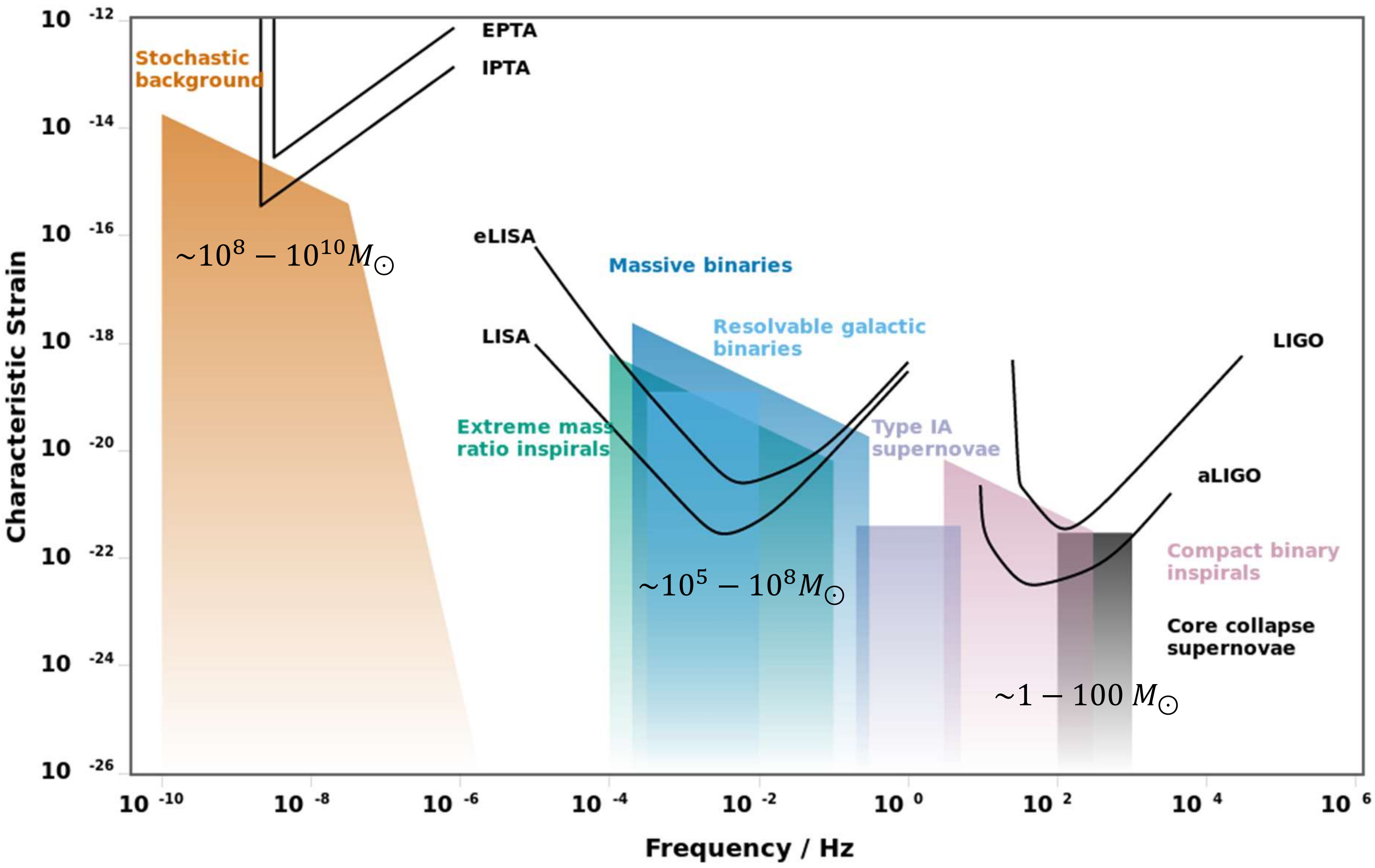
Black hole seeding schemes and their impact on merger rates: insights and perspectives for LGWA

Jasbir Singh

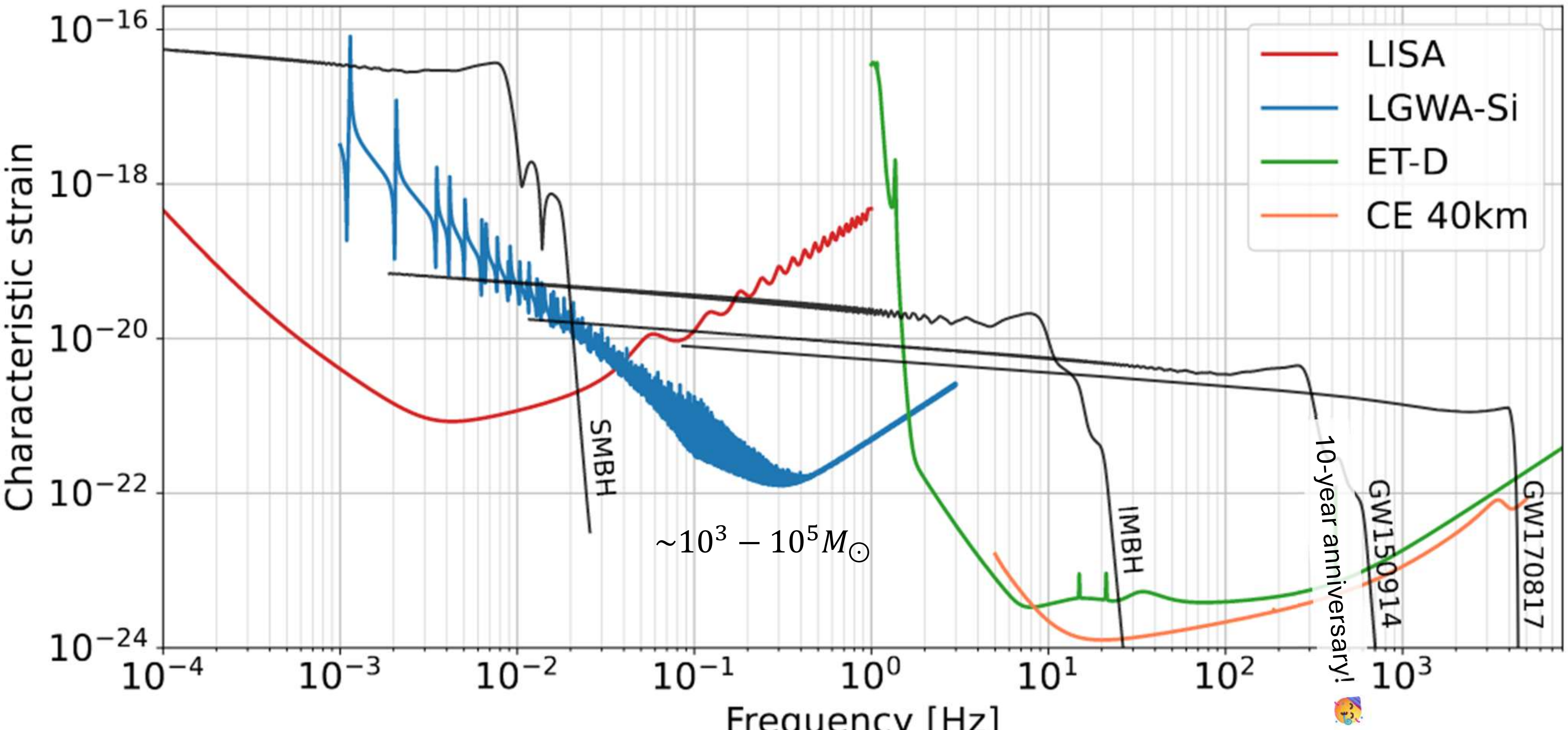
INAF-Osservatorio Astronomico di Brera, Milan

Collaborators: Paola Severgnini, Alessandra De Rosa, Cristian Vignali, Vieri Cammelli, Fabio Rigamonti, Rosa Valiante, Pierluigi Monaco, Jonathan Tan, Manali Parvatikar, Lorenzo Battistini and more!

