Astrophysical and cosmological Appearances of Intermediate-Mass Black Holes

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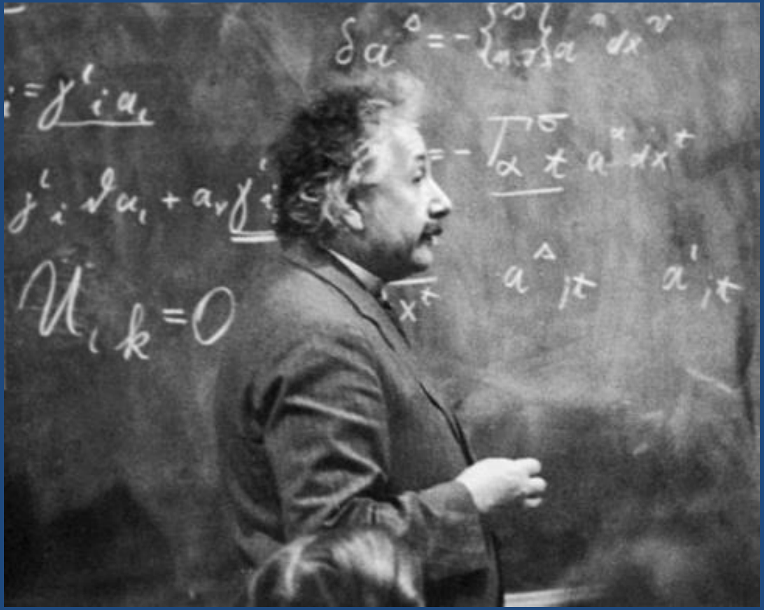
Plan

- Introduction
- BH Zoo
- Astrophysical IMBHs
- Cosmological IMBHs
  - Binary IMBHs from EPTA
  - Primordial binary IMBHs
- Prospects for binary IMBH detection

Black holes

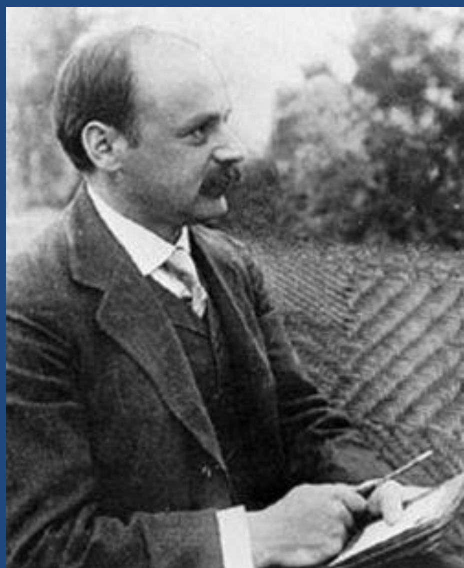


A. Einstein, 1912-1915
Gravitation = curvature of spacetime

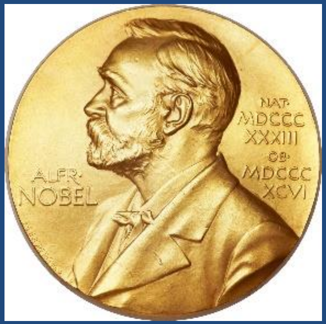
$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}, \qquad ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

$$R_{\alpha\beta} \equiv R^{\mu}{}_{\alpha\mu\beta} \qquad R \equiv R^{\alpha}{}_{\alpha}$$

From Schwarzschild to Penrose

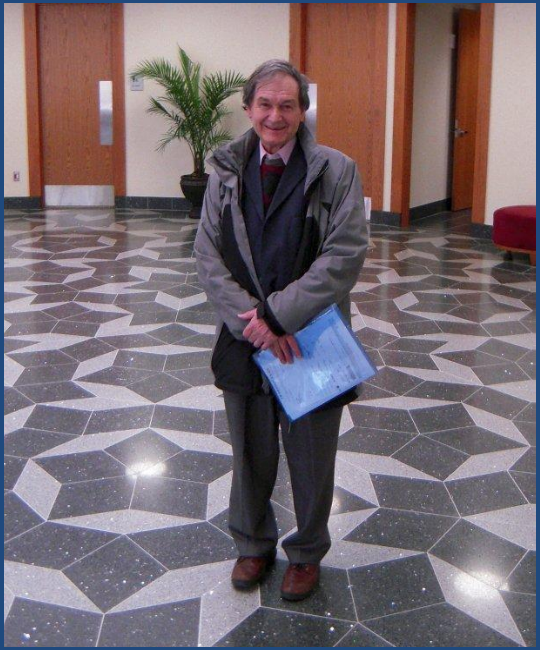


2020



1916, K. Schwarzschild, metrics of spherically symmetric spacetime outside a massive body

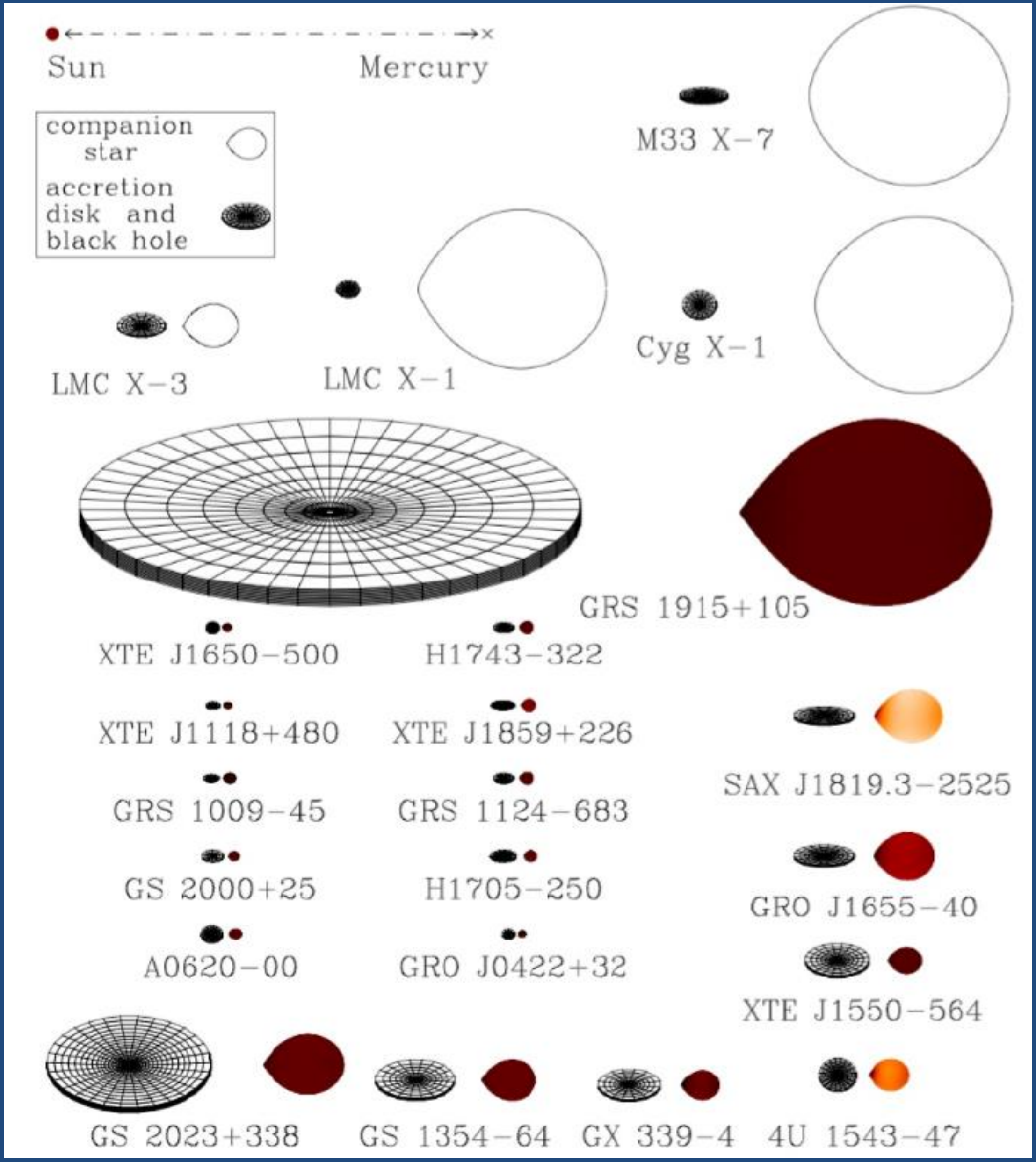
$$ds^2 = \left(1 - \frac{r_s}{r}\right) c^2 dt^2 - \frac{dr^2}{\left(1 - \frac{r_s}{r}\right)} - r^2 \left(\sin^2 \theta d\varphi^2 + d\theta^2\right),$$



Roger Penrose

Evidence for stellar-mass BH

- 1939, Oppenheimer & Volkoff, maximum mass of neutron star (GR: <3 $M_\odot$)
- 1939, Oppenheimer & Snyder, collapse of a pressureless star
- 1970s, Search for BH in X-ray binaries
- Presently, ~100 BH binaries are known in the Galaxy and in nearby galaxies

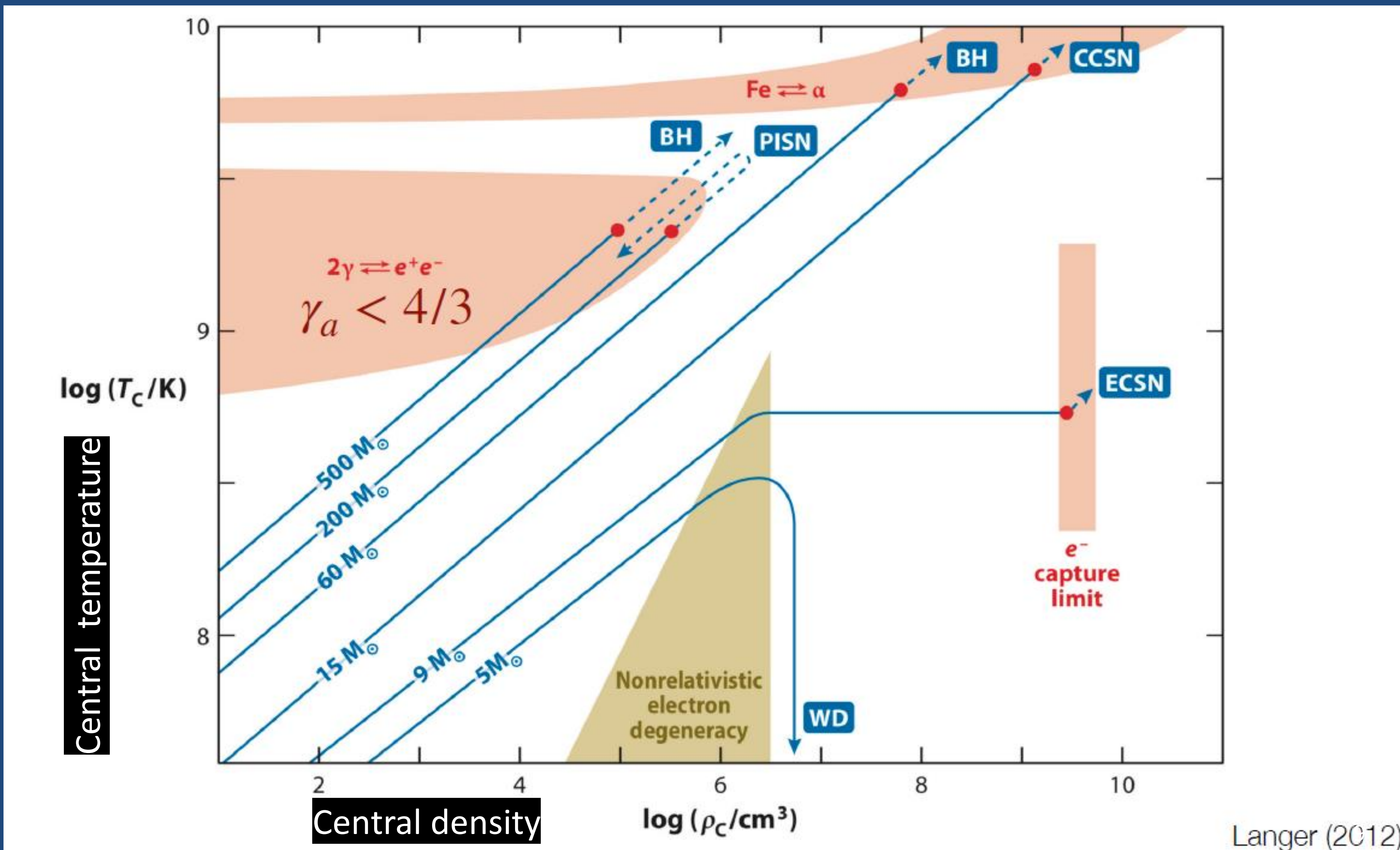


BH candidates in binary systems

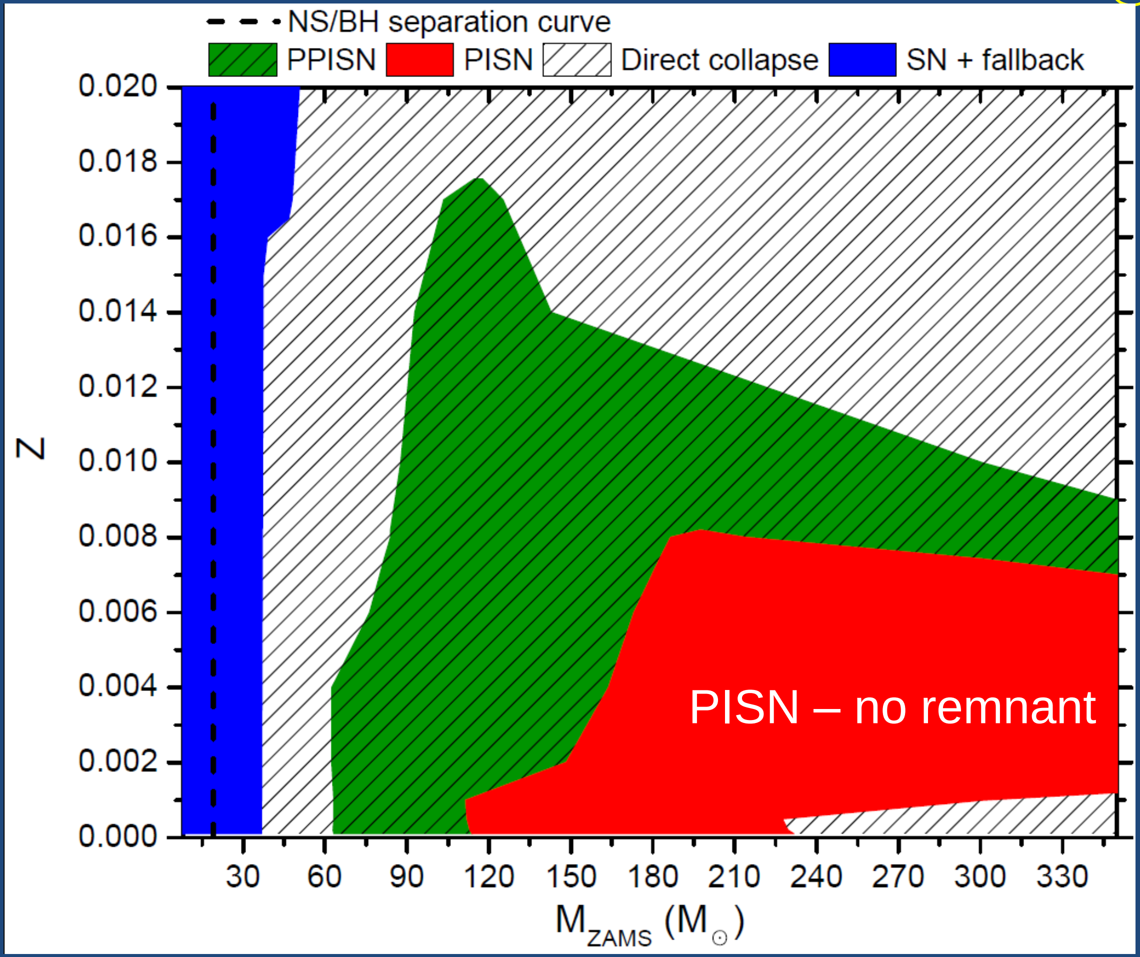
- $M_x > 3M_\odot$
- No signatures of surface
  - ***No periodic pulsations (X-ray pulsar)***
  - ***No explosions on the surface (X-ray type I bursts)***
  - ***No magnetic fields (radiopulsar)***

Cherepashchuk 2014

BH formation from stars (solar metallicity)



