Star formation over cosmic time in compact merger population synthesis

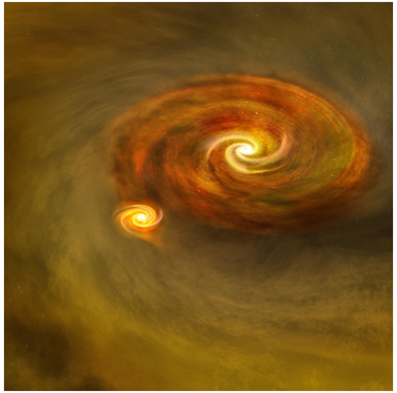
Participant talk for the FAPESP/BAYLAT Workshop
“High-energy astrophysics in the multi-messenger era“

Lucas M. de Sá
Ph.D. student, University of São Paulo
lucasmdesa@usp.br
@gardelpesquisa

The binary population synthesis (BPS) pipeline

Binaries may form **isolated**, from higher-order multiples, from dynamical capture…

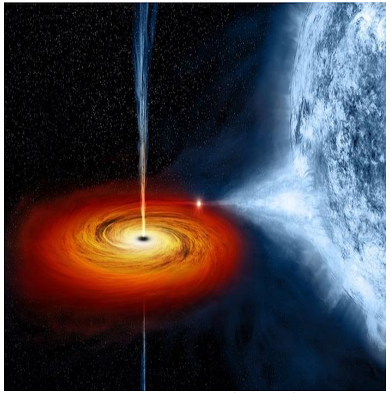
Initial conditions



B. Saxton, NRAO/AUI/NSF

- IMF,
- Mass ratio,
- Orbital period,
- Eccentricity,
- Binary fraction.

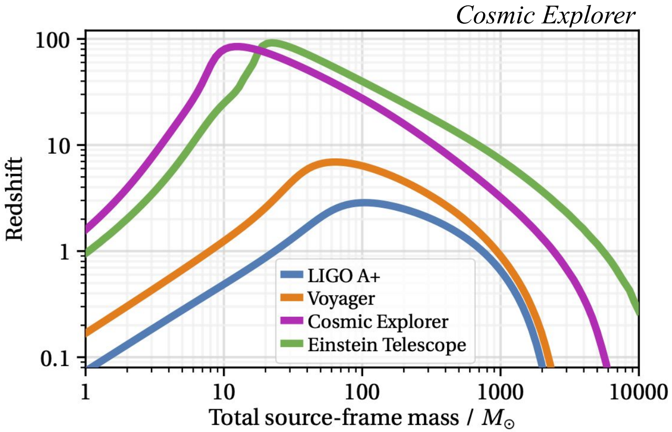
Evolutionary models



NASA/CXC/M.Weiss.

- Stable mass transfer,
- Common envelope evolution,
- Supernovae remnant masses,
- Supernovae kicks
- …

Selection effects



- Observational limits,
- Observational biases.

No step is free of uncertainty

Binary Interaction Dominates the Evolution of Massive Stars

H. Sana,[1*] S. E. de Mink,[2,3] A. de Koter,[1,4] N. Langer,[5] C. J. Evans,[6] M. Gieles,[7] E. Gosset,[8] R. G. Izzard,[5] J.-B. Le Bouquin,[9] F. R. N. Schneider[5]

Mind Your Ps and Qs: The Interrelation between Period (*P*) and Mass-ratio (*Q*) Distributions of Binary Stars

Maxwell Moe[1,1] and Rosanne Di Stefano[2]

The Close Binary Fraction of Solar-type Stars Is Strongly Anticorrelated with Metallicity

Maxwell Moe[3,1], Kaitlin M. Kratter[1], and Carles Badenes[2]

Not That Simple: The Metallicity Dependence of the Wide Binary Fraction Changes with Separation and Stellar Mass

Zexi Niu[1,2], Haibo Yuan[3], Yilun Wang[1,2], and Jifeng Liu[1,2]

Evaluating the impact of binary parameter uncertainty on stellar population properties

E R Stanway, A A Chrimes, J J Eldridge, H F Stevance

The influence of the distribution of cosmic star formation at different metallicities on the properties of merging double compact objects FREE

Martyna Chruslinska, Gijs Nelemans, Krzysztof Belczynski

Chemical evolution of the Universe and its consequences for gravitational-wave astrophysics

*Martyna Chruślińska**

On the variation of the initial mass function FREE

Pavel Kroupa

The effect of the environment-dependent IMF on the formation and metallicities of stars over the cosmic history

M. Chruślińska[1], T. Jeřábková[2,3,4,5,6], G. Nelemans[1,7,8] and Z. Yan[2,3]

The progenitors of compact-object binaries: impact of metallicity, common envelope and natal kicks FREE

Nicola Giacobbo, Michela Mapelli

The effect of the metallicity-specific star formation history on double compact object mergers FREE

Coenraad J Neijssel, Alejandro Vigna-Gómez, Simon Stevenson, Jim W Barrett, Sebastian M Gaebel, Floor S Broekgaarden, Selma E de Mink, Dorottya Szécsi, Serena Vinciguerra, Ilya Mandel

Towards a realistic explosion landscape for binary population synthesis FREE

Rachel A Patton, Tuguldur Sukhbold Author Notes

Impact of metallicity and star formation rate on the time-dependent, galaxy-wide stellar initial mass function*

T. Jeřábková[1,2,3], A. Hasani Zonoozi[2,4], P. Kroupa[2,3], G. Beccari[1], Z. Yan[2,3], A. Vazdekis[5] and Z.-Y. Zhang[6,1]

Comparing compact object distributions from mass- and presupernova core structure-based prescriptions

Rachel A Patton, Tuguldur Sukhbold, J J Eldridge Author Notes

The Effect of Supernova Convection On Neutron Star and Black Hole Masses

Chris L. Fryer[1,2,3,4,5], Aleksandra Olejak[6], and Krzysztof Belczynski[6]

Binary population synthesis with probabilistic remnant mass and kick prescriptions

Ilya Mandel, Bernhard Müller, Jeff Riley, Selma E de Mink, Alejandro Vigna-Gómez, Debatri Chattopadhyay

Common envelope evolution: where we stand and how we can move forward

N. Ivanova, S. Justham, X. Chen, O. De Marco, C. L. Fryer, E. Gaburov, H. Ge, E. Glebbeek, Z. Han, X.-D. Li, G. Lu, T. Marsh, P. Podsiadlowski, A. Potter, N. Soker, R. Taam, T. M. Tauris, E. P. J. van den Heuvel & R. F. Webbink

Impact of common envelope development criteria on the formation of LIGO/Virgo sources

A. Olejak[1], K. Belczynski[1] and N. Ivanova[2]

The Uncertain Future of Massive Binaries Obscures the Origin of LIGO/Virgo Sources

K. Belczynski[1], A. Romagnolo[1], A. Olejak[1], J. Klencki[2], D. Chattopadhyay[3], S. Stevenson[3], M. Coleman Miller[4], J.-P. Lasota[1,5], and Paul A. Crowther[6]

Impact of massive binary star and cosmic evolution on gravitational wave observations I: black hole–neutron star mergers FREE

Floor S Broekgaarden, Edo Berger, Coenraad J Neijssel, Alejandro Vigna-Gómez, Debatri Chattopadhyay, Simon Stevenson, Martyna Chruslinska, Stephen Justham, Selma E de Mink, Ilya Mandel

Which black hole formed first? Mass-ratio reversal in massive binary stars from gravitational-wave data

Matthew Mould, Davide Gerosa, Floor S Broekgaarden, Nathan Steinle

When Are LIGO/Virgo's Big Black Hole Mergers?

