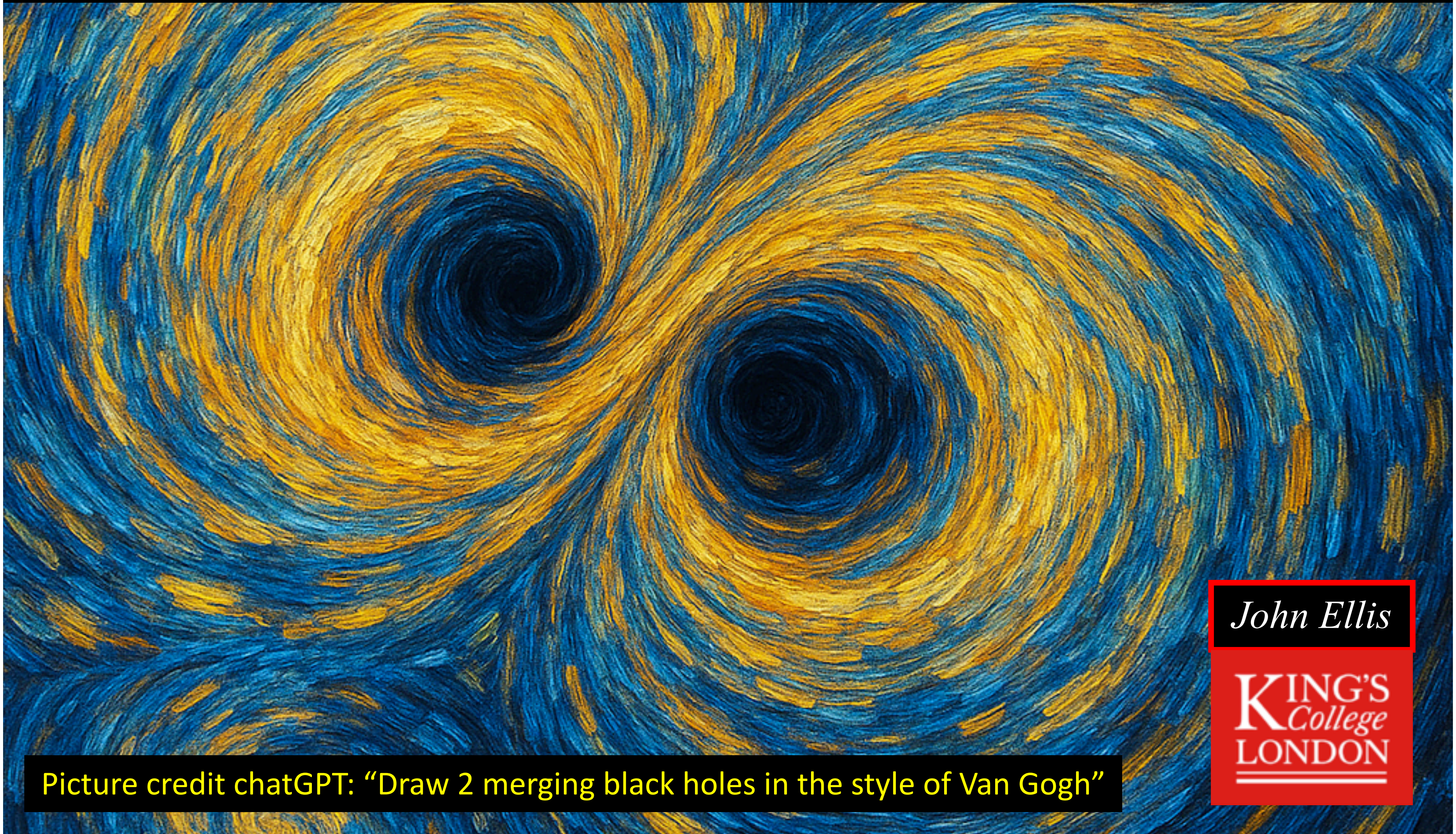
Seeking the Origins of Supermassive Black Holes with Gravitational Waves



Picture credit chatGPT: “Draw 2 merging black holes in the style of Van Gogh”