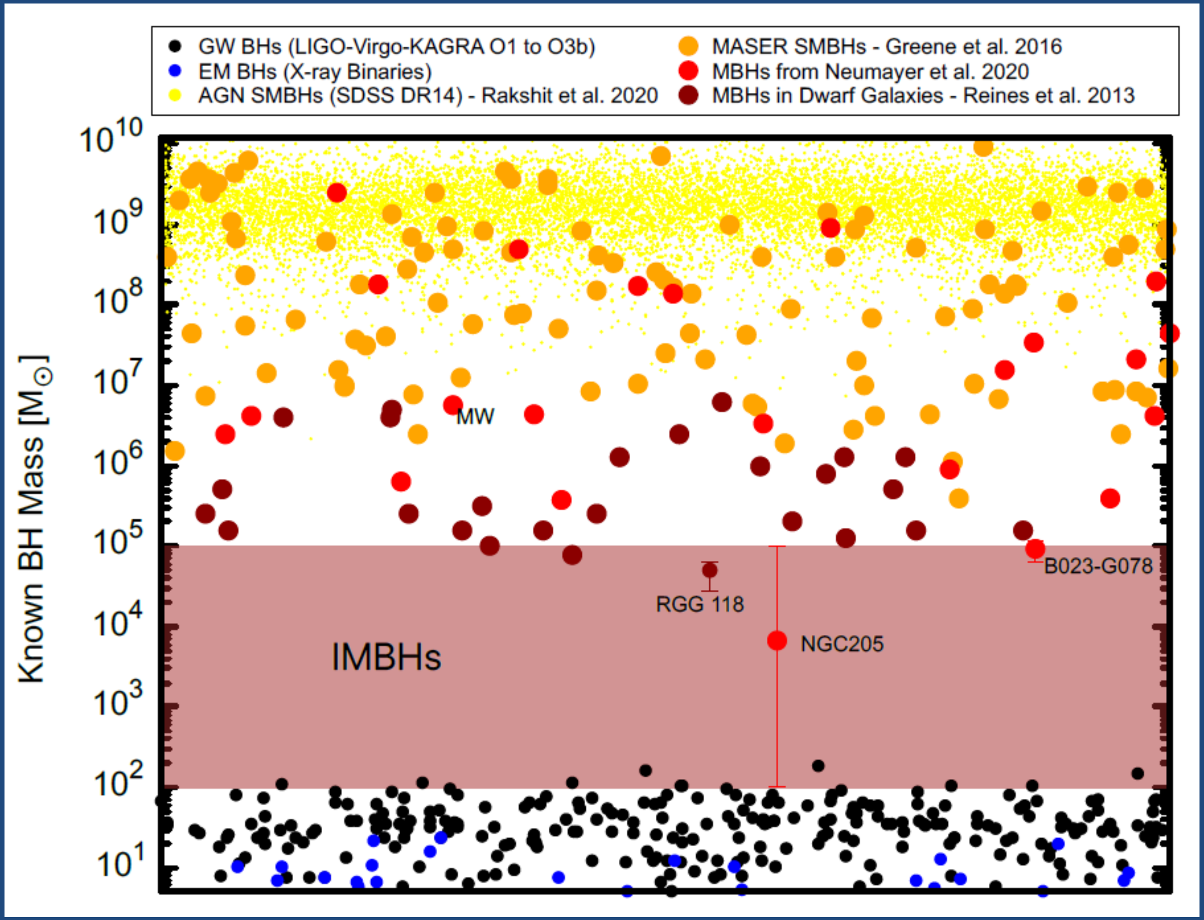
e+/e- pair creation in massive stars ➔ stellar BH 'upper mass gap' (60-130 $M_\odot$)



Spera,Mapelli 2017

Pair-instability SNe (PISNe, Fowler & Hoyle 1964), pulsational PISNe (PPISNe) (Woosley 2017)

BH: Astronomical Observations



SMBH

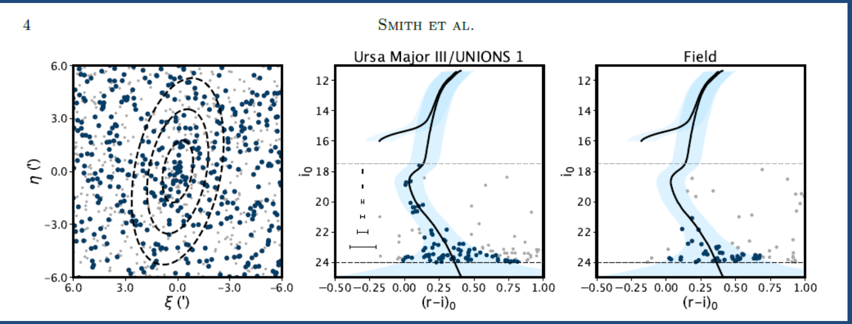
IMBH

Stellar-mass BH

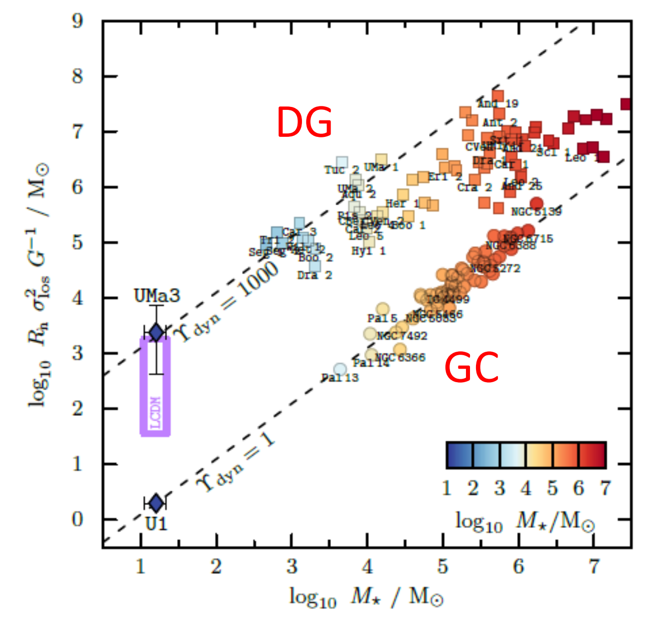
Askar et al. 2311.12118

IMBH in dwarf galaxies?

Smith et al 2311.10147



Errani et al 2311.10134

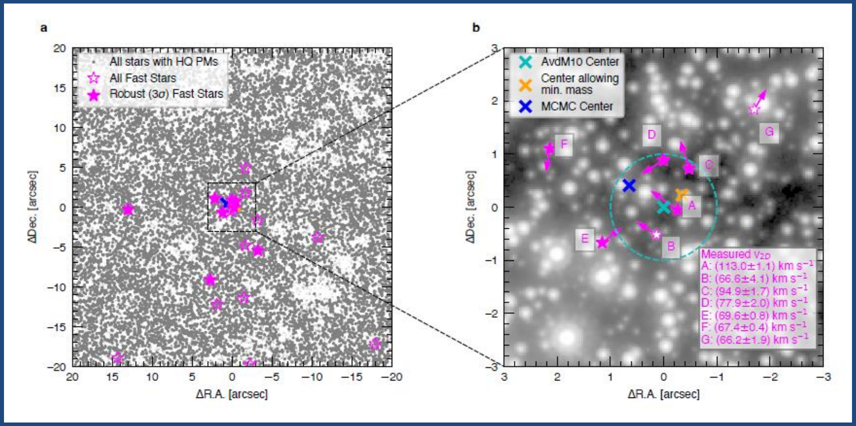


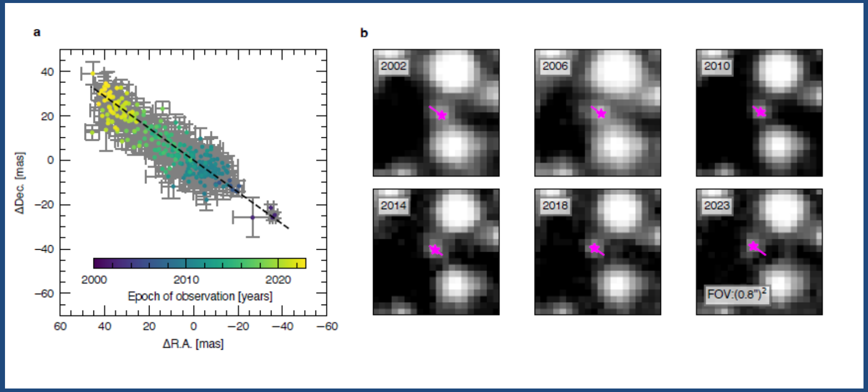
- Uma II/UNIONS 1 – the lightest MW satellite galaxy
- $M^*=16+/-5\ M_\odot$
- $r_h=3+/-\ 1$ pc
- Dynamical evidence – DM-dominated or an IMBH?

$$\Upsilon_{\rm dyn} \equiv \frac{M_{\rm dyn}(<r_{\rm h})}{M_\star(<r_{\rm h})} \approx 8\, R_{\rm h} \langle \sigma^2_{\rm los} \rangle\, G^{-1} M_\star^{-1}$$

IMBH in GC ω Cen (stripped nucleus of accreted dwarf galaxy)

Haeberle+ 2024, 2405.06015

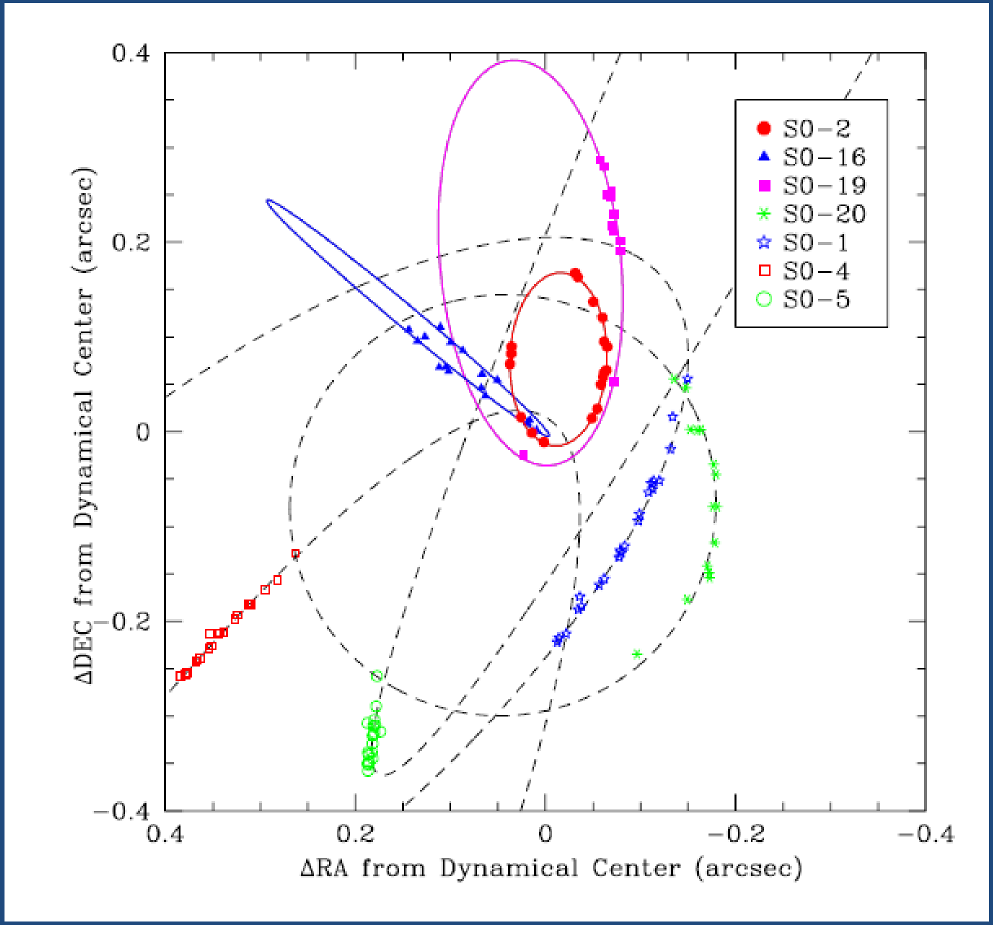




- Fast-moving stars with v> 3σ above v_{esc}=62 km/s in the center of ω Cen suggest IMBH with M>8200 $M_\odot$
- Similar IMBH in stripped nuclei of satellites around M31 (G1: ~20000 $M_\odot$, B023-G078 ~10^5 $M_\odot$)

Supermassive BH (SMBH)

Orbits of stars around Sgr A*



Chez et al. 2005

$$\theta \sim \frac{r_g}{d} \sim 0.05 \text{ milliarcseconds}$$

$$M_{\mathrm{Sgr\,A^*}} = 4.10 \pm 0.03 \times 10^6\ M_\odot$$

(GRAVITY collab. 2018)

Deviation of S0-2/S2 orbit (P=11.5 yr) from Keplerian motion (Do et al 2019)

Einstein Horizon Telescope

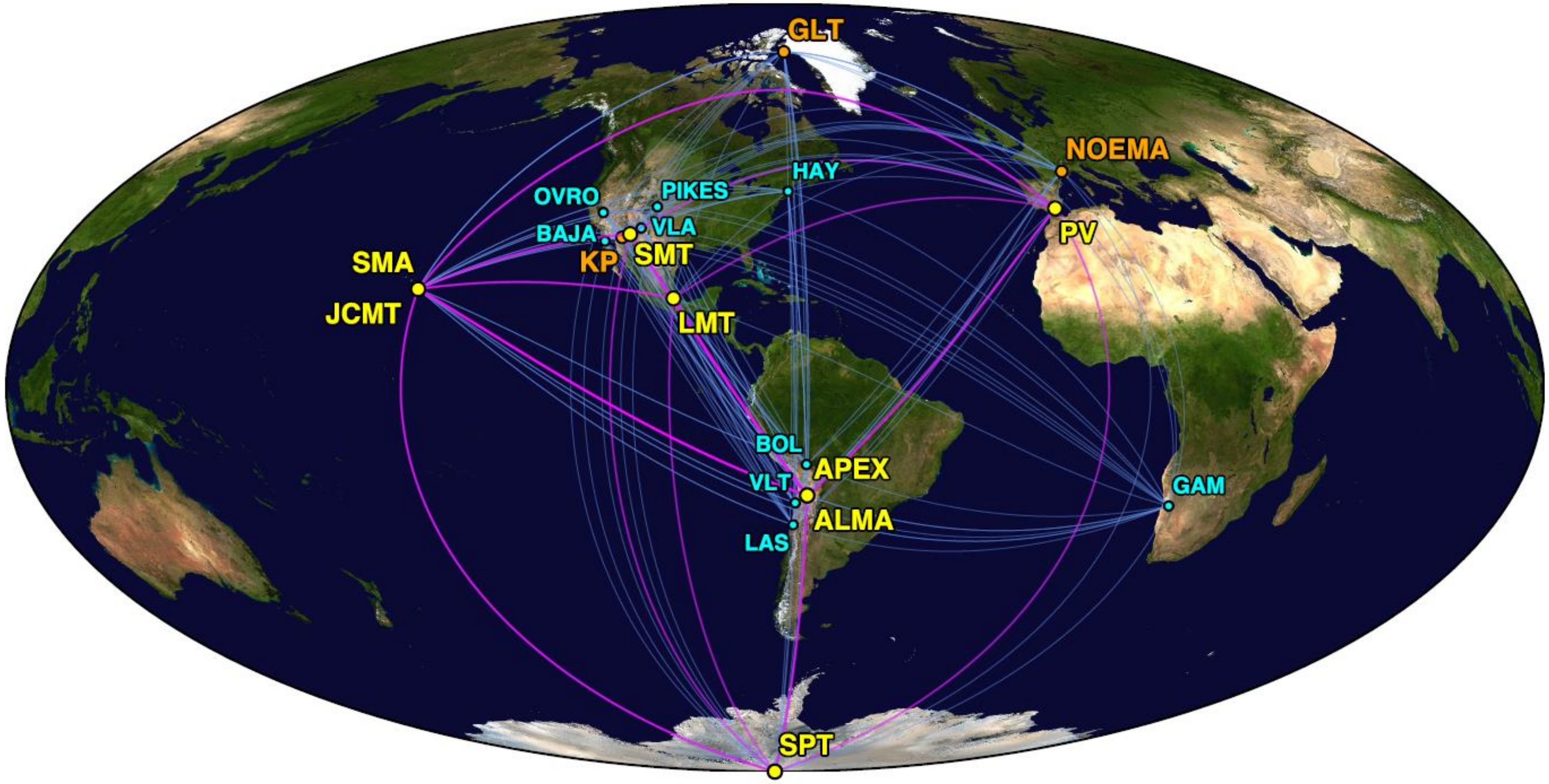
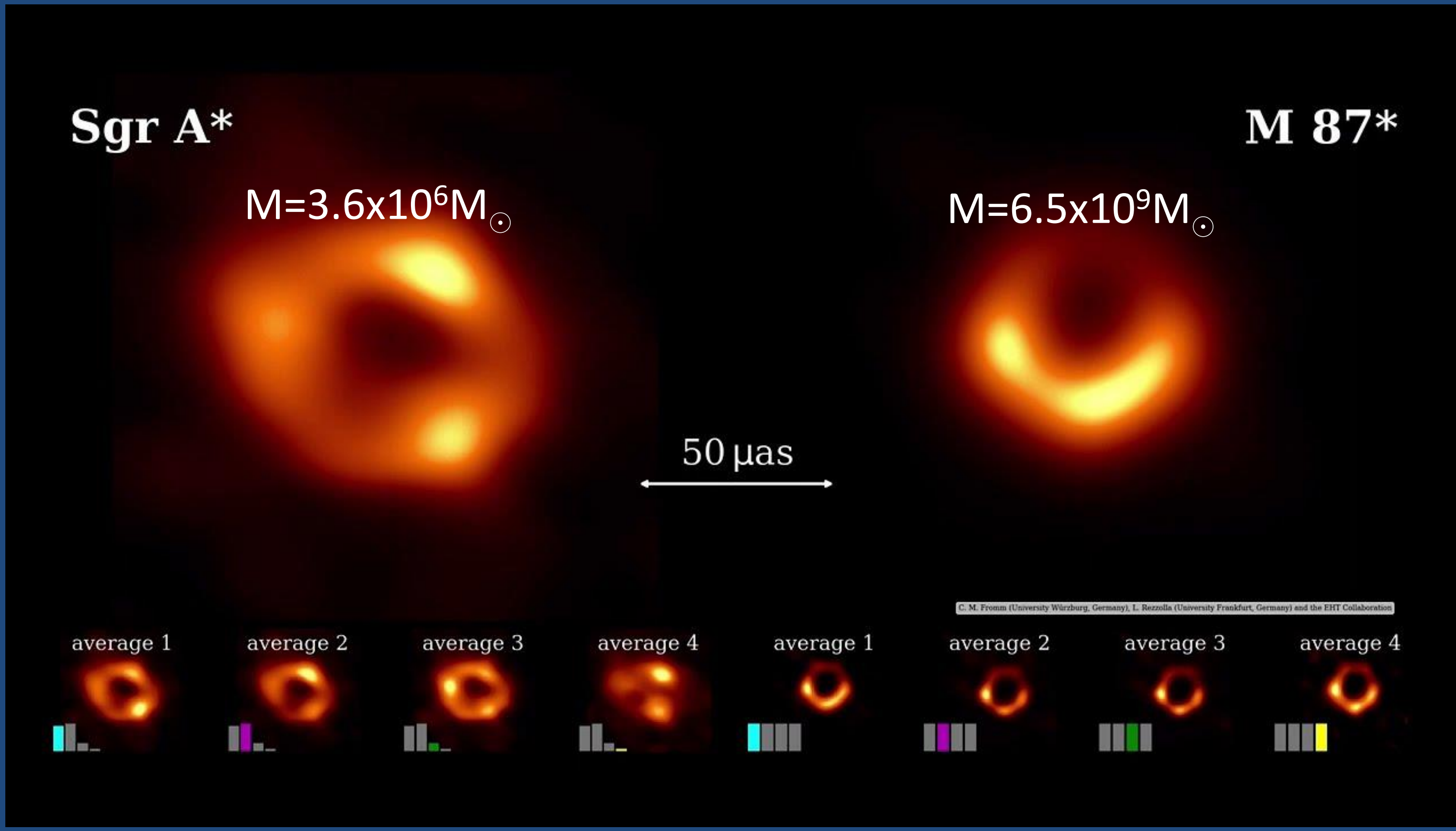