Maya Fishbach[1], Zoheyr Doctor[2], Thomas Callister[3], Bruce Edelman[2], Jiani Ye[4], Reed Essick[5], Will M. Farr[3,4], Ben Farr[2], and Daniel E. Holz[5,6,7,8]

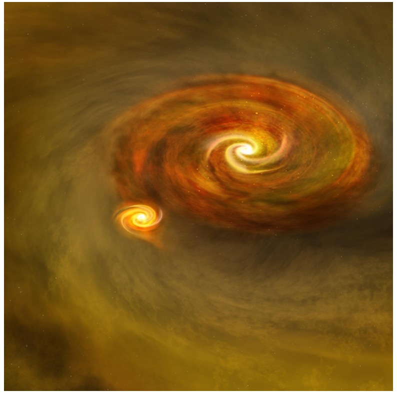
The Redshift Evolution of the Binary Black Hole Merger Rate: A Weighty Matter

L. A. C. van Son[1,2,3], S. E. de Mink[3,1,2], T. Callister[4], S. Justham[2,5,3], M. Renzo[4,6], T. Wagg[7,1,3], F. S. Broekgaarden[1], F. Kummer[2], R. Pakmor[3], and I. Mandel[8,9,10]

And many more…

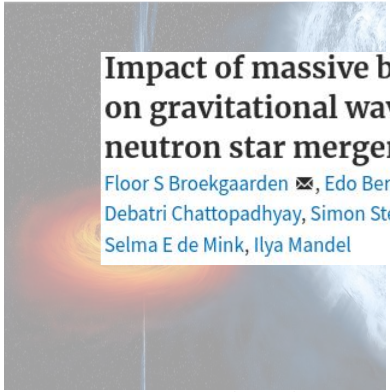
So we have to treat one problem at a time.

Initial conditions


B. Saxton, NRAO/AUI/NSF

- IMF,
- Orbital parameters,
- Binary fraction,
- Environment.

Evolutionary models


NASA/CXC/M.Weiss.

Impact of massive binary star and cosmic evolution on gravitational wave observations I: black hole–neutron star mergers FREE

Floor S Broekgaarden ✉, Edo Berger, Coenraad J Neijssel, Alejandro Vigna-Gómez, Debatri Chattopadhyay, Simon Stevenson, Martyna Chruslinska, Stephen Justham, Selma E de Mink, Ilya Mandel

- Stable mass transfer,
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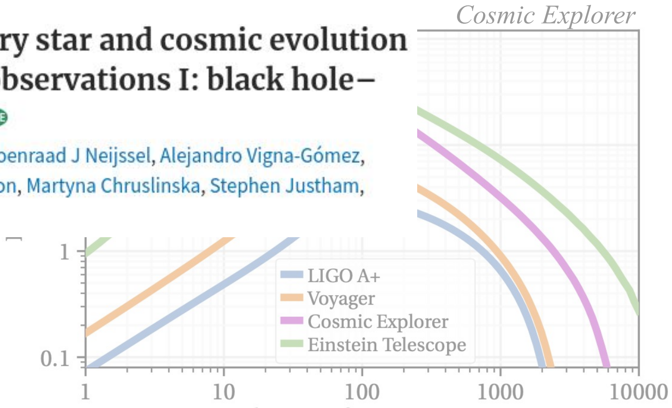
- …

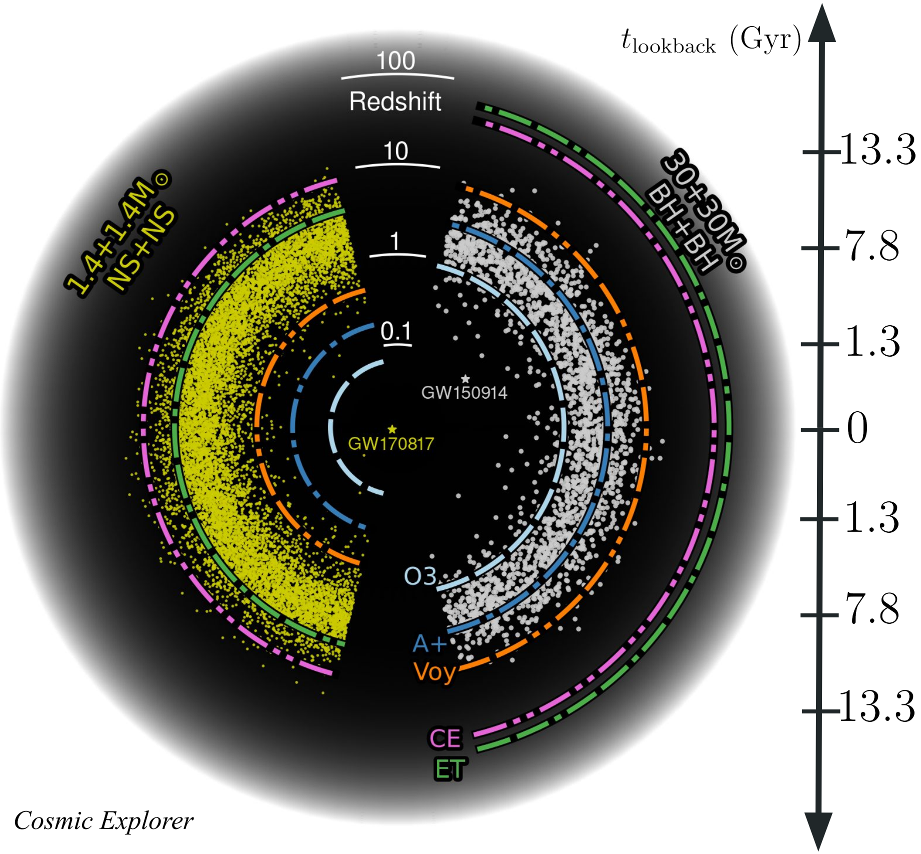
Selection effects



The effect of the metallicity-specific star formation history on double compact object mergers FREE

