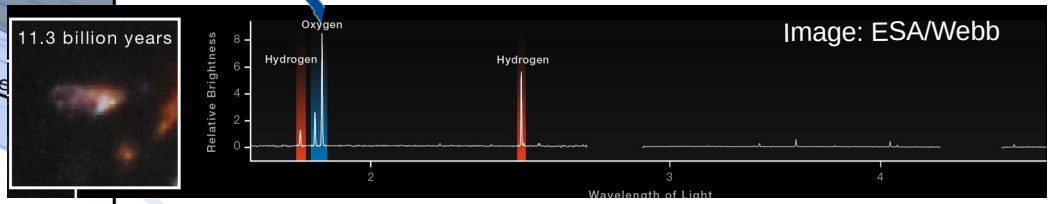
What we actually mean by “metallicity” is important



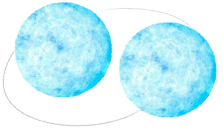
What we actually mean by “metallicity” is important



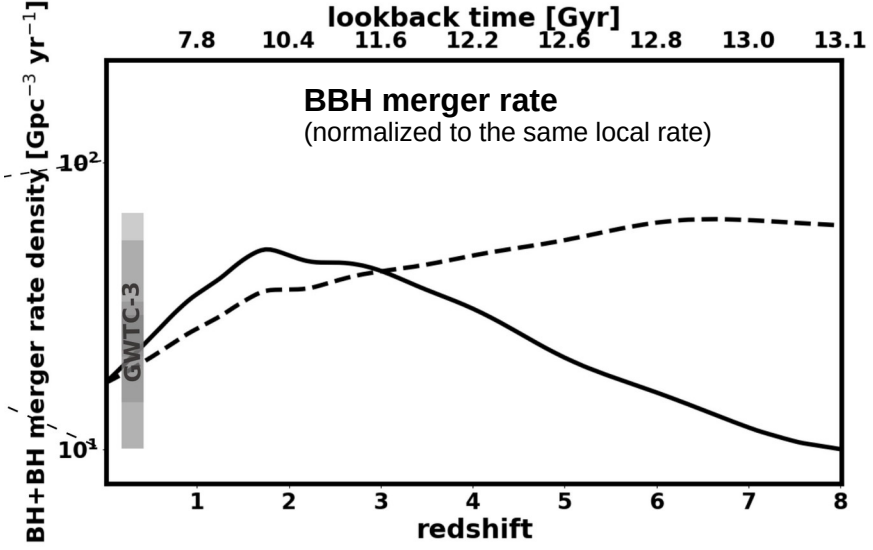
oxygen



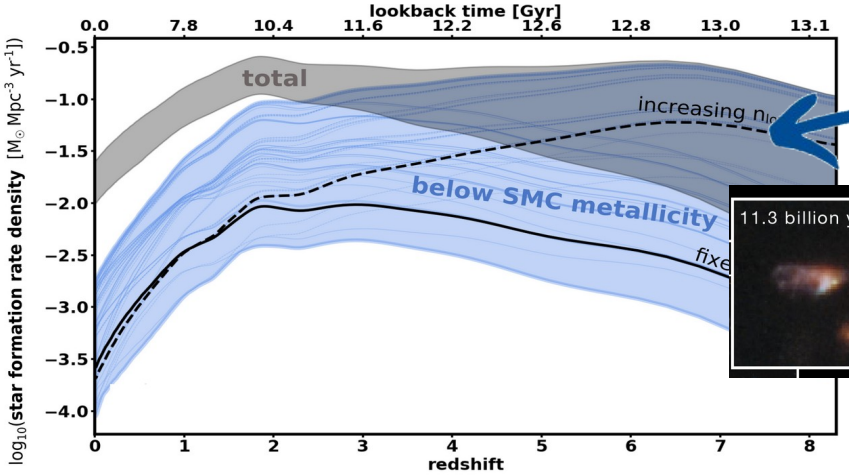
what we **measure is not** always what we **need**



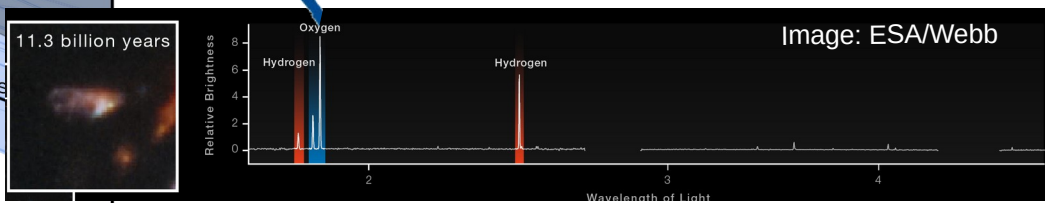
IRON - sensitive



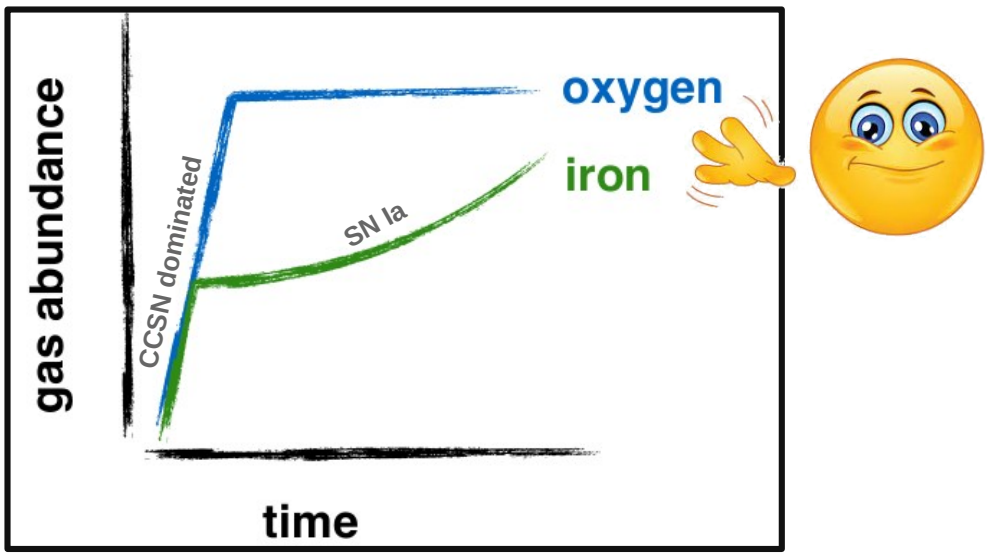
What we actually mean by “metallicity” is important



oxygen



Oxygen can be a very poor proxy for iron abundance!

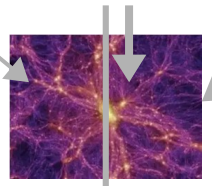


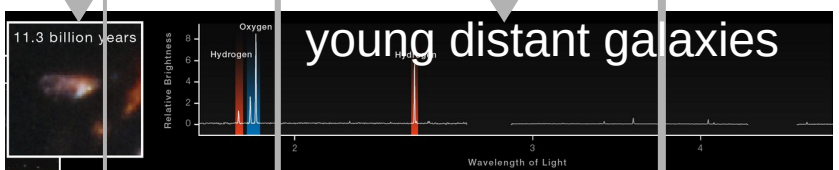
Workaround:

Method to relate *iron* to available star-forming galaxy properties

→ Chruslinska, Pakmor, Matthee, Matsuno (2024)

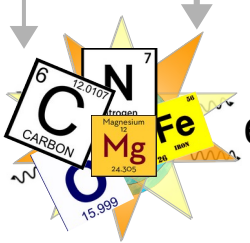
simulated Universe





young distant galaxies

old nearby stars



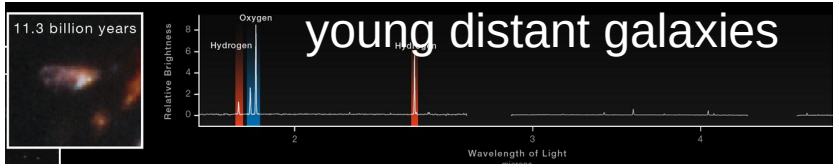
enrichment by stellar sources

Workaround:

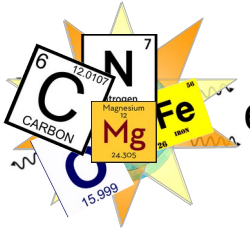
Method to relate *iron* to available star-forming galaxy properties

→ Chruslinska, Pakmor, Matthee, Matsuno (2024)

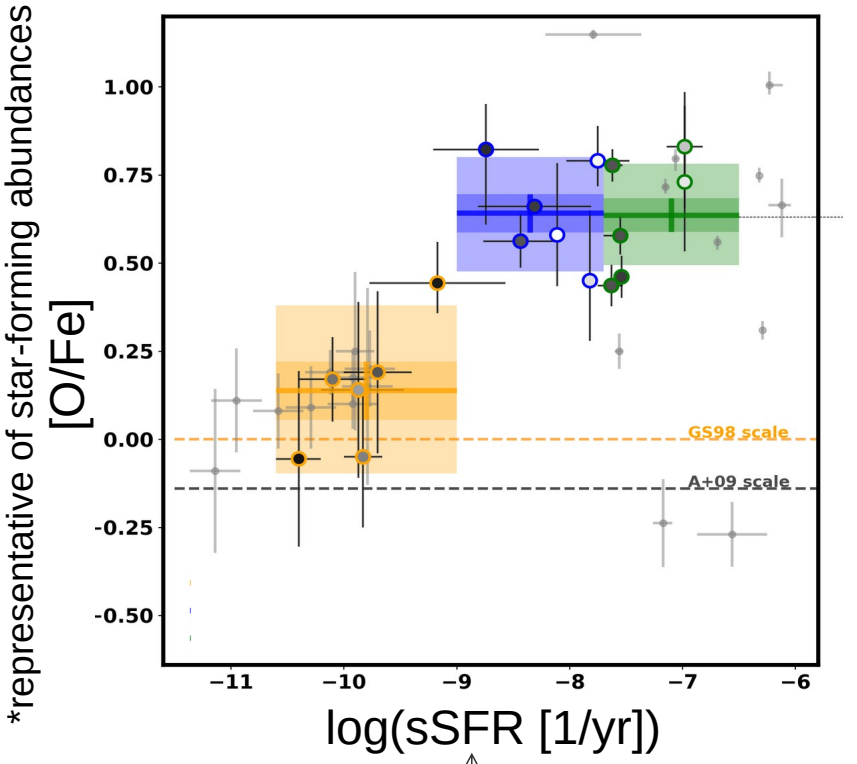
simulated Universe



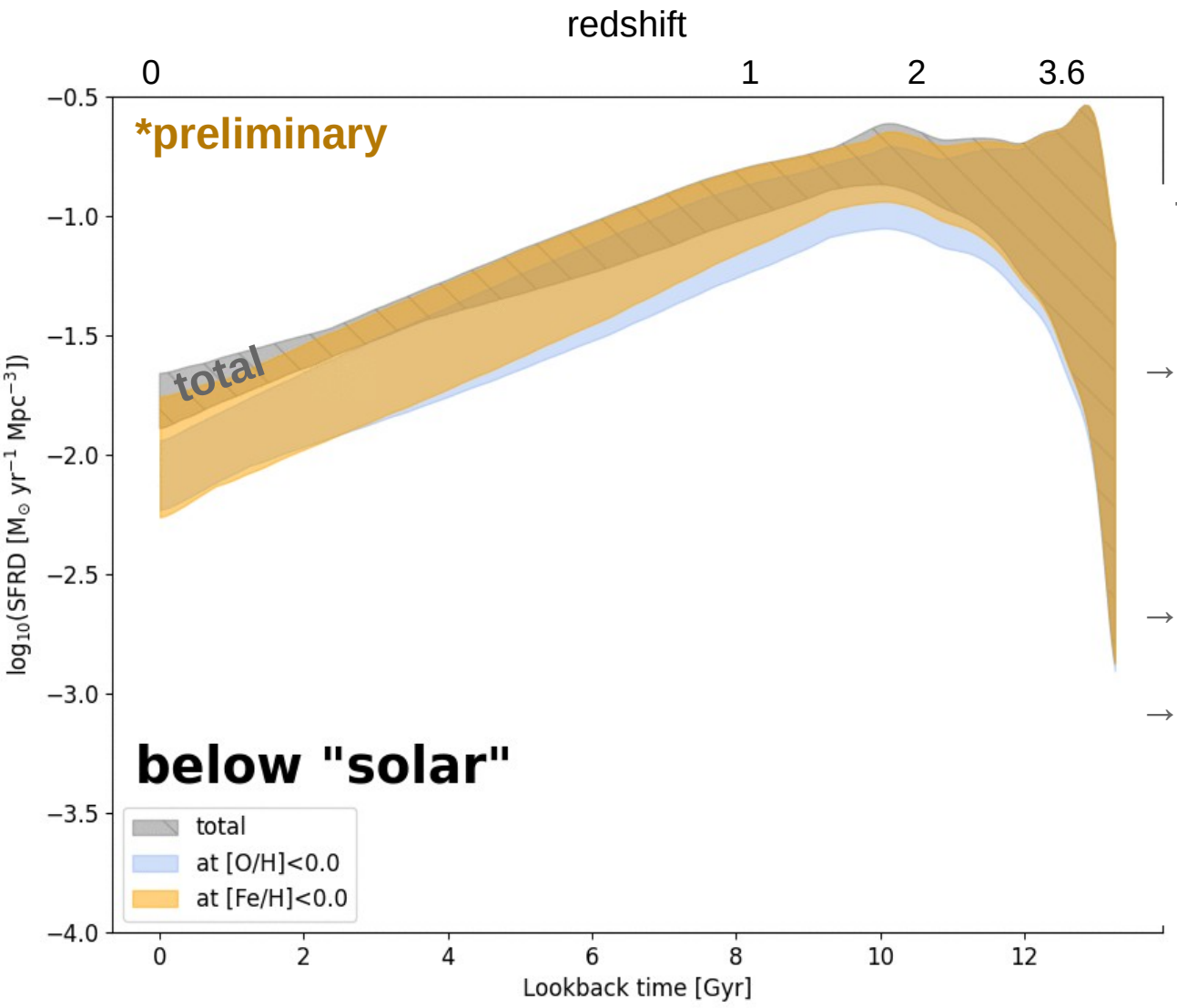
old nearby stars



enrichment by stellar sources



(one of the commonly derived galaxy properties)



That's a separate talk,
but the bulletpoints are:

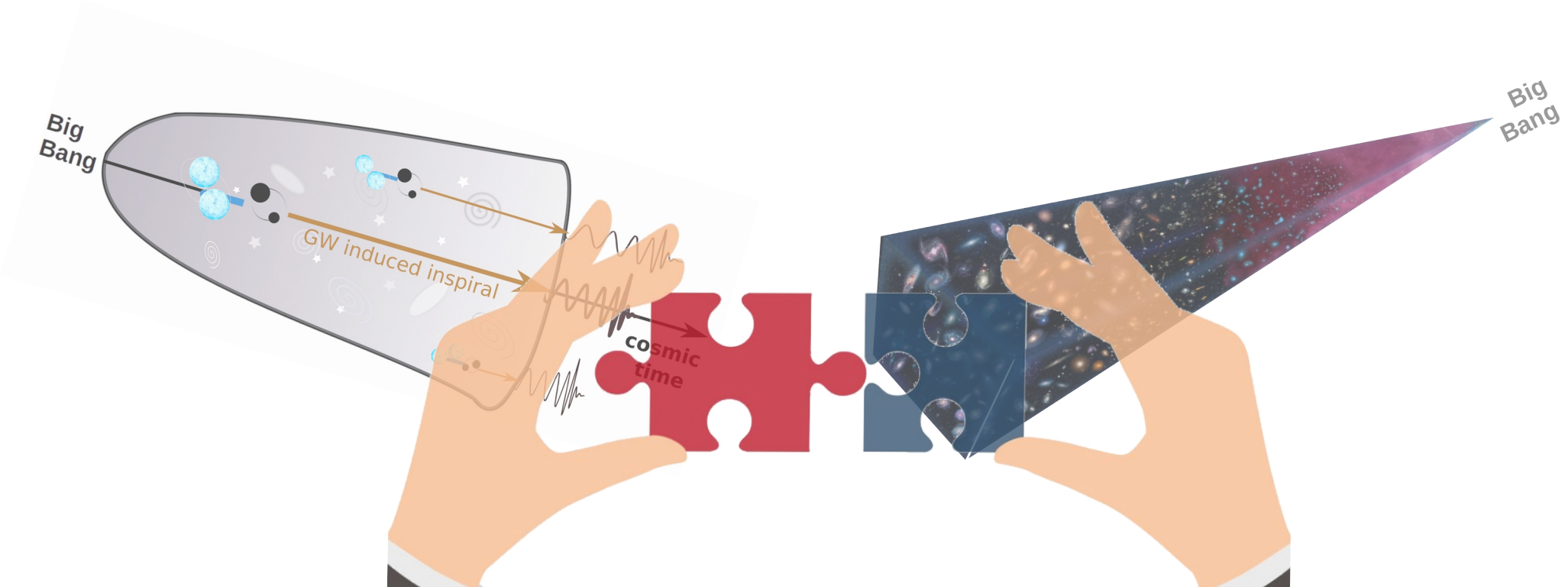
→ stars at redshifts >2
likely to form with
O/Fe ~ **3 times** "solar" O/Fe
abundance ratio