- What are black hole seeding schemes?
- Why does it matter for LGWA?



Credit: Christopher Moore, Robert Cole and Christopher Berry - http://rhcole.com/apps/GWplotter/



Ajith et al., 2024, arXiv:2404.09181

Black hole seeding schemes

- Implementing black hole formation mechanism in cosmological simulations.
  - BH formation spans orders of magnitude.
  - Impossible for large scale simulations to implement in-situ formation.

Black hole formation mechanisms

- Pop III remnants
  Initial Mass Function (IMF) of the stars peaking at $\sim 100\ M_{\odot}$, but with a tail extending to $\sim 10^3 M_{\odot}$ (e.g. Greif and Bromm, 2006; O'Shea and Norman, 2007; Tan et al., 2010).

- Dense stellar environments
  Runaway stellar mergers in young and dense metal-poor clusters to create stars with masses of the order $\sim 200 - 103_{\odot}$ (e.g., Portegies Zwart et al., 2004).

- Direct Collapse
  Collapse of a massive primordial composition gas cloud contained in a relatively massive, atomically-cooled halo of $\sim 10^8_{\odot}$ into a single, supermassive star of $10^4 - 10^6 M_{\odot}$ that then forms a SMBH. (e.g., Bromm and Loeb, 2003; Lodato and Natarajan, 2006;Maio et al., 2019; Bhowmick et al., 2022a).

Seeding in simulations

- Light seeds
  Pop III mechanism - requires resolving primordial gas at high redshifts and star formation with masses less than $\sim 10^3 M_\odot$.

- Heavy seeds
  Dense stellar environment – requires resolving stellar dynamics withing star clusters (e.g., Boekholt et al. 2018; Chon & Omukai 2020; Tagawa et al. 2020)

  Direct collapse – requires resolving the star formation with masses $\sim 10^{4-6} M_\odot$ in halos of $\sim 10^8 M_\odot$ and the suppression of fragmentation with an external source of Lyman-Werner radiation (Latif et al., 2013; Wise et al., 2019; Habouzit et al., 2016)

Seeding in simulations

- **Illustris** cosmological simulation suite
  Vogelsberger et al. 2014a,b; Genel et al. 2014; Sijacki et al. 2015; Nelson et al. 2015
  Volume – 106.5 cMpc side length
  Baryonic mass resolution - $1.26 \times 10^6\ M_\odot$
  DM mass resolution - $6.26 \times 10^6\ M_\odot$

$M_{BH} \sim 10^5 M_\odot$ in $M_{DM} \sim 10^{10} M_\odot$

- The Evolution and Assembly of GaLaxies and their Environments (**Eagle**) simulations
  Schaye et al. 2015; Crain et al. 2015
  Volume – 100 cMpc side length
  Baryonic mass resolution - $1.8 \times 10^6\ M_\odot$
  DM mass resolution - $6.26 \times 10^6\ M_\odot$

Seeding in simulations

- **DRAGON-II** simulations
  Arca-Sedda et al. 2023, 2024a, 2024b
  19 star cluster models
  Initial number of stars $= (1.2, 3, 6, 10) \times 10^5$
  Stars with masses $m_{\mathrm{ZAMS}} = (0.08\text{–}150) M_{\odot}$

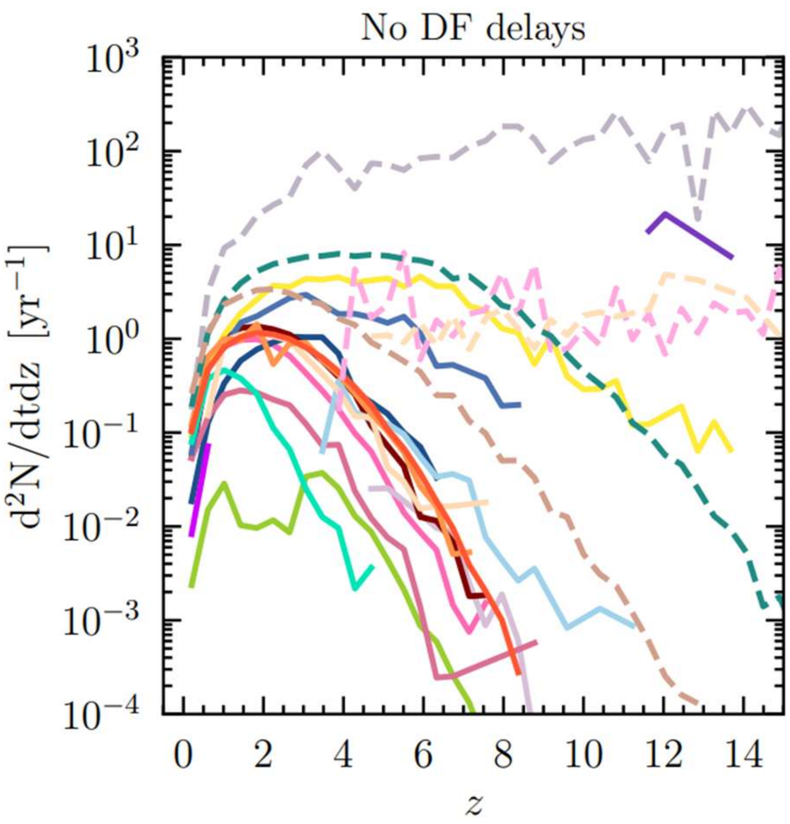
- Semi – analytical models (SAMs)
  - Cosmic Archaeology Tool (Trinca+22)
  - L-Galaxies (Izquierdo-Villalba+22, Spinoso+23)
  - PinGAEA (Cammelli+25)