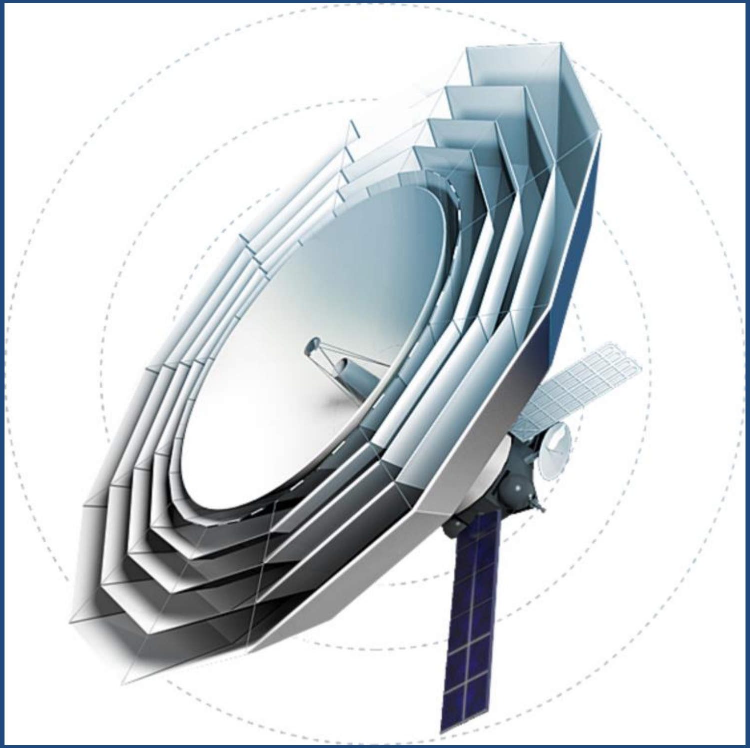
Figure 5: Distribution of stations around the globe. Stations that participated in the EHT2017 observing campaign are labeled in yellow, while the additional stations that will be present in the EHT2020 array are labeled in orange. Several possible new site locations for the ngEHT are labeled in cyan. Current EHT2017 baselines are shown in magenta.

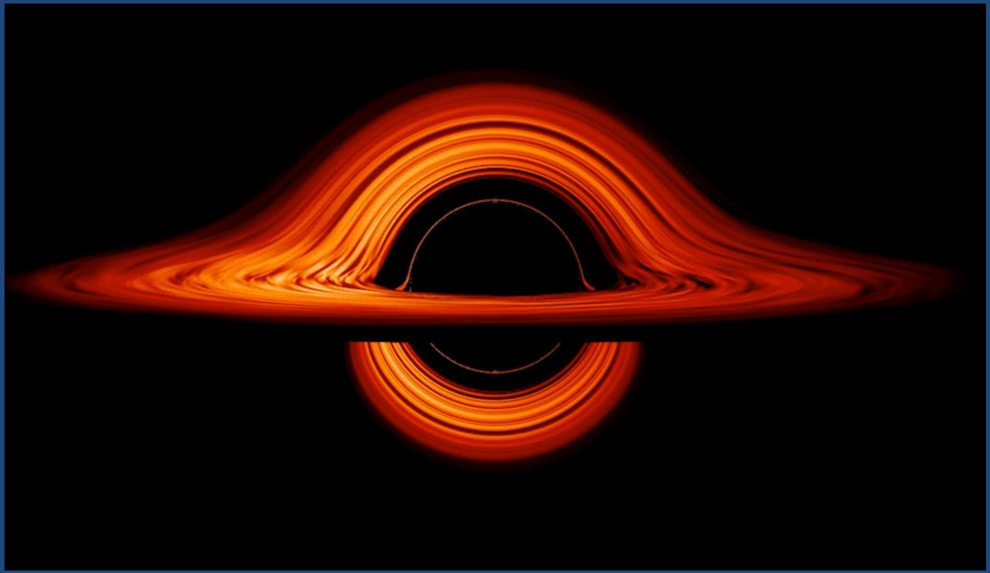
EHT image of local SMBH



λ=1.3 mm, θ~20 mas)

Future prospects: Millimetron space mission

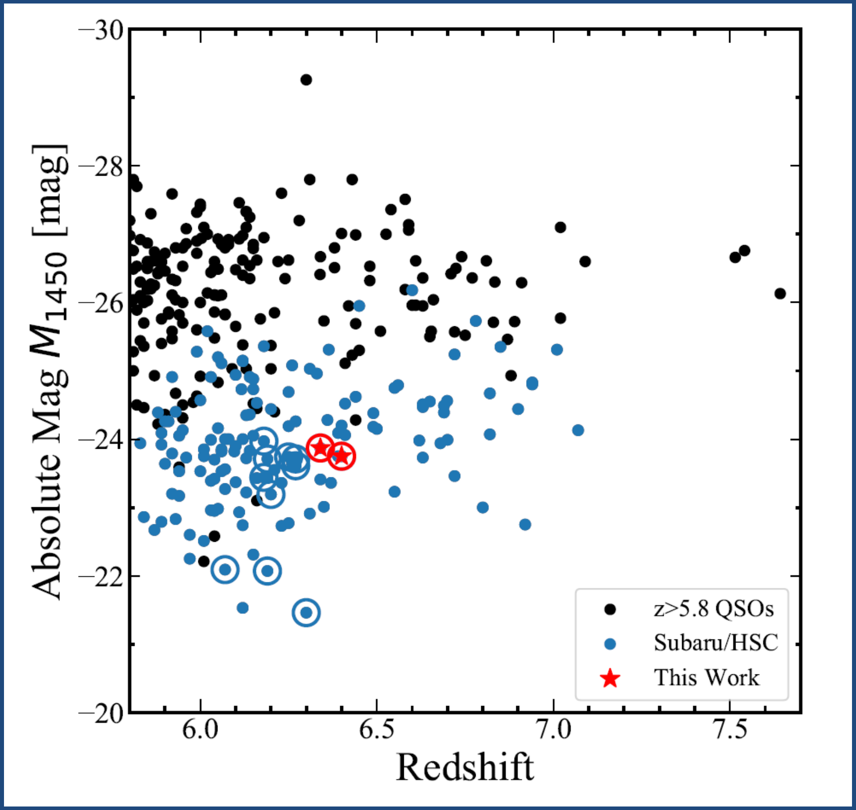




Credits: NASA's GSFC/Jeremy Schnittman

λ=0.07-10 mm
VLBI L2-Earth
θ~0.4-0.1 mas
~2030

High-redshift QSOs and SMBH growth

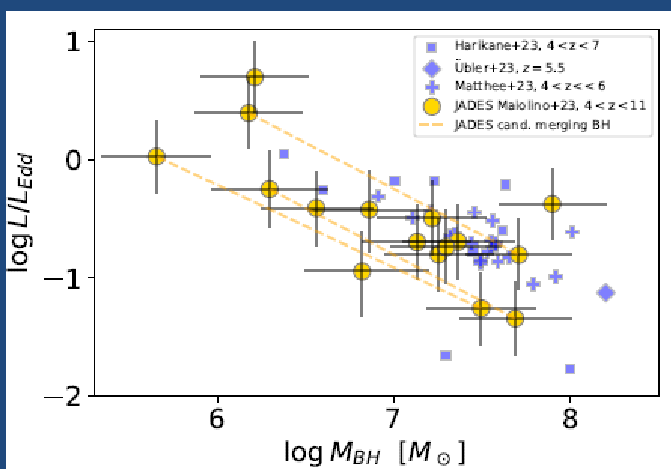


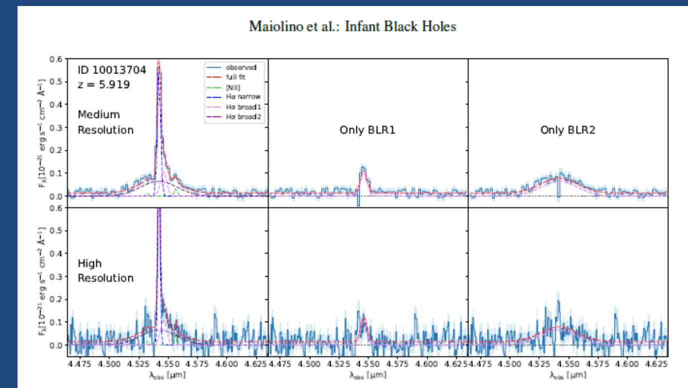
2211.14329

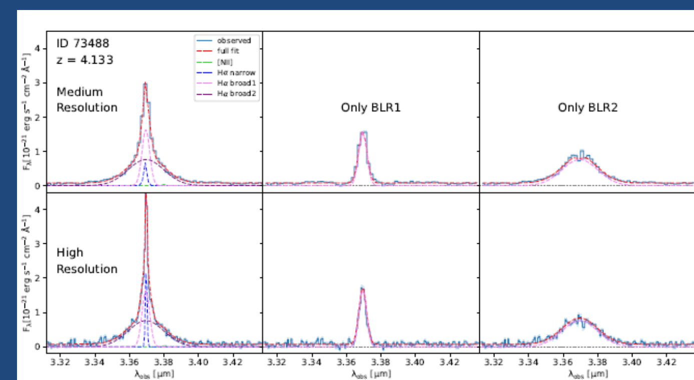
- >200 QSO z>6
- Central SMBH $M \sim 10^9\ M_\odot$
- Inefficient merging
- Eddington-limited accretion
- **Need for 'massive 'seeds' $M \sim 10^3$ -$10^4\ M_\odot$**
- Population III star? Primordial massive BHs?

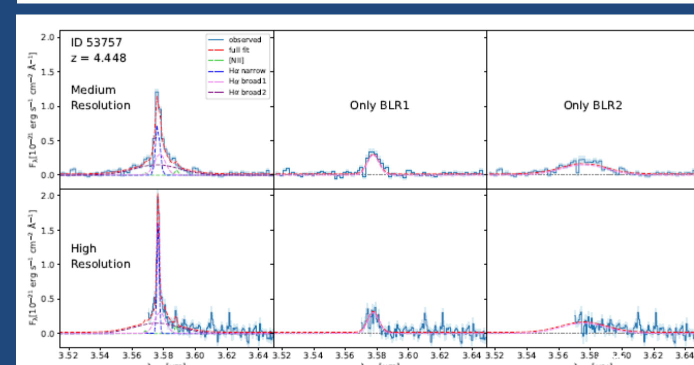
Double SMBH in JADES JWST

- Dual BLR H_α lines in three out 11 AGNs $4<z<6$ → merging accreting double BH









Maiolino et al. 2308.01230

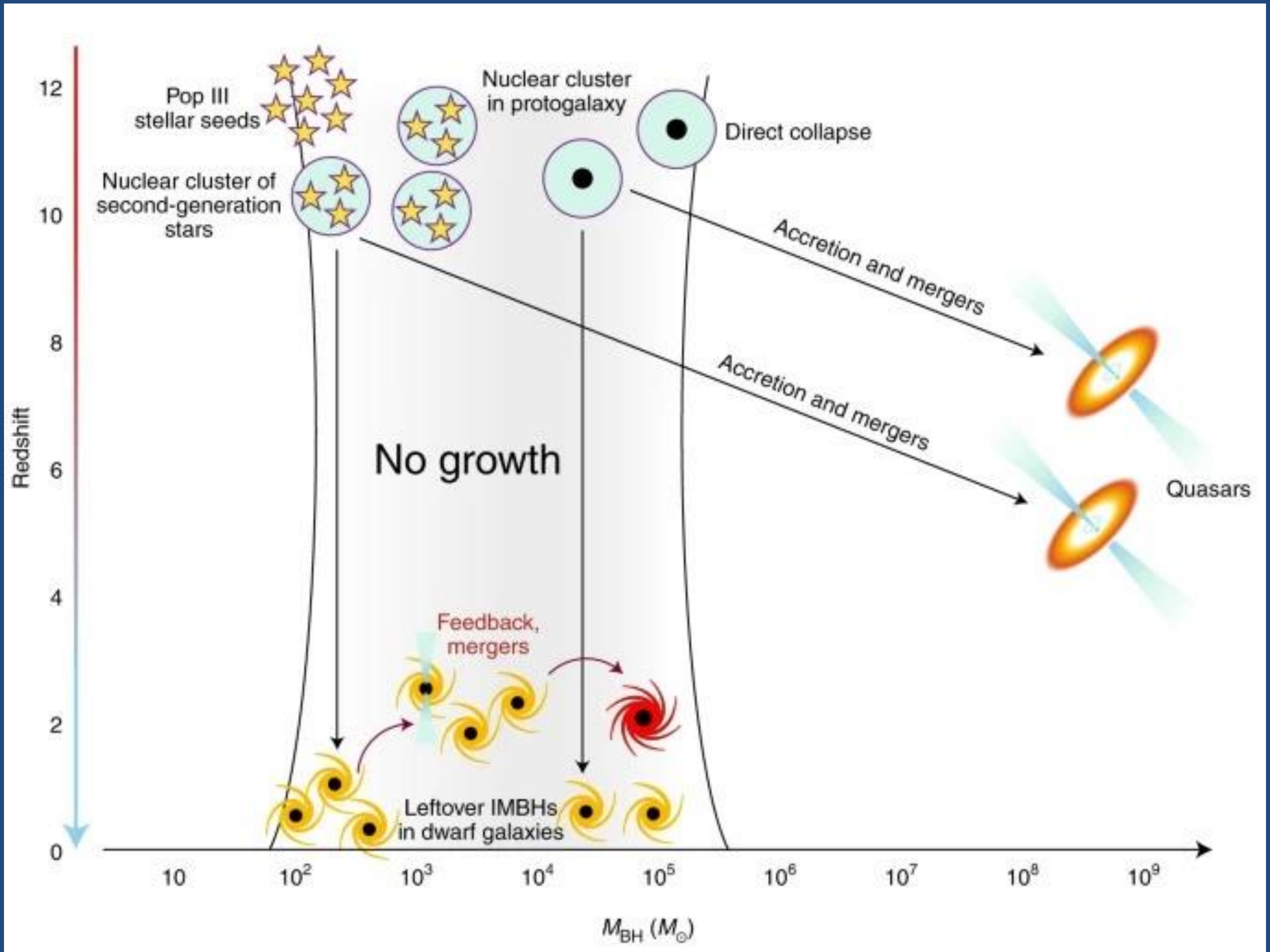
Merging binary SMBH candidates

Table 3: Parameters inferred for the broad line AGN presented in this JADES sub-sample, and including GN-z11 from Maiolino et al. (2023a).