→ different time evolution **O** vs **Fe**

→ there is more "**Fe-poor**"
than "**O-poor**" star formation

*Take home message

redshift (cosmic time) dimension is important for *making sense of* a jumble of everything

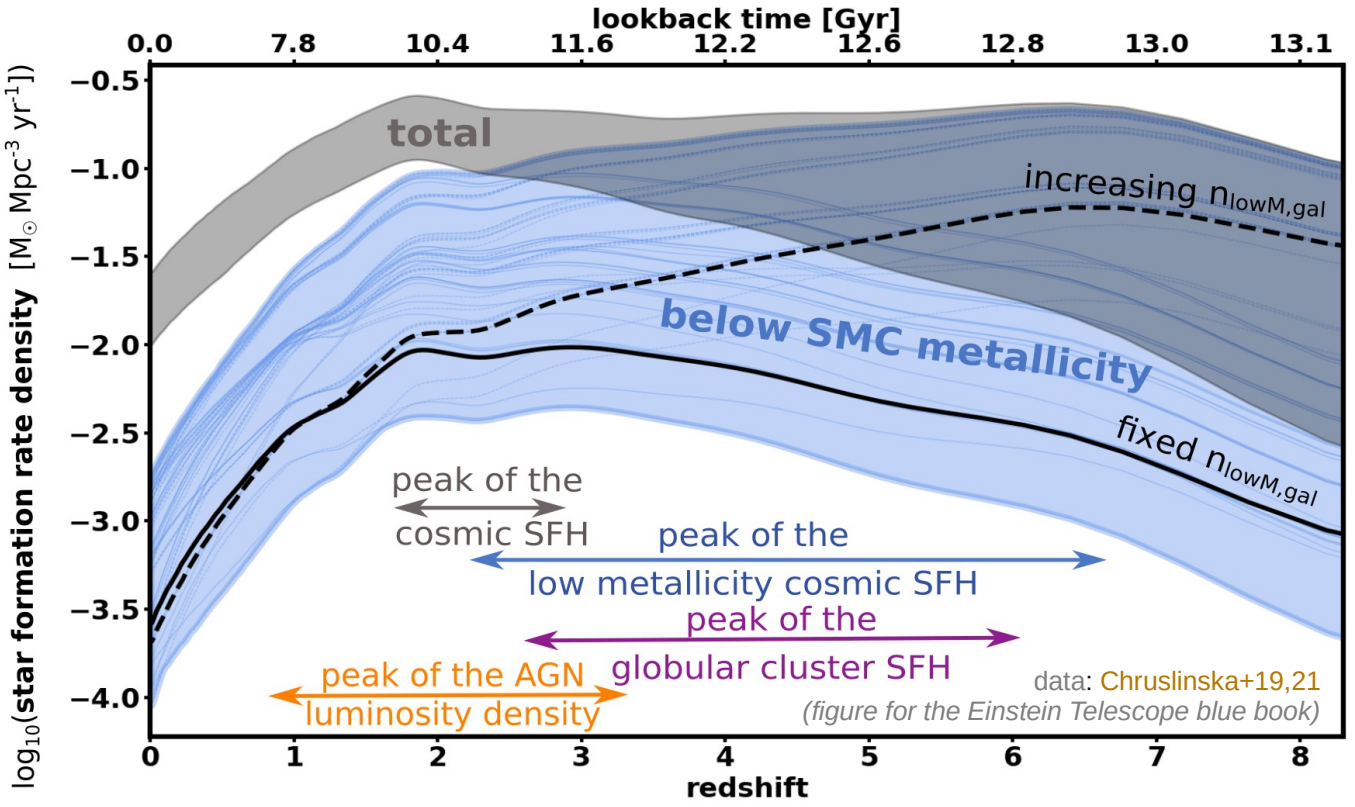


*Take home message

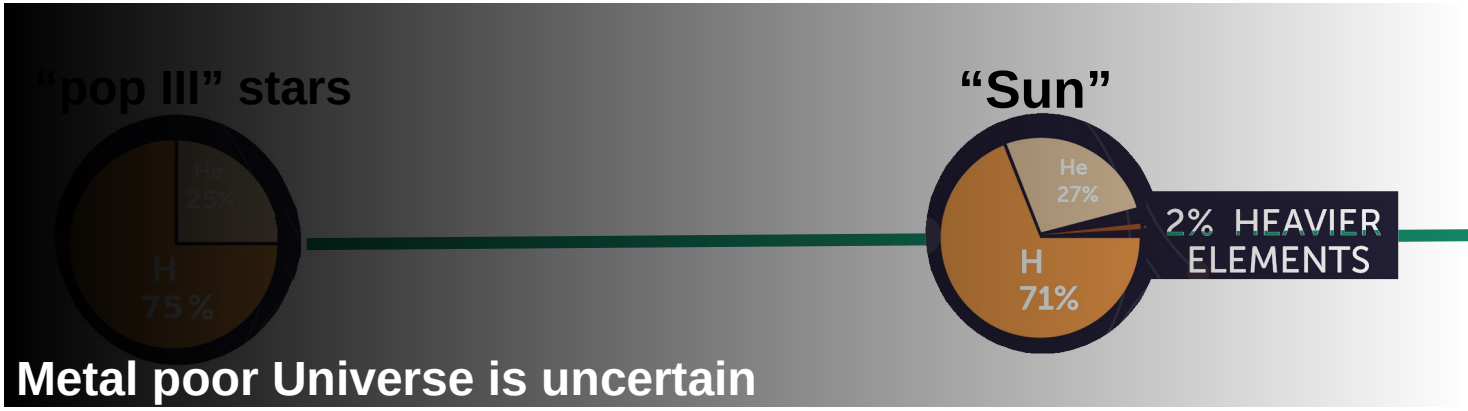
number, properties (chemical composition!), environment of BH/NS progenitors