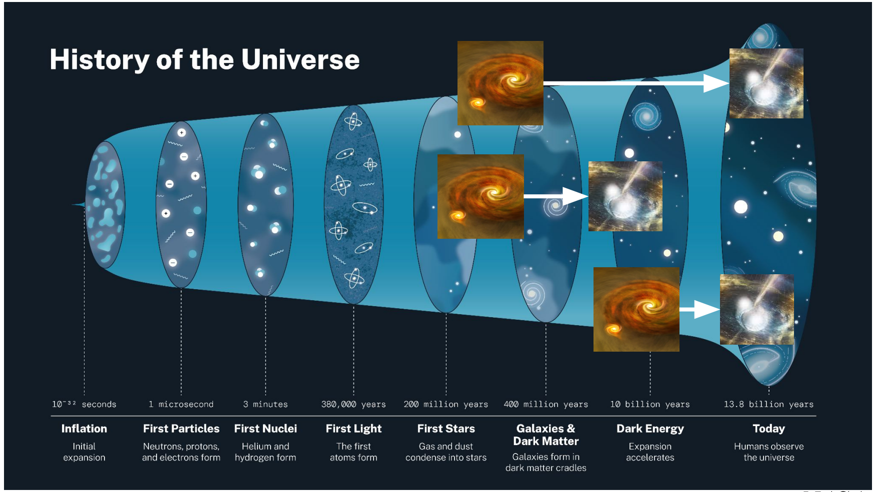
Coenraad J Neijssel ✉, Alejandro Vigna-Gómez, Simon Stevenson, Jim W Barrett, Sebastian M Gaebel, Floor S Broekgaarden, Selma E de Mink, Dorottya Szécsi, Serena Vinciguerra, Ilya Mandel

The issue of "when":



Cosmic Explorer

Coalescence times can be comparable to the age of the Universe.

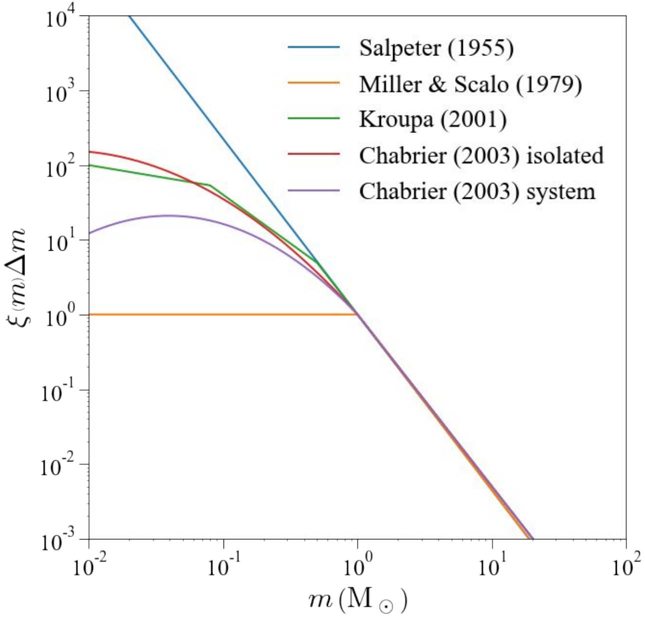


NASA

Did the progenitors of the oldest mergers form as local stars do? What is different?

A hot button issue from star formation: is the IMF universal?

The Salpeter (1955) IMF and its descendants: firm, but not without challenges.



- The usual choices for synthesis.

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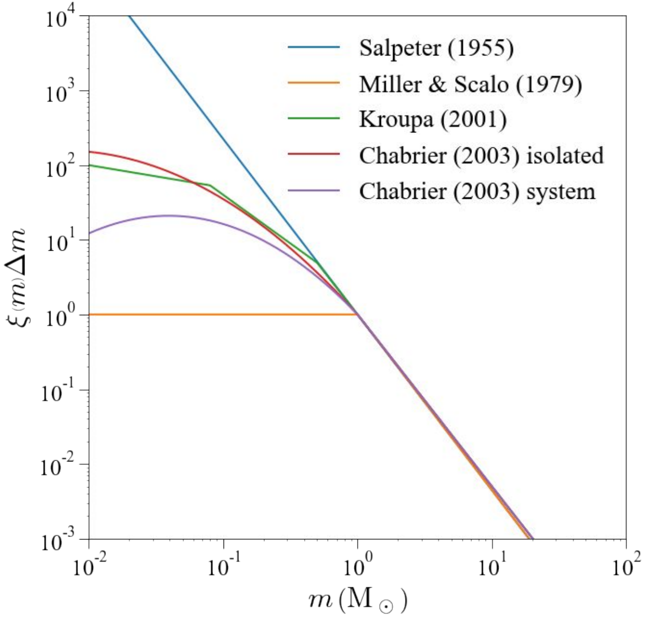
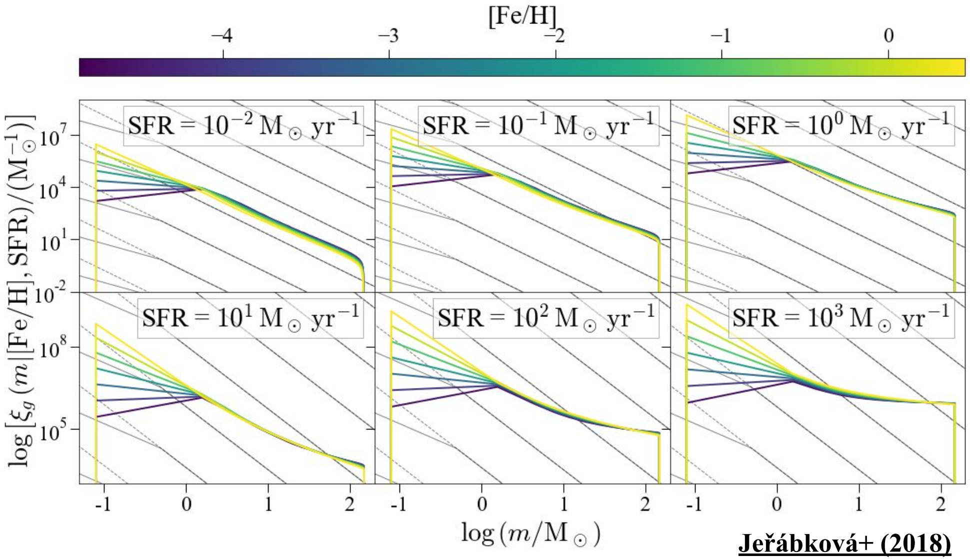


- The usual choices for synthesis.

Theoretical challenges are old , observational support is recent **(Gunawardhana+, 2011; Marks+, 2012)**