$M_{BH} \sim 10 - 10^5 M_{\odot}$

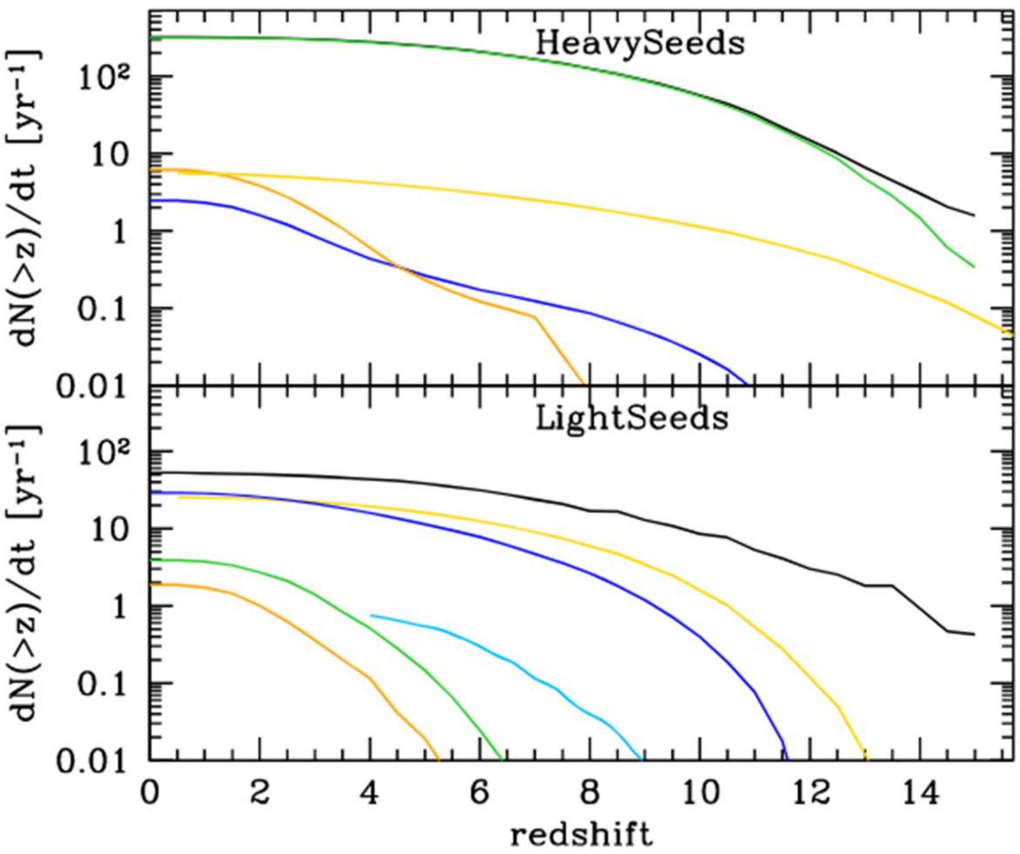
Formation to merger

- Seeding scheme
- Growth
  - Accretion mode
  - Feeback
  - Mergers
- Dynamical evolution
  - Halo mergers and galaxy mergers delays
  - Dynamical friction
  - Stellar hardening
  - Multiple BH interactions – recoil kicks
- Merger
  - Spin evolution
  - Eccentricity
  - Mass ratio

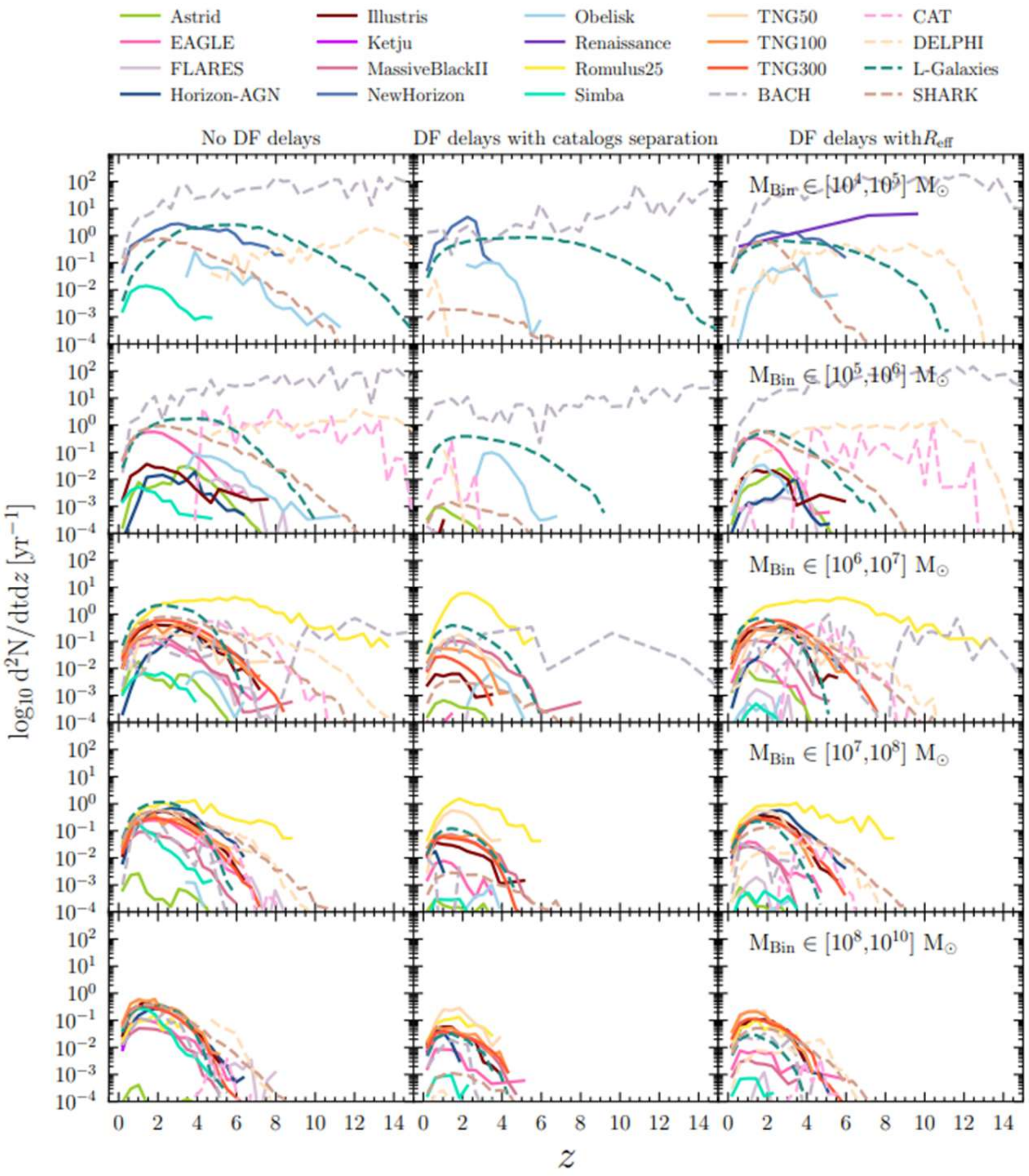
Merger rates



LISA Astrophysics Working Group, to be submitted



P. Amaro-Seoane et al. 2023



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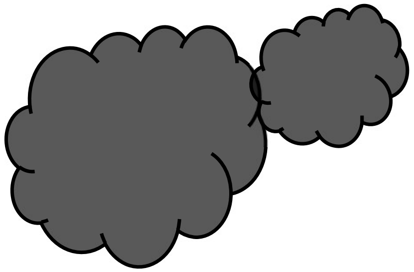
Summary 1

- Black hole formation scenarios span orders of magnitude, under different environmental and dynamical formation conditions.
- Formation of binaries detectable by LGWA requires implementing light seed scenario.
- Implementing different seeding mechanisms in large scale cosmological simulations infeasible.
- Plethora of assumptions need to treat the process from the formation to the merger of BHs.
- The merger rates vary by orders of magnitude.

jasbir.singh@inaf.it

Halo mergers to black hole mergers

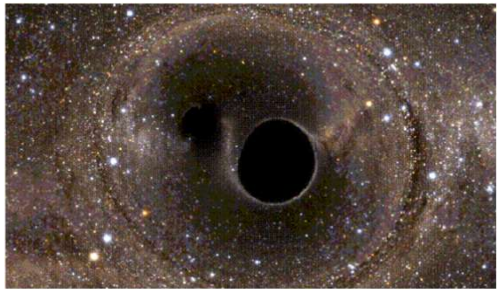


Halo merger

International Gemini Observatory/NOIRLab/NSF/AURA

Galaxy merger

https://www.youtube.com/watch?v=hhbMpe17fzA

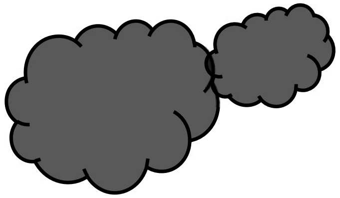


SMBH merger

Dual AGN phase

τ_{dAGN}

https://cseligman.com/text/atlas/ngc37a.htm



Halo merger

$\tau_{H \to G}$

Galaxy merger

τ_{merge}

BH merger

Arte e Vino, Castel Gandolfo

PINOCCHIO

(PINpointing Orbit Crossing Collapsed Hierarchical Objects)

Dark matter only code

Continuous time sampling of merger histories

60 Mpc side length box utilized

https://github.com/pigimonaco/Pinocchio

Minimum halo mass = $7.9 \times 10^7 M_\odot$

Light seed model:

- Mimics black hole seeds formed from the collapse of Pop III stars in the early universe.
- **All Light Seeds (ALS)** (Volonteri+11, Xie+17, Cammelli+25)
- Seeding every dark matter halo with a light BH seed ranging from ∼5 to ∼300 $M_\odot$.