ID	Comp.	$\lg(M_{BH})$ $[M_\odot]$	$\lg(L_{bol})$ $[\mathrm{erg\ s^{-1}}]$	L/L_{Edd}	$\lg(M_{star})$ $[M_\odot]$	$\lg(\sigma)$[a] $[\mathrm{km\ s^{-1}}]$	R_* [kpc]	Sersic index	$\lg(M_{dyn})$ $[M_\odot]$	M_{UV} [mag]	A_V[b] [mag]
10013704	BLR1	$5.65^{+0.31}_{-0.31}$	43.8	1.06	$8.88^{+0.66}_{-0.66}$	$1.93^{+0.05}_{-0.06}$	0.15	0.8	$9.23^{+0.1}_{-0.13}$	−18.89	0.27
	BLR2	$7.5^{+0.31}_{-0.31}$	44.3	0.06							
8083		$7.25^{+0.31}_{-0.31}$	44.6	0.16	$8.45^{+0.03}_{-0.03}$	$1.9^{+0.06}_{-0.07}$	0.11	5.7	$8.84^{+0.11}_{-0.15}$	−18.67	0.64
1093		$7.36^{+0.32}_{-0.31}$	44.8	0.2	$8.34^{+0.2}_{-0.2}$	$1.95^{+0.05}_{-0.06}$	–	–	–	−17.48	0.99
3608		$6.82^{+0.38}_{-0.33}$	44.0	0.11	$8.38^{+0.11}_{-0.15}$	$1.92^{+0.06}_{-0.07}$	–	–	–	−19.5	0.48
11836		$7.13^{+0.31}_{-0.31}$	44.5	0.2	$7.79^{+0.3}_{-0.3}$	$1.96^{+0.05}_{-0.06}$	0.48	0.8	$9.81^{+0.1}_{-0.14}$	−18.75	0.68
20621		$7.3^{+0.31}_{-0.31}$	44.7	0.18	$8.06^{+0.7}_{-0.7}$	$1.93^{+0.06}_{-0.07}$	–	–	–	−18.27	0.67
73488	BLR1	$6.18^{+0.3}_{-0.3}$	44.7	2.48	$9.78^{+0.2}_{-0.2}$	$1.64^{+0.11}_{-0.15}$	0.59	0.8	$9.28^{+0.21}_{-0.41}$	−18.73	0.45
	BLR2	$7.71^{+0.3}_{-0.3}$	45.0	0.16							
77652		$6.86^{+0.35}_{-0.34}$	44.5	0.38	$7.87^{+0.16}_{-0.28}$	$1.95^{+0.06}_{-0.07}$	–	–	–	−18.28	0.39
61888		$7.22^{+0.31}_{-0.31}$	44.8	0.32	$8.11^{+0.92}_{-0.92}$	$1.85^{+0.07}_{-0.09}$	0.09	0.9	$8.92^{+0.22}_{-0.46}$	−19.0	0.69
62309		$6.56^{+0.32}_{-0.31}$	44.2	0.39	$8.12^{+0.12}_{-0.13}$	$1.87^{+0.07}_{-0.08}$	0.21	1.3	$9.27^{+0.14}_{-0.2}$	−18.67	0.74
53757	BLR1	$6.29^{+0.33}_{-0.32}$	44.1	0.56	$10.18^{+0.13}_{-0.12}$	$1.77^{+0.09}_{-0.11}$	–	–	–	−18.9	0.36
	BLR2	$7.69^{+0.32}_{-0.31}$	44.4	0.05							
954[c]		$7.9^{+0.3}_{-0.3}$	45.6	0.42	$10.66^{+0.09}_{-0.1}$	$1.91^{+0.06}_{-0.06}$	0.35	0.8	$9.56^{+0.13}_{-0.18}$	−19.78	0.64
GN-z11[d]		$6.2^{+0.3}_{-0.3}$	45.0	5.5	$8.9^{+0.2}_{-0.3}$	–	0.20	0.9		−21.79	0.0

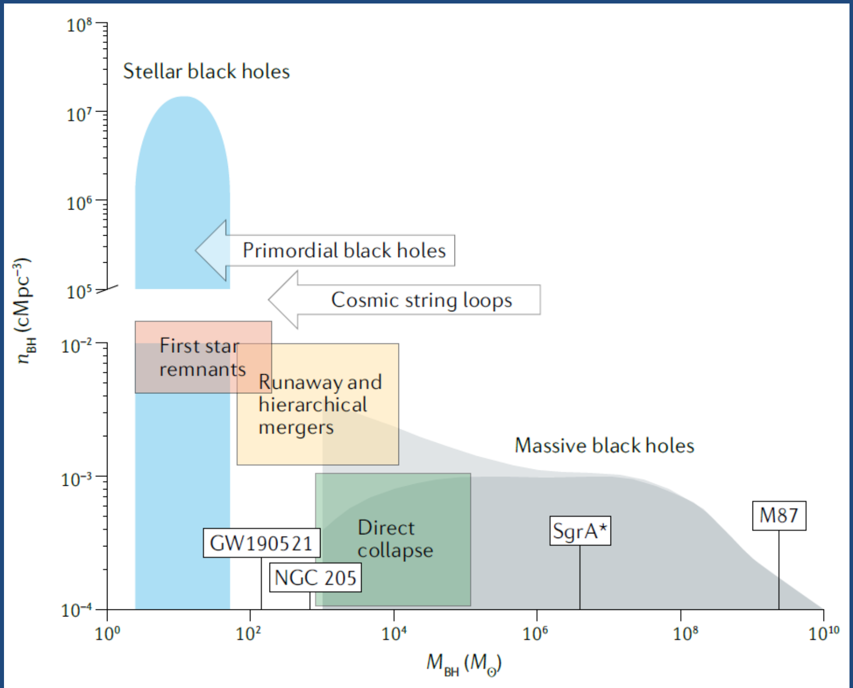
Maiolino et al. 2308.01230

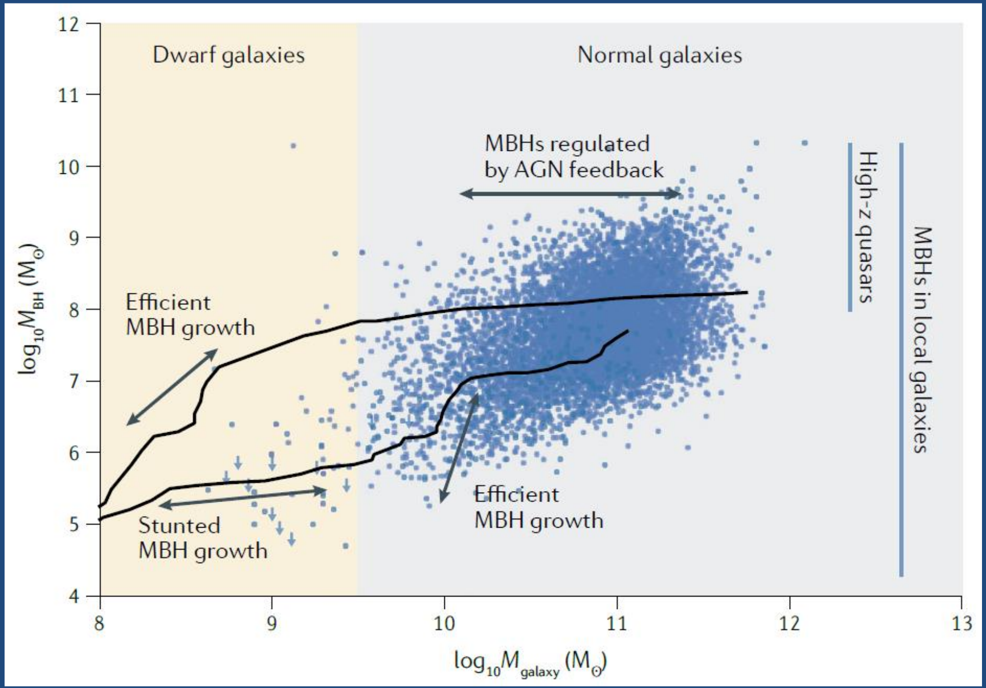
Growth of SMBHs from astrophysical seeds



Mezcua 2017

Massive BH formation

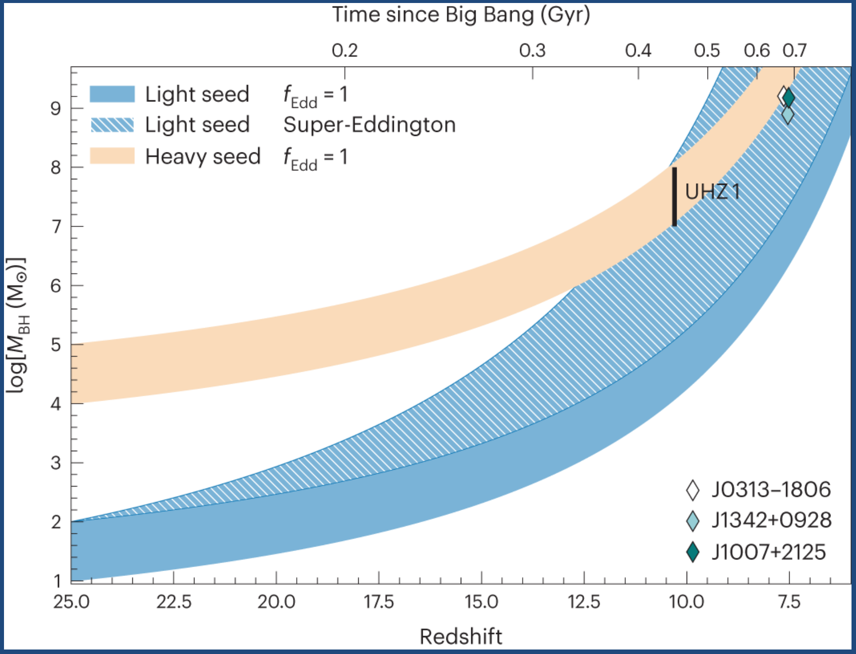




Whether and how the bridge between stellar and supermassive black holes was established when the first galaxies were forming is currently unknown (Volonteri et al. 2021).

SMBH growth from massive seeds

- A.Bogdan et al. 2023 NatAstronomy. UHZ1 z=10.3
- Growth from light seeds require super-Eddington accretion
- Growth from massive seeds is more natural



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SUPERMASSIVE BLACK H

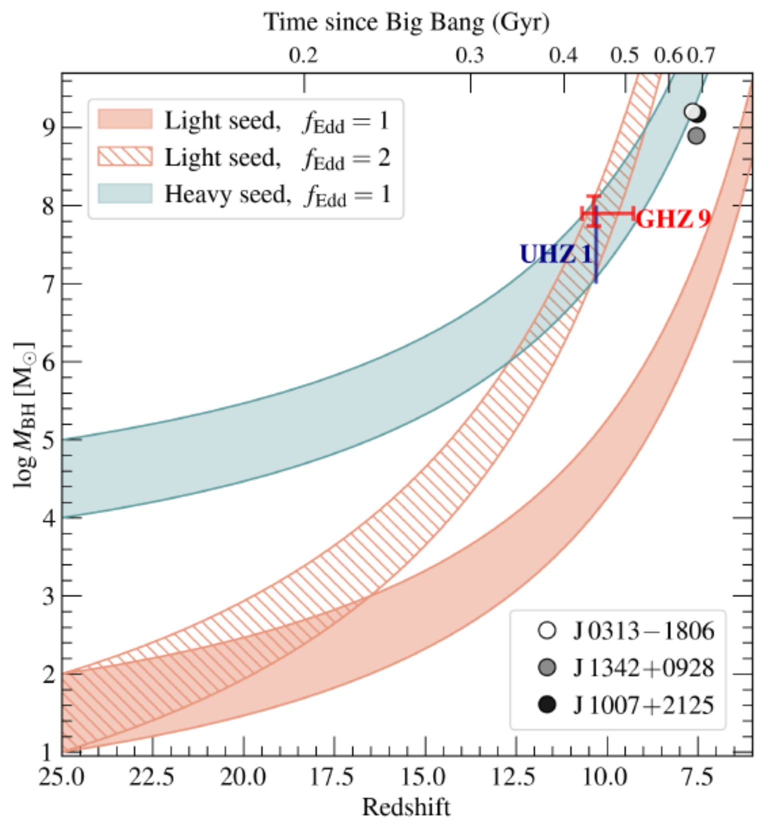
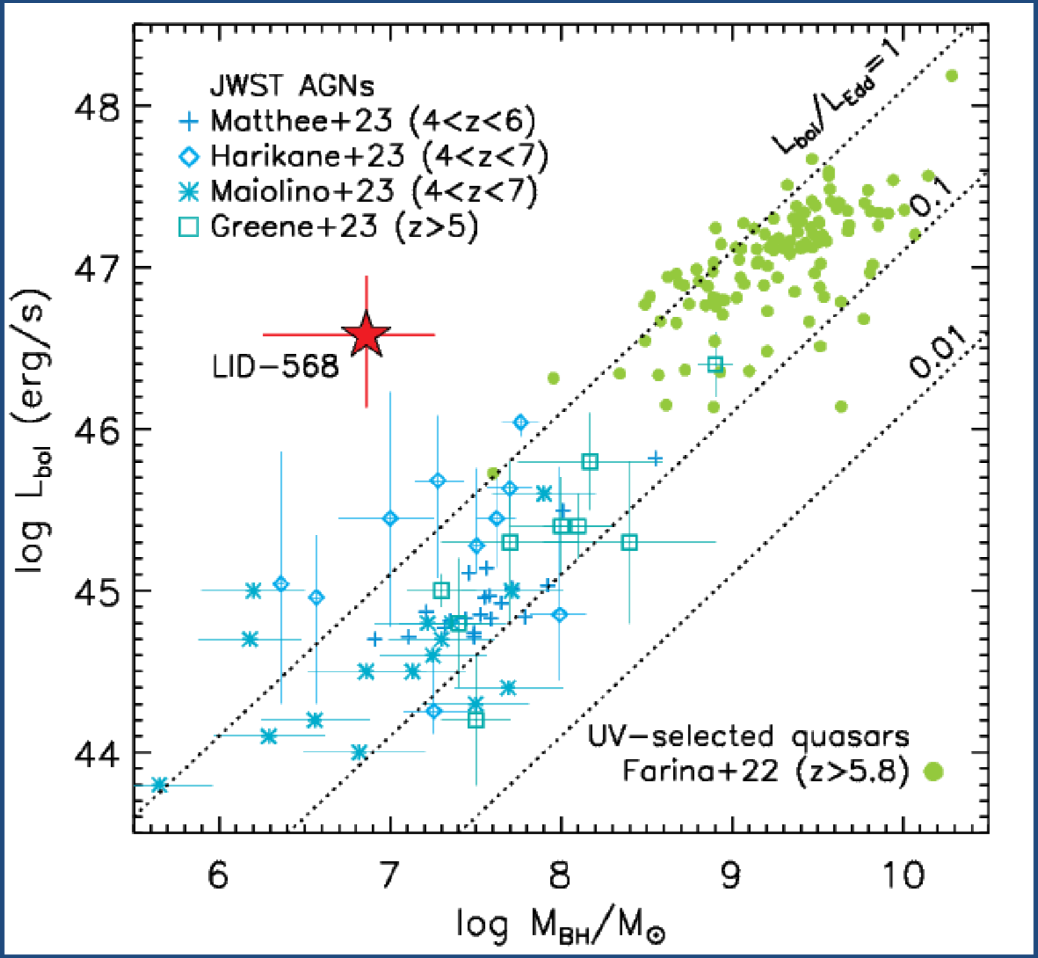


FIG. 3.— BH growth tracks for different initial seed masses and accretion rates assuming continuous accretion with a radiative efficiency of 10%. Light BH seeds only reach $10^4 - 10^5$ $M_\odot$ mass by $z \approx 10.4$ accreting at their Eddington limit. The estimated $\sim 8.0 \times 10^7$ $M_\odot$ mass for its redshift of $z \approx 10.37$, however, places the candidate BH of GHZ 9 as originating from a heavy seed, similar to UHZ 1 (Bogdán et al. 2024). While sustained accretion above the Eddington limit is unlikely (Willott et al. 2010; Smith et al. 2018), we also show the growth curves assuming $f_{Edd} = 2$ for light seeds with the hatched region, which would also be able to produce BH masses estimated for GHZ 9 and UHZ 1. We show three

Superluminal accretion onto SMBH?



$$L_{Edd} = 10^{38}[erg\ s^{-1}](\frac{M}{M_s})$$

Suh et al. 2405.05333

Astrophysical BH formation: summary

- Stellar-mass BHs: from stellar evolution (core collapse of massive stars). ~4-50 $\mathbf{M_\odot}$ (But: in dense stellar clusters, masses can be made higher due to previous coalescences)
- Supermassive BHs (in galactic centers, appear as AGNs and QSOs) ~10^5 $\mathbf{M_\odot}$ - 10^{10} $\mathbf{M_\odot}$. Seeds are highly debated, growing in galaxy mergings

