First stars in the universe

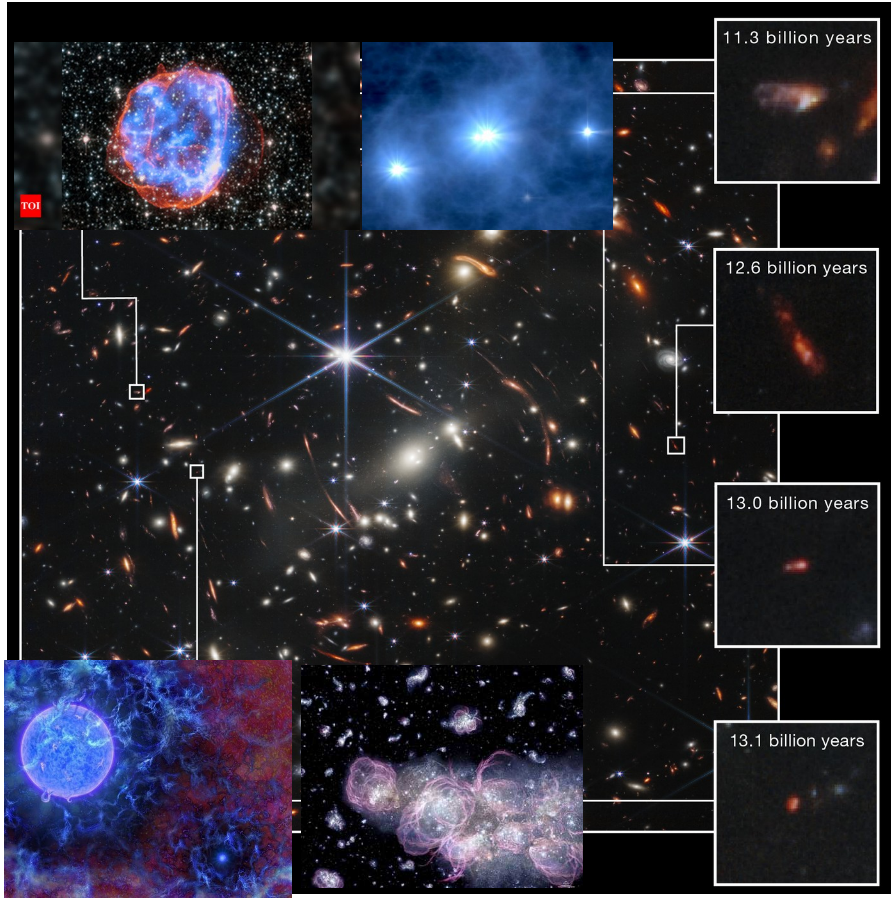
Outline:

PopIII: single/binary stars an Population

PopIII: simulations

PopIII: detectability

→ with e.m. signals
→ with GW Signals.



AMALDI RESEARCH CENTER

DIPARTIMENTO DI FISICA SAPIENZA UNIVERSITÀ DI ROMA

INFN ROMA Istituto Nazionale di Fisica Nucleare Sezione di Roma

ISTITUTO NAZIONALE DI ASTROFISICA INAF

First stars: definition and open issues

- **Defined as stellar objects with metallicity $Z_* \leq 10^{-4}$ $Z_\odot$**
- **Why this definition is highly problematic?**

1. Physical processes regulating star formation and evolution are mainly known at $Z_* \geq 10^{-2}$ $Z_\odot$.

2. Efficiencies are calibrated with observations.

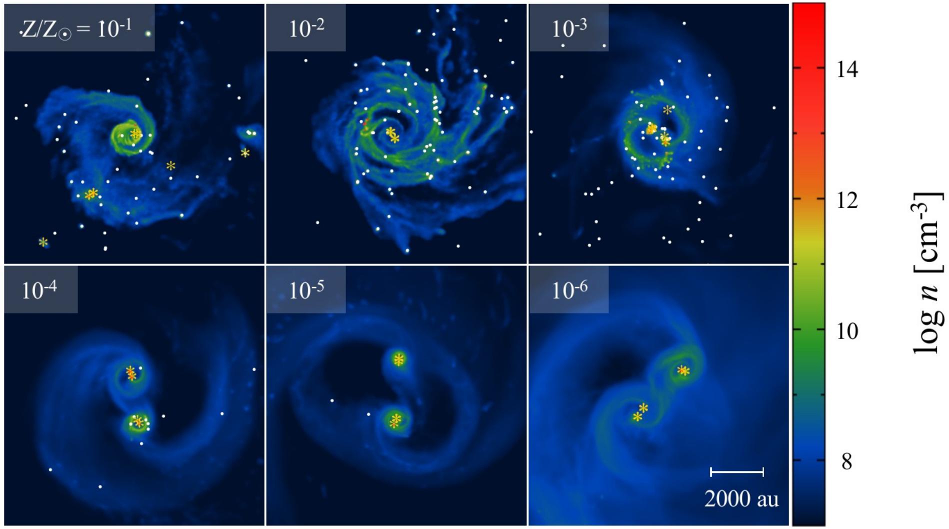
→ **A single Pop III star is difficult to model**

→ Hydrodynamical simulations of "zero"-metallicity cloud Fragmentation →

2.1 **High masses** $M_* \sim 10\text{-}10^3$ $M_\odot$

2.2 **Short lifetimes** $t_* < 3$ Myr

2.3 **End of life** as PISN or BH



white dots $M^* < 1$ $M_\odot$,
yellow asterisks $M > 1$ $M_\odot$

Chon et al. (2021)

First stars: definition and open issues

- **Defined as stellar objects with metallicity $Z_* \leq 10^{-4}\ Z_\odot$**
- **Why this definition is highly problematic?**

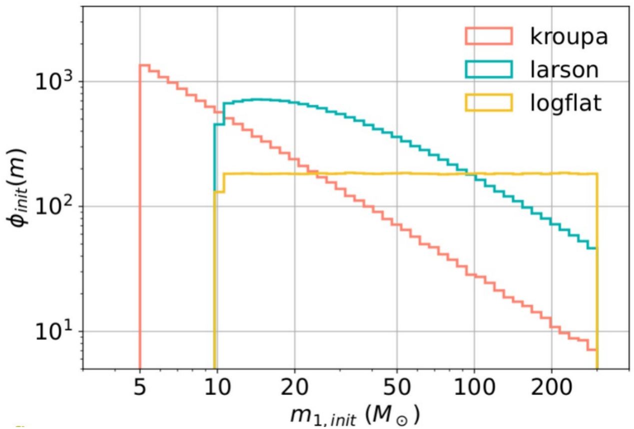
1. Mass distribution (IMF) unknown @$Z_* < 10^{-4}\ Z_\odot$.

2. Are Pop III mainly created as single or binary stars?
→ **A binary of Pop III stars is even more difficult to model**

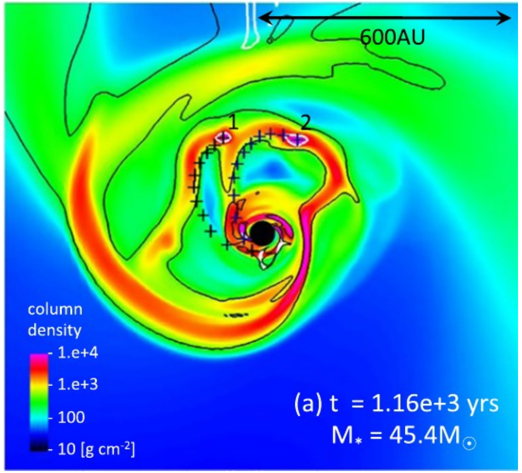
→ Hydrodynamical simulations of "zero"-metallicity of binaries ??