Heavy seed model:

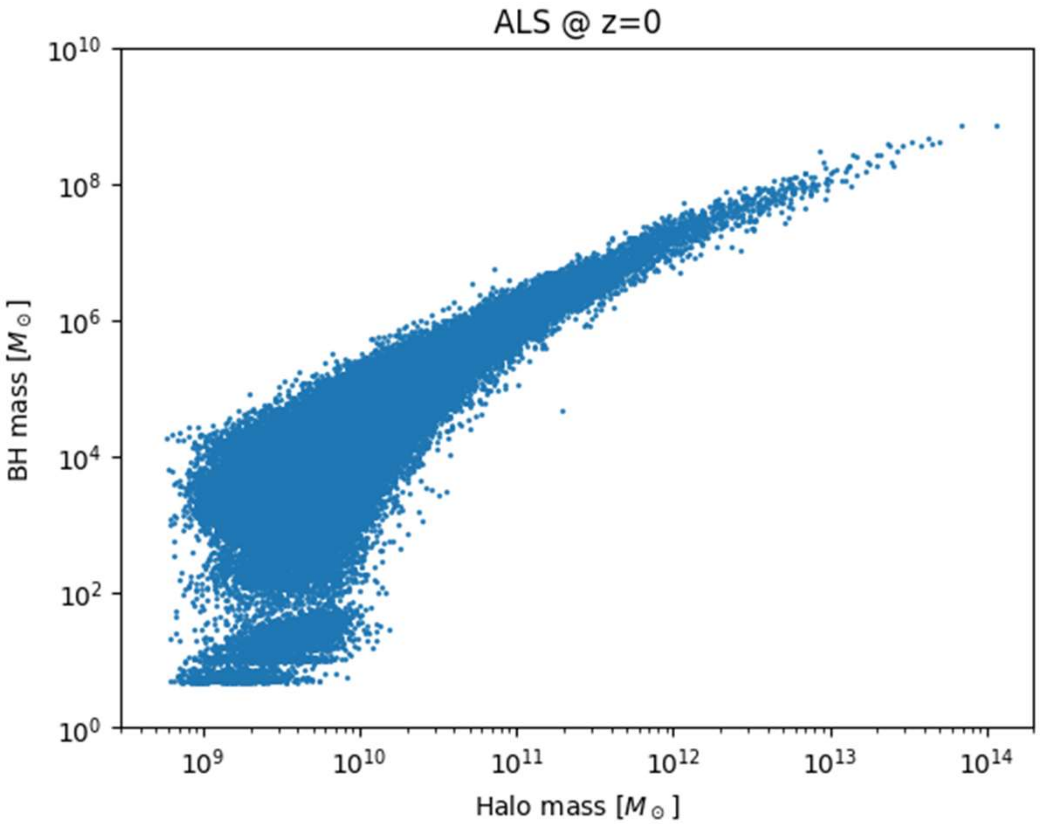
- Pop III.1 stars as seeds – Pop III stars growing in an isolated environment.
- With extra energy input from WIMP DM annihilation at the star's centre, they reach $\sim 10^5 M_\odot$ before collapsing in a $\sim 10^6 M_\odot$ halo (Spolyar+08, Natarajan+09, Fresse+12, Rindler-Daller+15).
- Isolation distance of **50 kpc** considered (Banik+18, **JS**+23).

