The hierarchical assembly of galaxies and black holes: predictions for LISA

Pratika Dayal









The cosmic timeline





- How many black holes exist and merge through cosmic time?
- Which sort of mergers (in terms of mass and redshift) will LISA see?
- How should we interpret the gravitational wave background seen by LISA?
- What about the electromagnetic counterparts for black hole mergers?

- How many black holes exist and merge through cosmic time?
- Which sort of mergers (in terms of mass and redshift) will LISA see?
- How should we interpret the gravitational wave background seen by LISA?
- What about the electromagnetic counterparts for black hole mergers?

- How many black holes exist and merge through cosmic time?
- Which sort of mergers (in terms of mass and redshift) will LISA see?
- How should we interpret the gravitational wave background seen by LISA?
- What about the electromagnetic counterparts for black hole mergers?











Numerous pathways for black hole seed formation and growth



Black hole masses correlate with galaxy mass at all z



Growth and mergers of black holes are intricately tied to the hierarchical assembly of their host galaxies

- DM assembly
- Gas/stellar mass from accretion & mergers
- Star formation
- Impact of supernovae in ejecting gas

- BH seeding
- BH growth
- Impact of BH feedback in ejecting gas
- Impact of reionization feedback



A complication: impact of reionization feedback on galaxy formation

Neutral hydrogen : T = T(CMB)



lonized hydrogen : T ~ 20,000K

A complication: impact of reionization feedback on galaxy formation

Neutral hydrogen : T = T(CMB)



lonized hydrogen : T ~ 20,000K

Low-mass halos in ionized (hot) regions can lose some/all of their gas mass limiting both star formation and black hole growth.



The multi-scale processes determining the formation of a BH binary



Credit: Lupi et al. (2019)





Credit: Capelo et al. (2015)



Mpcs: The large scale structure

1-100s kpcs: Galaxy interactions/merger



Credit: Souza Lima et al. (2017)



1-10s pc: Formation of a bound binary



Credit: Bowen et al. 2017



<1 pc: Hardening of the binary

"Astrophysics with LISA" white paper, 2023, LRR, 26, 2 arXiv:2203.06016

Complexity necessitates multitude of modelling techniques



Enormous ongoing theoretical effort to model galaxy formation

No.	Main aim	Technique	box size [cMpc]	$M_{DM} [\mathrm{M}_{\odot}]$	Key Physics	Code [reference]
				Small-scale models		
1	SF in GMC	Resimulated	1–10 <i>R</i> _{vir}	$\sim 10^{2} - 10^{6}$	AIKO	FIRE [136]
2	SF, GF, EoR	AMR	1	1840	DIKO	[137]
3	GF, EoR	AMR+RT	$4 h^{-1}$	$4 imes 10^6$	EO	EMMA [138]
4	UV fb	SPH+RT	5	$2.5 imes 10^5$	EIO	[139]
5	UV fb, GF	SPH+RT	3-6 h^{-1}	$0.18 - 1.4 imes 10^{6}$	GIKO	[140]
6	ISM,CGM	AMR	9.7 h^{-1} kpc	$9.5 imes 10^4$	AIKL	[141]
7	UV fb, GF	SPH+RT	$10 h^{-1}$	4.3×10^{7}	GIO	[142]
8	GF, EoR	Eulerian+RT	20	4.8×10^{5}	EIKO	[143]
9	GF, EoR	AMR	40	3×10^4	diko	Renaissance [144,145]
10	GF, EoR	AMR+RT	20–40 h^{-1}	7×10^{6}	AIO	CROC [146]
				Intermediate-scale models		
1	GF, EoR	N-body+semi-numerical RT	100	3.9×10^{6}	DIKO	DRAGONS [147]
2	GF	SAM	-	$M_{min}=10^8$	CIP	DELPHI [148]
3	EoR (LG)	Eulerian+RT	91	$3.5 imes 10^5$	EIO	CoDA [149]
4	GF, EoR	SPH+ RT	$12.5 - 100 h^{-1}$	10^{6} - 8 \times 10 ⁷	EIKO	Aurora [150]
5	f_{esc}	SPH	$10-100 \ h^{-1}$	$6 imes 10^6$ – $9 imes 10^8$	GIKLM	[151]
6	GF	SPH	$25-100 h^{-1}$	$1.2-9.7 imes 10^{6}$	FIJKM	EAGLE [133]
7	GF	Unstructured mesh	106	6.2×10^{6}	GIJK	Illustrus [152]
				Large-scale models		
1	EoR	N-body+RT	$114-425 h^{-1}$	$0.55-5 \times 10^{7}$	НО	[134]
2	GF	SPH	$400 \ h^{-1}$	1.7×10^{7}	GIJKM	BlueTides [153]
3	GF	SAM	$500 \ h^{-1}$	1.3×10^{9}	BIIKP	GALFORM [154]