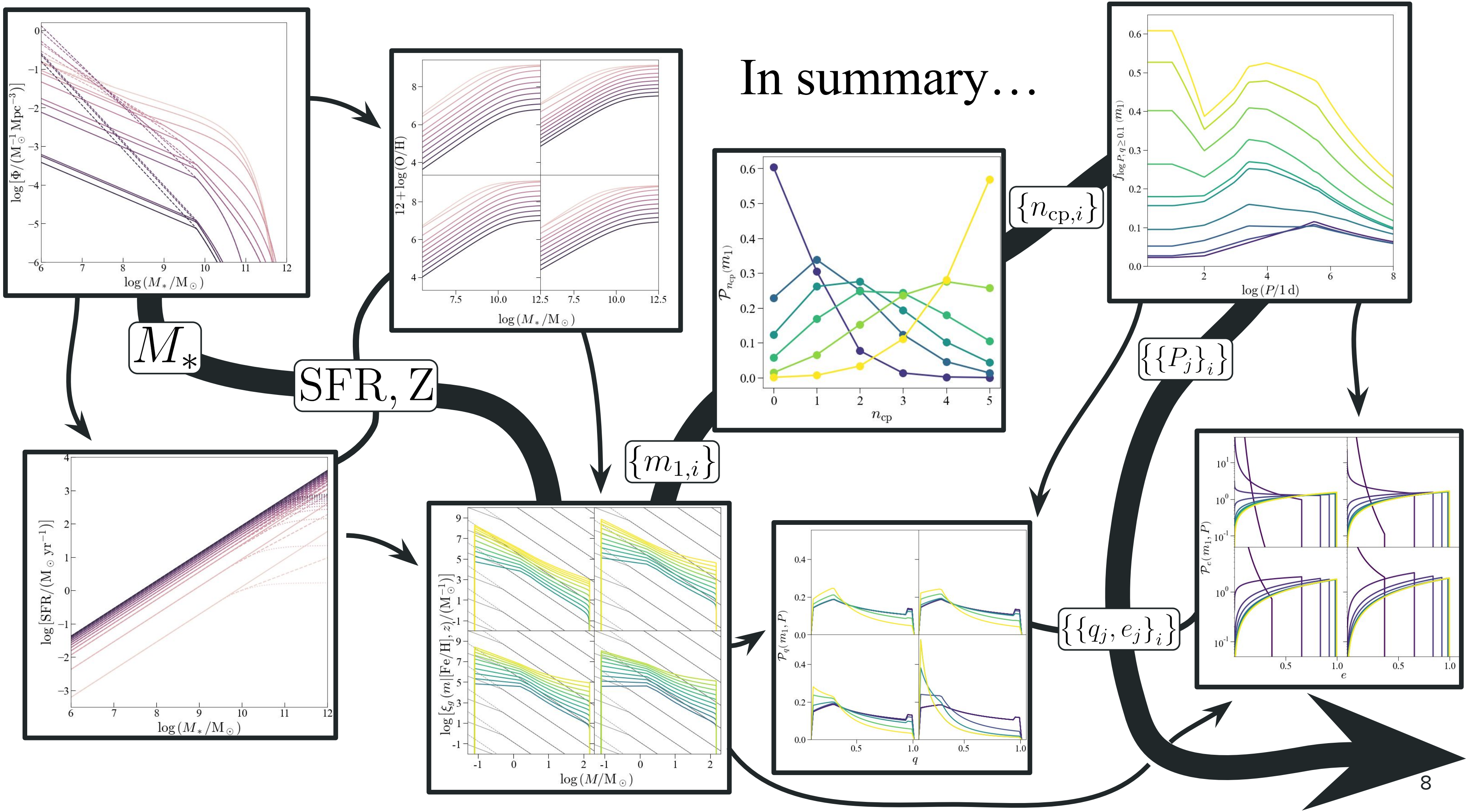
Integrated galaxy-wide IMF theory (Kroupa & Weidner, 2003)



Jeřábková+ (2018)

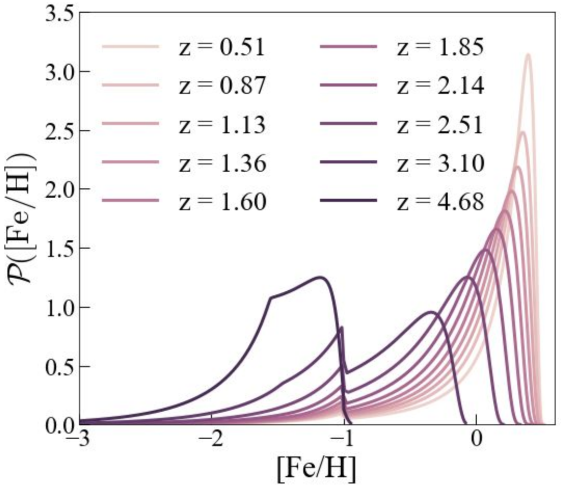
$$\xi_{\mathrm{g}}\left(m|[\mathrm{Fe/H}],\mathrm{SFR}\right) = \int_{\mathrm{galaxy}} \xi_{\mathrm{s}}\left(m|M_{\mathrm{ecl}},[\mathrm{Fe/H}]\right)\ \xi_{\mathrm{e}}\left(M_{\mathrm{ecl}}|[\mathrm{Fe/H}],\mathrm{SFR}\right)\ \mathrm{d}M_{\mathrm{ecl}}$$

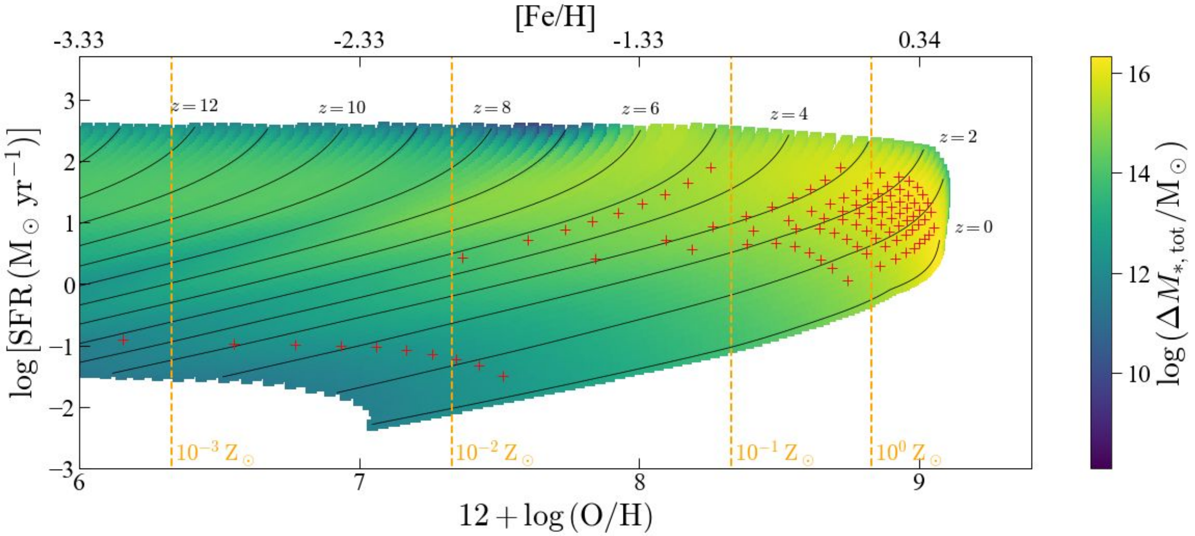
In summary…



$\log[\Phi/(\mathrm{M}_\odot^{-1}\,\mathrm{Mpc}^{-3})]$
$\log(M_*/\mathrm{M}_\odot)$
$12+\log(\mathrm{O/H})$
$\log(M_*/\mathrm{M}_\odot)$
M_*
SFR, Z
$\log[\mathrm{SFR}/(\mathrm{M}_\odot\,\mathrm{yr}^{-1})]$
$\log(M_*/\mathrm{M}_\odot)$
$\{m_{1,i}\}$
$\log[\xi_g(m|[\mathrm{Fe/H}],z)/(\mathrm{M}_\odot^{-1})]$
$\log(M/\mathrm{M}_\odot)$
$\mathcal{P}_{n_\mathrm{cp}}(m_1)$
n_cp
$\{n_{\mathrm{cp},i}\}$
$f_{\log P, q\geq 0.1}(m_1)$
$\log(P/1\,\mathrm{d})$
$\{\{P_j\}_i\}$
$\mathcal{P}_q(m_1,P)$
q
$\{\{q_j,e_j\}_i\}$
$\mathcal{P}_e(m_1,P)$
e

Synthesizing a Composite Binary Population





- Galaxies: star mass-weighted sampling, $10^6 \leq M_*/\mathrm{M}_\odot \leq 10^{12}$.
- Systems: all masses from a single list, without repetition, $0.8 \leq m/\mathrm{M}_\odot \leq 150$.