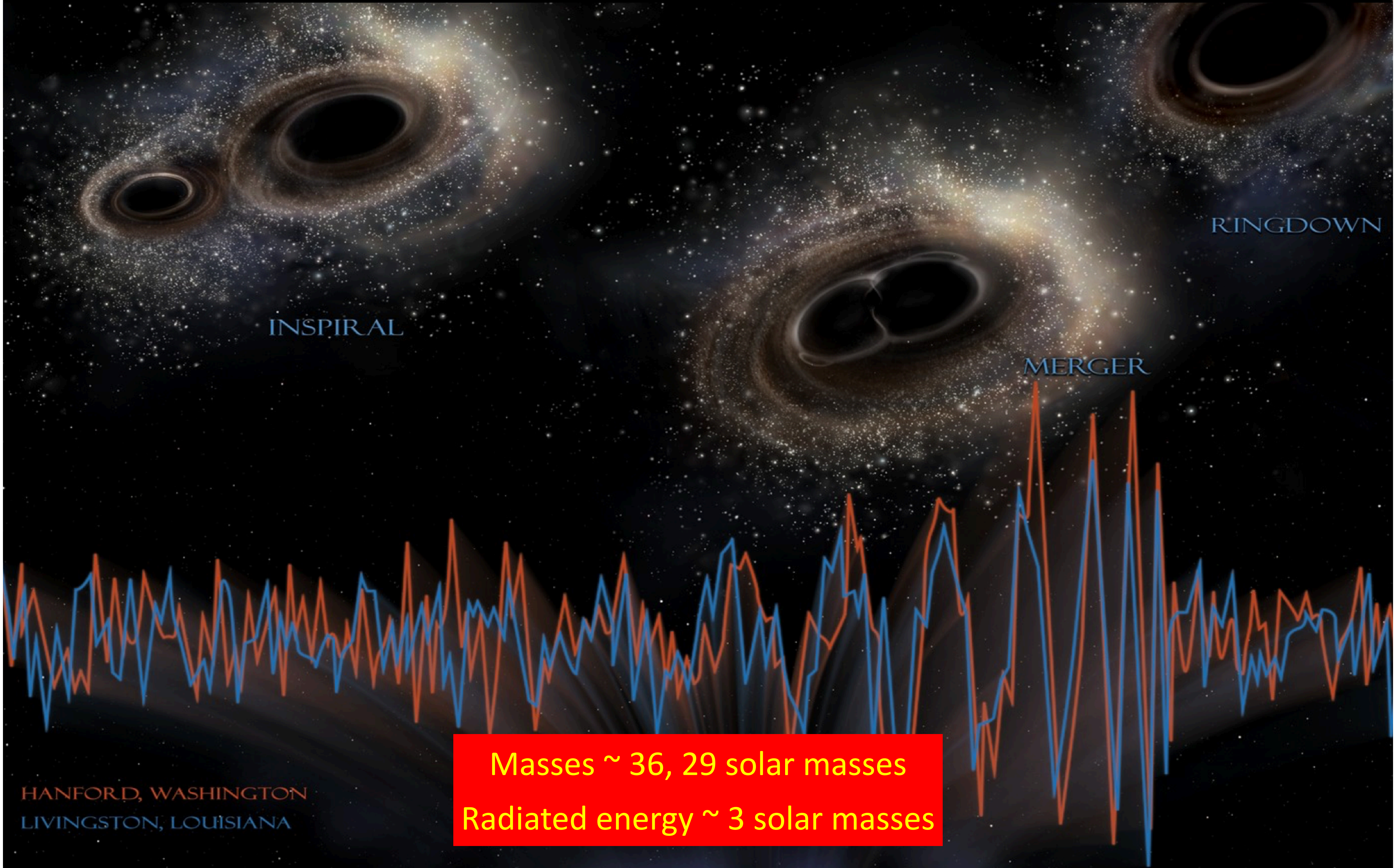
John Ellis

KING'S College LONDON

The Biggest Bangs since the Big Bang

- New observations probe the mergers of Supermassive Black Holes (SMBHs) and their formation
- **GWs from Pulsar Timing Arrays (PTAs) and JWST observations provide new arenas for confronting astrophysics and particle physics**
- **NANOGrav data are consistent with GWs: their origin could be astrophysical or BSM cosmological scenarios, e.g., cosmic strings?**
- JWST observations of UV light emission and SMBHs at high z challenge models of SMBH assembly