+Atraeus, Thesan, Obelisk, Sphinx, Astrid, Romulus, Horizon-AGN..

PD & Ferrara, 2018, Physics Reports, 780, 1

Unprecedented datasets from cutting-edge instruments instruments



A continually expanding frontier for black hole detection



Datasets allowing unprecedented opportunity to baseline models



Datasets allowing unprecedented opportunity to baseline models



Different types of BH seeds - stellar (PopulationIII) and direct collapse black holes (based on strength of Lyman alpha background)

Different types of BH seeds - stellar (PopulationIII) and direct collapse black holes (based on strength of Lyman alpha background)

> Impact of reionization feedback in photoevaporating gas from low-mass halos and slowing black hole growth

Different types of BH seeds - stellar (PopulationIII) and direct collapse black holes (based on strength of Lyman alpha background)

> Impact of reionization feedback in photoevaporating gas from low-mass halos and slowing black hole growth

> > Black hole growth regulated by both halo mass and gas availability (due to the impact of Supernova and reionization feedback)

Different types of BH seeds - stellar (PopulationIII) and direct collapse black holes (based on strength of Lyman alpha background)

> Impact of reionization feedback in photoevaporating gas from low-mass halos and slowing black hole growth

> > Black hole growth regulated by both halo mass and gas availability (due to the impact of Supernova and reionization feedback)

> > > Impact of instantaneous versus (dynamically) delayed galaxy mergers on the black hole merger rate

Number densities of seed black holes



• Stellar BH seeds dominate DCBH seeds by about two-4 orders of magnitude.

• DCBH seeds can grow into QSOs at z~6 but *only if* they are seeded into the progenitors of the most massive halos by construction.

What shapes the black hole mass-stellar mass relation?



• In instantaneous merging (*black*), BH mass-stellar mass correlated for $M_* \ge 10^{9.5} M_{\odot}$.

- Adding the effects of reionization (*red*) result in a "stalling" of BH growth for $M_* \leq 10^9 M_{\odot}$ galaxies.
- Delayed BH mergers introduce larger scatter in relation although still consistent with average *fiducial* trend.

What shapes the black hole mass-stellar mass relation?



• In instantaneous merging (*black*), BH mass-stellar mass correlated for $M_* \ge 10^{9.5} M_{\odot}$.

- Adding the effects of reionization (*red*) result in a "stalling" of BH growth for $M_* \leq 10^9 M_{\odot}$ galaxies.
- Delayed BH mergers introduce larger scatter in relation although still consistent with average *fiducial* trend.

The LISA-detectable GW event rate as function of redshift



Delayed merging

• In *fiducial case (ins1)* Most detectable mergers (~67%) are those from SBH-SBH, followed by SBH-DCBH mergers (32%). DCBH-DCBH mergers negligible.

• Due to delayed mergers + reionization feedback, importance of DCBH-SBH mergers decreases. No detectable DCBH-DCBH mergers (with SNR>7).

The LISA-detectable GW event rate as function of redshift



• In *fiducial case (ins1)* Most detectable mergers (~67%) are those from SBH-SBH, followed by SBH-DCBH mergers (32%). DCBH-DCBH mergers negligible.

• Due to delayed mergers + reionization feedback, importance of DCBH-SBH mergers decreases. No detectable DCBH-DCBH mergers (with SNR>7).