Mass distributions over redshift

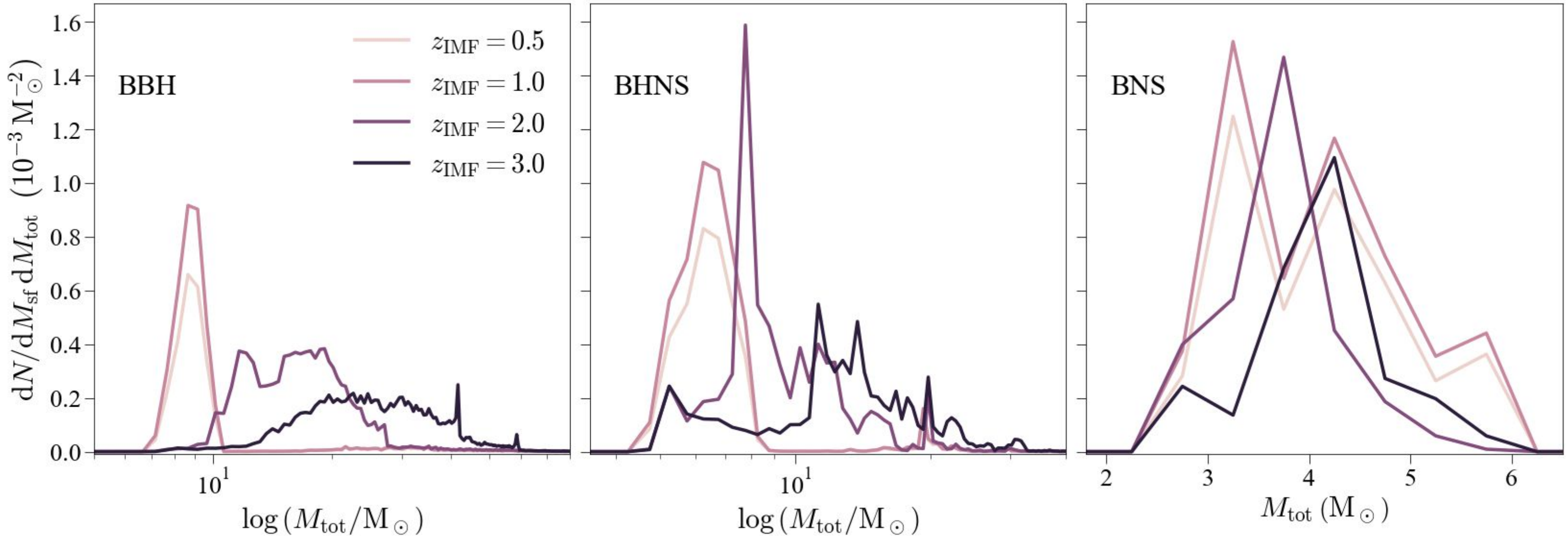
COMPAS
Compact Object Mergers: Population Astrophysics and Statistics

Team COMPAS: Riley+ (2022)

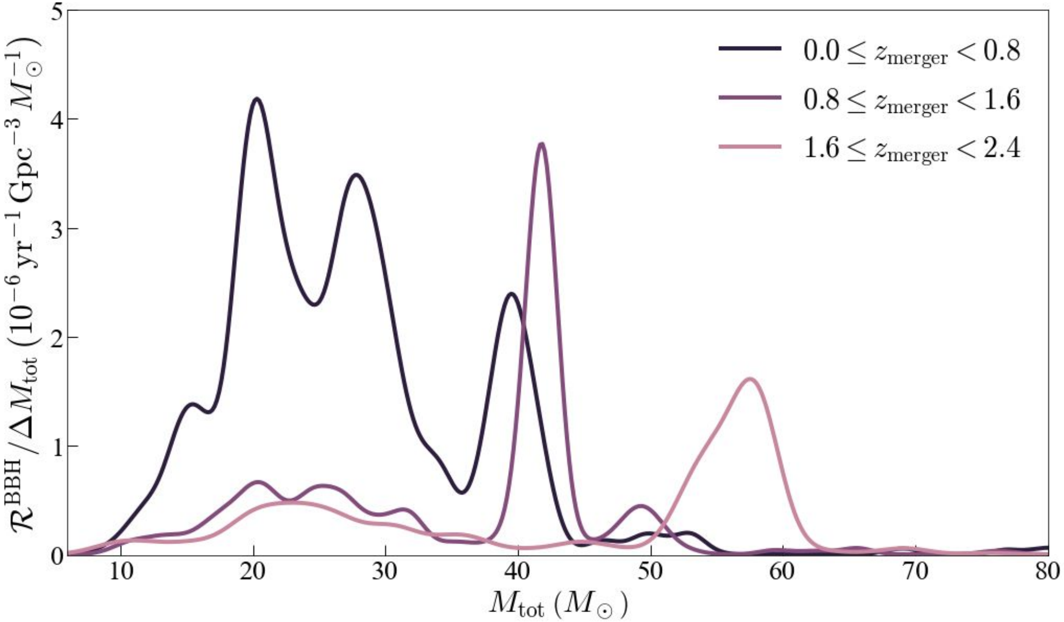
Effects of a non-universal IMF and binary parameter correlations on compact binary mergers

Lucas M. de Sá | Antônio Bernardo | Riis R. A. Bachega | Livia S. Rocha | Jorge E. Horvath

- Preliminary 4 redshift, 3 metallicity per redshift grid.