→ evolve over the cosmic history

→ necessary for population interpretation/modelling



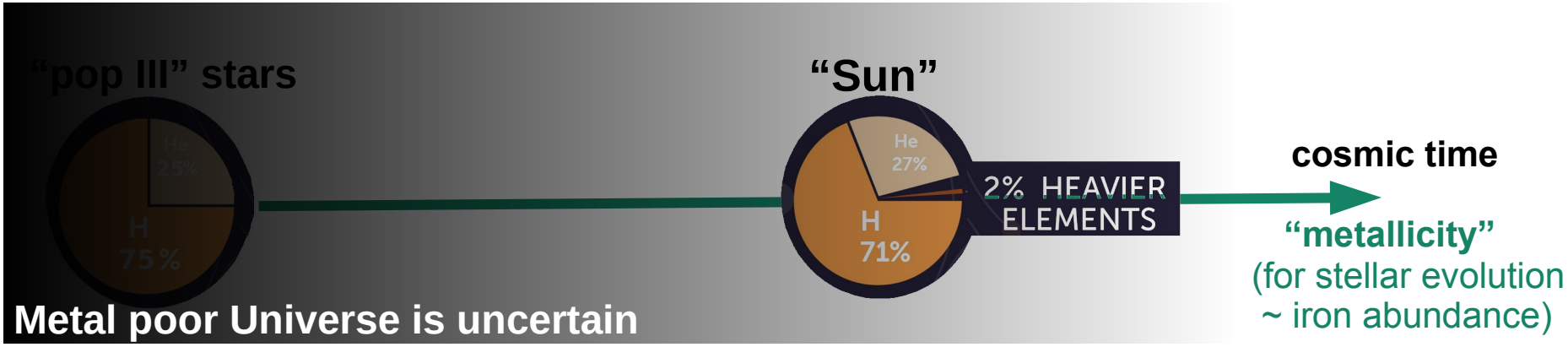
*Take home message



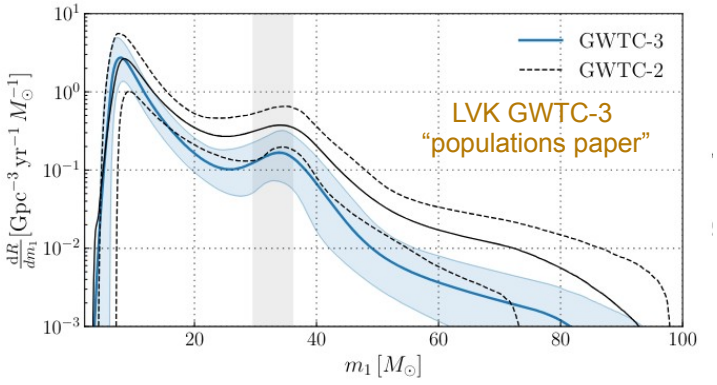
cosmic time

“metallicity”
(for stellar evolution
~ iron abundance)

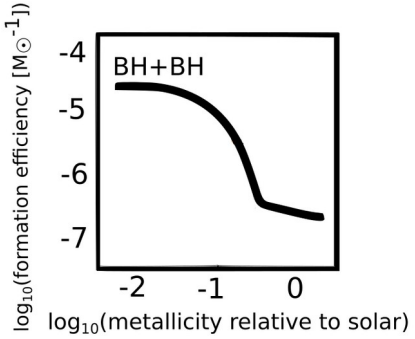
*Take home message



GW: low metallicity regime important (!)



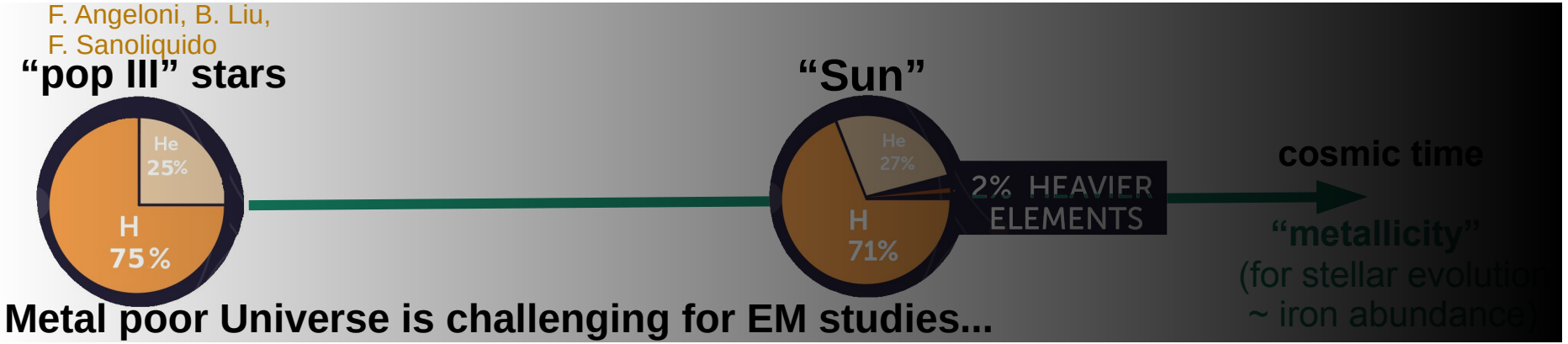
mass, rate (+ redshift evolution!)



preference for low metallicity progenitors

*Take home message

→ talks by R. Schneider, F. Angeloni, B. Liu, F. Sanoliquido



BH mergers know about **low metallicity** **regime (!)**

[early (iron) enrichment history; properties of low-mass galaxies in the reionisation epoch population III; lives, deaths and interactions of massive stars at low metallicity]

Thank you !

Martyna Chruślińska
(read: Hroo-shlin-ska)

MPA fellow → ESO fellow

Max Planck Institute for Astrophysics

European Southern Observatory

Metallicity-dependent cosmic star formation history

- necessary part of the GW population interpretation & modelling
- may dominate uncertainty of BBH mergers vs redshift
- constraints can be derived *(statistical galaxy properties)* but *(will remain)* challenging at “low metallicity” for EM studies *(even at low redshift!)*

+ *metallicity* mostly probed by ***oxygen*** (workaround → [O/Fe] – sSFR relation)

- GW observations can provide **complementary constraints**
  [early (iron) enrichment history, properties of low-mass galaxies in the reionisation epoch]
- different method, biases and systematics