The LISA-detectable GW event rate as function of mass



• LISA will preferentially detect BHs with mass $M_{BH} \sim 10^{4-7} M_{\odot}$. In *fiducial case (ins1) m*ost detectable mergers are those from SBH-SBH, followed by SBH-DCBH mergers. DCBH-DCBH mergers negligible.

• Although same mass range true for the *tdf4 model, d*ue to delayed mergers + reionization feedback, importance of DCBH-SBH mergers decreases. No detectable DCBH-DCBH mergers (with SNR>7).

LISA detectability of early BH mergers

Model	All_7	Type 1_7	Type 2_7	Type 3_7
ins1	19.8	13	6.8	0.05
tdf4	12.5	12.1	0.4	0
ins1 (heavy)	23.3	13	10.3	0.04
tdf4 (heavy)	12.5	12.1	0.4	0

LISA detectability of high-z BH mergers over a 4-year duration using a SNR>7.

- SBH-SBH mergers dominate the detectable event rate followed by SBH-DCBH mergers.
- DCBH-DCBH mergers extremely rare.
- Changing seed mass of DCBH changes numbers slightly for detectable SBH-DCBH mergers.

Assumptions on BH seeds masses, feedback and merger timescales crucially determine event rates



arXiv:2203.06016

The need for a physical-results comparison project

										COSMOLOGY MODEL PROPERTIES					DARK MATTER HALO GALAXY								MASSIVE BLACK HOLES								Additional Notes						
Name of the mode	Kalas	Add your name in this column if you are filling the table	MDHCatalogs Pe Model team members	Non-members with expertise/knowledge of models	Official model P(s)	References	Public Data (RawDerland No)	Type of model (N- BodyMydruSAMEEnpirical)	Cosmologic al model	CA,0 C p .1	C#0	-	-	Box size (comoving Mpc)	Redshift Di range covered by [Me the model	r Ca ricon uni) (Ma	as Spatial Internation (comoving kpc]	Statur resolution (Mean)	tito Galaxy I tficato identificatio n n	range ha (Meun) 1	rist mass Hato M sto range 200 (M (Mean)	(_crit, Spatial Asun) position the halo (yealing	af farmation at sate () (yesho)	Galaxy webcity ispersion (yealto)	a Gulaxy bulge (yestic)	Galaxy Galax position radiu (pesitio) (yesitio Specify the radiu comput	y Galaxy 4 <1 Khaf 4 H (yesha) 1 how 6 is 9d	stellar mass 2 Khaif < 10 Khaif Jesilio) (yesilio)	Black hole B Mass (yesha) 4 6	Black hule Black t accretion respon do (pesito, ng tyee way is scluded e.g	tole Radiative Seeding ticel efficiency (fix or value) description	Steeding: Initial black hole mass (Meun)	Seeding: parameters (e.g. specify the halo or galaxy mass where	H delays (H delays) (H delays (H delays) (H delays)	Dynamical friction for the Milbis type or no for DF from	Hartes Hardening Me of the tre binary (yes ma or no for black gas/stars) (yes	eger es of estive kholes shatevity
L-Galaxies		Caritie Tpinose	Daniele Epinese, Cavel Septembri Vilatia, Birle Banali	Desiries Indiana, Fana Valurio, Eina Eschian	Curiote Typeson, Cardel Loguine	Party and State 2010 Sectore 2011 (Sectoria Vilate 2010 Sectoria Vilate 2020) Sectoria Vilate 2022 (Sectoria	televiser of the second participation of the second	1000 on N Baly nerger trees	Plant 2014	5.6ME 0.316	556 647	586	94/9	-	- 16 2.654	+	1 (Kpulli)	pro.)sa 20 + 00	ahlina): yen b N em)	167-3616 1.56	7.54 157.5	le 14 yea	-	n yn	-	n jes (dette bare hale - pen spin)		yes		Bandi, Eddingtan m Eddingtan mind or 2 hears growth	Localdor Parkingsof Parking Incomplete -	10 - LeS	Geoding GCGAR(3) Tals and gas per mass, local metallisity and	an the Ty	Offictureliga el prolynolyna pr	anijan jan	-