2.1 Are **High masses in a binary stables?**

2.2 **Coevolution ??** → **Binary BH-BH**



Valli 2022, MsC Sapienza)



Hosokawa et al. (2016)

First stars: definition and open issues

- **Defined as stellar objects with metallicity $Z_* \leq 10^{-4}\, Z_\odot$**
- **Why this definition is highly problematic?**

1. Cosmological evolution linked to feedback during EoR .

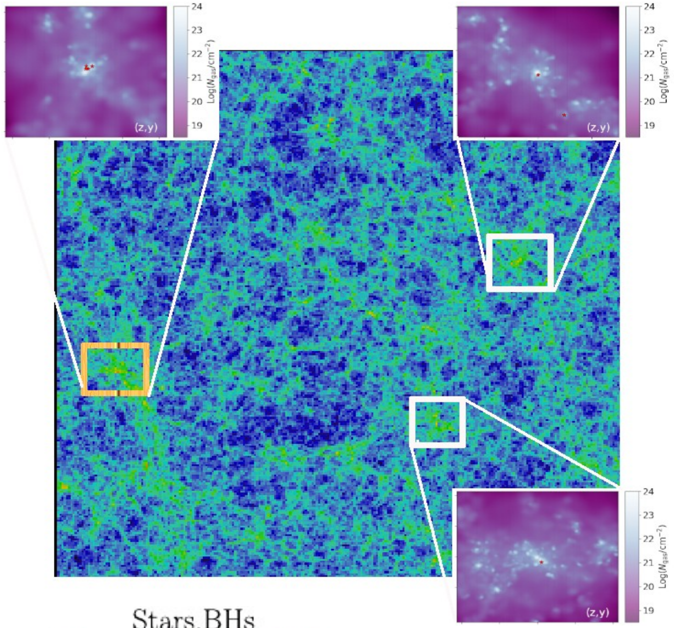
→ **Radiative Feedback →**
Reionization ← Pop III suppression

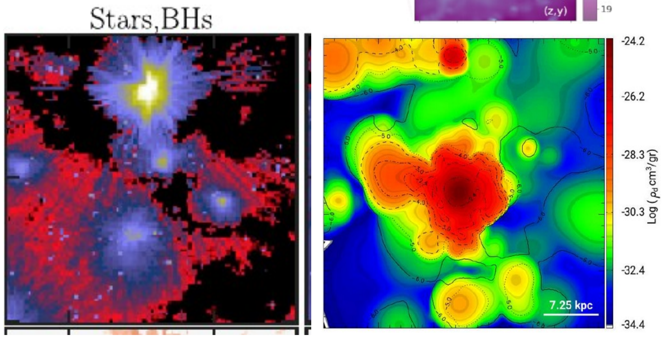
→ **Chemical Feedback →**
Enrichment ← Pop III suppression

When Pop III star formation ends?
→ Transition Pop III/II

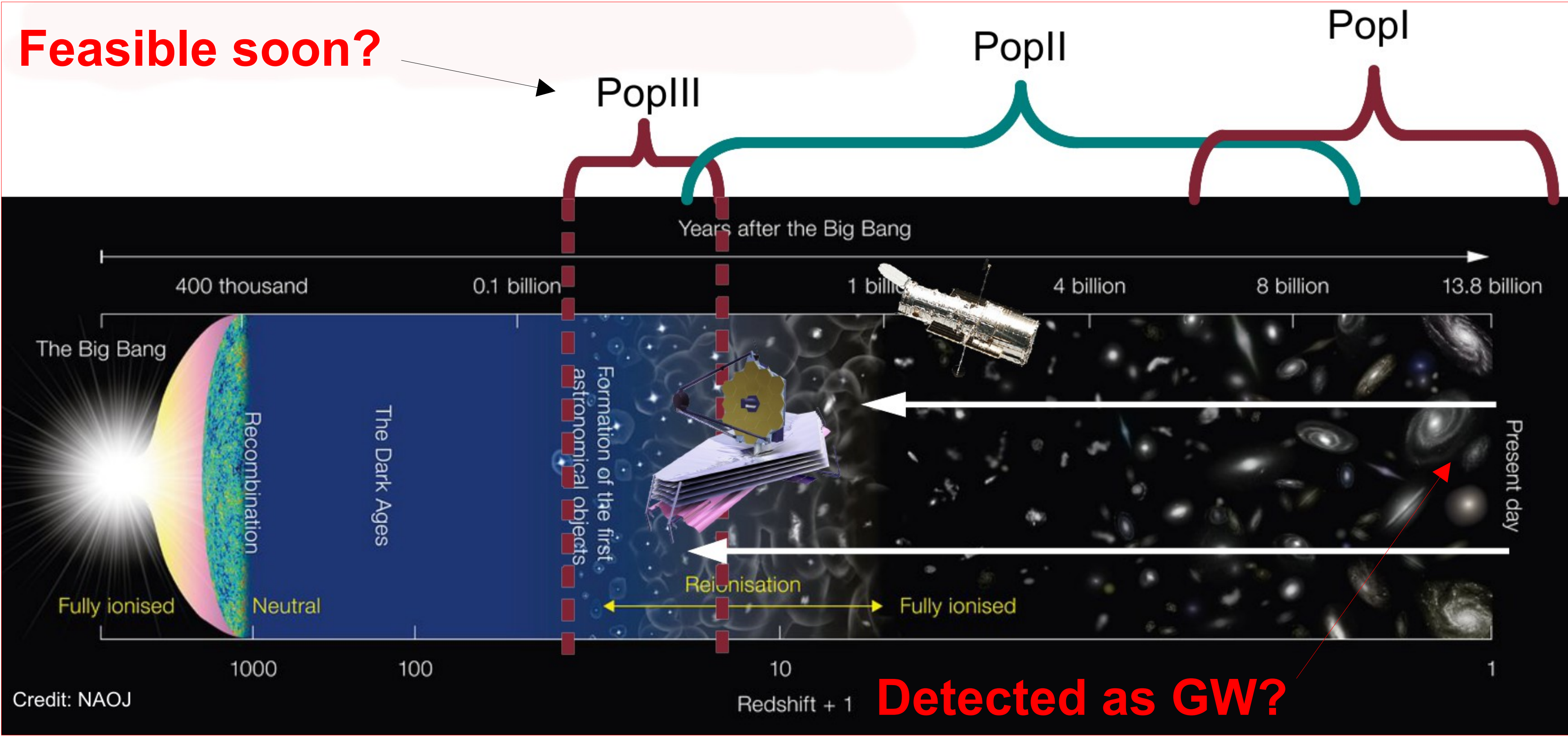
Galaxy hosting Pop III?

Pop III Signatures? → e.m. HeII lines
→ GW emitted by coalescing binaries with high BH mass.