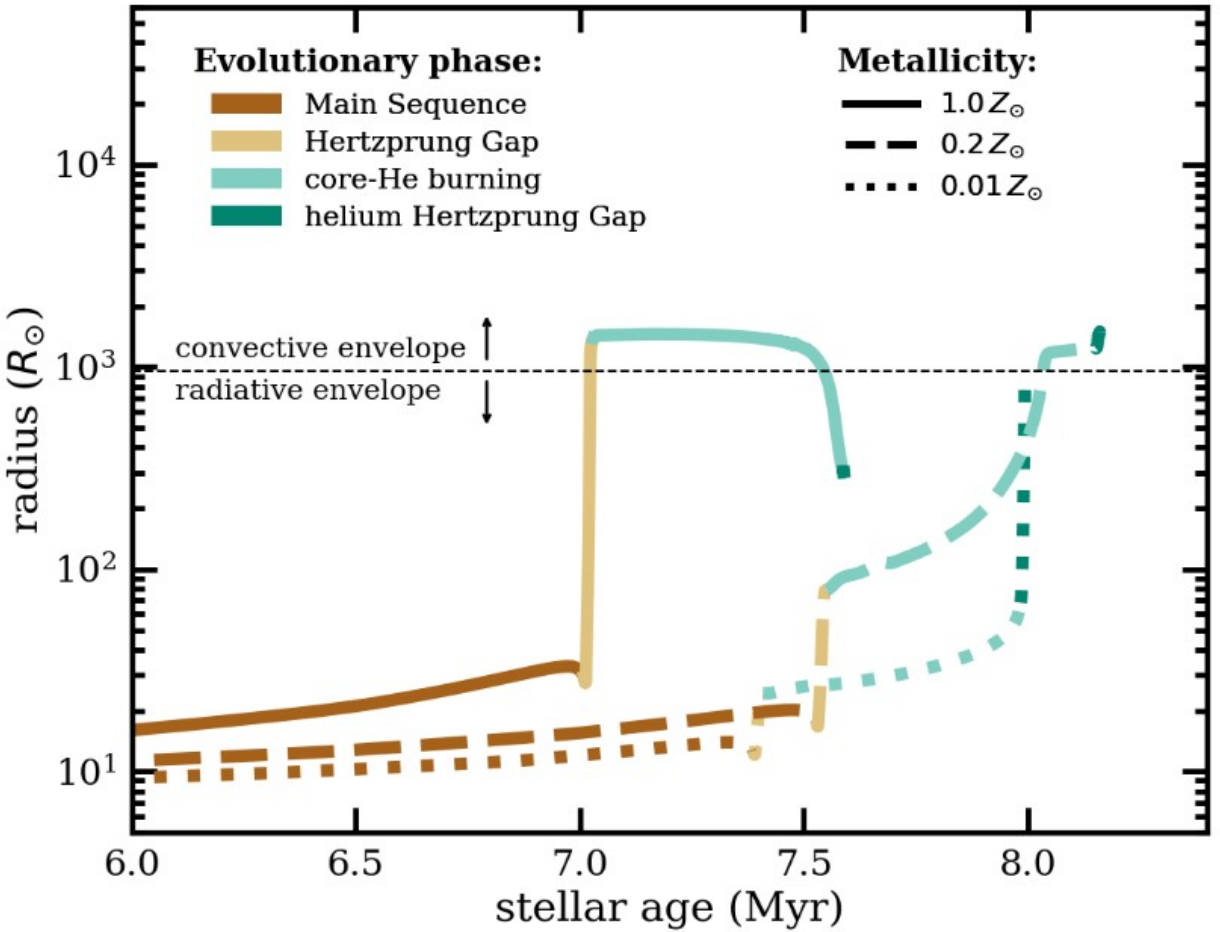
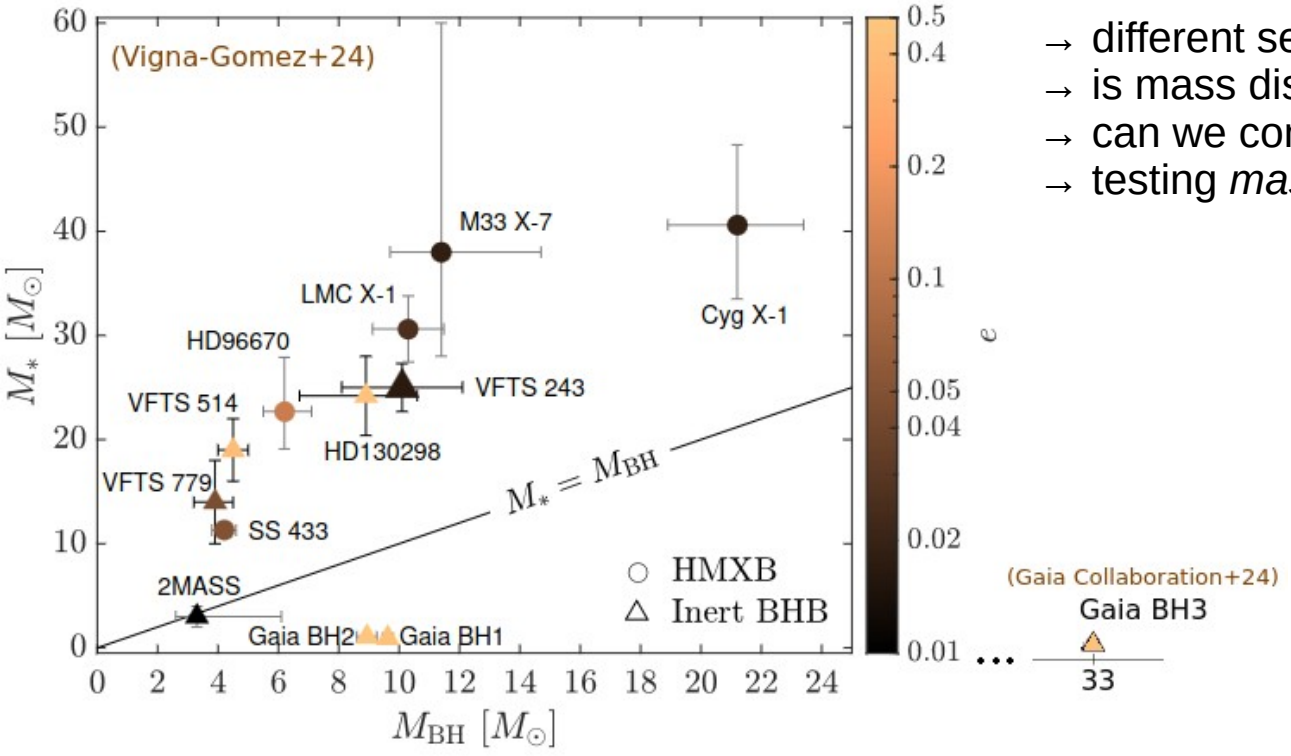


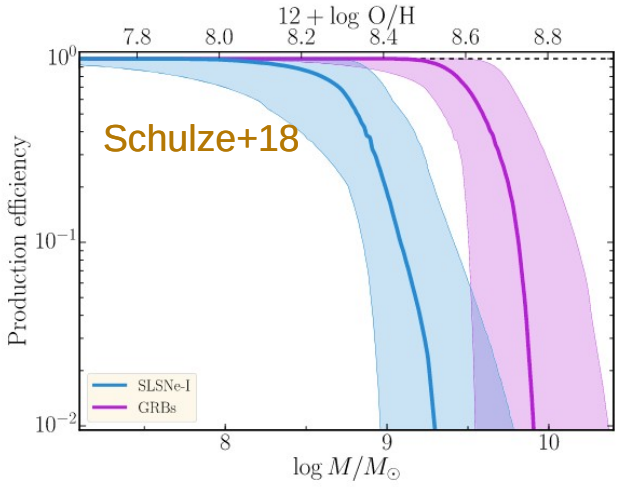
Fig: Chapter 1 ‘BHs in the Era of GW Astronomy’ ed. Arca Sedda, Bortolas, Spera *arXiv:2311.15778* *(results from Klencki+20)*

Growing population of stellar-mass (EM) BHs in binaries *of all shapes and sizes*



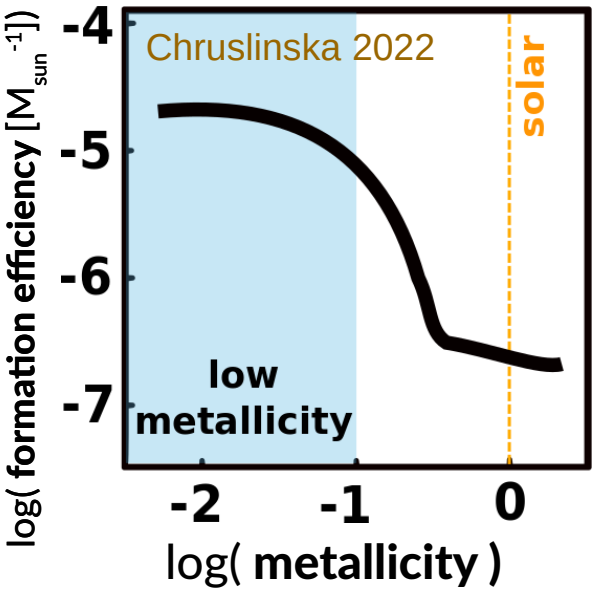
→ different selection effects!
→ is mass distribution consistent with GW?
→ can we constrain natal kicks?
→ testing *massive BH ↔ low metallicity star* link

Long GRBs,
H-poor superluminous SNe
(observed host galaxies)



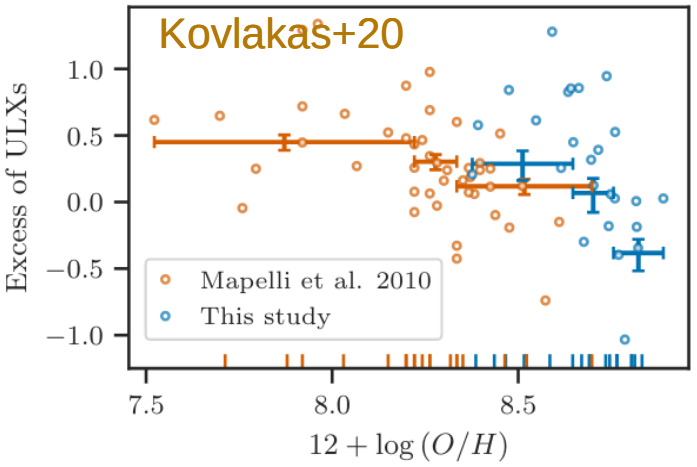
BH+BH mergers
(isolated channels, theoretical)