Garausso's SAM (I she find a fancy name)	ud	Into Lancos	Doise Earson	Neud Çalışları, Alanta Margiagi	E wise Tarance	Remains 2010, Reserve 2014; Gain-2016, Rowells 2010, Reserves 202	www.ukev.data.auadatile.at.biiya.lipengile.skwa.li=karau-moriudatagai	EAX on extended PE trees		1.de.,0 0.338	533386 ^{1/2} 8414	8 2941	SATWI	NA	5.20 adapter	- 14		u u	161. 1	elo tello tel	10.1.418 84	~	-	n yn	-	yes (the location) of the second)es	1 12	ingliende Varlaer-2020) en jaarspulied na un nuclear as mates)	Utility ton construction by (post) or bases (constru- tion) bases (constru- tion)	100 Let Mare	And Gran Alexandra Late mass, spin pro- perameter		+ +		+-
NewHorizon		Marka Valantini	Blaria Valueleri		Honoung Chei, Julien Devriendi, Yahan Dularis, Bugata Karang Separa Kimen, Kalantra Karjin,	2021A&A. 2010.108,202089648 488-2219	-	596a		6734 6375	5548 E81	640	9.794	-11.40ps (mm)	124	•	Signa (proper)	1,228+56 pm		46 14 D		jm	-	, ja	-	n pecelaria	ur (re. /fait) (an	(54) ···	-	n (fam), ra Manten Han	Variable Distance of a	1.04	per density per	Bellarja for de Tablique in pendi presare		internant pre-	Data proprietary Phy laser to be
Anticid	Onto an and a served data	iran Nani Den	Error Eri, Varina N. Talana D. Males.	Colo DeCod Milaria Malaudi Jame Isanibilari	Picture, Maria Volenier, Dahmerg D. Maline	KON 2110, WIM ACCV 2112 DBBB	Public wareholds and stations III details down to and and details for	Pudra .	Pend 202	E4011 E3389	0.0M 0.410	646	8475	Oli dhesh	2.0 6.569	1 2246	M. Ulatanh 3	at Million and K	OF an an admini 1	-		-	_		an brendal a	n on hele		or de l		n ibrai. na	Rend (2.1) Early range	and and lines	AU-140 No.				adura a' agen
Bronadara	Namia pani processing 644	Yunying N	Nanyi Dani, Rajini Dak, Yu Pang	Palan Capita (sum Insulinip)	Column Transmit	Manufactor and 1807 (2011)	andelik iyo ngani an iliyo ta ku ngani di katan		Family 201	2.074 2.326	5580 843	a 2.60	54277	21 digs	5 Star	Abun J. Cotti	When KM proper lys		negotire.									randod		an bonnet)	daram in the many (2nd) Danaba Saith Banaba	1	bhath - 3d bhath - 3d bhath	lari i Zolge	- despectae		
RET II simulations	Cervales in calculated? Seya	Menut Calaban	Peler Johannan, Malan Mannekasik, Shihang		Civilizias Institutas, Pater	Change & and a Mark		Nytion Millioly (hytical approach)	Planuk 2018	1486 0.316	0.041 E.41	0.040	SIN	-11-00pe	02.00 1.04	2	(Plantenie registe 2.22 kpm) for ar < 0, 2, 12 obges for ar > 0 22 physical parts =				102413		-	n yn		n ym (dalar	-	100		es jillensi, pes unit a	rG3 Tani, 0.1 Demoni yas	lel bach	Di Maryo an				
	al negets saler ban tertal.		Can, Devidens Irainins, Alexander Fanzing, Ab Reliammaria, Pranaman Pinis Filmuin, Jonaica Bay Halap		Likanson, Dikang Can									_			onii a-Git anei 30 physical puth Itenastariti pros salitemesi 84:814 Interactione									New Cold				alogion nimi	artist monories etc. D'antiste		mann fortig Dhumh Dud de nel alteraty Name a EM		Number of Street	Reduct	