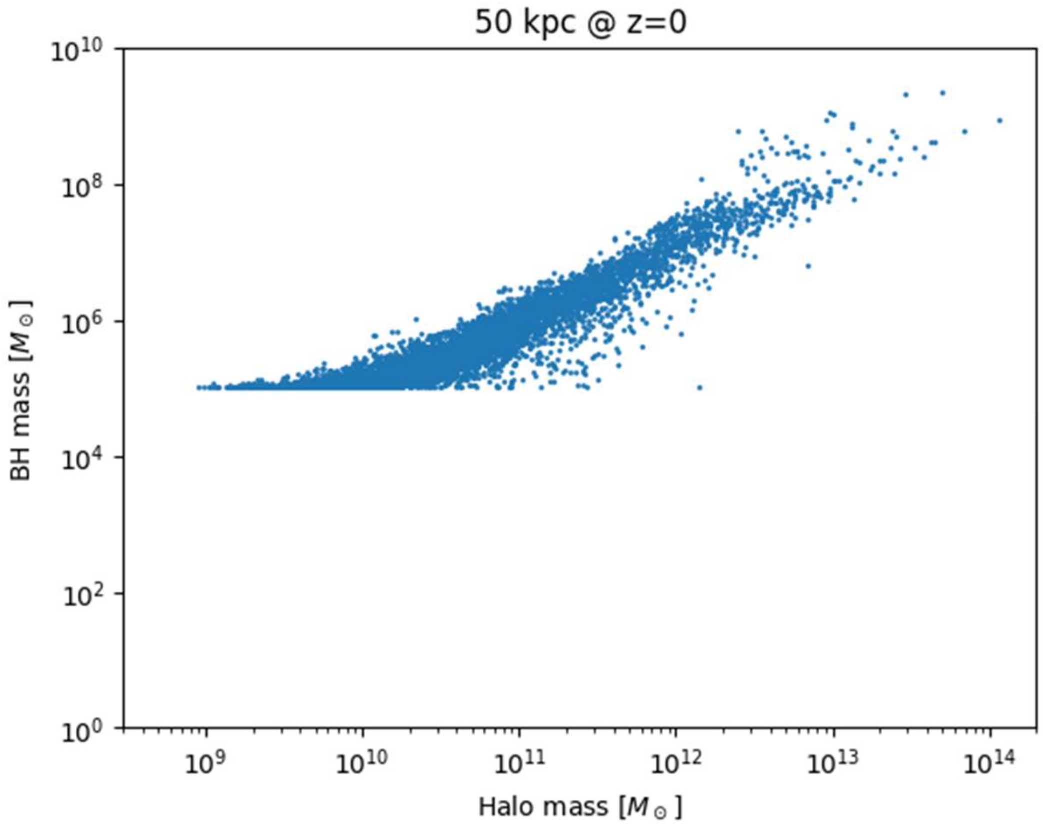
PinGAEA semi analytical model

Cammelli et al. (**JS** included), 2025

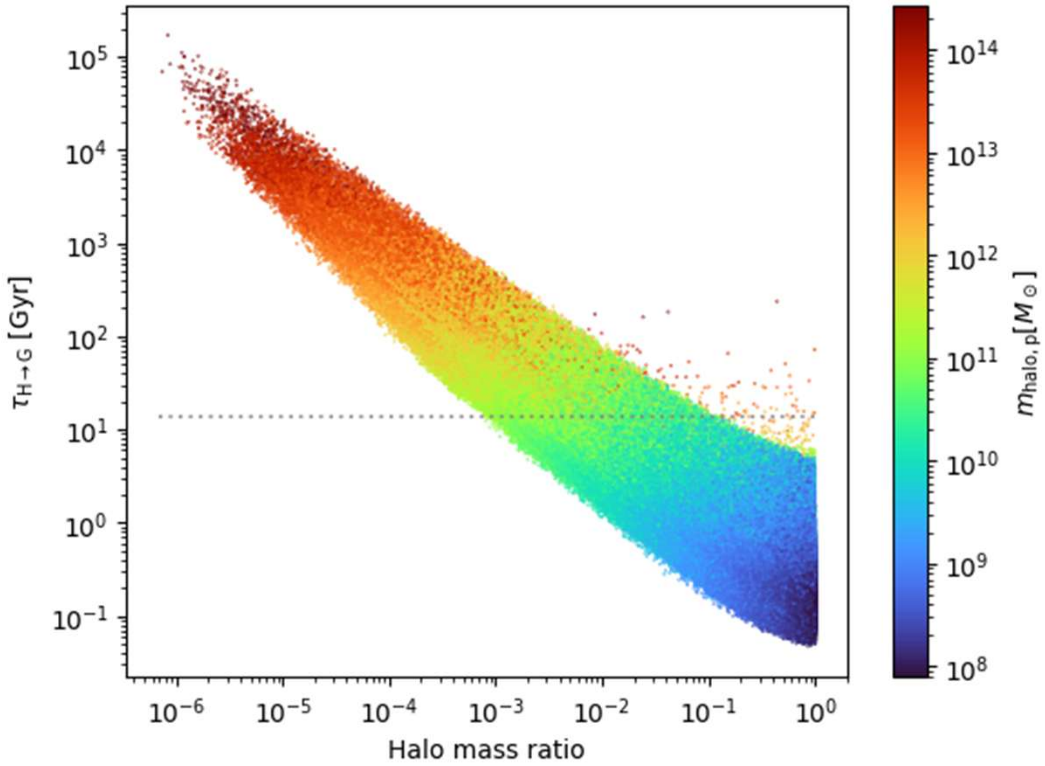
PinGAEA semi analytical model

Cammelli et al. (**JS** included), 2025

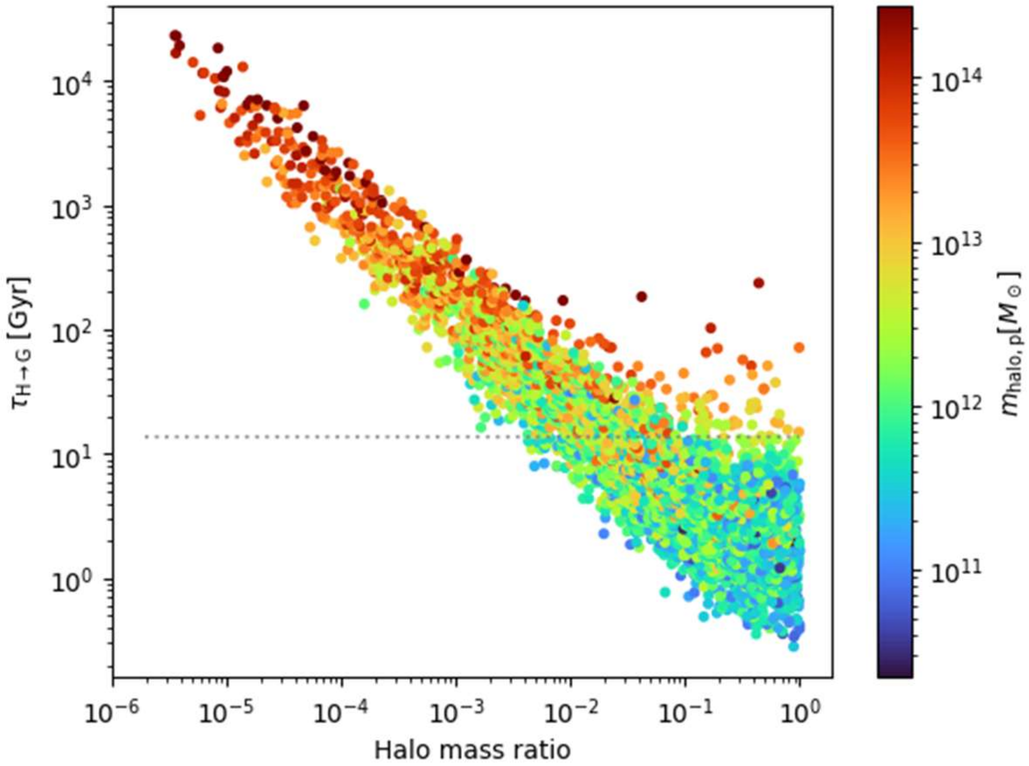




ALS



$d_{iso} = 50$ kpc



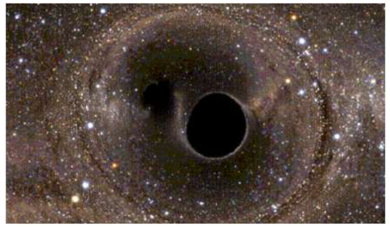
$\tau_{H\to G}$

$\tau_{H\to G}$

Halo merger

Galaxy merger

τ_{merge}
$=$
T_{dyn} (~kpc to pc)



BH merger

Chandrasekhar timescale:

$$T_{\text{dyn}} = 19\left(\frac{r_0}{5\ \text{kpc}}\right)^2\left(\frac{\sigma}{200\ \text{km/s}}\right)\left(\frac{10^8 M_\odot}{M_{\text{BH}}}\right)\frac{1}{\Lambda}\ \text{Gyr}$$

r_0 - remnant galaxy radius
σ - velocity dispersion
M_{BH} - secondary black hole mass
$\Lambda = \ln(1 + M_\star/M_{BH})$

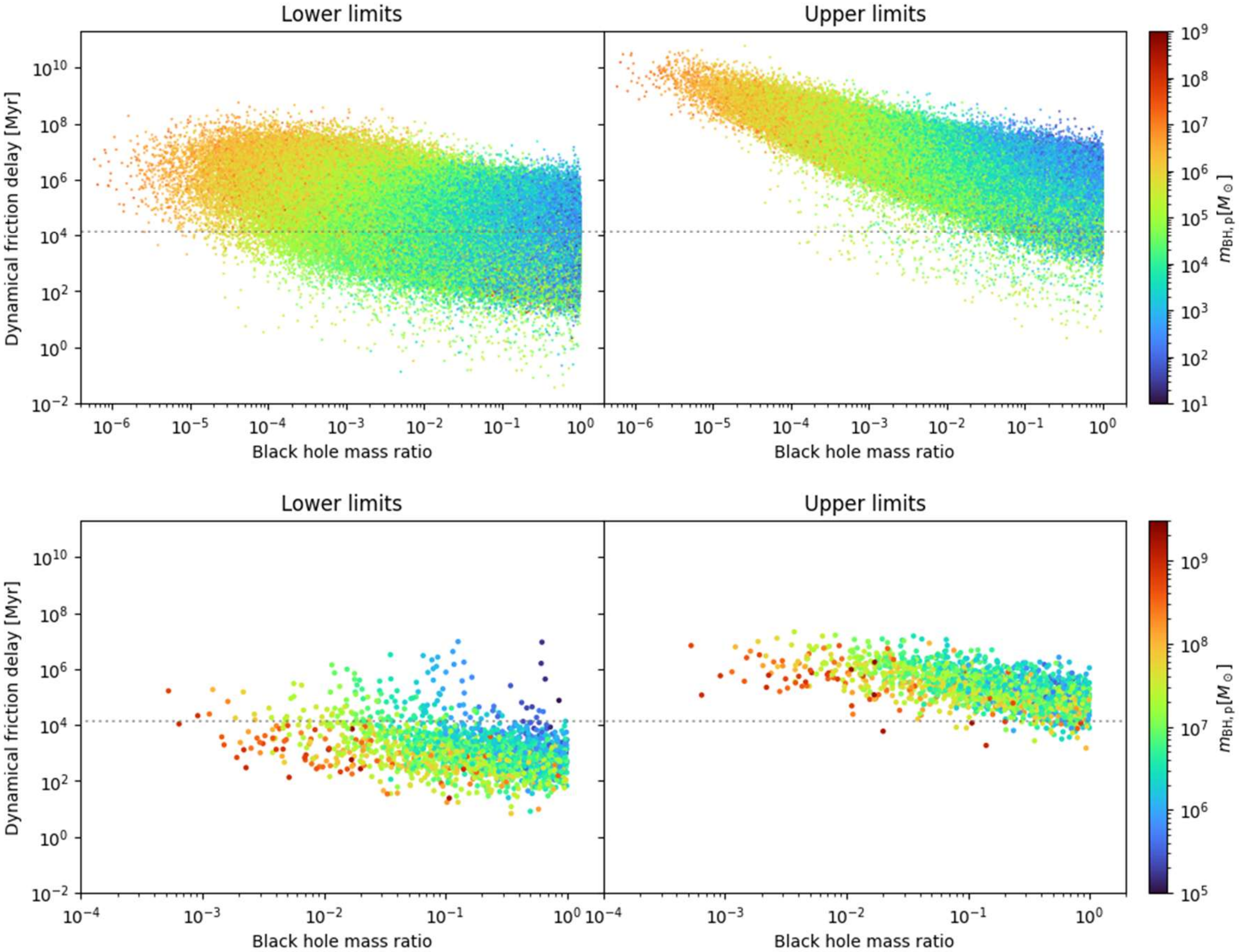
$$T_{\text{dyn}} = 19\left(\frac{r_0}{5\ \text{kpc}}\right)^2\left(\frac{\sigma}{200\ \text{km/s}}\right)\left(\frac{10^8 M_\odot}{M_{\text{BH}}}\right)\frac{1}{\Lambda}\ \text{Gyr}$$