  - **Hierarchical mergers** from seed BHs and/or **accretion**
    - **Light seeds**: relics of Pop-III stars? Masses ~ 10^2 - 10^3 Sun
    - **Heavy seeds**: collapses of halos of first galaxies? Masses ~ 10^5 - 10^6 Sun?
- JWST data constrain models of dark matter: CDM vs Fuzzy DM and Warm DM
- **Future GW observations may help measure seed masses, probe DM models**

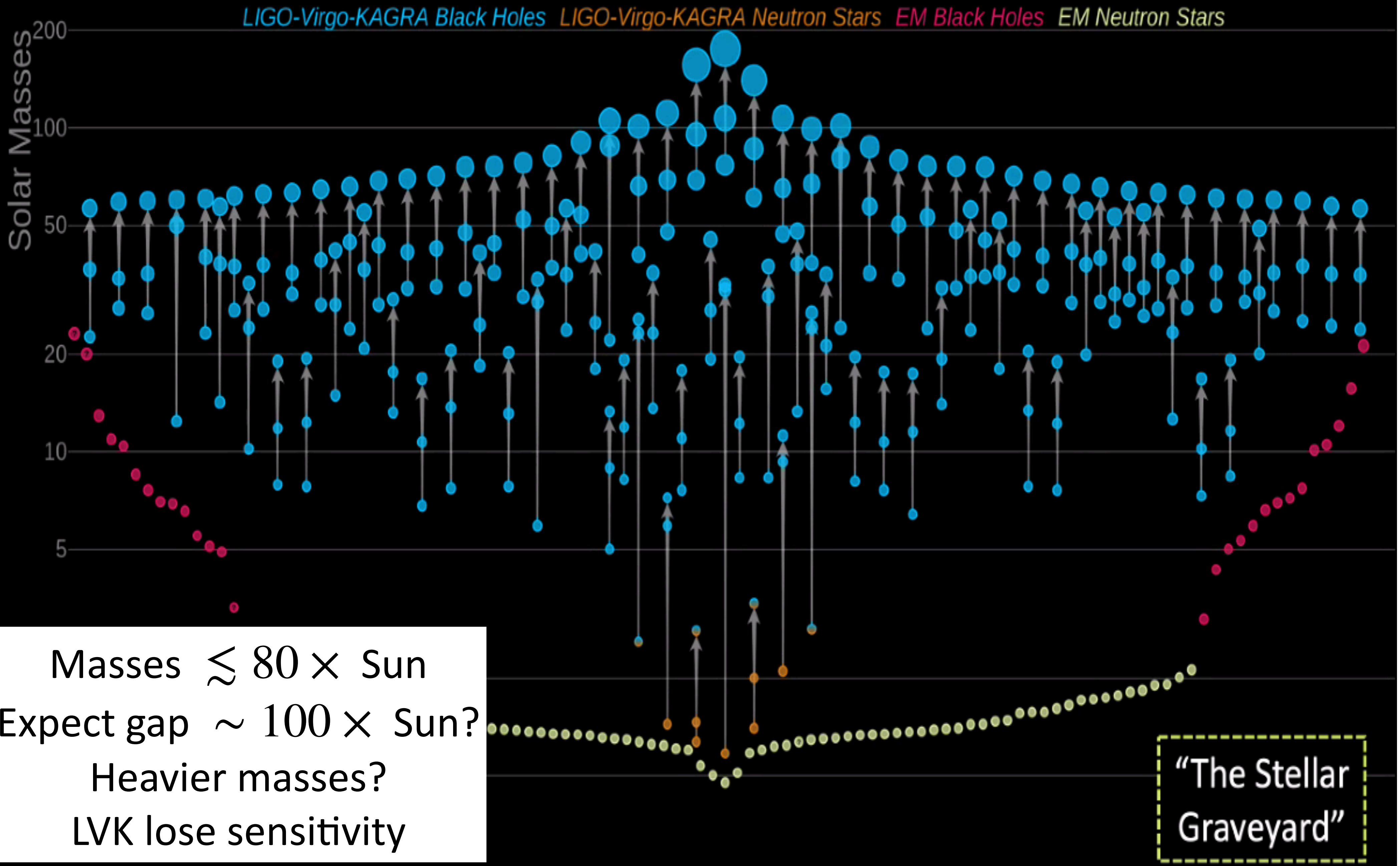
Discovery of Gravitational Waves from Merger of Black Holes (2016)