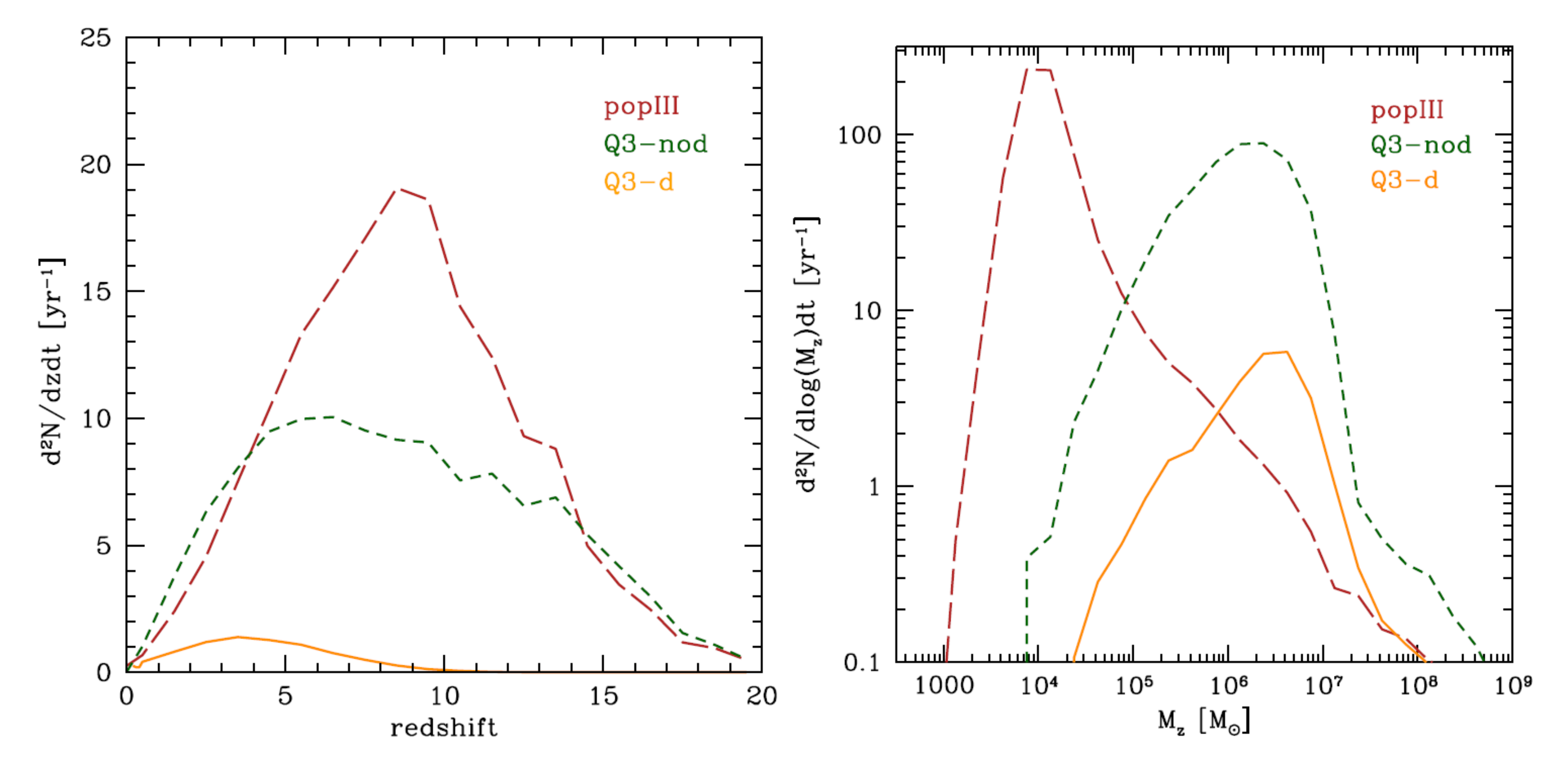
Why IMBH are interesting?

- Can seed the formation of SMB in early galaxies
- Coalescing binary IMBH can be primary sources for future space GW observatories (eLISA, TianQin, Taiji etc.)

How much binary IMBH can we expect?

- Astrophysical formation channel: galaxy mergings at $z<20$
- Cosmological formation channel:
  - Primordial binary IMBH
  - Binary IMBH from mergings of DM halos with central primordial BH

Astrophysics: model binary MBH populations



Klein+ 2016

Constraints from recent PTA results

- NANOGrav
- EPTA
- InPTA
- CPTA

Stochastic GW signal from collection of individual sources

$$\Omega(f) = \frac{2\pi^2}{3H_0^2} f^2 h_c^2(f)$$

Energy density per logarithmic frequency

PSD in timing residuals

$$S(f) = \frac{h_c^2(f)}{12\pi^2 f^3}$$

RMS timing residuals in frequency bin i/T

$$\mathrm{RMS}_i = \left(\int_{\Delta f_i} S(f)\mathrm{d}f\right)^{1/2} \approx (S(f_i)\Delta f_i)^{1/2} = \left(\frac{S(f_i)}{T}\right)^{1/2}$$

$$h_c(f) = A\left(\frac{f}{f_0}\right)^{\alpha}$$

→

$$S(f) = \frac{h_c^2(f)}{12\pi^2 f^3} = \frac{A^2}{12\pi^2 f_0^{2\alpha}} f^{-\gamma}$$

$$\gamma = 3 - 2\alpha$$

SMBH mergings: stochastic GW signal

$$h_c^2(f) = \int_0^\infty dz \int_0^\infty dm_1 \int_0^1 dq \frac{d^5N}{dz\,dm_1\,dq\,de\,dt_r} \frac{dt_r}{d\ln f_{K,r}} \times h^2(f_{K,r}) \sum_{n=1}^{\infty} \frac{g[n, e(f_{K,r})]}{(n/2)^2} \bigg|_{f_{K,r}=f(1+z)/n}$$

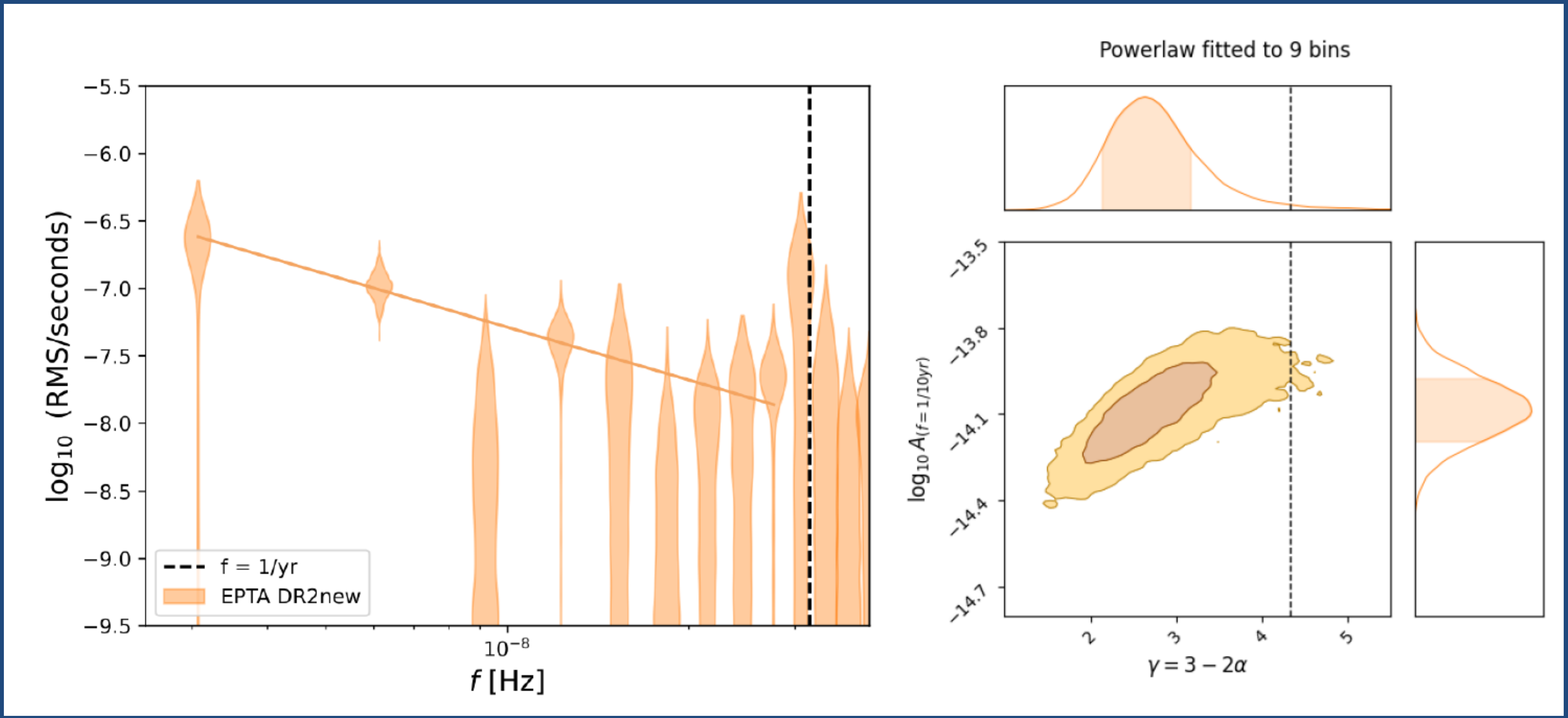
Circular binaries:

$$h_c^2(f) = \int_0^\infty dz \int_0^\infty d\mathcal{M} \frac{d^3N}{dz\,d\mathcal{M}\,d\ln f} h^2(f)$$

$$h_c^2(f) = \frac{4G^{5/3}}{3\pi^{1/3}c^2} f^{-4/3} \int d\mathcal{M} \int dz\,(1+z)^{-1/3}\,\mathcal{M}^{5/3} \frac{d^2n}{dz\,d\mathcal{M}}$$

$$h_c \propto f^{-2/3}$$

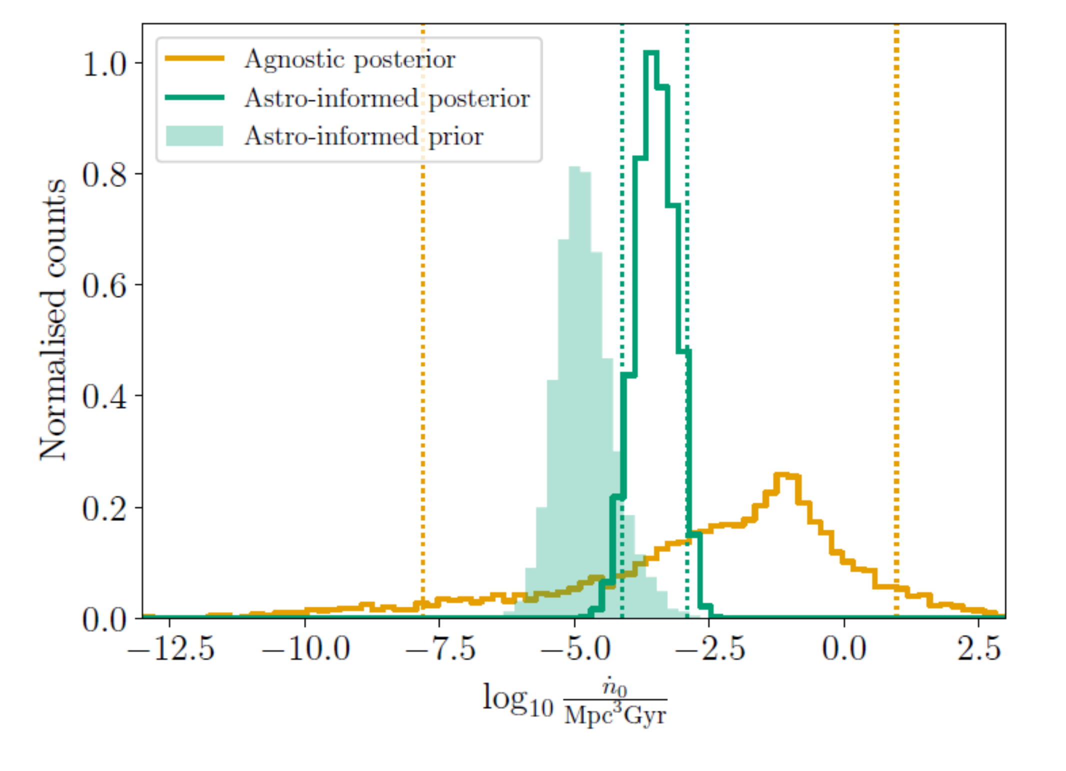
IPTA+InPTA results



γ=13/3 for binary mergings

Antoniadis+ 2306.16227 (AA 2024)

Implications from EPTA+InPTA



Antoniadis+ 2306.16227

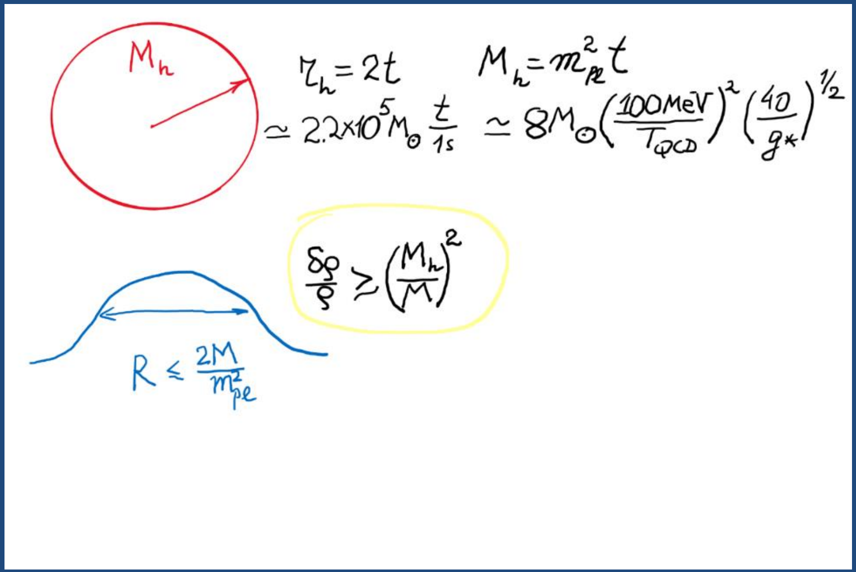
$$\frac{d^2 n}{dz\, d\log_{10}\mathcal{M}} = \dot{n}_0 \left[\left(\frac{\mathcal{M}}{10^7 M_\odot} \right)^{-\alpha_{\mathcal{M}} e^{-\mathcal{M}/\mathcal{M}_\star}} \right] \left[(1+z)^{\beta_z} e^{-z/z_0} \right] \frac{dt_R}{dz}$$

Cf: SMBH merger rate $10^{-2} - 10^{-3}$ yr^{-1} Gpc^{-3} up to z=4 (Wang, Zhang 2403.06416)

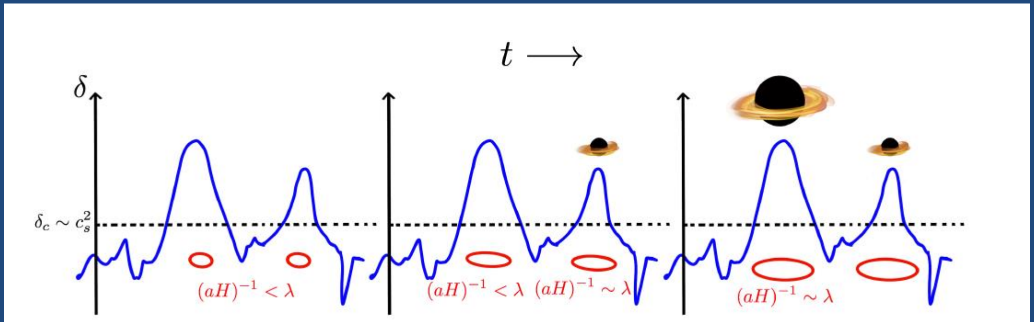
Primordial BH formation

Zeldovich, Novikov'67, Carr, Hawking'74….

- PBH mass = mass inside cosmological horizon



Dolgov+KP 2004.1699



Some PBH formation scenarios

- Primordial density fluctuations, $\delta>\delta_c\sim0.45$ (model-dependent)
- Collapse of scale-invariant fluctuations ➔ power-law mass spectra $dn/dM\sim M^{-\alpha}$, $\alpha=2(1+2w)/(1+w) = 2.5$ at RD ($w=1/3$)
- Inflationary models ➔ log-normal mass spectrum

$$\frac{dn}{dM} = \mu^2 \exp\left[-\gamma \ln^2(M/M_{max})\right]$$

(Dolgov, Silk 1993)

- QCD phase transition at T=100-200 MeV:

$$M \sim \left(\frac{m_{Pl}}{m_p}\right)^3 m_p \sim M_{Ch} \sim 1 M_\odot$$

- Bubble collisions, cosmic strings …

Positive evidence for PBHs?