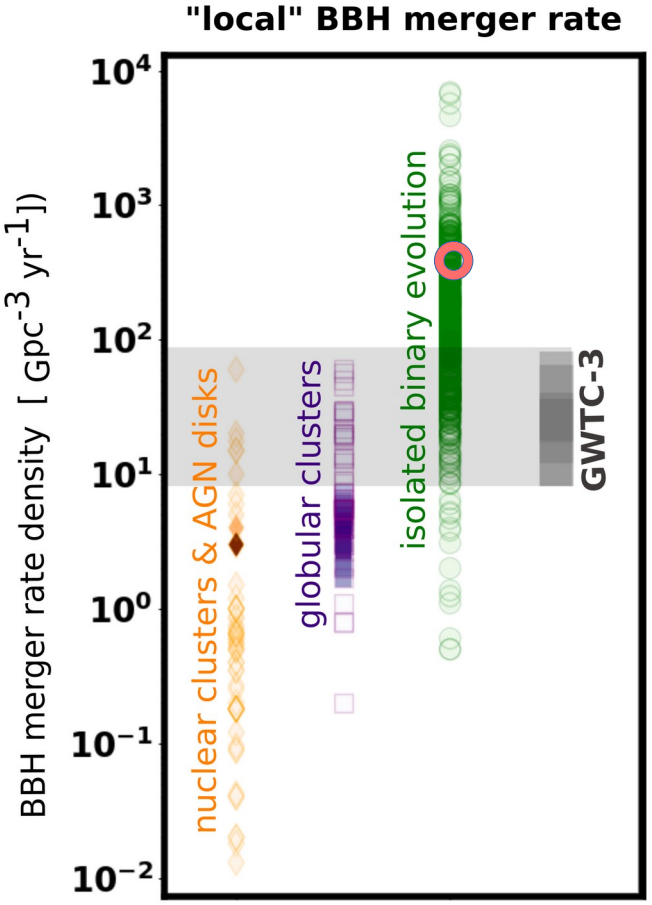
sketch, for comparison of different evolutionary models
see e.g. Chruslinska+19, Santoliquido+21, Broekgaarden+22



Ultraluminous X-ray sources,
High mass X-ray binaries
(observed host galaxies &
X-ray luminosity functions)

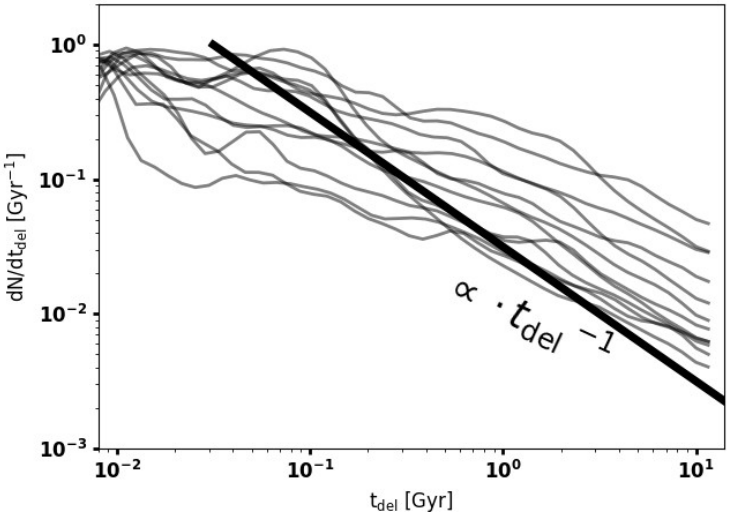
→ Fragos+13,Fornasini+20,Lehmer+22

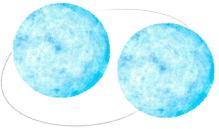




data: literature compilation by
Mandel & Broekgaarden 2022
(living review)