Masses ~ 36, 29 solar masses

Radiated energy ~ 3 solar masses

LIGO-Virgo-KAGRA Black Holes & Neutron Stars



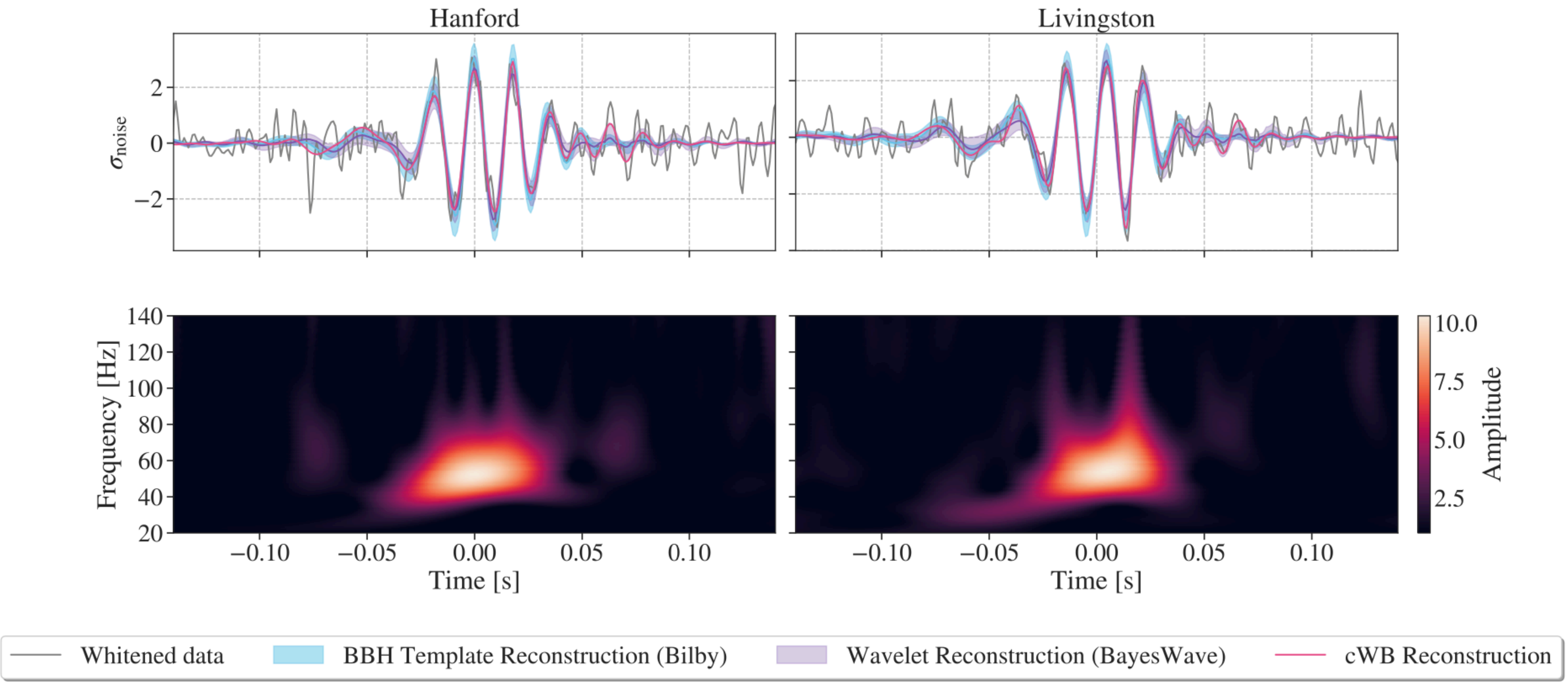
Masses $\lesssim 80\times$ Sun

Expect gap $\sim 100\times$ Sun?