Observational Evidence for Primordial Black Holes

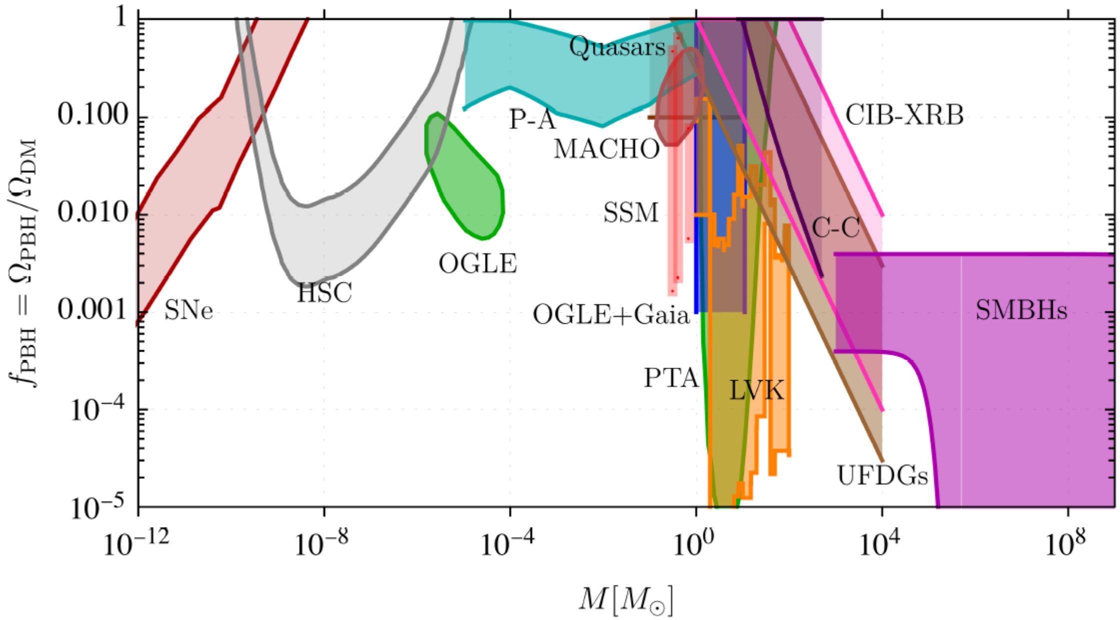


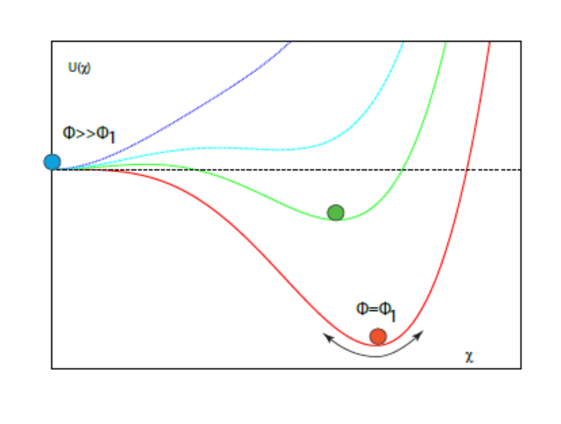
Figure 1. Summary of positive evidence for PBHs in terms of $f_{\rm PBH}$ values required by or consistent with the claimed detections. These come from PBH-attributed signals from supernovæ (SNe), various microlensing surveys (Gaia, HSC, OGLE, MACHO), POINT-AGAPE pixel-lensing (P-A), gravitational waves (LVK), ultra-faint dwarf galaxies (UFDGs), supermassive black holes (SMBHs), core/cusp (C-C) profiles for inner galactic halos, and correlations of the source-subtracted cosmic infrared and X-ray backgrounds (CIB-XRB). The

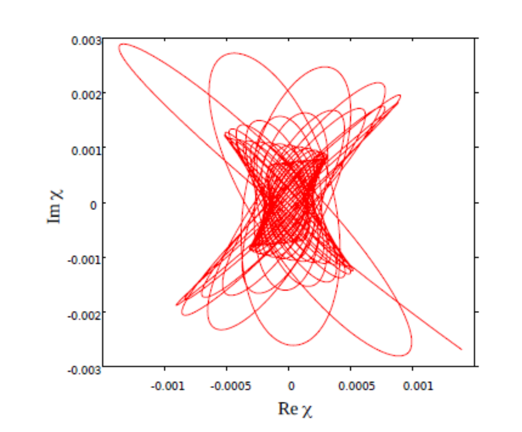
Carr et al. 2306.03903

Modified Affleck-Dine baryogenesis (Dolgov and Silk , 1993)

- Complex scalar baryon field χ+ Inflaton field Φ

$$U(\chi,\Phi) = U_\Phi(\Phi) + U_\chi(\chi) + \lambda_1(\Phi - \Phi_1)^2|\chi|^2$$





- Along 'flat directions', field χ rotates ➔ regions with baryonic charge (HBB) by the end of inflation
- HBB turns into density fluctuations after QCD phase transition at T~100 MeV with log-normal mass spectrum

$$\frac{dn}{dM} = \mu^2 \exp\left[-\gamma \ln^2(M/M_{max})\right]$$

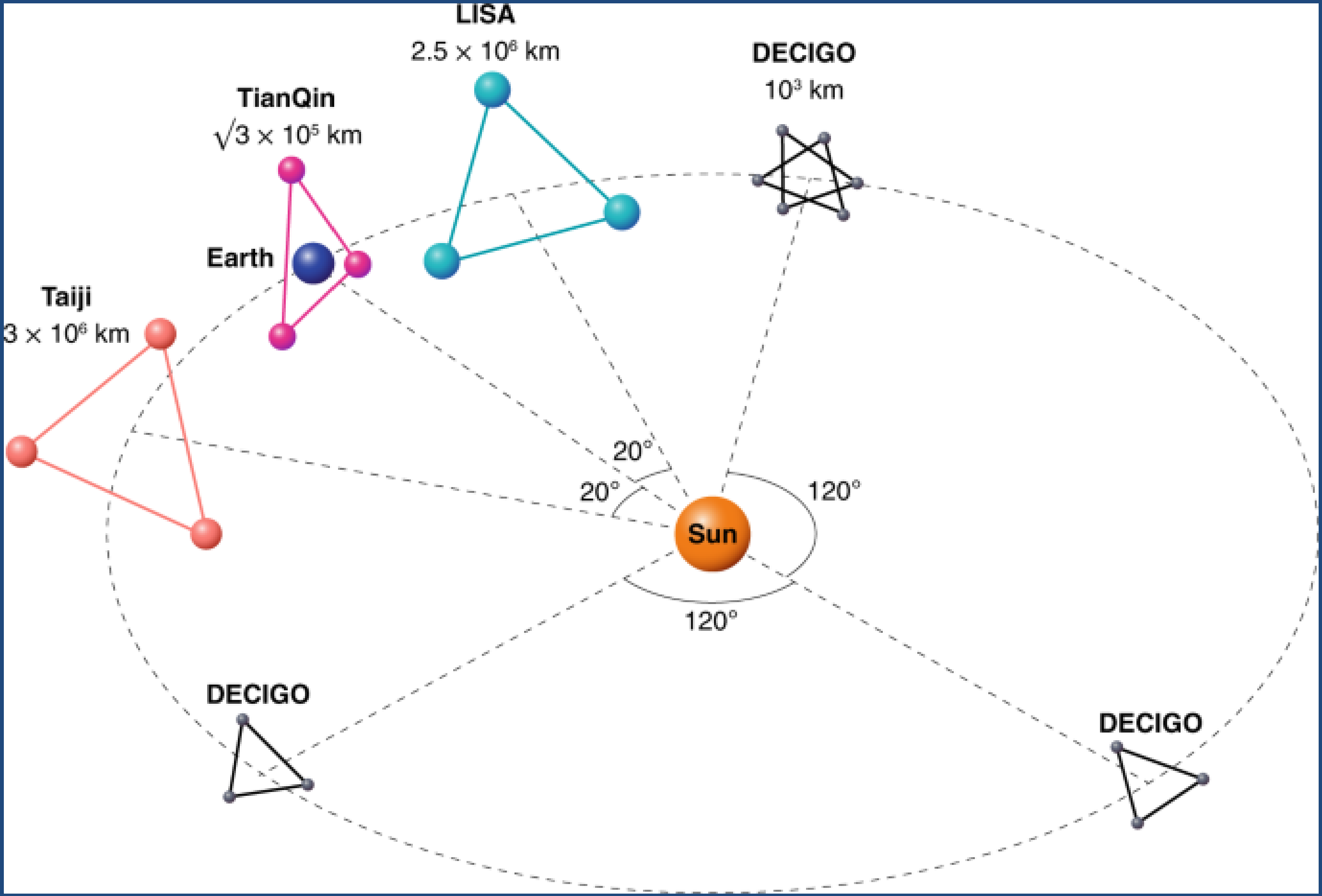
Primordial IMBH

- Maximum BH mass depends on the duration of inflation after 'opening' of flat directions of the χ potential

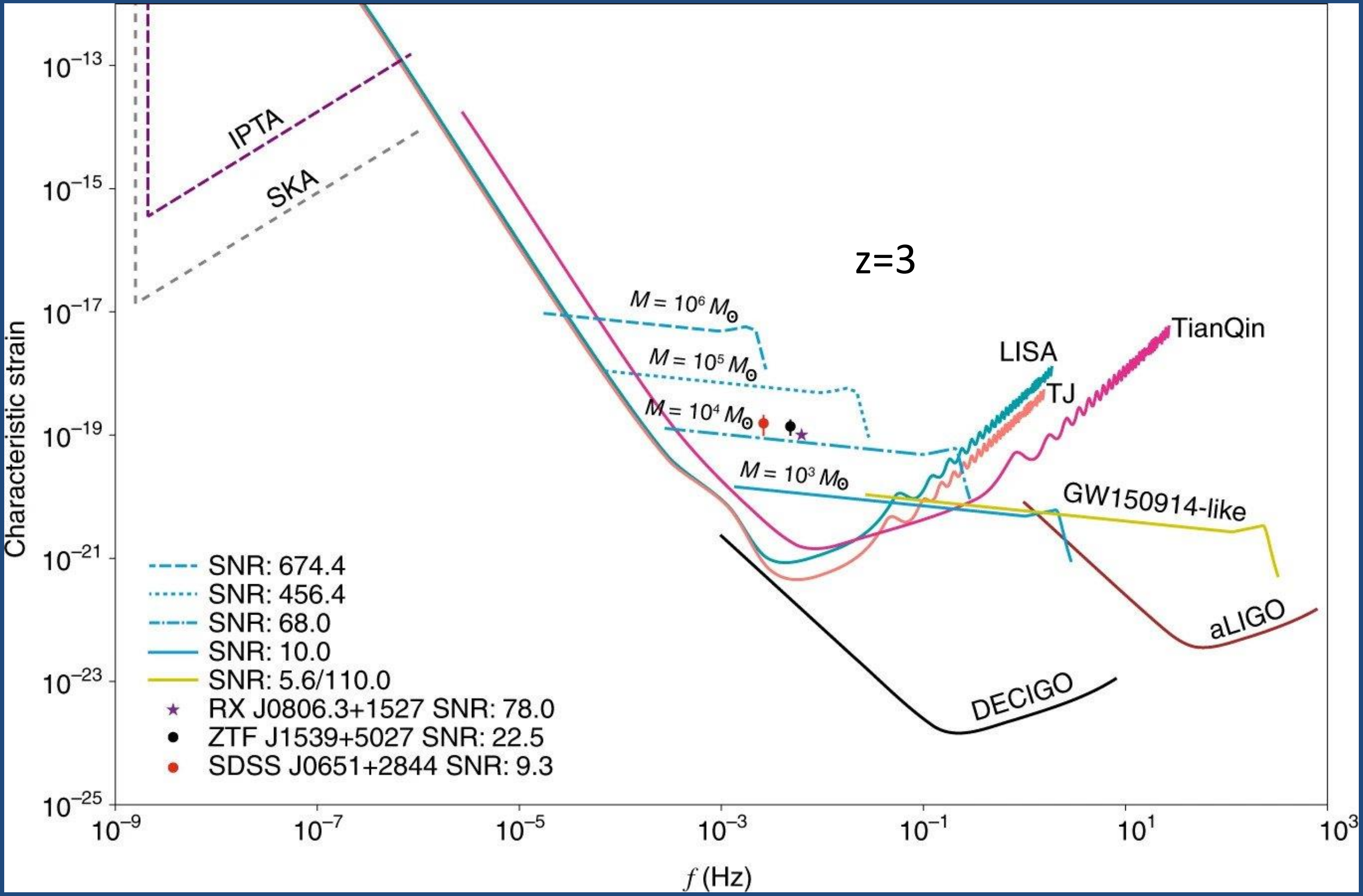
$$e^{3H(t_e-t_1)} = 10^{37+5-10+15}\left(\frac{T_h}{10^{14}\mathrm{GeV}}\right)^3 \frac{M_{\mathrm{BH}}^{(\mathrm{max})}}{10^4 M_\odot}\frac{100\ \mathrm{MeV}}{T_{\mathrm{MD}}}$$

- $H(t_e - t_1) = 36$ is required to create PBH up to $10^4\ M_\odot$ (Blinnikov,Dolgov,Porayko,PK 2016 JCAP)

Space laser interferometers

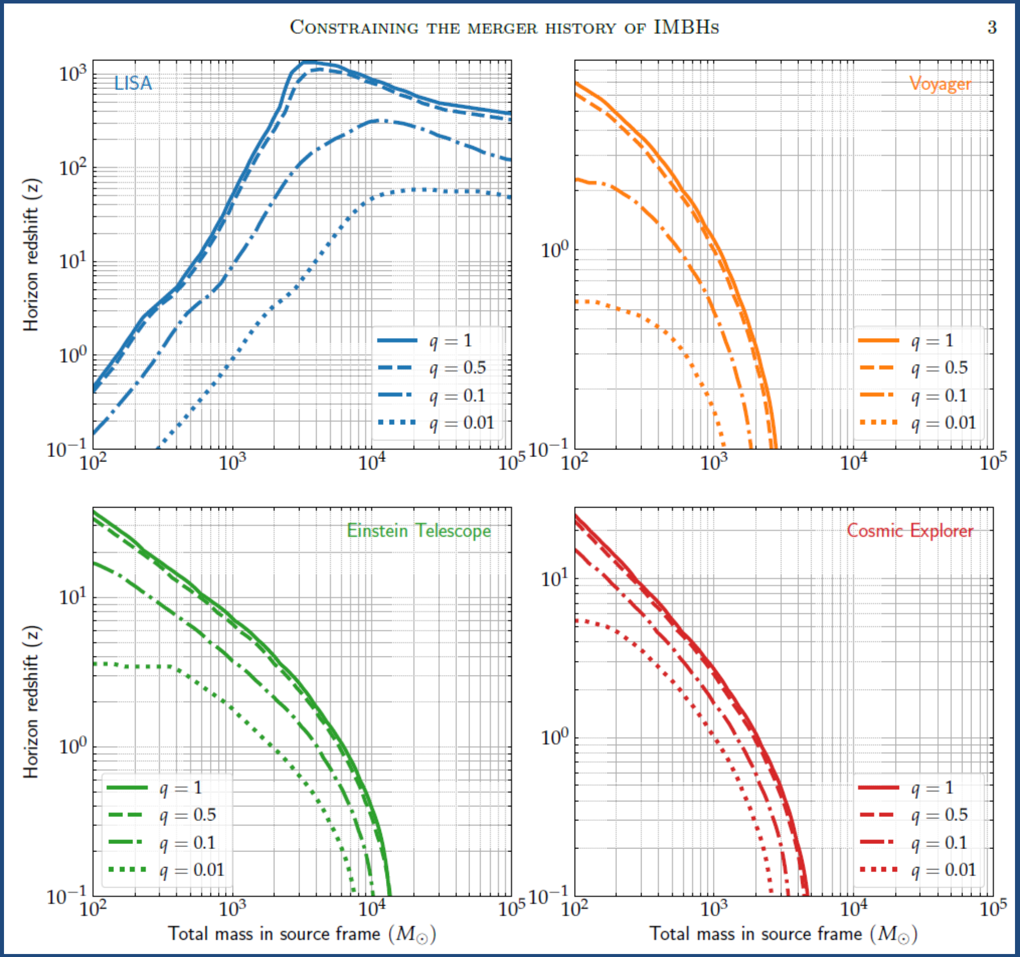


Coalescing binary IMBH



Gong et al 2021

Detection horizon for merging binary IMBH



Fragione, Loeb 2023

TianQin project (SYSU, China)