delay time distribution

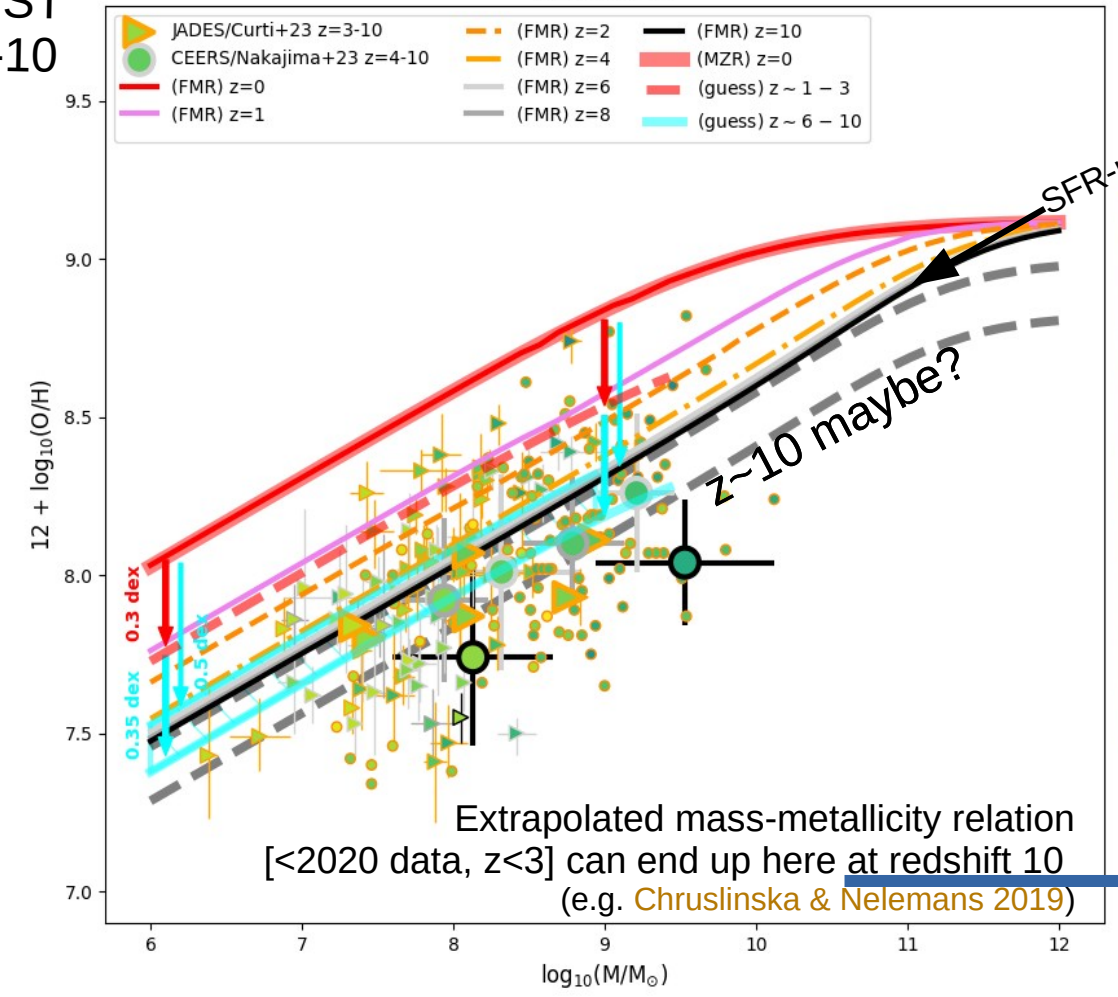




“typical” model

example models from
Boesky+24

recent JWST data z~3-10



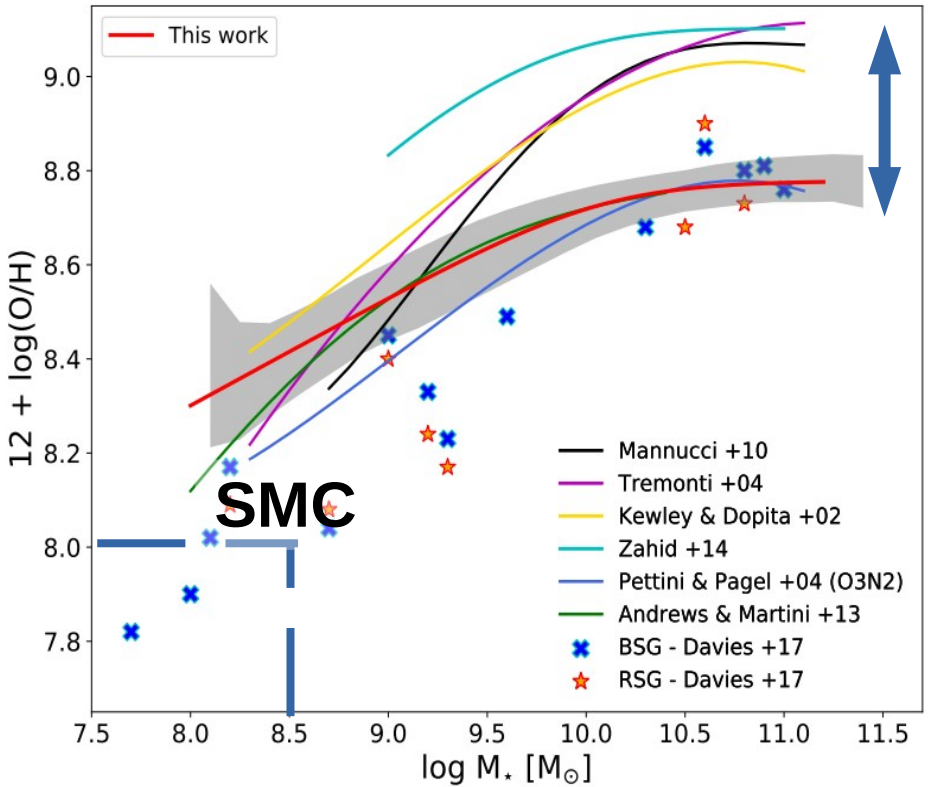
Extrapolating (non-evolving) SFR-mass-metallicity relation to redshift 10 Chruslinska+21

z~10 maybe?

Extrapolated mass-metallicity relation [<2020 data, z<3] can end up here at redshift 10 (e.g. Chruslinska & Nelemans 2019)

(we now know it's definitely not here)

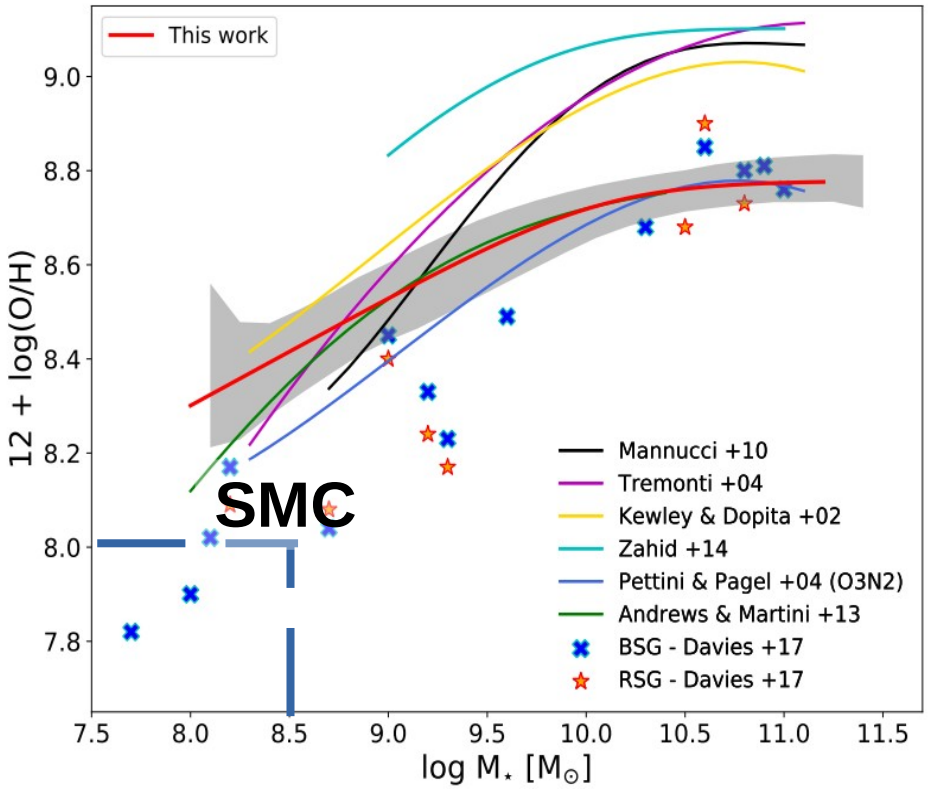
(**Which**?) Mass – metallicity relation