$$T_{\text{dyn}}^{ll} = 19\left(\frac{r_{0,p}}{5\ \text{kpc}}\right)^2\left(\frac{\sigma}{200\ \text{km/s}}\right)\left(\frac{10^8 M_\odot}{M_{\star,s}}\right)\frac{1}{\Lambda^{\text{ll}}}\ \text{Gyr}$$

$\Lambda^{\text{ll}} = \ln(1 + M_{\star,p}/M_{\star,s})$

Dynamical friction timescale

JS+, submitted to A&A



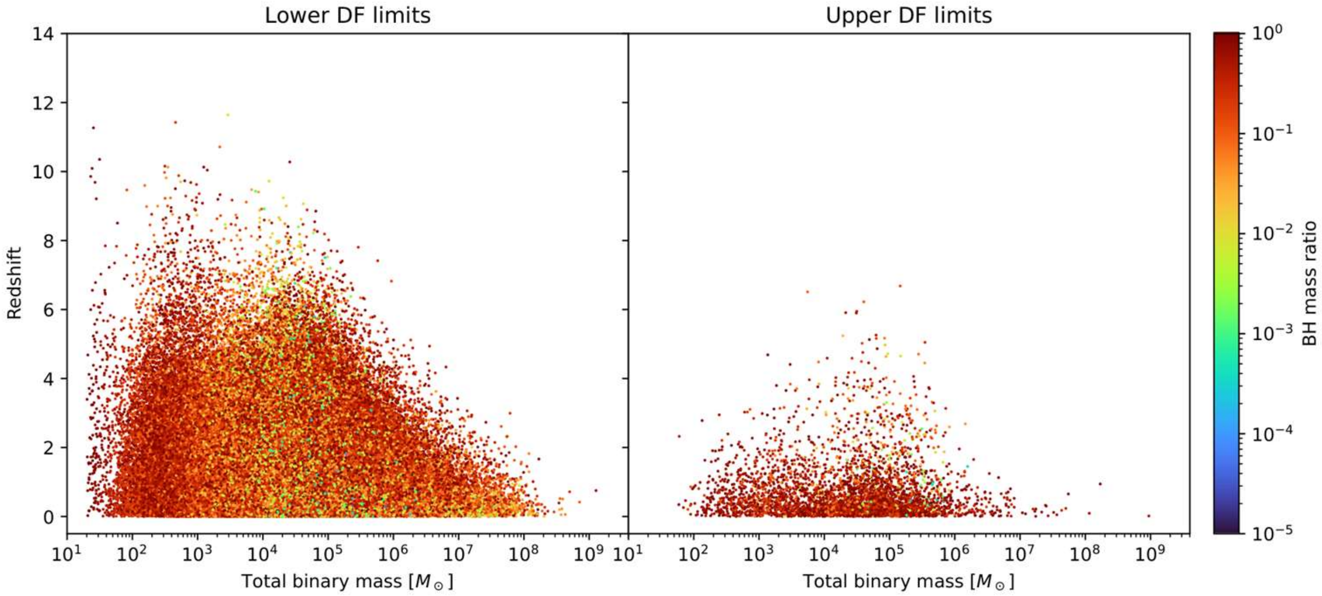
ALS

$d_{iso} = 50\,\mathrm{kpc}$

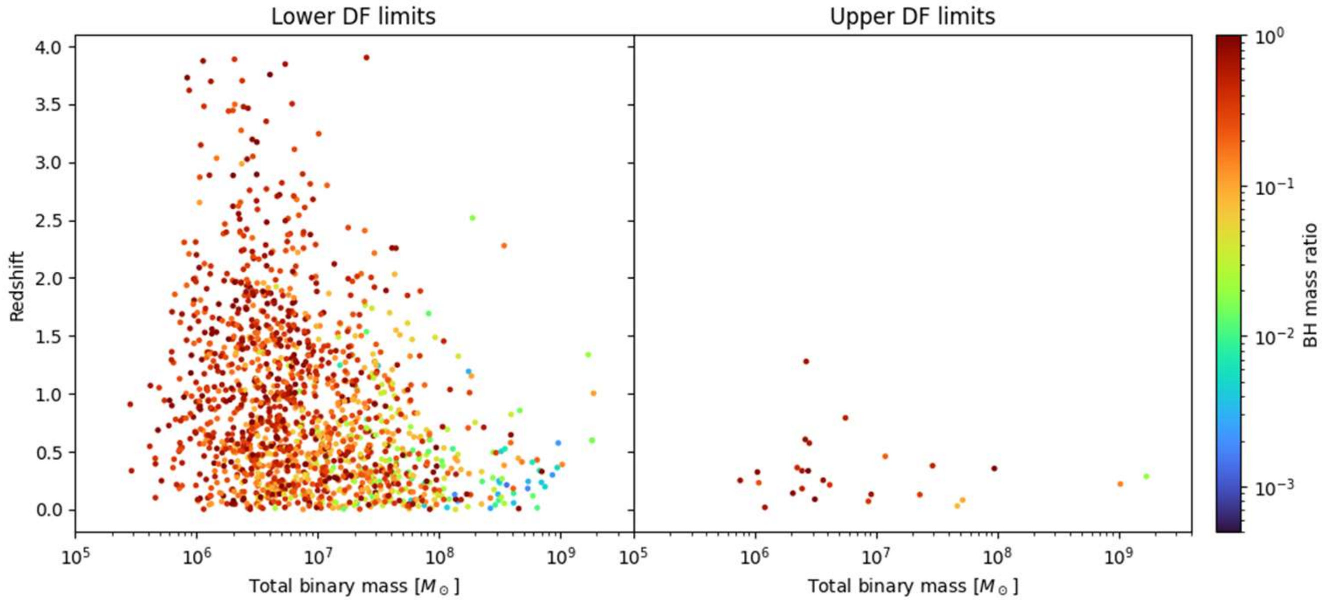
Preliminary

Mergers distribution

JS+, submitted to A&A



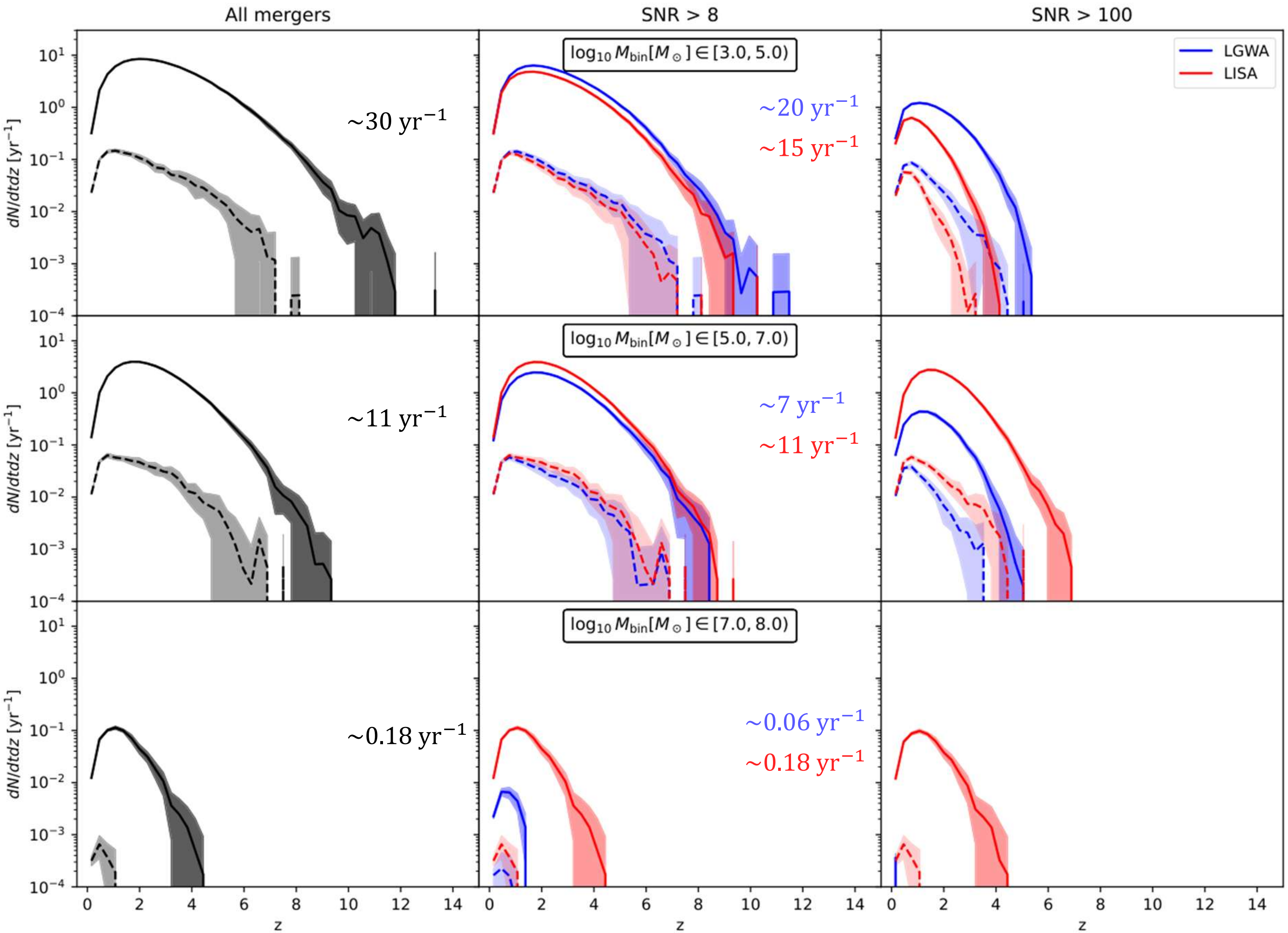
ALS



$d_{iso} = 50$ kpc

Preliminary

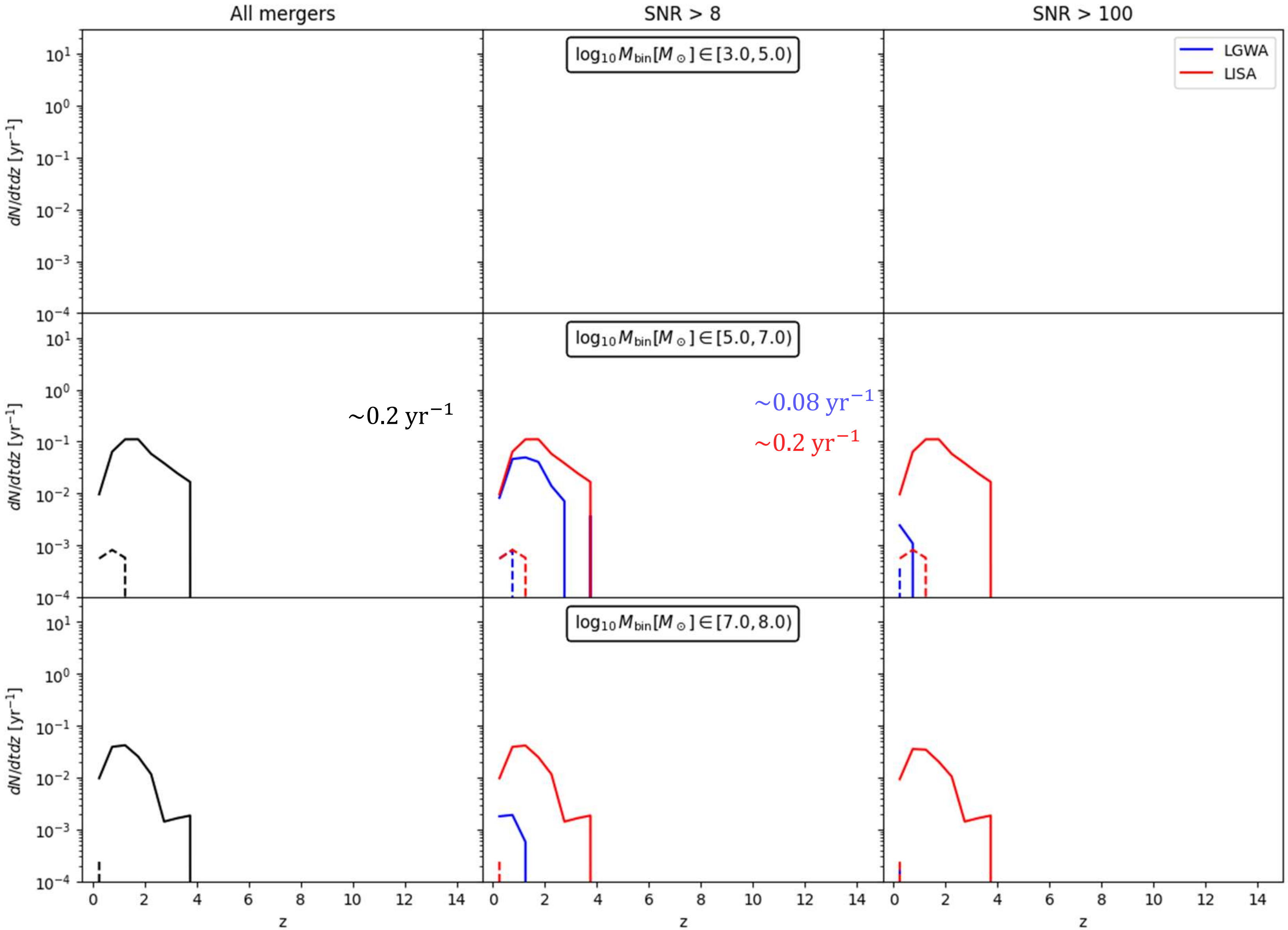
Merger rates



ALS

JS+, submitted to A&A

Merger rates



$d_{iso} = 50\ \mathrm{kpc}$

Preliminary

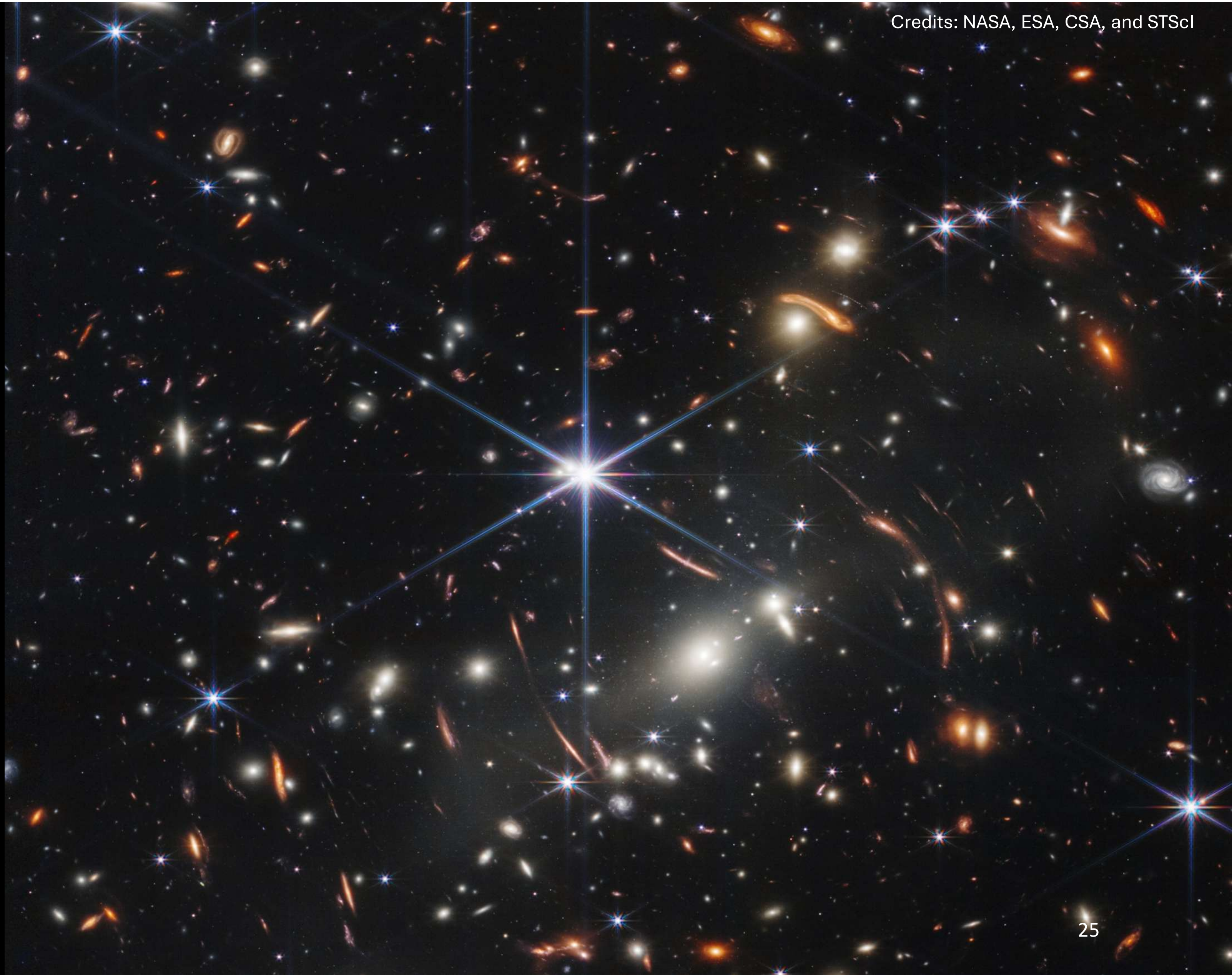
Summary 2

- ALS model can be used to implement seeding mechanism from Pop III star remnants.
- Pop III.1 model can be used to model the entire SMBH population.