Bustris TNG 100	Sand's builde delays in a opasitoring. Can's an disappe Ens?	el Calo DeCraf (same aning data), Ritmi Delpenis, Indonael		Calin Dellind, Matania Halancal, Ridre Delpech	Volue Apringel, Naciger Palance, Annalisa Pilayohi (ku)	- Karingah 2018, Hannah 2018, Karingah 2018, Nekaro 2018, Karingah 2019 (Ke)	94	7984	Plant 2015	22011 23365	5.538 E.F.1	6 0.648	54754	123	0.00 (a. june 104) - 2.06480 7.0640	(ref. 1.644)	nyaa taaan a	india pa	per julih conte lana, kul surne laga adalah te saga adalah dalapita dalapita dalapita		~	~	ſ	n (in	ter Bat malatir uti pa arts computation)		100 (100	. Na		n (linn), yn Mingian wini) nais Milinal Minia gylei Iarion gylei ar Jobo	Frank of C3 had live forward in solar satisfies and solar of table samping with Mor 7 efficiency 20 of Disco	1 tild thur	1 Marillines		-	Cont, its Sector (r	and a state
Bustris TNG 50	Keed to include data to an association	Colle DeGraf (some data), Remi Delpech, helenard, Konyang Li		Colin DeCruit, Mataria Halawat, Alare Delpesh, Konyang Li	Dylan Nalson, Annalisa Pilayish	Renegativ 2018, Phopsish* 2018, Nationary 2018, Nation* 2018, Nationary 2020 (Rec)	jas	7987	Plan 2011	6.000	554K C41		54704	a.7	130 y. (*****) 1.441)	(sat Sata) Lini)	(mi b2quit		pro (with some lands, but some langs antided to dentify disparant dignolo()es		n fin	No Bat exalation with per order computations)	n 3n	1m (m	. Ne	1 10	tor jords Mingdan Mingdan Miland Miland Masur Meter against	Front at 0.2 but tole sprint maping efficiency afficiency 2010 Main	1 fiel these	7.36/0864 66 20	(J. 2020 Post process) [11040]	8 B	eli (Liri 2000) fen, in citar 201 11088) resy tr	i sana anisang
CAT(Cosmic Archaeol Tool)	BOY Evolution of DOD to include all range of halo masser. Dynam	largar Anna Vallania nias	Alexandro Torca, Kafanla Schooler, Ana Valarie, Losa Daxiari	R Volenier, D. Sproete, B. Barell, M. Calpi	Klessandro Toreza	Trivia et.al. 2022a,5 a/X+0908.2746 a/X+1006.2287	-	LAM on extension PE views	Paret 2020	CAM 0.316	556 647	0.000	SEN		-50 (52-30				a ou fa	1400-14	e14 %	-					18		all Josephine 201 (2012) Millional, 14 Millional, 14 Milli	variable light-basry	New 25 120 Mars 200 300 Mars median 10/3 Mars Mary 12/5	nu nelativstysty nelativstysty 201 level, per nuo	*	+ +		
SINDA	Assed to include delays loss republicating Baller Di nasaw wone pilany masars	et hallmark		Bilana Halawat	Rowed Dave			1984 -		0 G	55 8 687	647	0.00	121	5.100 9.667	0.547	0.74 ayılışın					~	-	n yn		n ym				anali kar hal as (Trr (ad Kr) nd kengan nintel mastel restel as	Rand (5.1) Solation Solation and Pure State and Pure State and Pure State and Pure State and Pure State and Pure State S	(Inc.	Unior-Fail I Unio		++		++
Bluebie (2014)	Read to build delays. 21 mil	anan Cala Debua		Calle Dellind, Malante Halansan	Volar Springel, Law Hermond		(ex	nyên	10076	63736	554 0 540		0.764	7. dðju	12 1360	Anar (galadi) Sel	y = 1. 1.4 April In CAU	-	m			an.	-	n (n			-	-		(hel K) in (famil, ill briefed)	Panel (0.2)	1 abel these	7.00 Bas		-	Con. In Concept Concep	A same
Horizon-AGN	Er manne beskelten deby podpensening udsalded	ya in - Nilania Visioniina d		Eleria Uniorieri, Aldonie Fielmanii	Roburt Dalaris, Orielanda Piaten, Jalen Devienal	6-X-14221145, 323384444, 484 2218	No (dela referera in program)	Nydes		8734 8272	5500 841	0.40	5764	an a	510 4	308-37 ka	(hps (proper)	2.02+36 jan		al3.1a11		jan .	, ,	n 981	yen (dramata) (n ya (da) Halud	yas (Find)		·* 6	n (fand, na de brûne)	Final Differential per and dans second a density torebuilt pilot observation, an adaptive depression, an dans are no adaptive file at o	1,000-0	S gan densiy and per velocity dependent methodor-radion	delays for delays in you prostation	, har (ba) , he	idynamiai yn	Data propiniany Ph later to be ashert to be ashert of papers