A new era of GW Astronomy, Astrophysics, Cosmology



Future: both E.M. and G.W. accessing high-z universe

Hydro: dustyGadget → Details on galaxy ISM, better star formation, improved chemistry

- The assembly of dusty galaxies at z > 4

  (Graziani L. et al., MNRAS, 2020)

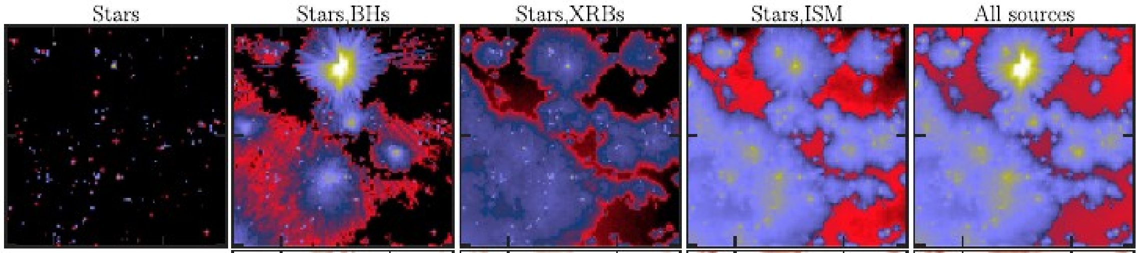
GAMESH+BSEEMP → Low metallicity binaries

- Merging black hole binaries with BSEEMP (Tanikawa et al., ApJ 2022, Valli 2022, MsC, Sapienza)

RT: CRASH/SKIRT → Reionization/SED of dusty galaxies

- Large scale Reionization

  (Eide M., Ciardi, B., **L.G.** et al., MNRAS, 2020)



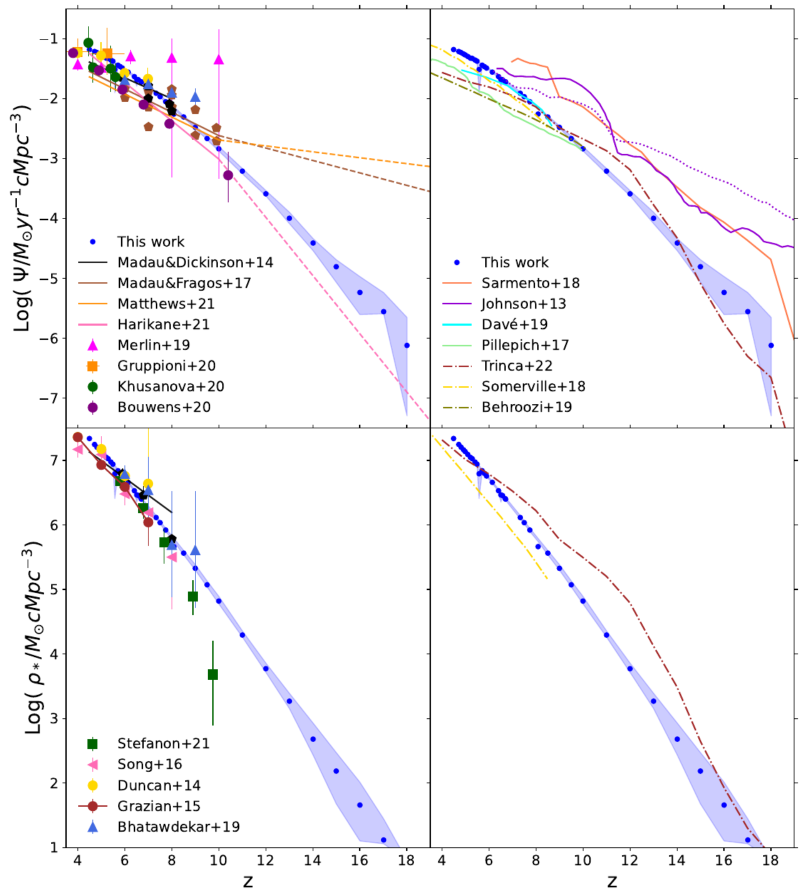
Statistical Properties → Scaling relations

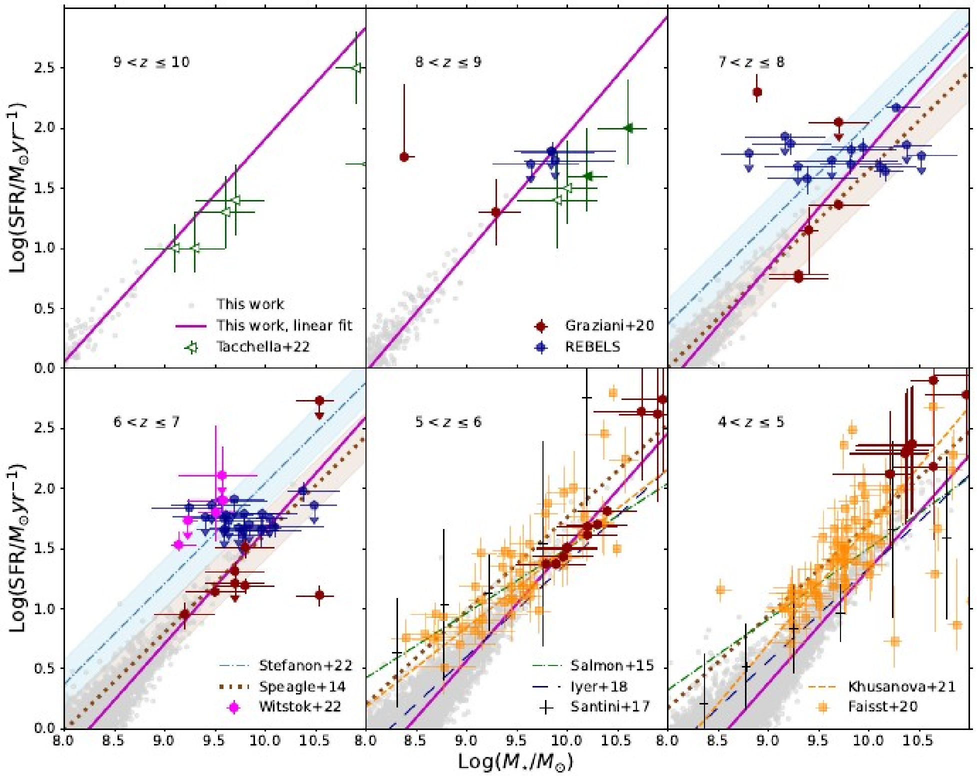
i.e.

Connecting M*, SFR, Z, dust
in a unique statistical framework

(Claudia di Cesare, PhD, Sapienza)

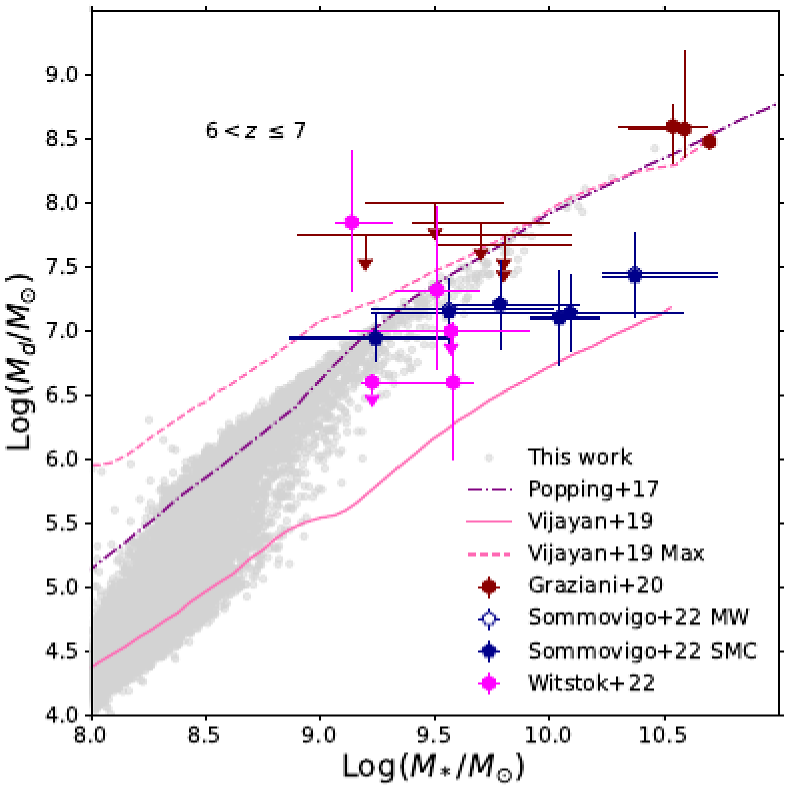
Build-up of stellar mass and galaxy scaling relations