- Using PinGAEA semi-analytical model, various properties of the galaxies and black holes can be calculated.
- The framework provides a simple and quick way to test seeding schemes and their merger rates.
- Merger rates of more than $25\ \mathrm{yr}^{-1}$ expected of events with SNR > 8 in both LGWA and LISA for the ALS scheme. The Pop III.1 model predicts a much lower merger rate.

jasbir.singh@inaf.it

Extra slides

need backup!



	Merger rate [yr^{-1}]			
	All masses			
	Pessimistic		Optimistic	
	LGWA	LISA	LGWA	LISA
All mergers	0.61 ± 0.07		49.11 ± 0.85	
SNR>8	0.49 ± 0.06	0.45 ± 0.06	27.60 ± 0.53	26.20 ± 0.50
SNR>100	0.17 ± 0.02	0.16 ± 0.02	3.52 ± 0.12	7.25 ± 0.21
SNR>1000	$(1.15 \pm 0.08) \times 10^{-2}$	$(2.14 \pm 0.32) \times 10^{-2}$	$(4.62 \pm 0.15) \times 10^{-2}$	0.71 ± 0.04
	$M_{\rm bin} \in [10^3, 10^5] M_\odot$			
All mergers	0.39 ± 0.06		30.34 ± 0.69	
SNR>8	0.34 ± 0.06	0.29 ± 0.05	19.89 ± 0.47	14.91 ± 0.41
SNR>100	0.12 ± 0.02	0.06 ± 0.01	2.66 ± 0.11	0.91 ± 0.05