EAGLE	Need to include delays. Bit was included in	anan falinari		Volania Poliscust	lay ling	<u>200 100 200</u>	a.	7989		Len 2307	5580 683	u 060	\$400		5100 8746	Cital	6.7 pagas					;es				n 3m			E 01 15 0	natiferi Bandi ding inte samari angular samarikan Tenan larama*10=10	Read (3.1) is all balan and Mar I aller 10 Maren	1.004	in di false with Mort Alaria Maan				
Massive@lackl	Omit Ris in Juliei and Barl Onese and Omit Barlies in Maximil	Sales? Calle DeDual Sales? Fueging N	Colo DeCod Yanying Vi, Talana DiMalleo, Ruperi Coli, Ya	Nitaria Natural (sana Insalalge), Nanji Dan	Totana Di Maline	900x 1422 3888	Vec (vige: Netwides yes adu)	Nydra Nydra	20057 2007-5	5736 5376 5758 53876	554 E818	1 0348 0 0471	5.701	-122 oldge dill objech	8-44 (297)	Ause Alleria	inun 263pe M1 18.abpub 3	MIN1 Barr Jan 70	OP ges an addeded in	a. 140		-	-	n yn	-				5 170	in (Band) nded is diskingtor) in (Band) ym	Friend (5.1) Trans (5.1) Fishis haven	7 Tell Uhum	7 Julii Mean Selli Meanh	_	-	_	
SHARK	and Ashiel County and No dynamics, requires dela) Aya Bankalar Matimusa	Pang			wXxx 1807.11180	Nala apalley <u>No. (plta) and CONstan</u>	2021 kanad on X keely margaritoon	Pana 211					210	536 235418	-			Safred 1		6.1011 04.10		-		-				-	nind is <u>distinctori</u> M	Tani (2.1) Searcy senit 1 Marcin	a lore tellowik	NJadar 10/10 He Milanh			-	tan la shuta
Astracus	Alexandra at ani. 5. Norski la delan (El la menja) menjal	alli Patka Depi		Bacine Telduk	Profile Days	Teldes et 2, 3035, 680007, 018, 301	wade on following	Sent runarical	Paris 2018	Calca 6.3071	5.548 3 6.825	28 0.36	2.8777	236	5-100 B.316-11	~	2.88		~	04313 101	43-13 10:43-1	13 Jes	~	yes.		na ywa (virad	, pes 10	na -		es jäependis ina n ges antentr-puten ef)	fixed System Sealing (ALM) Lased on LIT-metabolic Schedule	182 Tor Popula diff rations letaness 10'0 It multired for DORH	C DM per metabuly LM D balagrand r solue gas mass shelar	an ty	-		been Militik pulatikai papersitikan ner olidarja ner oljutarisai
DELPHI	Eatler is use to merge rules a comparison with Tensionance 00201 Bring extended door is with a larger halo mean rang	n kara Land gel	Mata Valatini, Kena Riser	Maxima Tukihuh	Profile Depai	Сере н. и. 2014, Марик, 188, 2186. Рани и. 2021, Марик, 188, 2146	-	DMI or analytic margar break	Plana 2018	C 4911 C 3589	0.049 0.81	0.86	5.67		15-02 10%			can.	care 5	PR-13 101	eta 19613		9n		-	yes (ve a		-	,	er jängendis ina n ges antentrigation ef)	faced Egits (sapit) heavy (sabit) based on Life-inetable offerior	 180 for Pupility off values ordures ordures ordures ordures ordures ordures 	COM pre- metabuly, LIF backgraind r salue, gas mass, stellar	on ty		5 946	-
FLARES	Drip and, reconcerning, respin	ines Dimitrias Instalatios	Combine Instalator		Desiries Institute Civit-Local, Anato Vjayan, Will Rayan, Basen Wilson, Pater Tramas		-	79 0 9	Pana 20	Lett 0.32 ⁴	5340119		\$400	Suite of 23 mean simulations of 142h oldjas math. Parami	1.15 9.74	04	246	r.	,m 1	50.60 GA	565 61561	a m	-	n jan	-	n yn (han a palaine a philoneid	4, f	jan	,	n jame a - ym Adlej	0.1 Devoted per particle Diff particle Diff particle	14DA	in Grigh Wase Ma	-	-		