Heavier masses?

LVK lose sensitivity

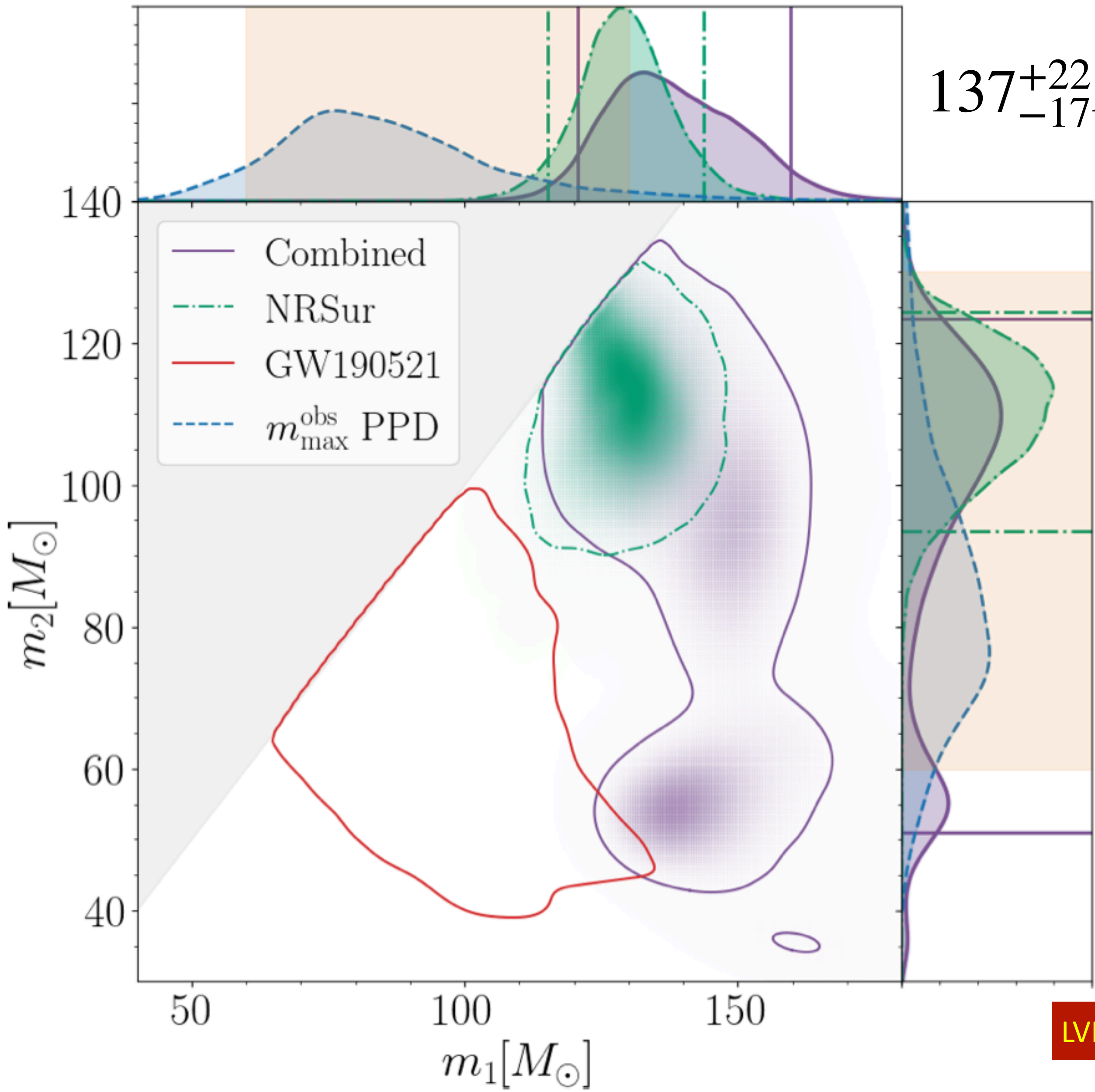
Most Massive BH Merger so far



Measured by LIGO
Starts with a chirp