SNR>1000	$(8.93 \pm 0.75) \times 10^{-3}$	$(2.91 \pm 0.28) \times 10^{-3}$	$(3.69 \pm 0.16) \times 10^{-2}$	$(1.50 \pm 0.06) \times 10^{-2}$
	$M_{\rm bin} \in [10^5, 10^7] M_\odot$			
All mergers	0.16 ± 0.04		11.34 ± 0.32	
SNR>8	0.13 ± 0.03	0.16 ± 0.04	7.18 ± 0.26	11.08 ± 0.30
SNR>100	0.05 ± 0.01	0.10 ± 0.02	0.85 ± 0.06	6.18 ± 0.19
SNR>1000	$(3.08 \pm 0.41) \times 10^{-3}$	$(1.80 \pm 0.31) \times 10^{-2}$	$(8.51 \pm 0.70) \times 10^{-3}$	0.65 ± 0.04
	$M_{\rm bin} \in [10^7, 10^8] M_\odot$			
All mergers	$(4.68 \pm 3.09) \times 10^{-4}$		0.18 ± 0.02	
SNR>8	$(1.81 \pm 2.17) \times 10^{-4}$	$(4.68 \pm 3.09) \times 10^{-4}$	$(6.48 \pm 1.77) \times 10^{-3}$	0.18 ± 0.02
SNR>100	$(1.77 \pm 0.78) \times 10^{-5}$	$(4.68 \pm 3.09) \times 10^{-4}$	$(1.09 \pm 0.25) \times 10^{-4}$	0.15 ± 0.02
SNR>1000	$(3.54 \pm 3.91) \times 10^{-6}$	$(4.29 \pm 2.85) \times 10^{-4}$	$(9.04 \pm 8.35) \times 10^{-6}$	$(4.85 \pm 0.89) \times 10^{-3}$

JS+, submitted to A&A