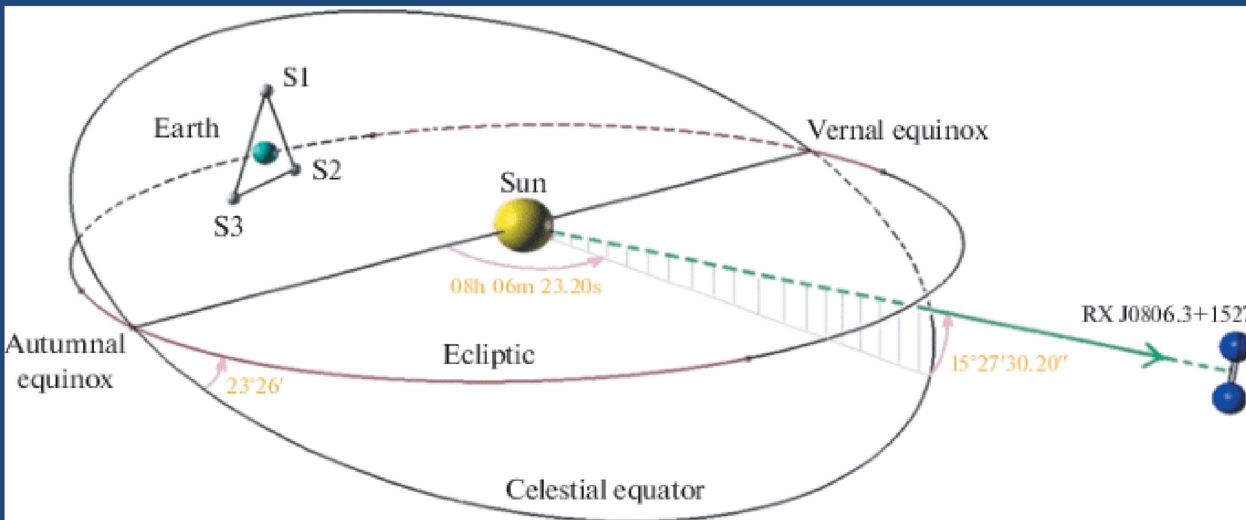
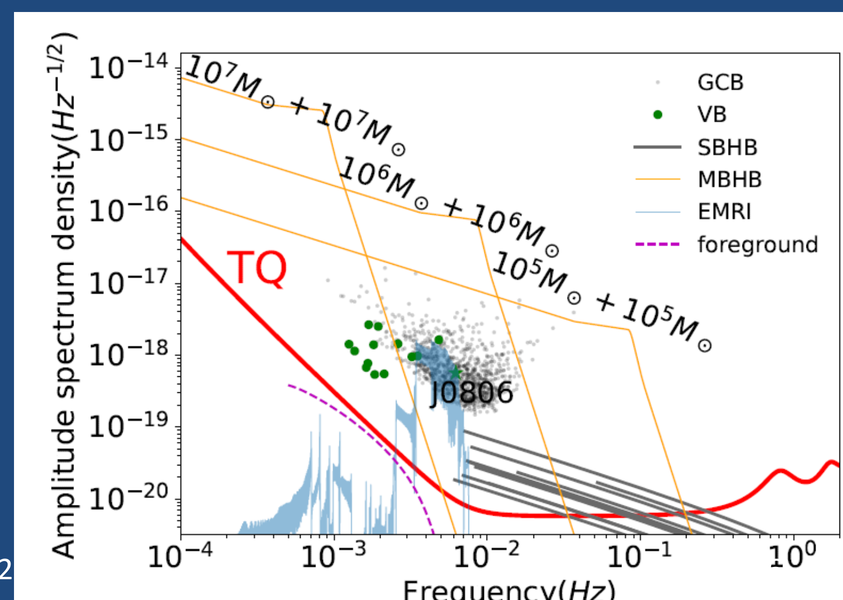


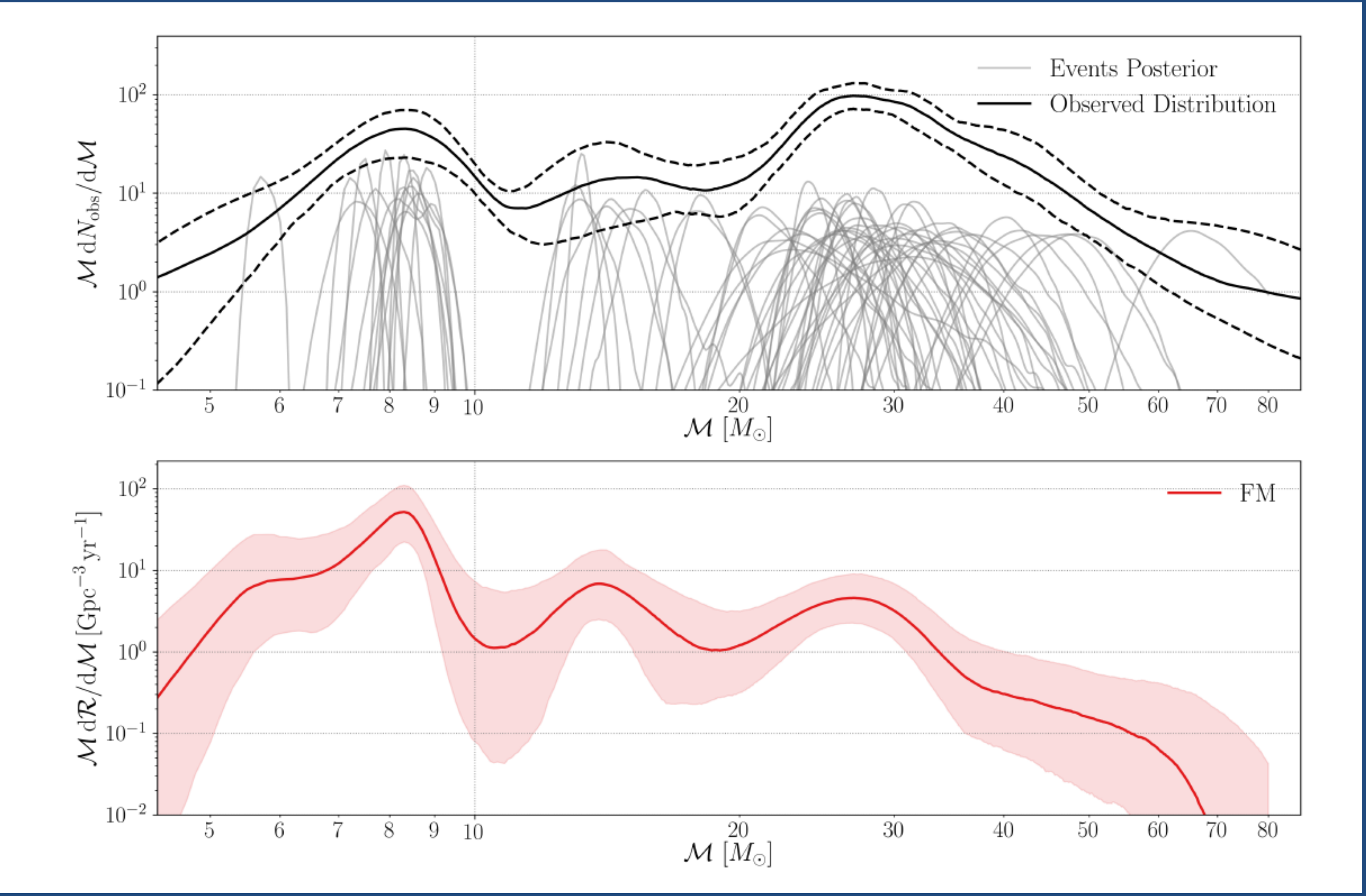
Table 1. Basic parameters of TianQin.

Parameters	Value
Type of orbit	Geocentric
Number of satellites	N=3
Arm length	$L = \sqrt{3} \times 10^5$ km
Displacement measurement noise	$S_x^{1/2} = 1 \times 10^{-12}$ m/Hz$^{1/2}$
Residual acceleration noise	$S_a^{1/2} = 1 \times 10^{-15}$ m s^{-2}/Hz$^{1/2}$



Connecting LVK coalescing BH+BH with IMBH

GWTC-3 features (wait for O4 results)



2111.03634

Binary PBH (distinctive feature: zero spins, only sources with z>20)

- Merging rate (e.g. Raidal+ 2404.08416)

$$\frac{d\mathcal{R}(z)}{dm_1 dm_2} = \frac{3.2\times 10^6}{\mathrm{Gpc}^3\mathrm{yr}^{-1}} S(m_1, m_2, z) f_{pbh}^{\frac{53}{57}} F(m_1)F(m_2)\frac{m_1 m_2}{\langle m\rangle^2}\left(\frac{t(z)}{t_0}\right)^{-\frac{34}{37}} M^{-\frac{32}{37}}\eta^{-\frac{34}{37}}$$

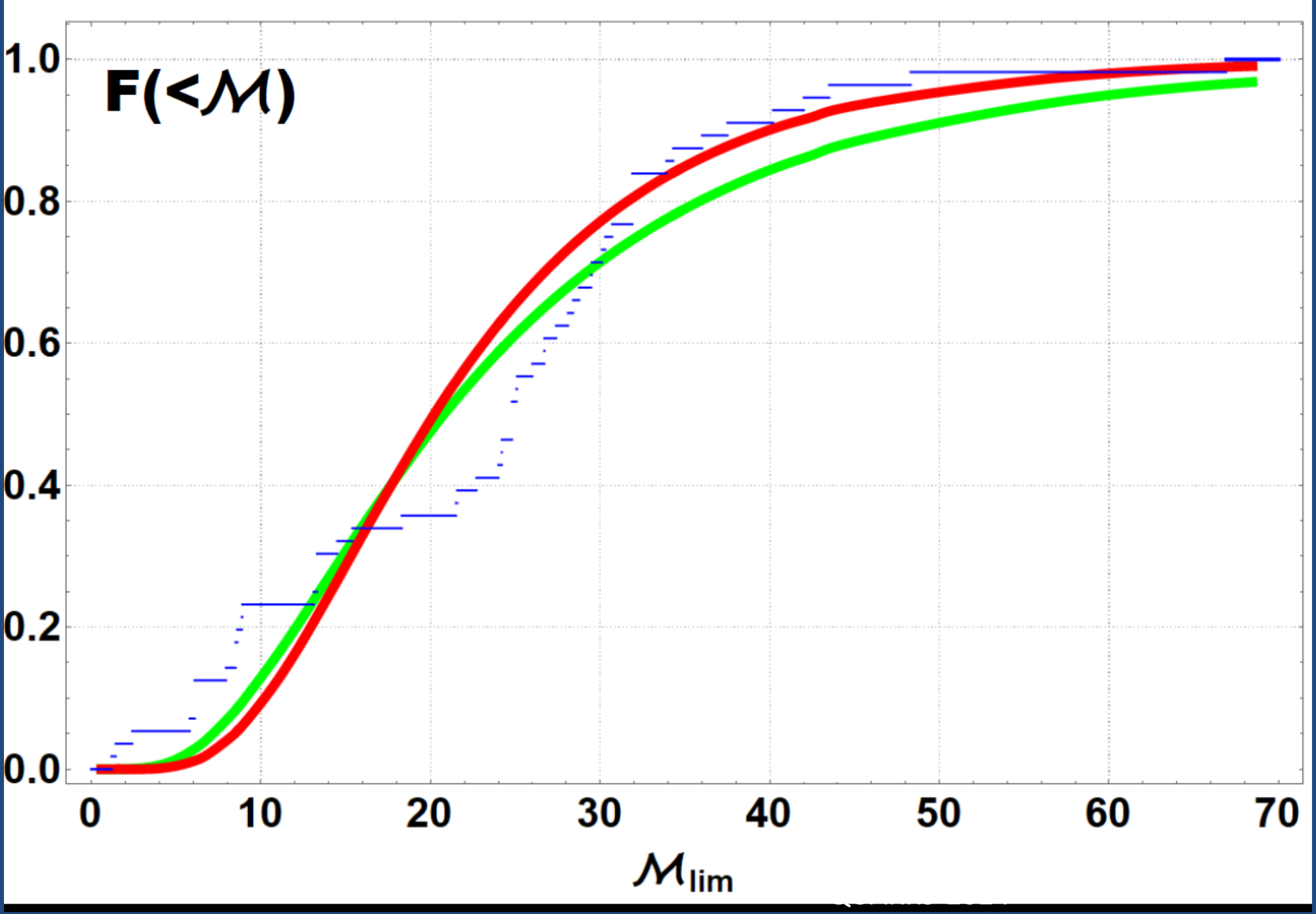
$$\frac{d\mathcal{R}(z)}{d\mathcal{M}dq} \propto f_{pbh}^{\frac{53}{57}} F(\mathcal{M})F(q)\frac{(1+q)^{\frac{8}{5}}}{q^{\frac{9}{5}}}\frac{\mathcal{M}^{\frac{79}{37}}}{M_c^2 e^{\frac{1}{2\gamma}}}\left(\frac{t(z)}{t_0}\right)^{-\frac{34}{37}}$$

- Chirp mass cumulative distribution

$$\mathcal{R}(<\mathcal{M}) = \int_0^{\mathcal{M}}\int_0^{z_{\rm lim}(\mathcal{M})}\int_0^1 \frac{d\mathcal{R}}{d\mathcal{M}dq}\frac{dV}{dz}\frac{dz}{1+z}dq, \quad F(<\mathcal{M}) = \frac{\mathcal{R}(<\mathcal{M})}{\mathcal{R}(<\infty)}$$

Example: log-normal PBH mass function fits GWTC data

$$F(M) = A\exp[-\gamma \ln^2(M/M_0)]$$



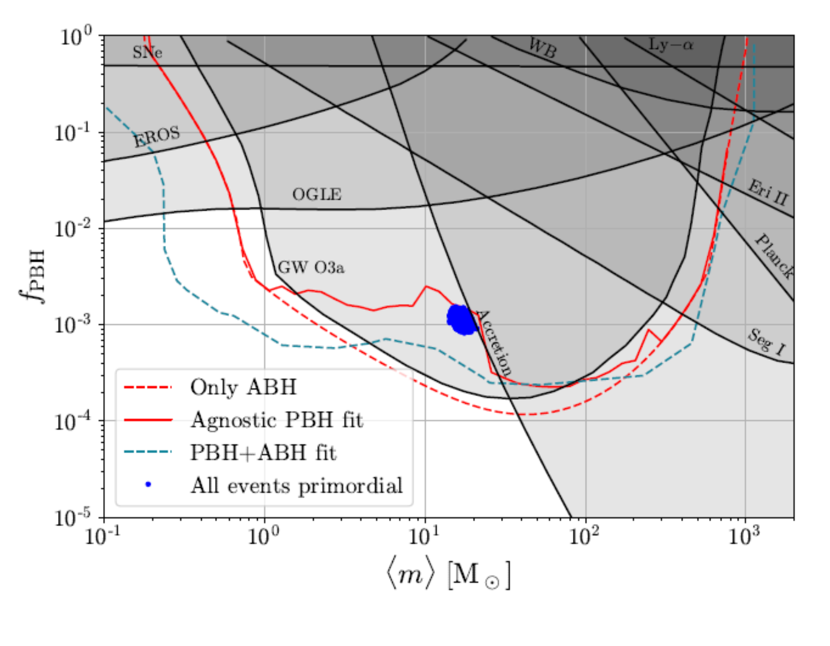
$$\gamma = 0.7,\ M_0 = 19$$

$$\mathrm{DR}(M_{ch})dM_{ch} \sim Ae^{-B\ln^2\left(\frac{M_{ch}}{M_0}\right)}dM_{ch}$$

Dolgov+'19

Independent analysis: Lang Liu et al 2023 (2210.16094) M_0~17, γ~1, f_{pbh}~10^{-3}

PBH abundance constraints from GWTC-3



$$\psi(m) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left\{-\frac{\ln^2(m/m_c)}{2\sigma^2}\right\}$$