Merger rates over redshift



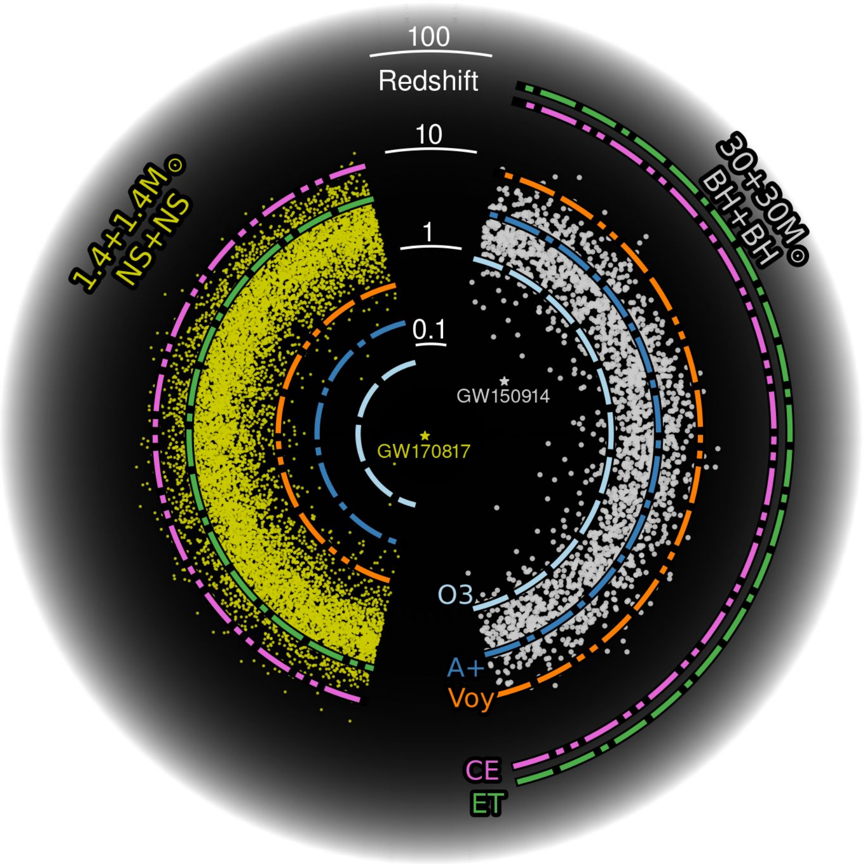
Results from a preliminary sample,

Source	Local merger rate ($\mathrm{yr}^{-1}\,\mathrm{Gpc}^{-3}$)		
	BBH	BHNS	BNS
This work	432	124	63
GWTC-3	16 – 130	7.4 – 320	13 – 1900

at the time missing

- Higher-order multiples
- Higher (z,Z) resolution

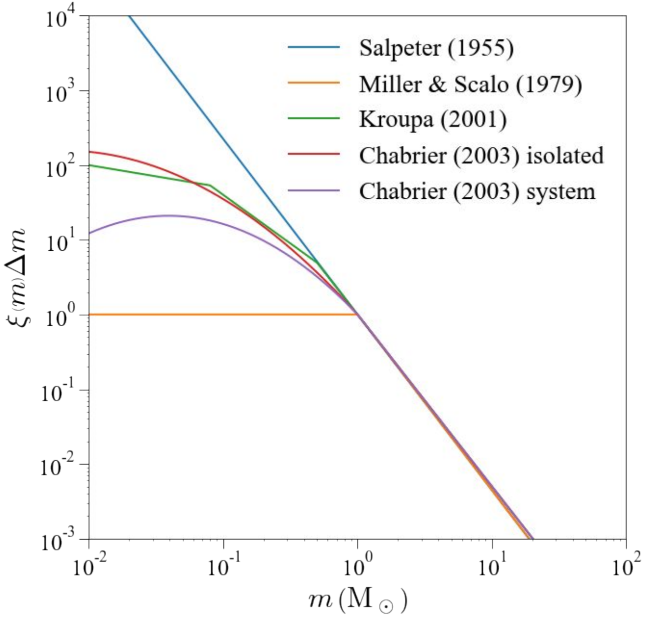
- We are now running the 10x10 z,Z sample, a total of ~10^8 binaries.
- Selection effects in the future.


100
Redshift
10
1
0.1
1.4+1.4M⊙
NS+NS
30+30M⊙
BH+BH
GW150914
GW170817
O3
A+
Voy
CE
ET

Thank you!

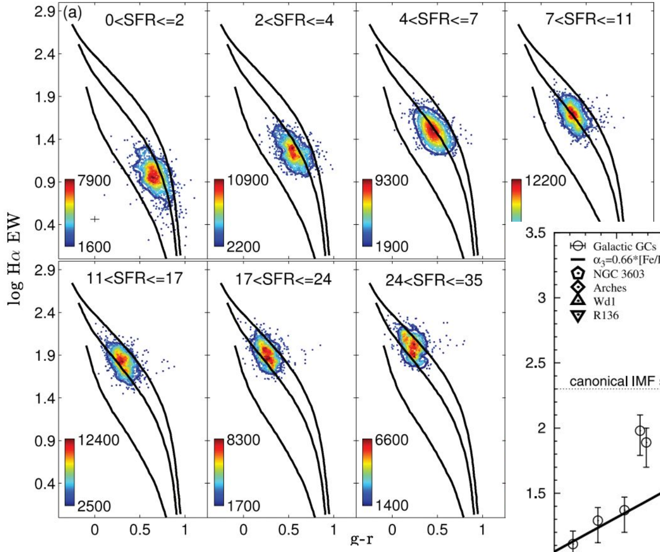
A hot button issue from star formation: is the IMF universal?

The Salpeter (1955) IMF and its descendants: firm, but not without challenges.



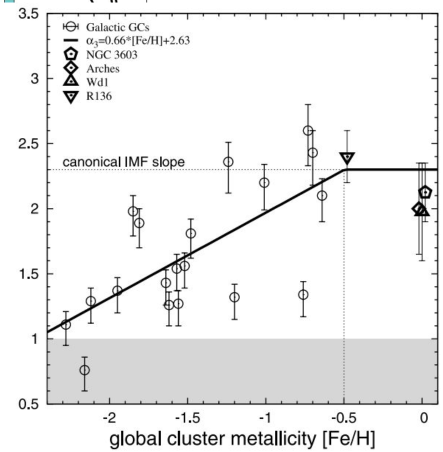
- The usual choices for synthesis.

Theoretical challenges are old (Jeans mass, fragmentation…). Observational support is recent.



Gunawardhana+ (2011)

Reviews:
Kroupa+ (2013)
Hopkins (2018)