Obelisk	unity of 3.6, rescation, limit Mill programming, result of Brailing dynamics comparent for NeurInsteiner	lit Os An Dong Pierr n Ion n	Barla Valenieri, Chi An Dang Piler		Maxime Twisisch	Telden-300	-	nyeles (82)		6756 8275	DOWN EAT	6867	3.764	-Color (energy) -Color (energy) - Color	124		36 yu 1	Chel pre	~			jes	-	n j#s	-	n (maa baa dada partaina)	ini ja			ng (Barrat) - 14 	variable Bit constant & pre and size second a density	3.04	Eff constant if pro pars and stars manual a density foreshold, gan a-minister and mension and fores are not	dirlanga Kar din Talibiga in pandi panaman	a the law period	-siperarmati per	
Uchau	Robland John, Socialize to U meson, Requires a large area web	In En Co An Dong Para	Octo Dag Film		Tamada Infogana, Francisco Frada, Analisiy Kippin	axo-2007.14720	-	v liniy	Famil 2020	2200	5538 531		547%		sta strukt	-	27.011.64	21.	perc)		12/2 68.241			-							-	-	No sheet		-		So Dis order simulation (nat
ASLOTH	Life black hole physics, small s	volumer Muhammad Lalit, Timan Kabelg	Timer Helsig Distyl Rav, Usbermal Lef	Timan Harlorg, Shaliyat Kon, Shihanmad Latif	Torum Hartung, Shalipi Har, Buharonal Laif	Namey et al. 2016, 459-520 Ramey et al. 2018, 479-520 Ramey et al. 2016, 459-520 Ramey et al. 2015, 460, 574 Ramey et al. 2020, ApJ, 506, 45	Pakis onle republicy: klys liptic conversion (adult https://opuienes.op.org/orbid=10.382511586.20151w21160.pdf	BAN kanad an X kody merger inen ar EPE	Pana 2018					investis lana Shilipar/23, Ianand an Iabiyamar-18 Millither (2), Sabiyar/23, Iamind an Codines (1)	532 -fei	-1864	. 80	ndividud oları və mudund	5	Alger hann bilgen hat an Dahnbard Alf Han Lington for and Alf Han Lington for		2006/ FIL	-	. jes		n 60	-	48			na Pagil nanagi anito 2004	n light Hage Ciliande Ga DCBH leis Jeffikken	, 2,3X TH. 2	(n nation la nation)	-		ulda public
GQD (Galaxy and Quasars with Dust	Chip Tert3 Maun halas at anno Agnamius	0 No. Rosa Vallania	Rona Valante Alexandro Trina, Rafaela Bolonide, Luna Graniani	M. Velaniari, G. Spinson, E. Sanali, M. Calpi	Fona Valanie	Valante et al. 2016, 2016a k. 2021; Lessance et al. 2021	-	2000 on submitted PE towns	Math / Planck Inco Adar 2014)	174(0486) 034(1314)	55400K) 574	0.024	MC) 0.73(6473)	PT etter	6224 (1224 (202-30				a. 60 - 64	. 90 (3	000-13 m	-		-			10		n (Bank, ra Mantan Mari	Tami Split - Teacy 7 Split - Teacy 7 Split - Teacy	tight 23 120 Mars 260 300 Mars medium	and all of all o	(decay by both by by better by bette		. yn	No care use bob 10500° (m Valante et al
Renaissance	shock light service compare Remainsment on GGG for a ser- fermation of GGG for a service."					20144 H J. 2015, Wat H J. 2015 Regard H J. 2020, JKN 1804 23588, JKN 1901 275830	The plans and exclusion satisfy-are available)	njës	2009-1	6346	5548 (31	5945	6.71	-Collys (man b) Parent Ban - 42 olige	1.2		(m. (m. day)	Dishan (Pari) a Dishanis naisi ke Papil dar kenation)	parti la	2.20 2	1240	~	r r		r 1	n jan (han) parinina)		,m				-	-	~			fangen ander Inner en blande Inner i ban Vall an registaret