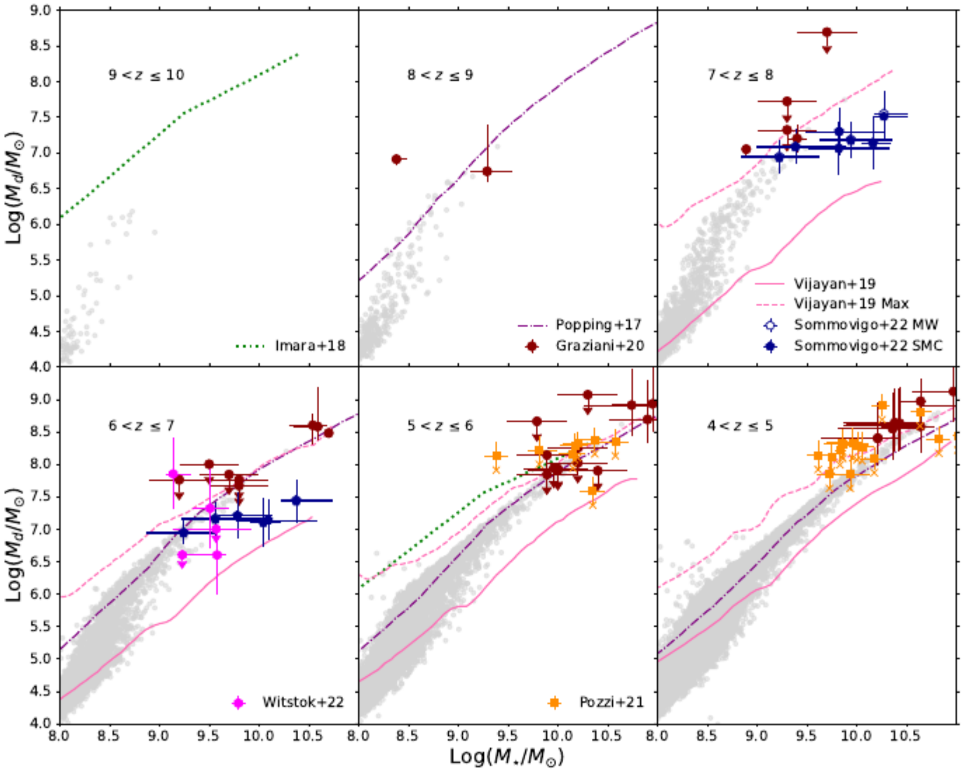




Claudia di Cesare, LG, R. Schneider et al., arXiv:2209.05496

Build-up of stellar mass and galaxy scaling relations





Claudia di Cesare, LG, R. Schneider et al., arXiv:2209.05496

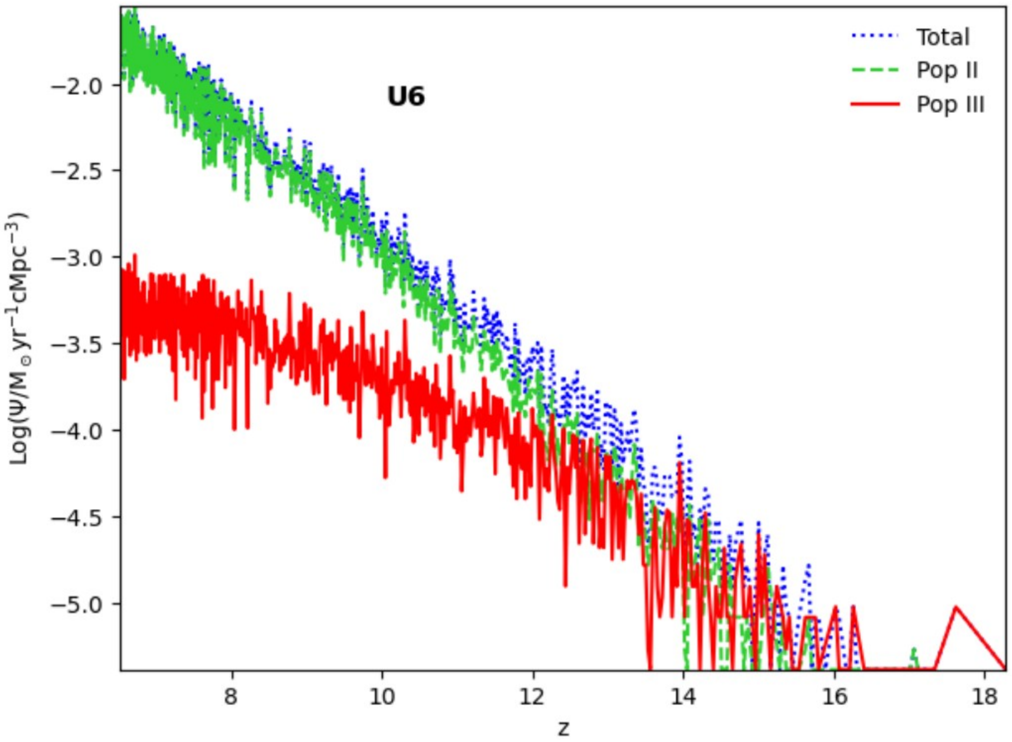
Pop III hosts & Detectability

i.e.

Connecting Pop III hosting galaxies with RT signatures

(Alessandra Venditti PhD, Sapienza)

Catching Pop III stars in EoR: a needle in a haystack?

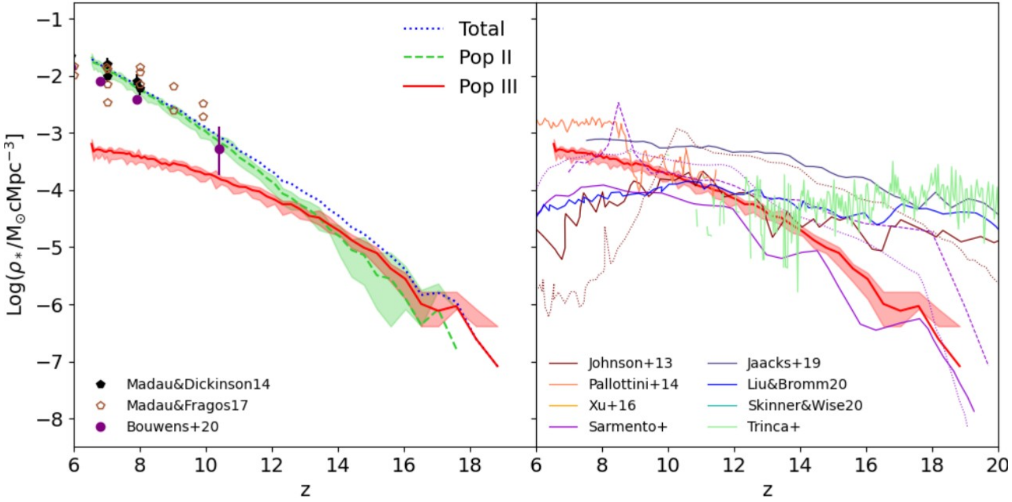


Alessandra Venditti, LG, R. Schneider,
L. Pentericci, et al., in prep.

Pop III → Pop II transition strictly depends on global Feedback.

Pop III star formation suffers progressively large Oscillations as far as the UV background due to Cosmic Reionization establishes

Catching Pop III stars in EoR: a needle in a haystack?