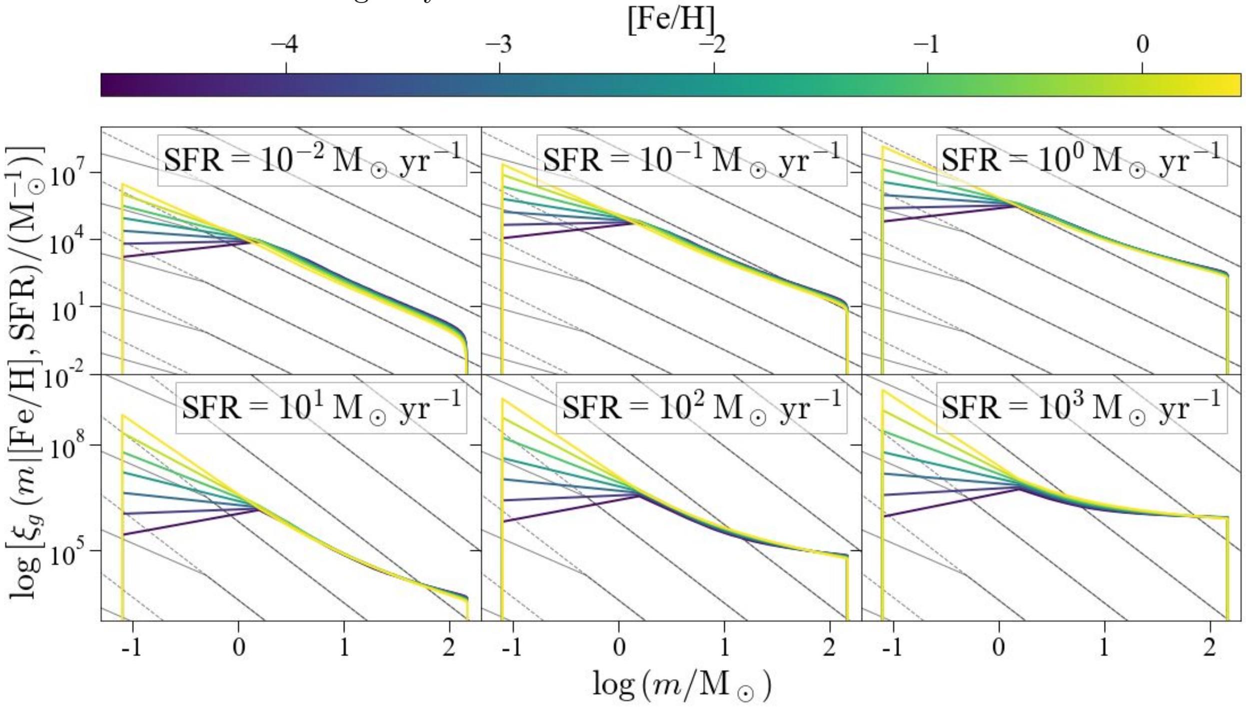


Marks+ (2012)

A hot button issue from star formation: is the IMF universal?

- Alternative**: Integrated galaxy-wide IMF theory (IGIMF) (Kroupa & Weidner, 2003)**

$$\xi_{\rm g}\left(m|[{\rm Fe/H}],{\rm SFR}\right)=\int_{\rm galaxy}\xi_{\rm s}\left(m|M_{\rm ecl},[{\rm Fe/H}]\right)\ \xi_{\rm e}\left(M_{\rm ecl}|[{\rm Fe/H}],{\rm SFR}\right)\ {\rm d}M_{\rm ecl}$$



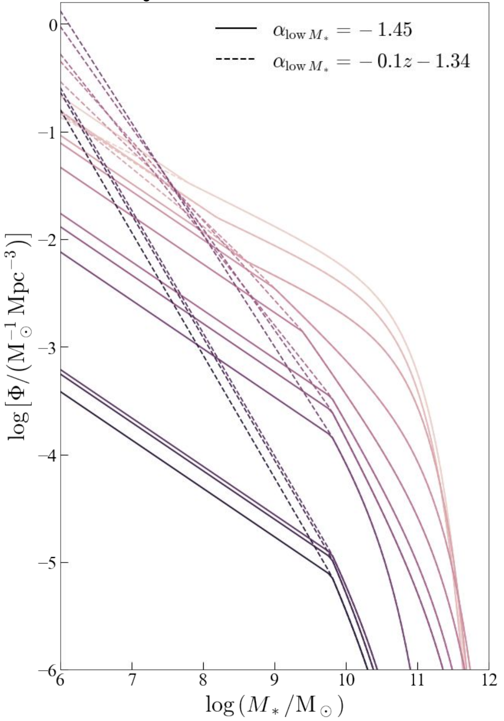
Jeřábková+ (2018)

Star-forming mass and galaxy properties

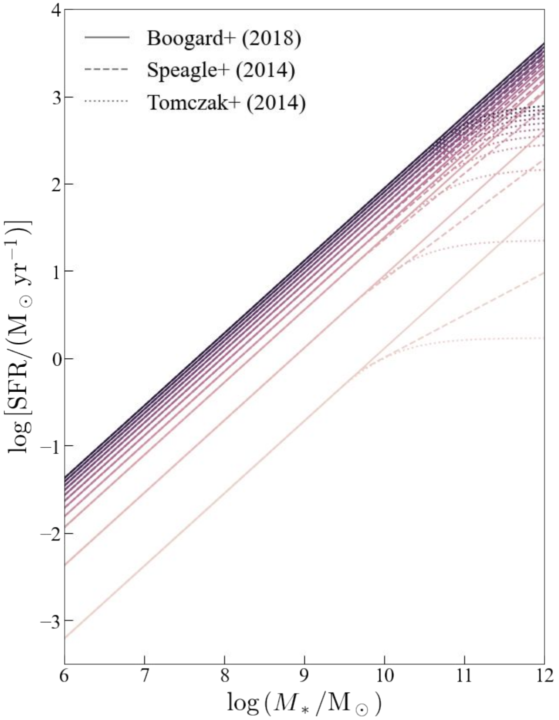
Chruślińska & Nelemans (2019), Chruślińska+ (2020)

Average star mass, SFR and metallicity empirical distributions up to z=10.