Evidence for high-order modes in ringdown

LVK: arXiv:2507.08219

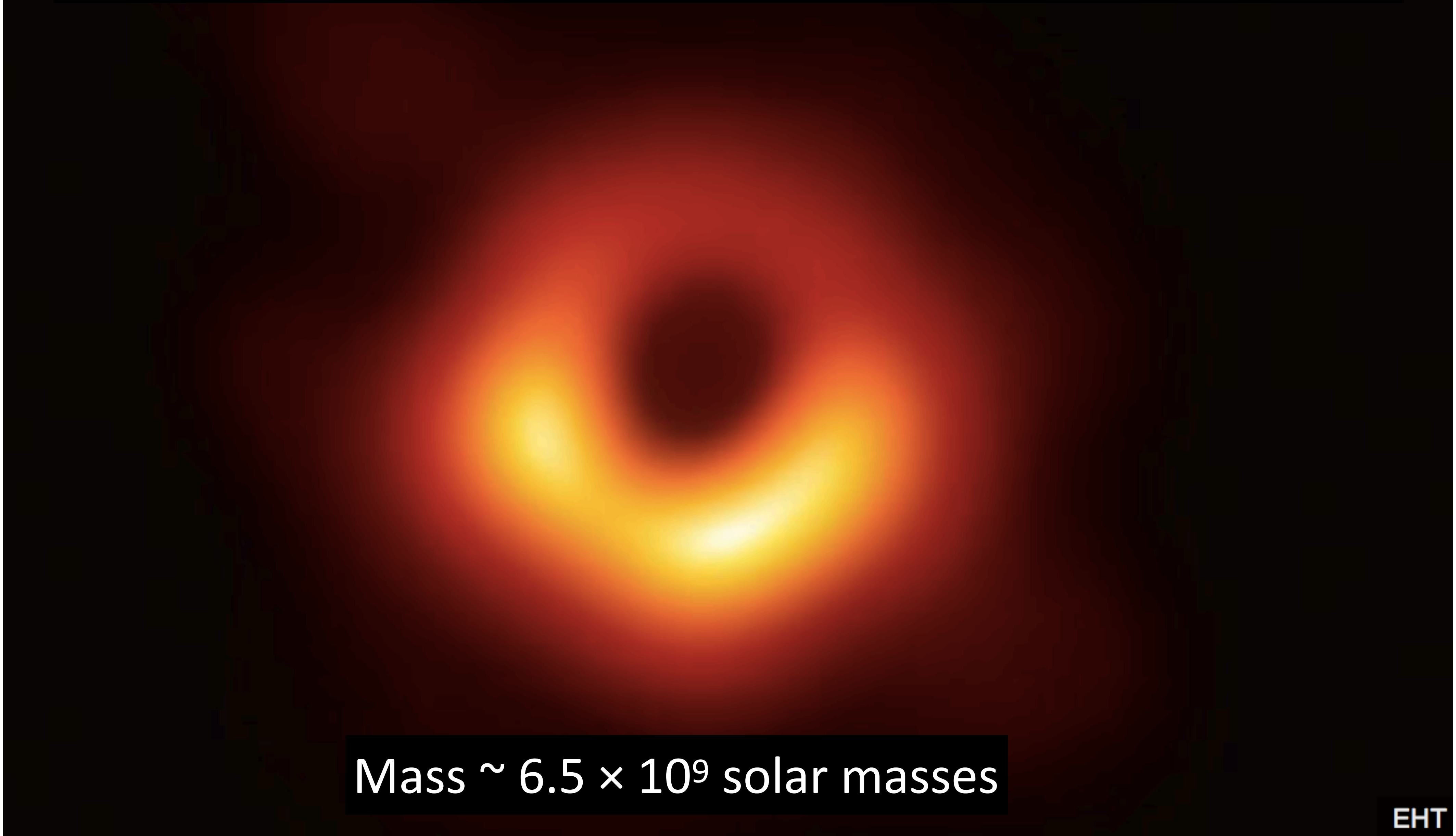
Most Massive BH Merger so far



$137^{+22}_{-17}M_\odot, 