$$\langle m \rangle = m_c e^{-\sigma^2/2}$$

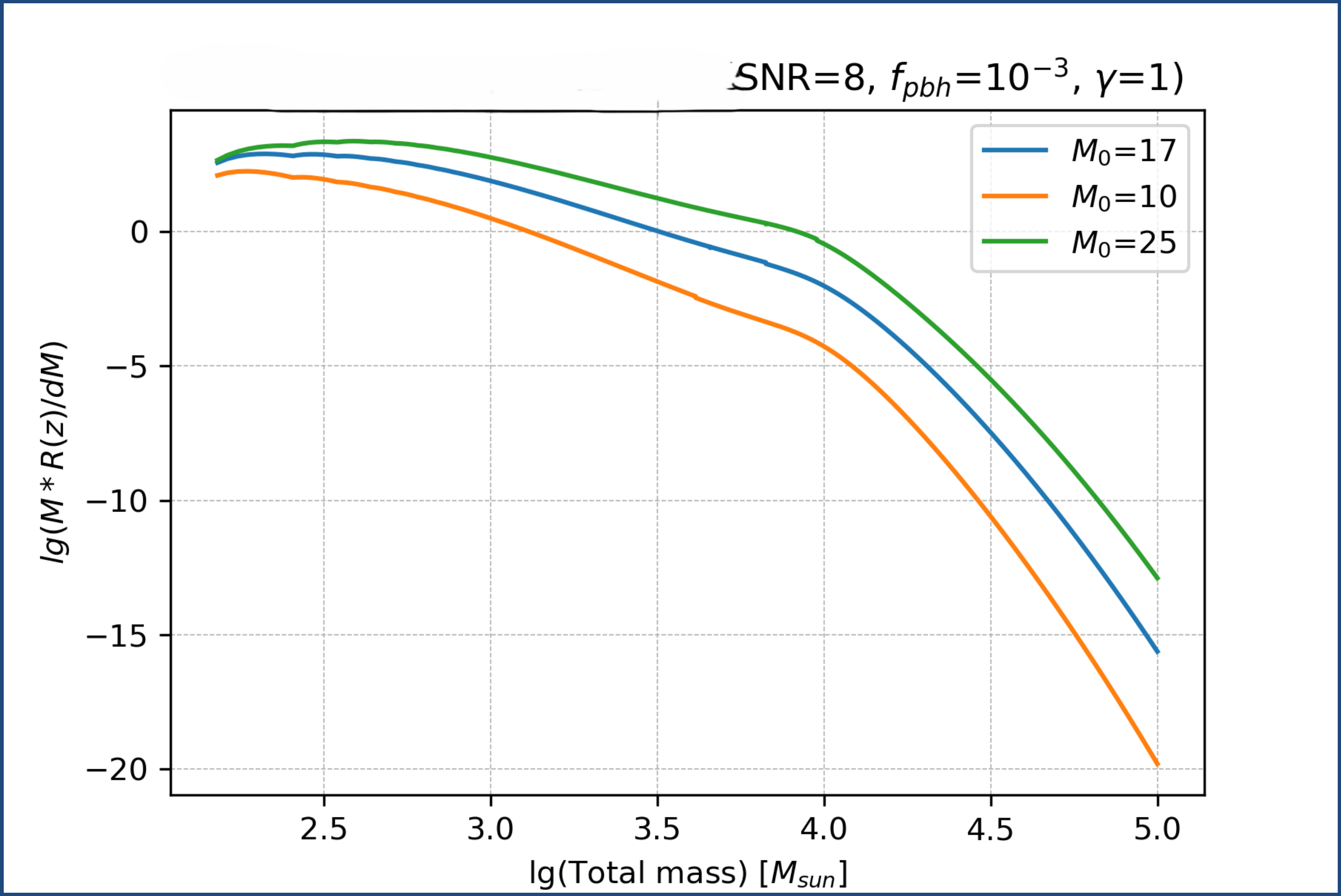
$M_0 = 17 M_\odot$ $\sigma = 0.6$

Andres-Carcasona et al 2405.05732

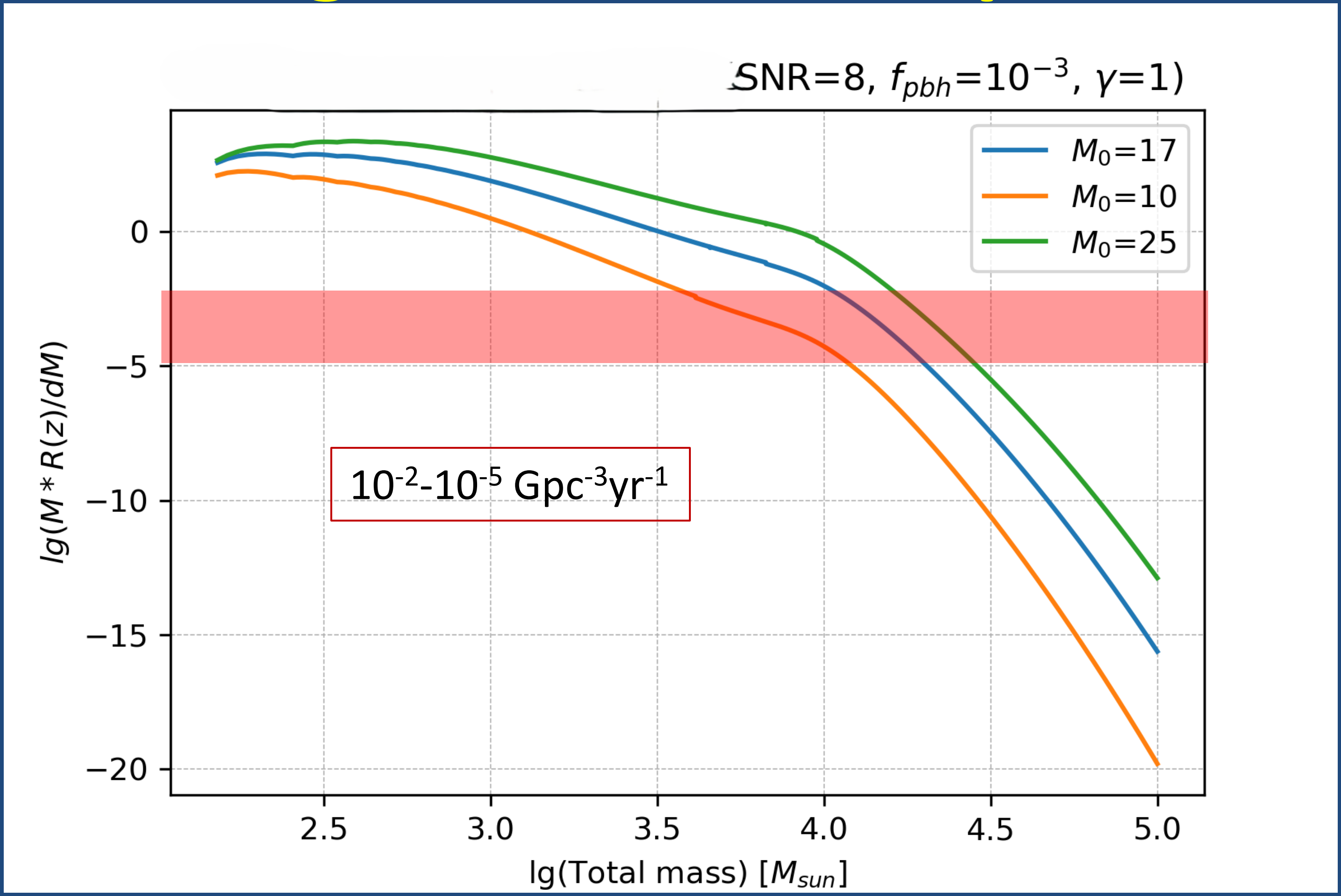
- Initial log-normal PBH mass function → log-normal PBH mass distribution
- Rate estimate

$$m = \frac{M}{M_0} \qquad \frac{d\mathcal{R}(z)}{dm\,dq} \sim F(q)F(m)e^{-2\gamma \ln^2(m)} \left(\frac{t(z)}{t_0}\right)^{-34/37}$$

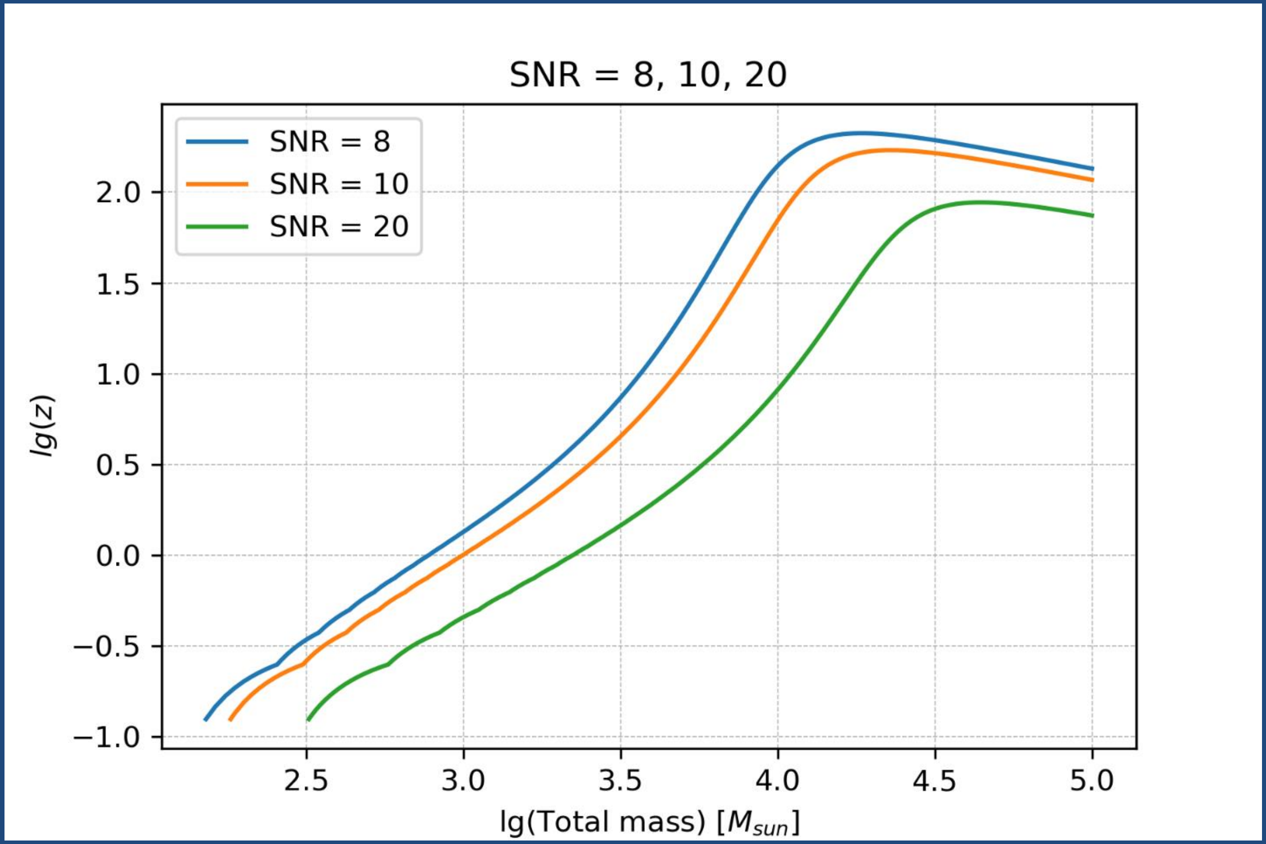
MdR/dM [Gpc^{-3} yr^{-1}], z=0



Comoving merging rate of binary PBH with log-normal mass spectrum



TQ detection horizon for BH+BH

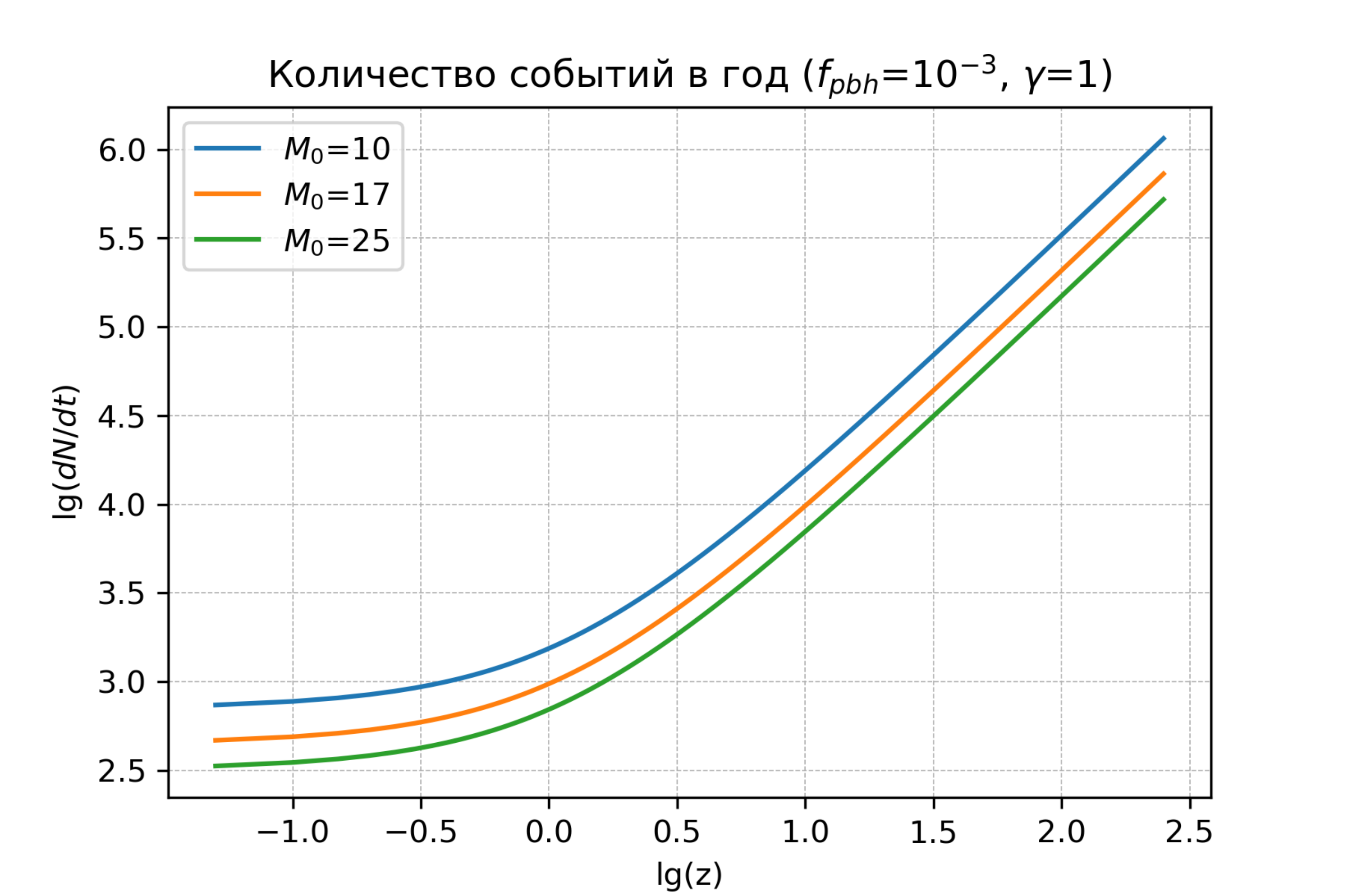


$$SNR \propto \frac{[\mathcal{M}/(1+z)]^{5/6}}{d_l(z)}$$

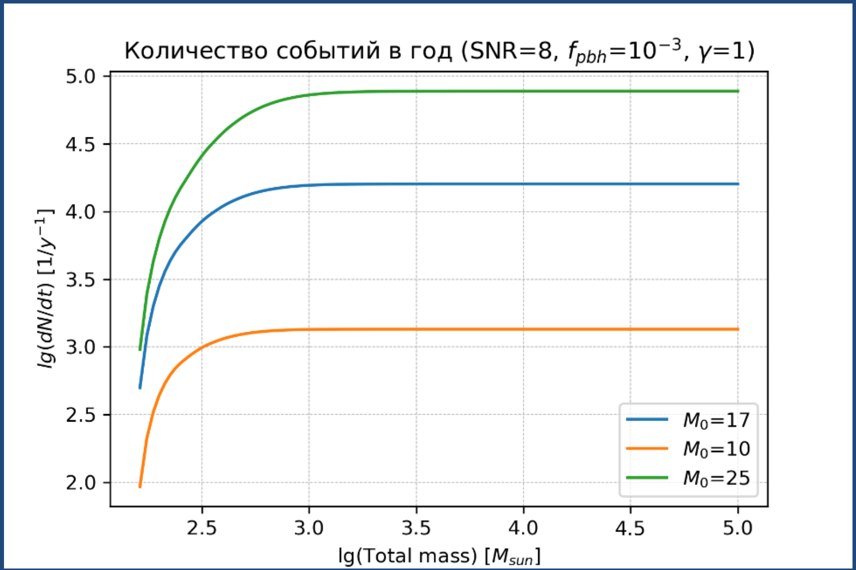
$$\mathcal{M} = \frac{(M_1 M_2)^{3/5}}{M^{1/5}}$$

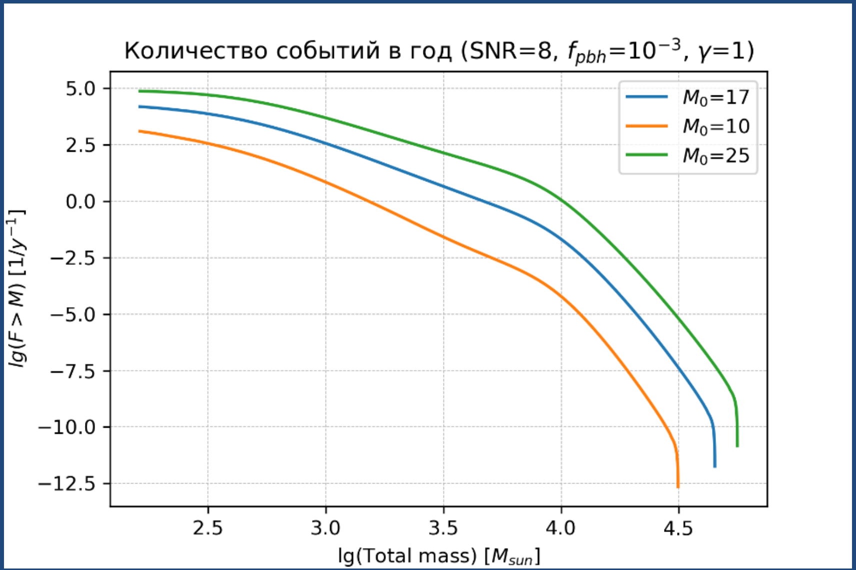
(chirp-mass)

$dN/dt/dz \sim t(z)^{-34/37}$



Expected TQ detection rate (yr^{-1})





Conclusions

- Astrophysical IMBH with masses ~1000-10000 $M_\odot$ are (almost) found in centers of dwarf galaxies
- Emerging evidences for **binary IMBHs** in galactic centers (JWST observations)
- Binary IMBHs are among primary sources for future space laser GW interferometers
- **IMBHs can have primordial origin.** In Dolgov&Silk (1993) baryogenesis, IMBHs can have masses up to 10^4 $M_\odot$ and can be seeds for early SMBH formation in galactic centers.
- **Distinctive feature of binary primordial IMBH – zero spins & high redshift (z>20)**
- Assuming ~0.1% of DM in PBH with log-normal mass spectrum consistent with LVK detections, IMBH mergings with masses > 1000 $M_\odot$ can be detected in a few year of observations by planned laser GW interferometers like LISA or TianQin.