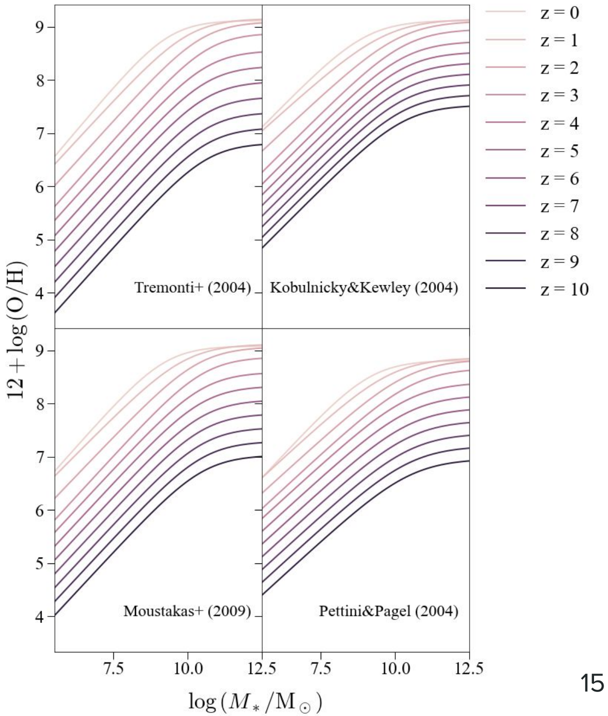
Galaxy stellar mass function



Star formation-mass relation



Mass-metallicity relation

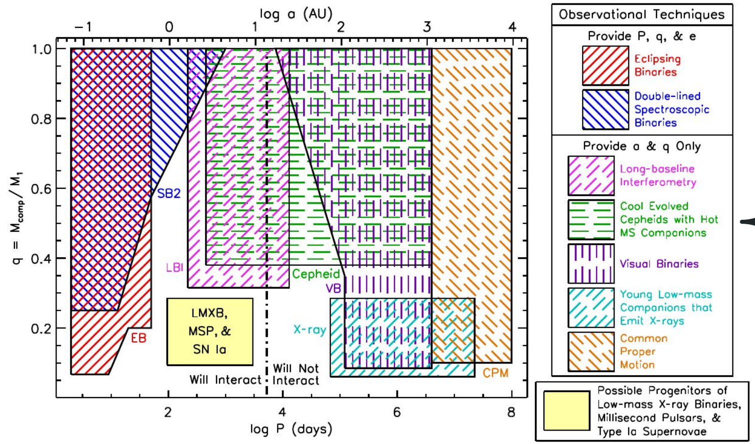


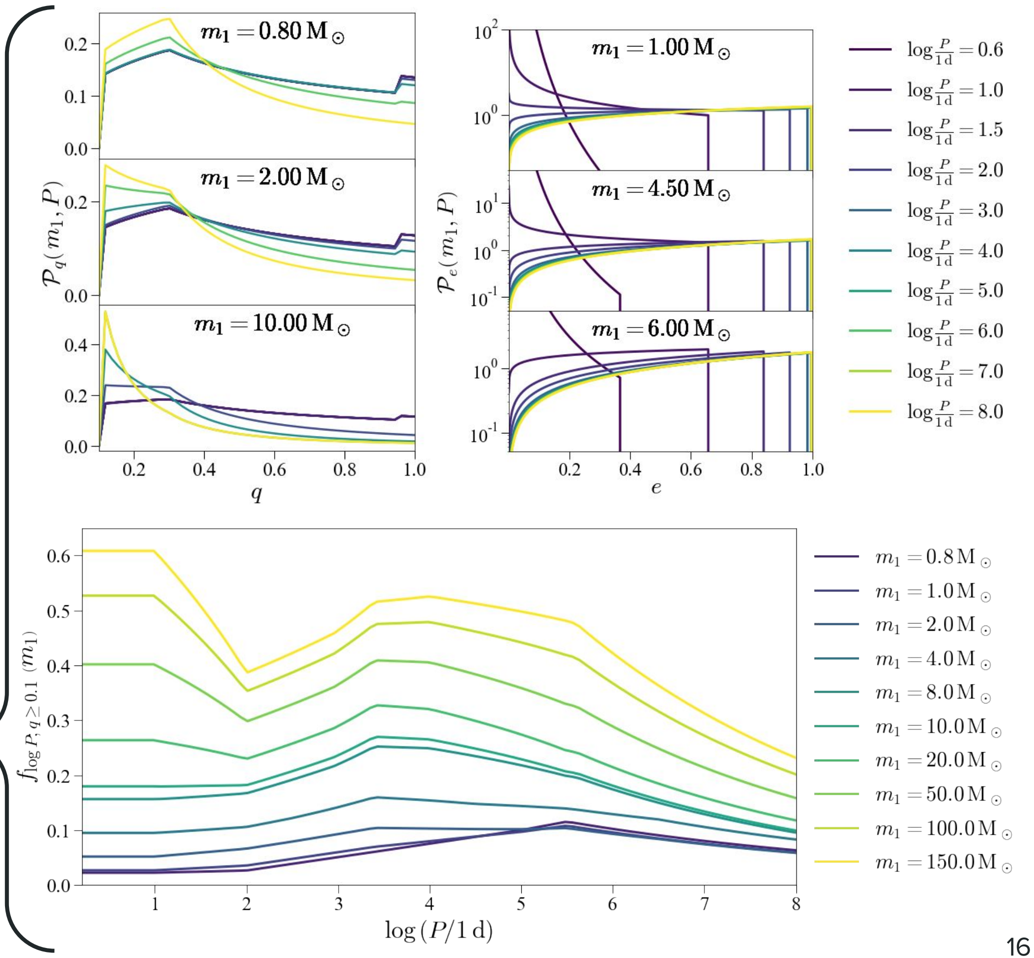
Orbital parameters

Usual choices:

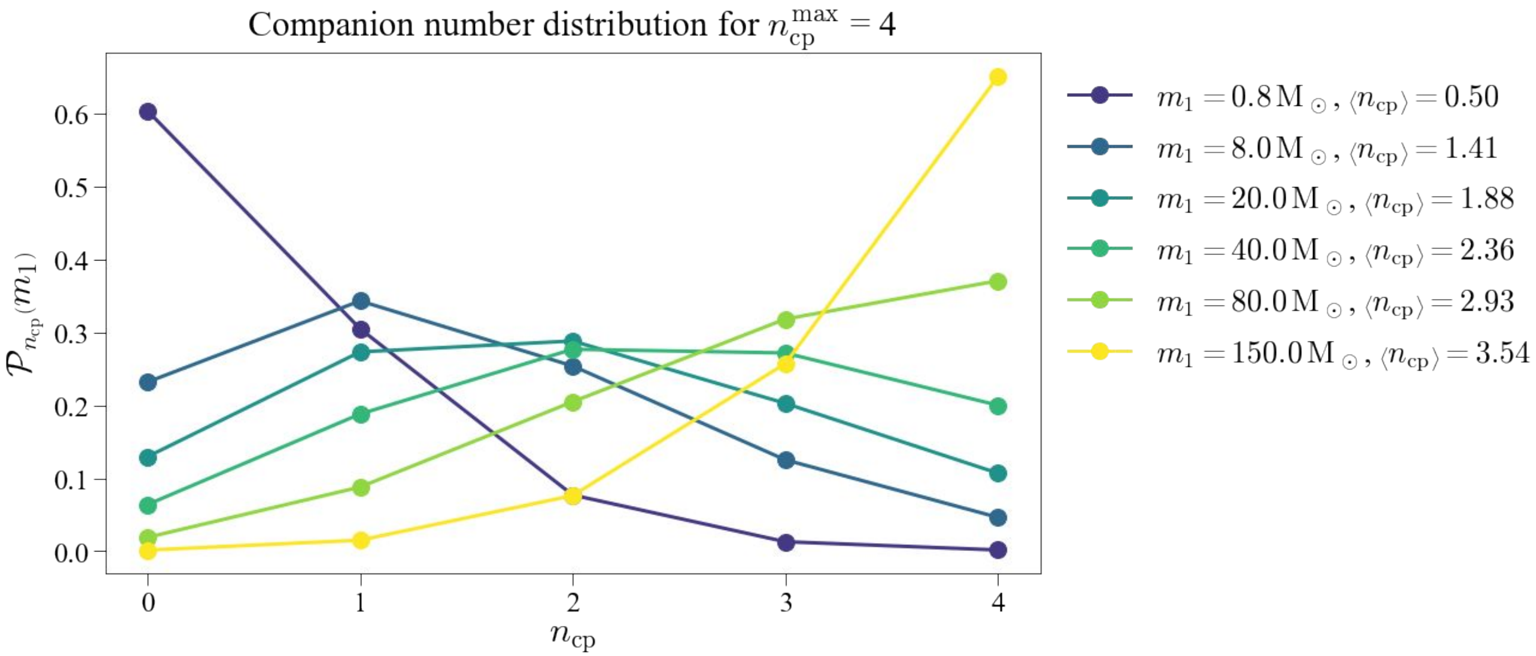
- Uniform (**Sana+, 2012**) $0 \leq q \leq 1$,
- Log-uniform $10^{-2}\,\mathrm{AU} \leq A \leq 10^{3}\,\mathrm{AU}$, (**Öpik, 1924**)
- Circular orbits $(e = 0)$.

However, **Moe & Di Stefano (2017)** found that they are significantly correlated.





Computing the binary fraction requires allowing for higher-order multiples.



We can account for all companion masses, but only evolve inner binaries.