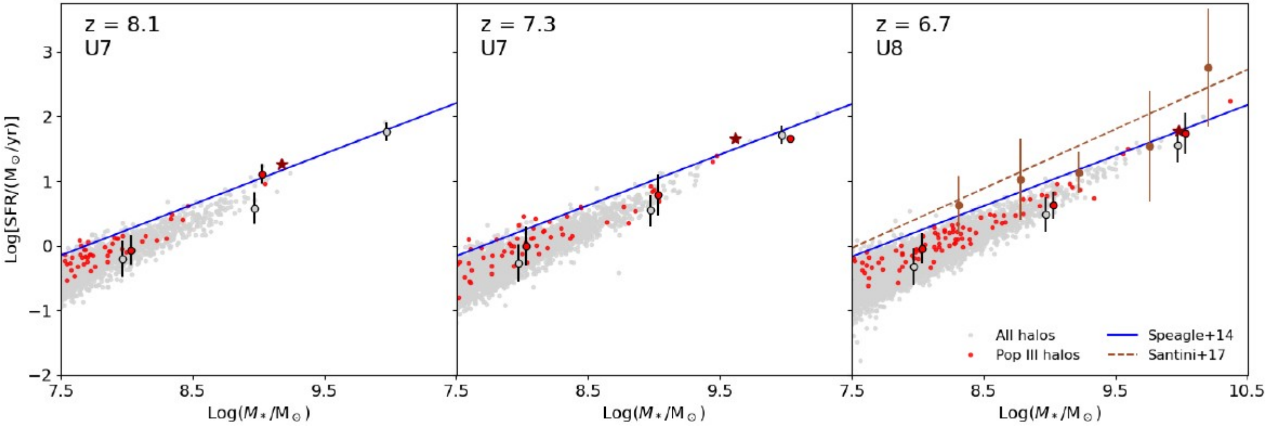


Alessandra Venditti, LG, R. Schneider,
L. Pentericci, et al., in prep.

Pop III → Pop II transition strictly depends on global Feedback.

At present no models have all feedback processes included.

Extended Pop III star formation
Can be present in all MS Galaxies
→ large galaxies could
host Pop III star forming
regions



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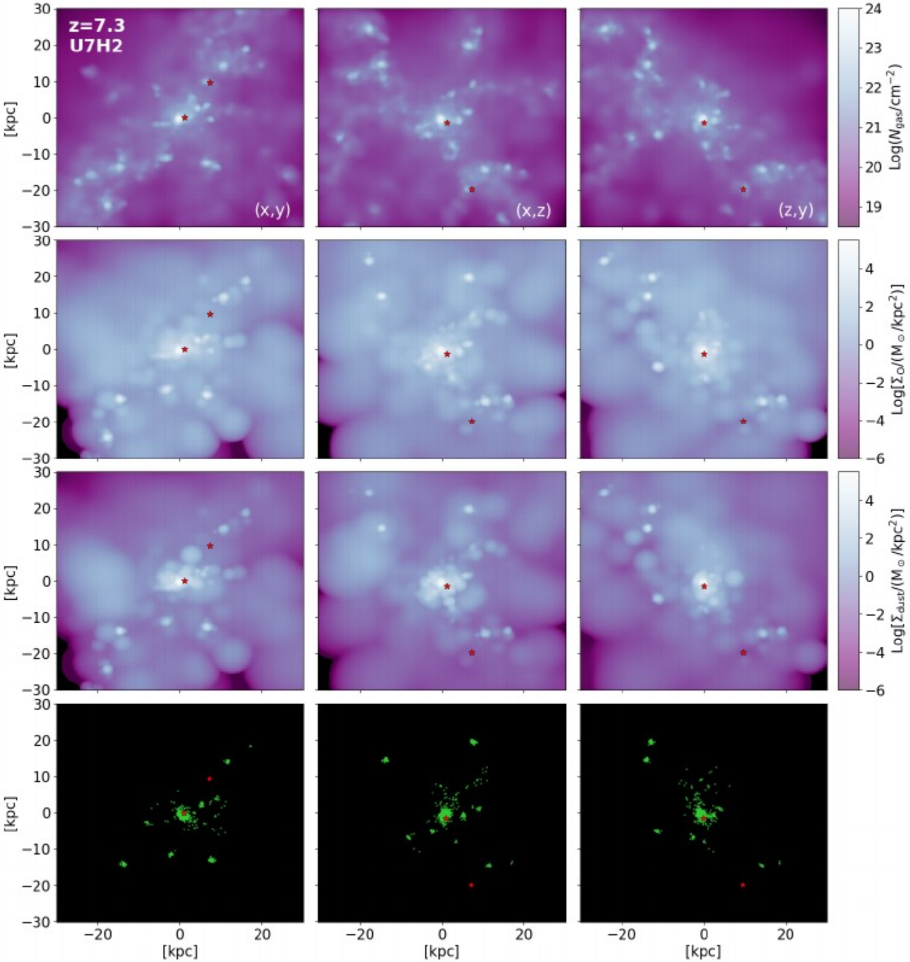

Alessandra Venditti, LG, R. Schneider,
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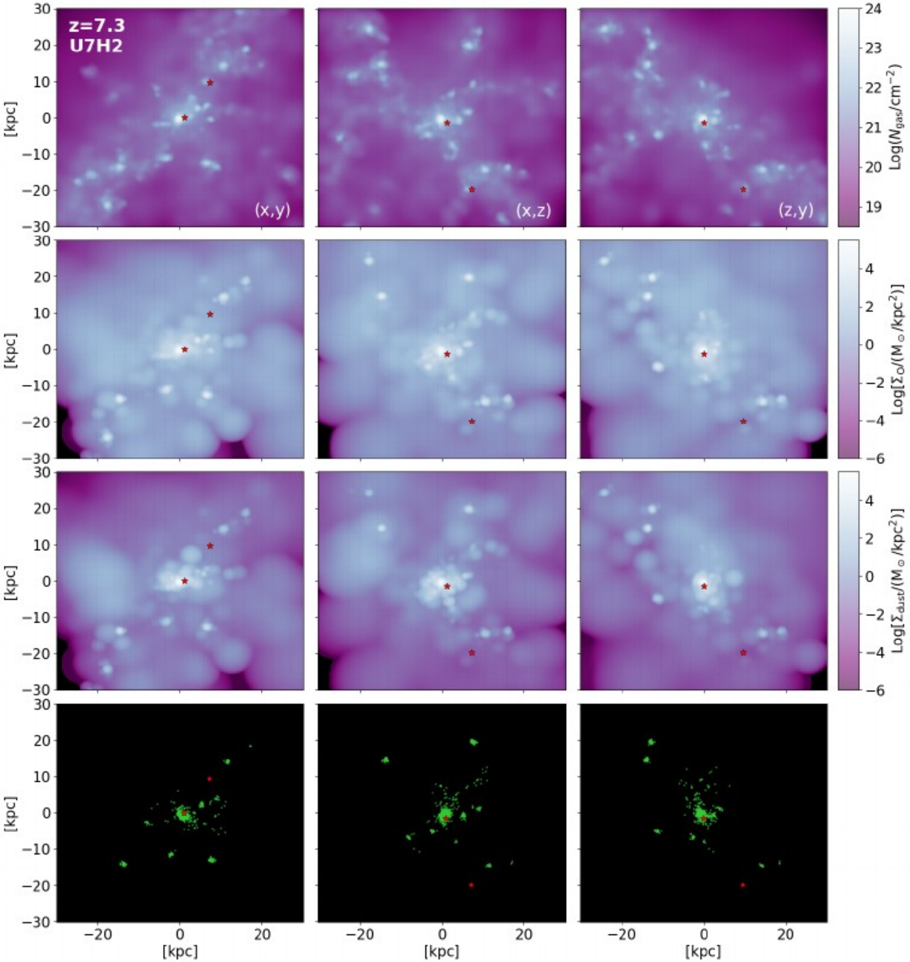
Halo ID	LogM_*/M$_\odot$	LogM_3/M_*	SFR [M$_\odot$ yr^{-1}]	Log$M_{\rm dust}$/M$_\odot$	Log$M_{\rm gas}$/M$_\odot$	Log$M_{\rm DM}$/M$_\odot$
			$z = 6.7$			
U8H0	10.37	-4.05	176	8.27	11.25	12.04
U8H1	**9.97**	**-3.66**	**61**	**7.61**	**11.19**	**11.94**
U7H6	9.90	-3.50	42	7.75	10.85	11.61
U13H0	9.75	-3.44	53	7.29	10.97	11.73
			$z = 7.3$			
U6H0	10.00	-3.59	67	7.83	10.85	11.66
U8H0	9.99	-3.68	78	7.78	11.08	11.85
U8H1	9.83	-3.52	57	7.46	10.96	11.70
U7H2	**9.62**	**-2.91**	**46**	**7.16**	**10.81**	**11.56**
U12H2	9.50	-3.19	25	7.05	10.81	11.57
U8H4	9.49	-3.18	25	7.21	10.66	11.41
U6H2	9.44	-3.13	18	7.14	10.63	11.40
U7H3	9.44	-2.83	20	6.76	10.80	11.55
U10H2	9.41	-2.80	26	6.86	10.63	11.40
U13H2	9.38	-3.07	17	6.87	10.59	11.35
U13H0	9.35	-2.69	19	6.92	10.73	11.46
U10H3	9.33	-3.02	15	6.87	10.62	11.35
U7H95	9.00	-2.38	7	6.10	10.18	10.59
			$z = 8.1$			
U12H3	9.40	-3.08	18	7.15	10.42	11.20
U8H2	9.37	-3.06	24	6.88	10.65	11.39
U12H1	9.35	-3.04	23	6.80	10.63	11.37
U8H1	9.33	-2.93	28	6.76	10.68	11.44
U7H4	**9.18**	**-2.26**	**18**	**6.58**	**10.55**	**11.30**
U8H5	9.02	-2.61	11	6.46	10.45	11.20
U10H2	9.01	-2.70	10	5.95	10.43	11.18
U10H5	8.99	-2.68	8	6.51	10.22	10.99
U6H5	8.97	-2.65	8	6.25	10.37	11.12