TRNITY Bustris TNG 300	Una smaller volumes make	eri Colin DelDori (some Add), Riteri Delpech, halmuni		Calm Endford, Uldanov Halon, al, Reine Delpech	Solar Springel, Naliger Felorer, Arnalise Pilepish, (im)	arXiv:2108.10474 Represent 2018, Manuali 2018, Namuer 2018, Network 2008, Manuali 2018 (he), with 102142070 arXiv:1716.04880		nyan	Plants 2011	0.3365	558M 0.811	16 C 642	54704	30.6	535 (c. e. C. 6) 5 (b e c)	(met 7.65ebb) Ula7)	k jank 10apach 7	and the second sec	pro (with same fano, had same lapa added to dentify dilgana digana		jes.	~	-	n fin	No (Bot modulity with pay or la computations)	n jan	5m 6m	- Se	E	n (famil, ym ddogtan ddiniod ddinod muur ddinod muur defana agalad ar Actor	Francis at 0.2, but SPA Serveral in rode variable mapping efficiency State 10 Maur	1 Hel blue	7.36/10 Maun			Sar, Sa Ang Pa Ang Pa	data national national
Ricarte Natarajan Sesana/Chen/Middletr tc model*	City of united	hale - Hannah Löstleton ann	Alberto Ilesana Hannah Mobileton		Alaria Istana Eguan Dan	www.1211.8375	Once alout the model in GH \$275 The parameterized models (only maily have a data whose in the same on an administration. The and the and the models in the factors of the	Impilial							lenara 2010 n 1.3		+ +			-							+		olog man dabladam(?)	in a c				a-2015	Ħ	5am-2018 4a	Data many of
	senses reliable and point families. Used to product recept to pather lexing array slower "Size are also han parameter models of the papelines (Diese Waldderwer 2018), the hour of place consistents where produ- place consistents where produ- tion maint parameters	ng diana diana n 2010, and the bit an			Participation (Second		panty a parameteria con esta esta de la partera debidida esta de antidade esta esta esta esta esta esta esta est								Den 2018 et Li Militateur 2018 er E. (essenal)																			leter+2018		aldistar=2018 ex	negled ned apply in this work

• As of now, 35 models under study

• Key properties for comparison include: cosmological model, galaxy properties (masses, sizes, star formation rates) and BH properties (seeding prescriptions, accretion models, merger timescales implemented, feedback..)

Outstanding issues 1: BH seeding mechanisms



Outstanding issues 2: sources of the stochastic background



"Cosmology with LISA" white paper arXiv:2204.05434

GWs: interface of cosmology, astrophysics and BH physics

Cosmology

- Cosmological model
- Large-scale structure
- Reionization..

Galaxy formation

- Galaxy populations and their time evolution
- Impact of galaxy formation on BH growth
- BH feedback impact on galaxy formation..

GWs

BH physics

- BH seeding
- BH growth
- BH binary formation, hardening and merger timescales..

Instrumental effects

- S/N limits
- Instrumental noise
- Deconvolving backgrounds..

Towards a holistic picture of BHs in the first billion years







Global properties of galaxy populations

link between halos and their baryons, constraints on efficiency of star formation and feedback

Individual galaxy properties

constraints on assembly histories, dust formation mechanisms, gas masses

21cm cosmology

constraints on source population and its redshift evolution, constraints on topology and history of reionization

Gravitational wave astronomy

constraints on black hole masses, abundances; constraints on black hole seeding and growth channels