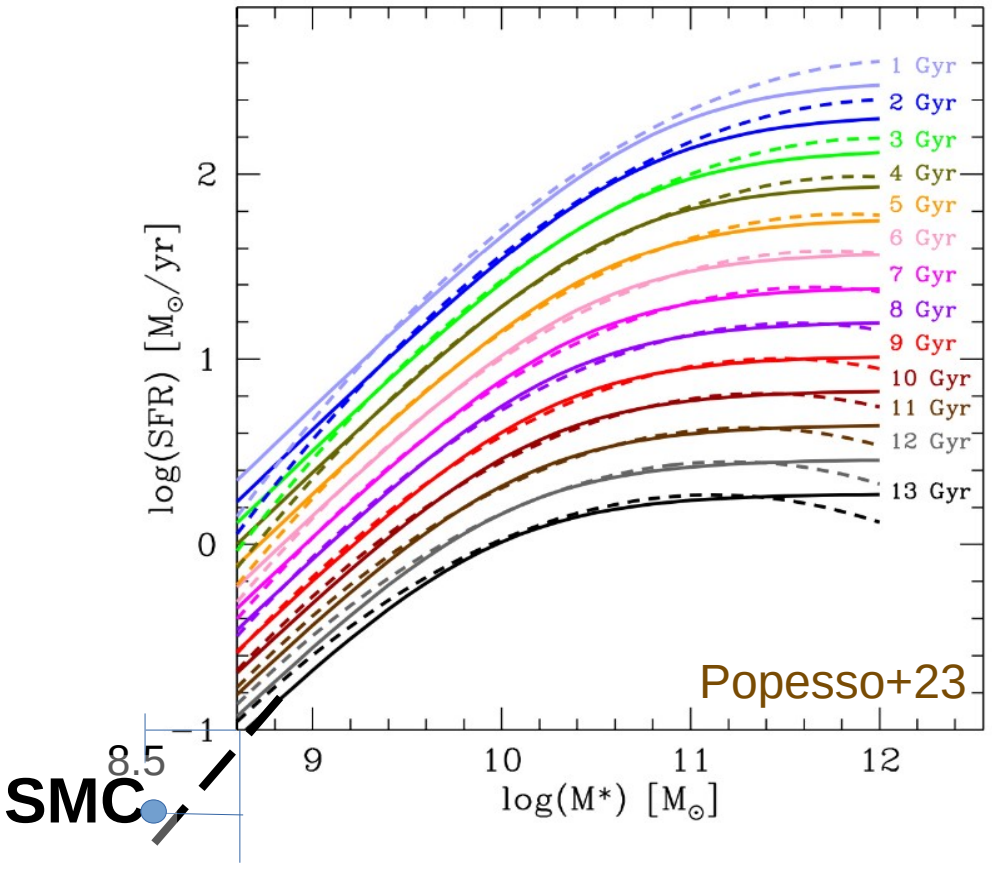


review Maiolino & Mannucci (2019)
comparison of the z~0 relations

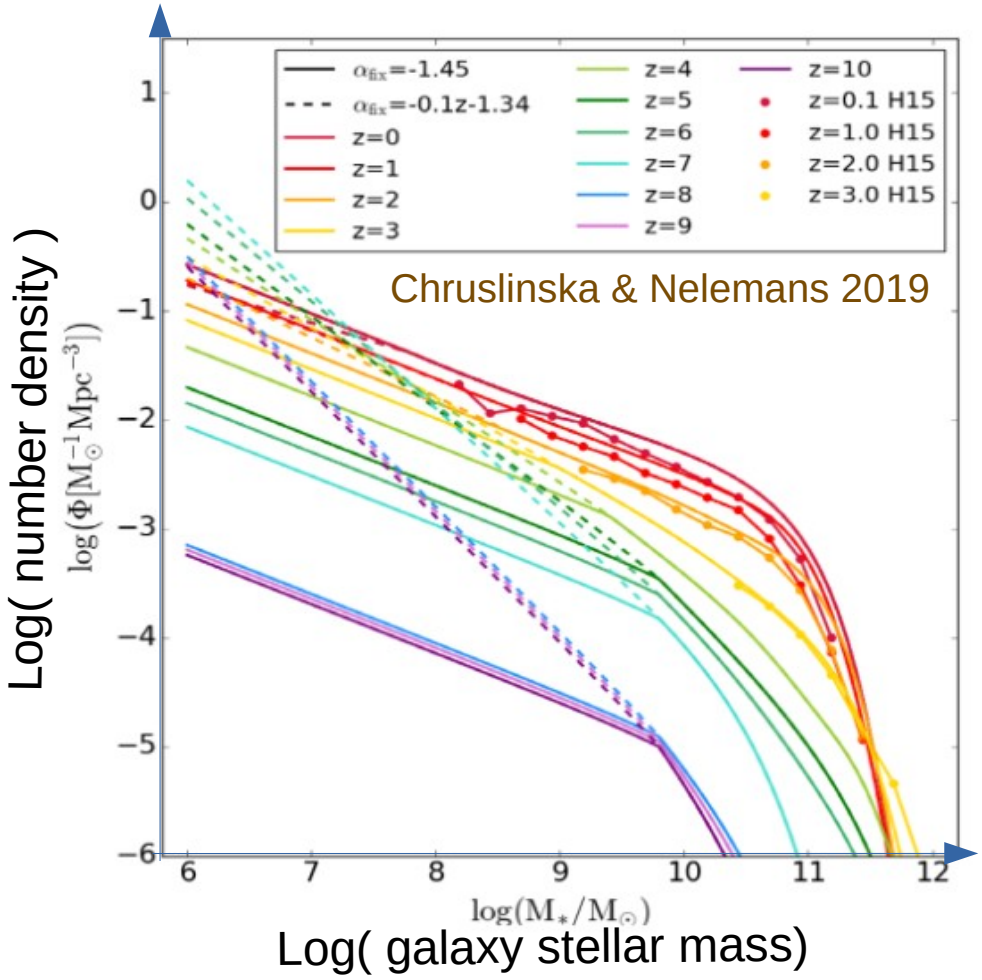
Different ways to translate observed line ratios to metallicity
(see recent reviews Maiolino & Mannucci '19, Kewley+19)

SFR of such galaxies?





How common are such galaxies?

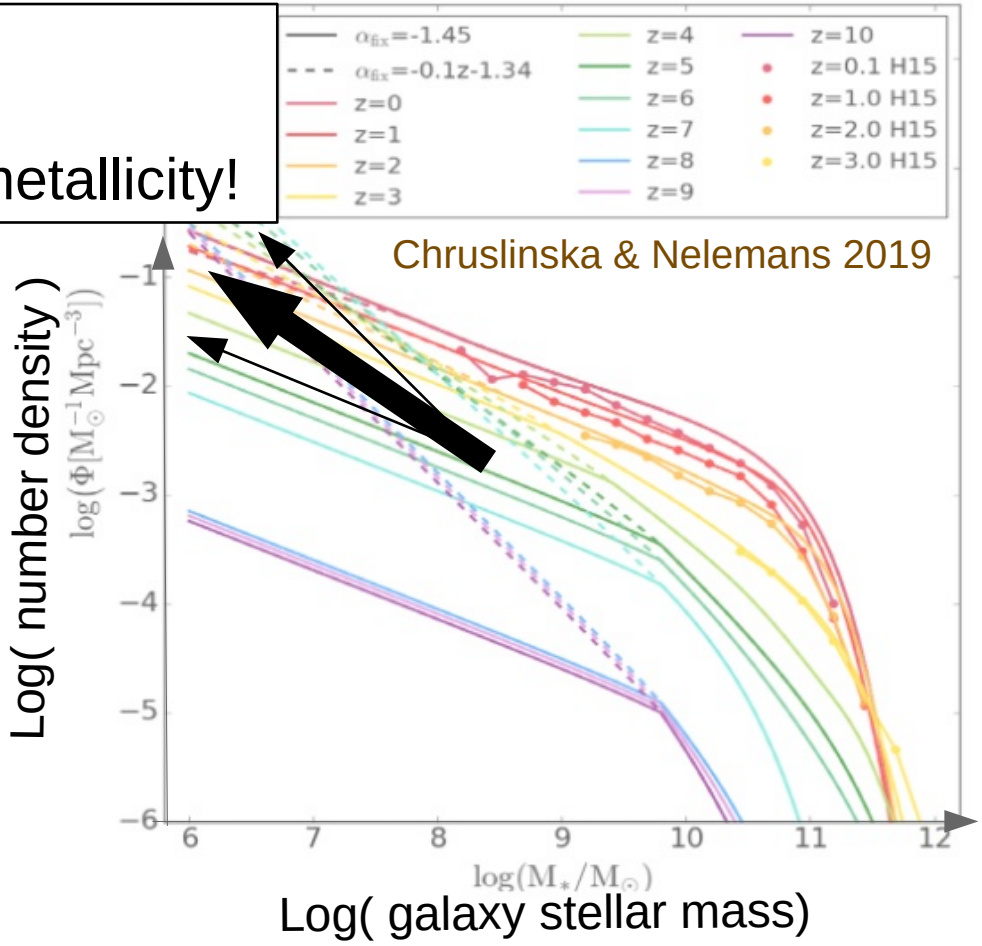


Common.

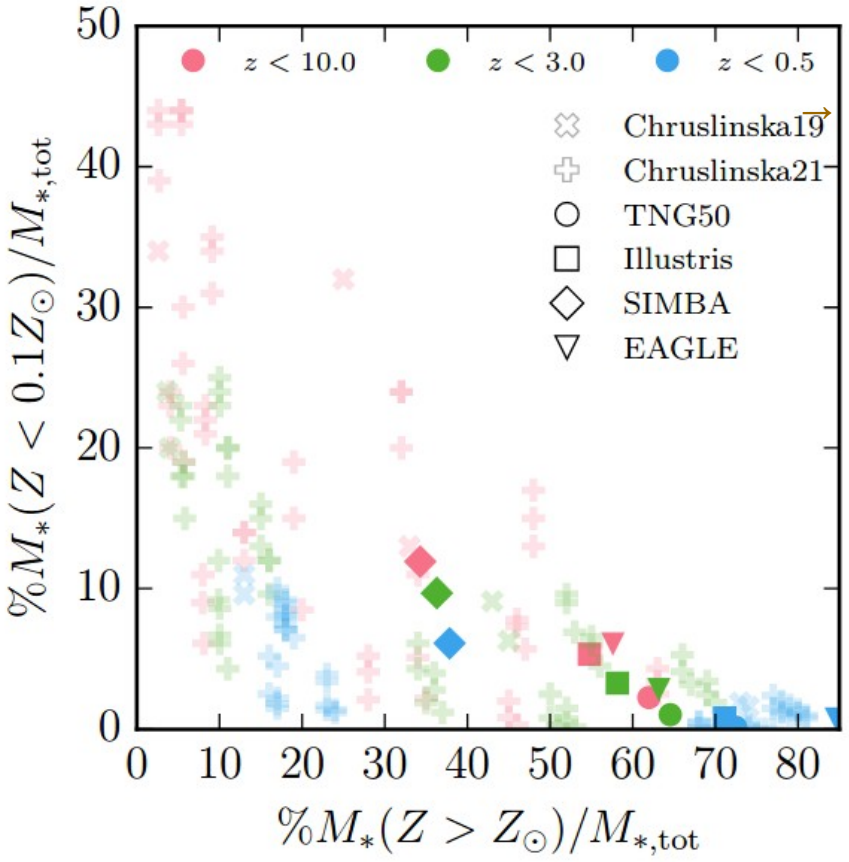
Do not just ignore them:

→ low SFR *but* there is plenty!

→ uncertain *but* crucial for low metallicity!



Comparison with the cosmological simulations of galaxy evolution



Pakmor et al.+MCh (2021)

Figure 2. Percentage of stellar mass with metallicity smaller than $0.1\,Z_\odot$ vs. stellar mass with metallicty larger than $Z_\odot$ for all stars formed after $z = 10$ (red), $z = 3$ (green), and $z = 0.5$ (blue). Data is shown for the most

SFRD distribution over metallicity and redshift ($f_{SFR}(Z,z)$)

(example variation) → Chruslinska+21