Catching Pop III stars in EoR: a needle in a haystack?



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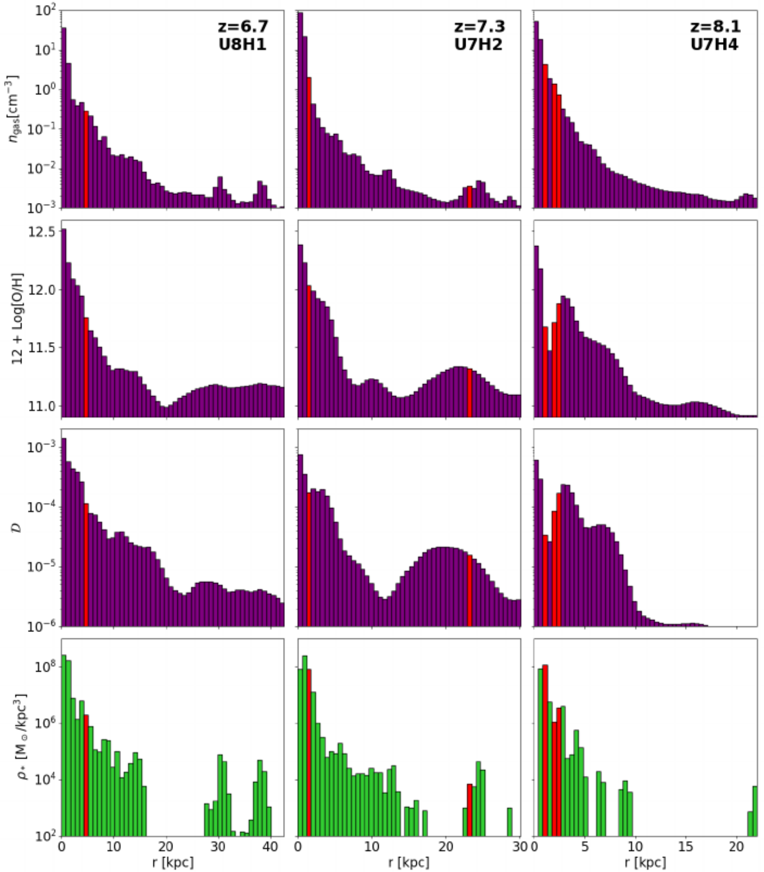
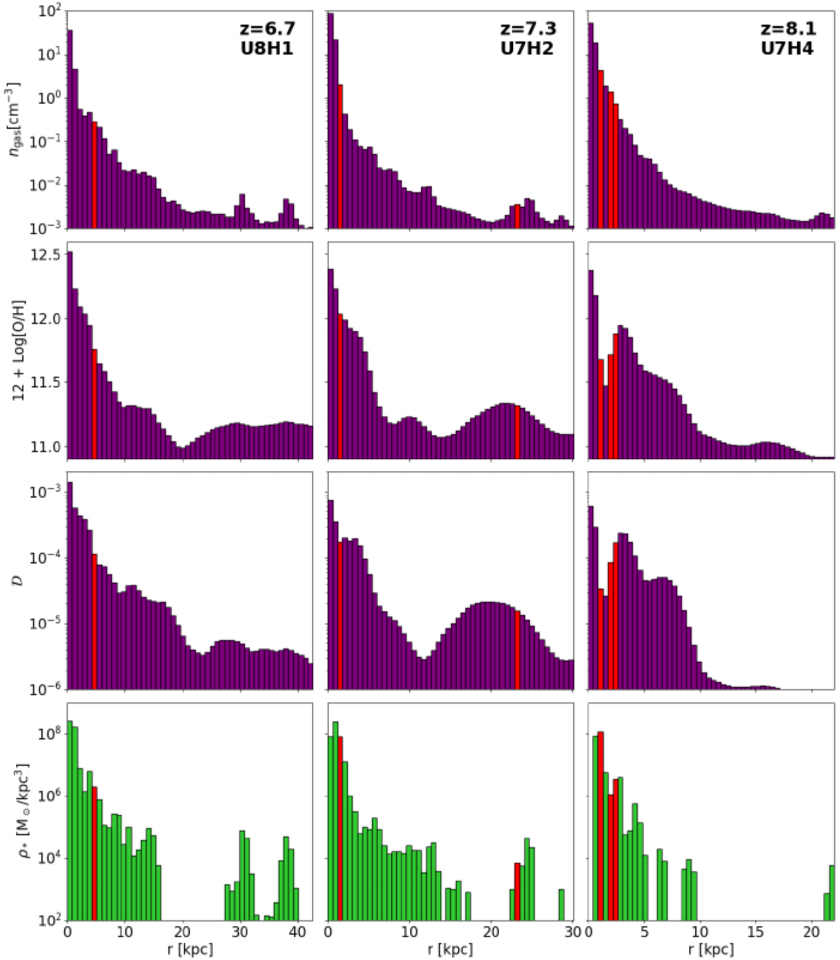


Can we recognize these Pop III stars?



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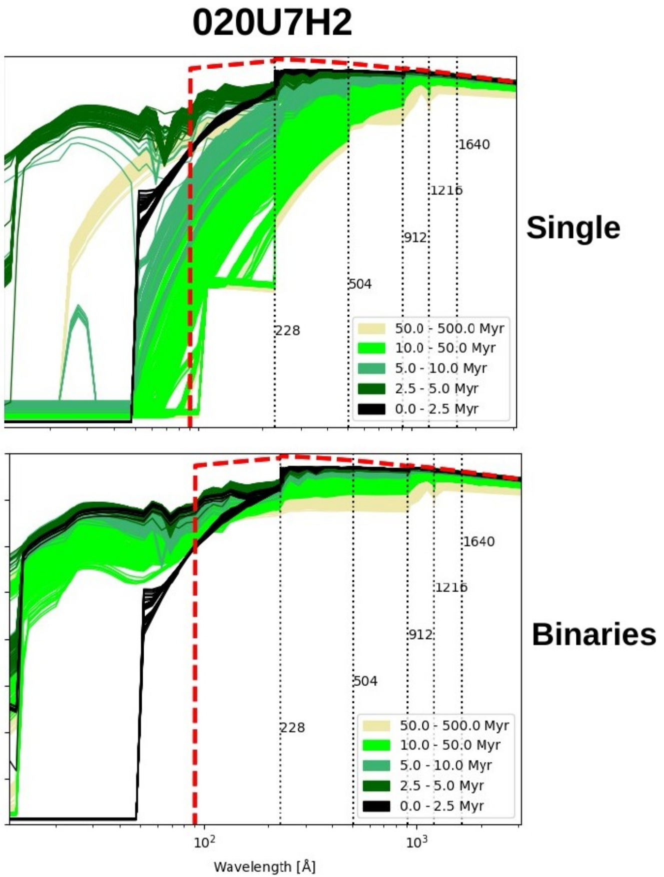

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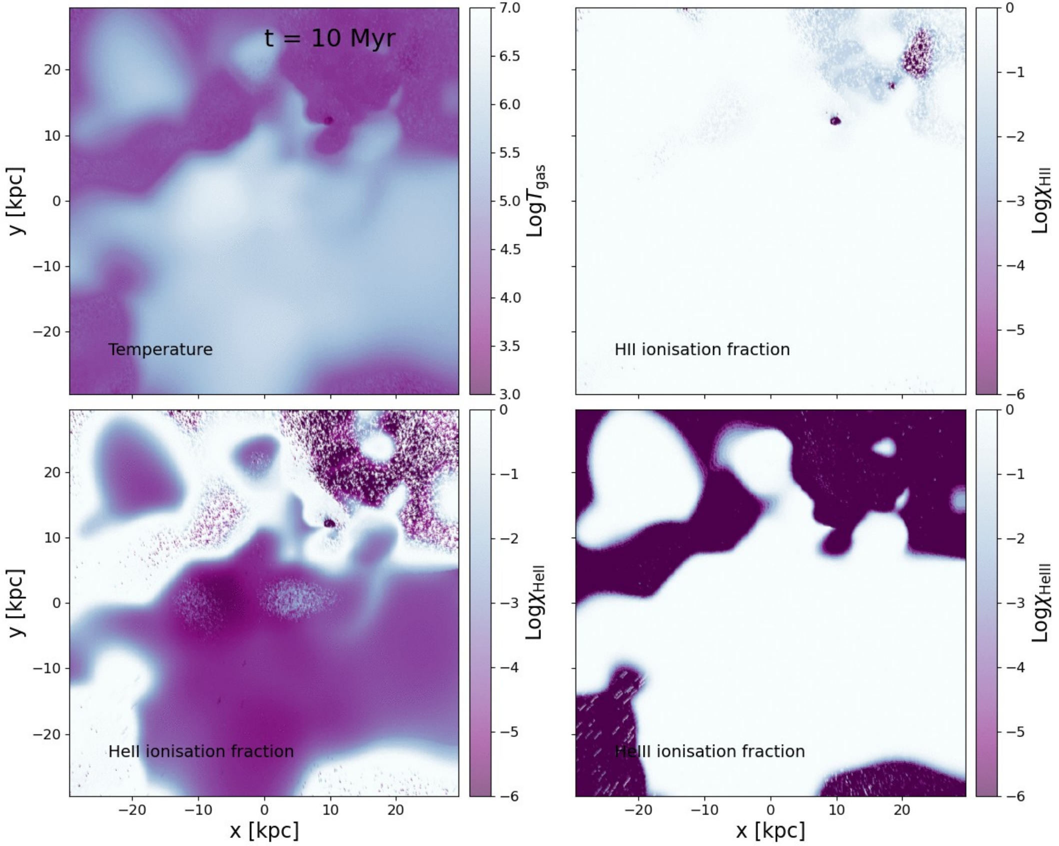


RT simulations tracking the escaping Spectrum can predict transient HeII lines

Pop III and X-rays binaries could be Confused in a low metallicity case..

Archaeology as complementary tool

i.e.

Gravitational Waves from Pop III binaries
(Ruggero Valli, MsC, Sapienza)

Cosmic archaeology with massive stellar black hole binaries

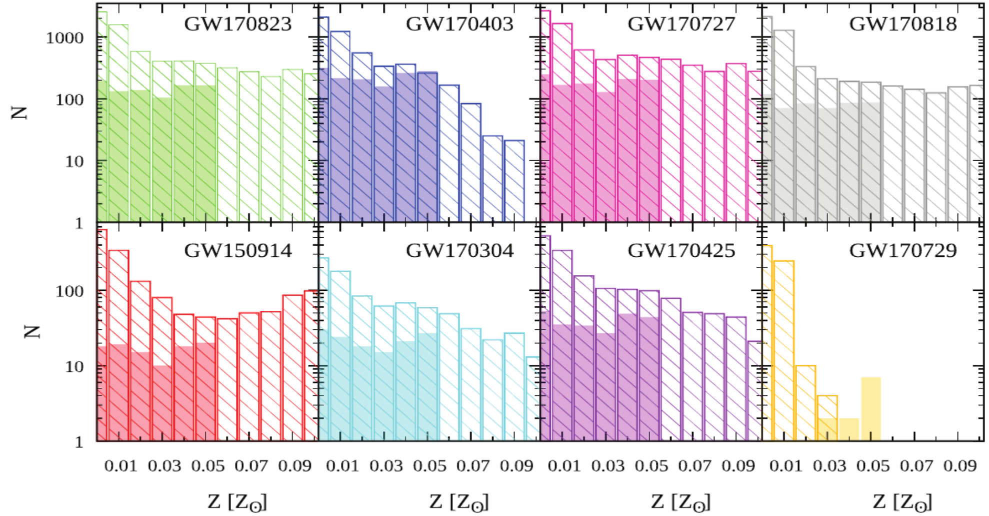
Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

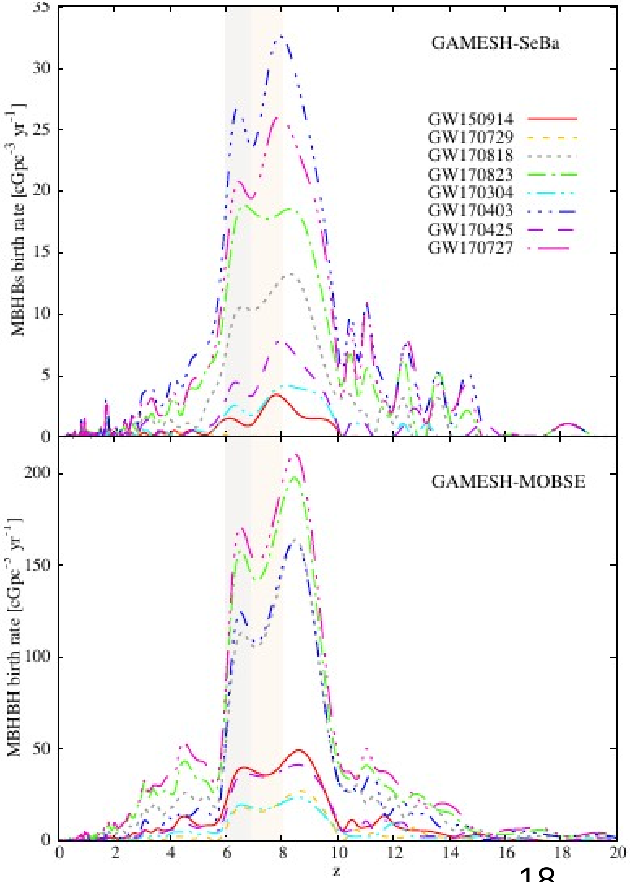
L. Graziani [1,2,3★] R. Schneider [1,2,4] S. Marassi,[1,2] W. Del Pozzo [5] M. Mapelli [6,7,8] and N. Giacobbo [6,7,8]

MNRAS 495, L81–L85 (2020)

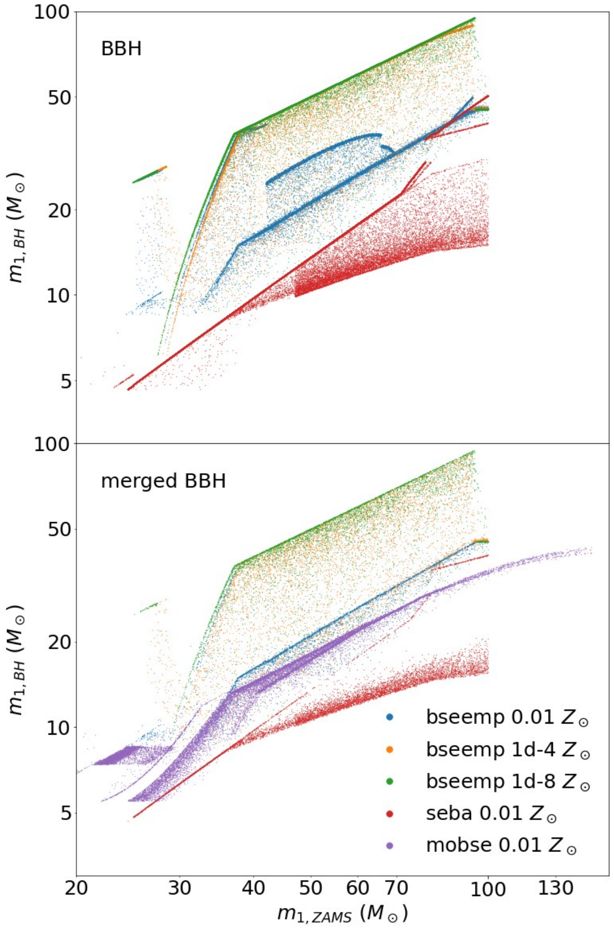
Statistical evidence of a high formation rate during reionization!

Are we probing high-z, low metallicity environments with coalescence of massive stellar binaries?



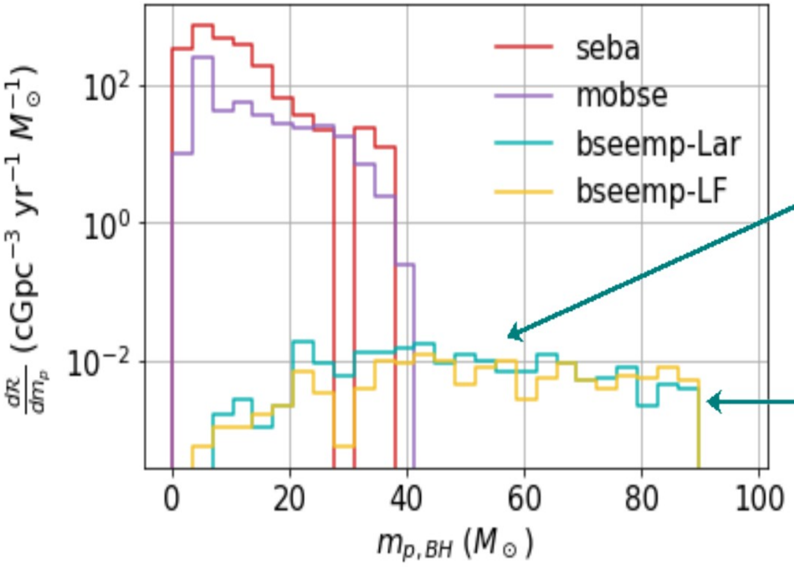


BSEEMP: Pop III binaries



Ruggero Valli, LG, R. Schneider, MsC Sapienza.

Coalescence rate as a function of primary BH mass



Buchi neri di massa m>40 M⊙ sono possibili candidati di origine PopIII.

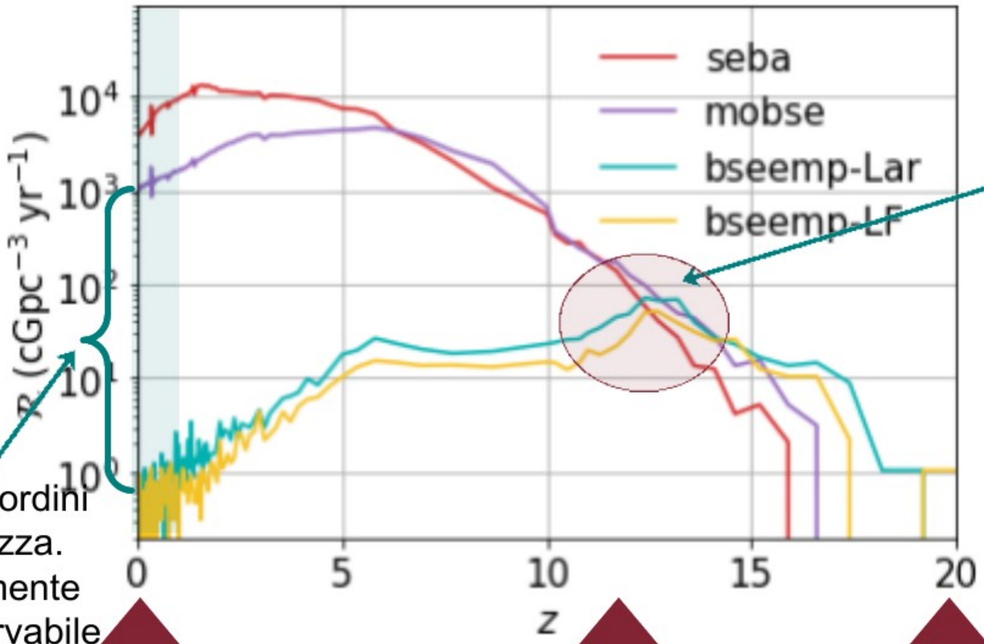
IMF ha un effetto piccolo

Low-Z binaries during EoR with long delay times would be a natural channel to explain high-mass coalescing binaries already in O3!

BSEEMP: Pop III binaries

Ruggero Valli, LG, R. Schneider, MsC Sapienza.

Coalescence rate as a function of redshift: comparing Pop II and Pop III events



Tasso più alto tra redshift 10 e 14.
ET può vederlo

Più di tre ordini di grandezza.
Probabilmente non osservabile oggi.

13.7 Gyr

400 Myr

200 Myr

Big Bang

CONCLUSIONS

- **New signals from the Remote Universe** from both **E.M.** and **G.W.** observations already available and will increase in statistics in the years to come thanks to **new facilities.**

- Discovery of Pop III stars requires **updates in theoretical models of both star formation and galaxy formation**, especially in the low-mass / low-metallicity regimes.

- GAMESH was successfully applied to **interpret both E.M. detections and sources of G.W. consistently with the assembly history** of our Local Group galaxies →

  BSEEMP is ready for Pop III binaries while their detectability in GW at z = 0 remains problematic !

- Hydro and RT codes are ready to improve models of IGM reionization but New RT schemes are required to interpret the ISM ionization and spectral signatures of Pop III stars.

- dustyGadget is ready to interpret present observed dusty galaxies while its ISM requires a more detailed dusty physics on galactic scales of the ISM → low scale metal enrichment affects Pop III in big galaxies.

- **Not the whole story**: improvements can be made both on Galaxy models and BPS Stellar models to predict new kind of signals as they will be discovered by future facilities.