103^{+20}_{-52}M_\odot$

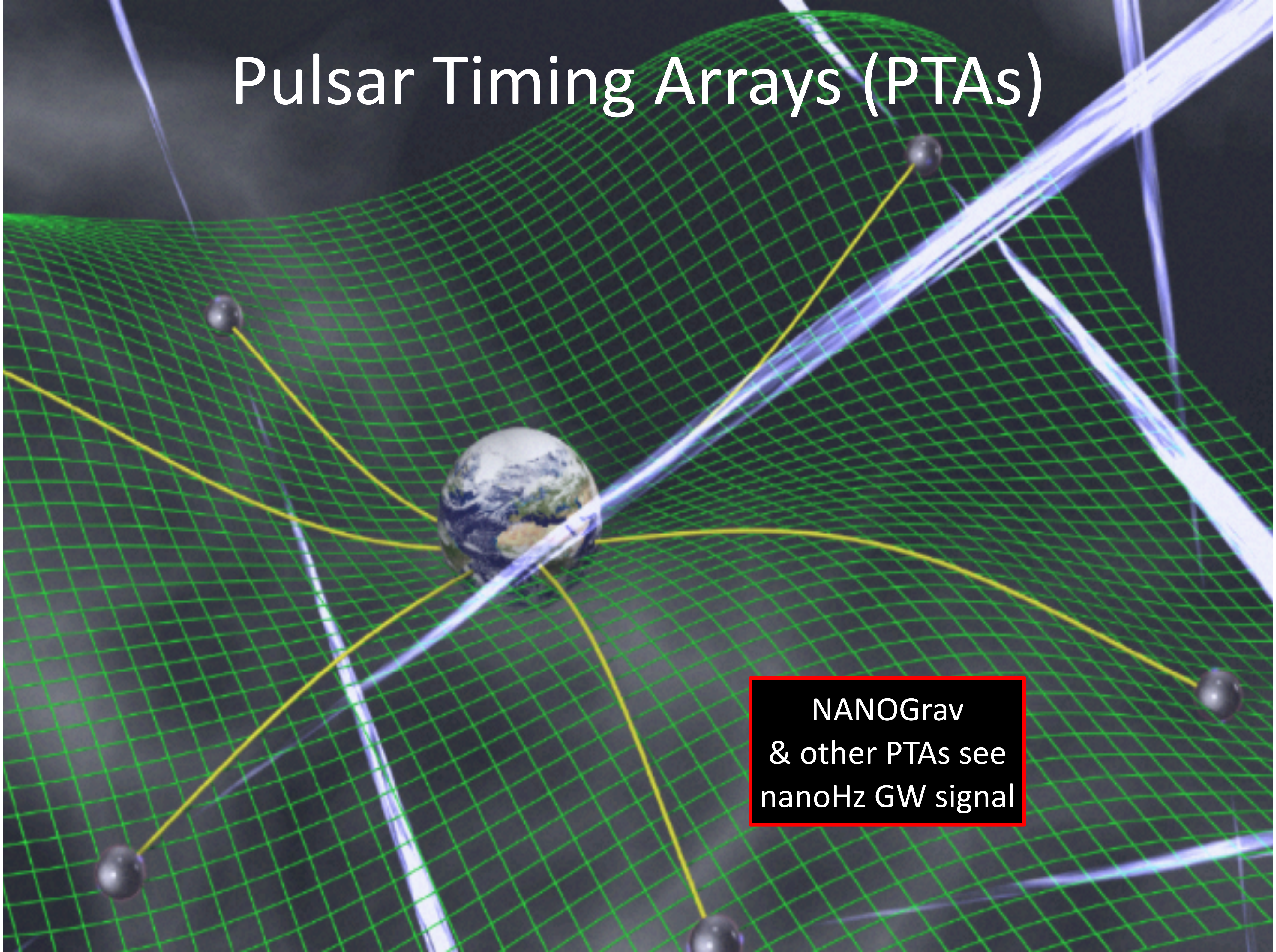
LVK: arXiv:2507.08219

Supermassive Black Holes in Active Galactic Nuclei: Image of M87



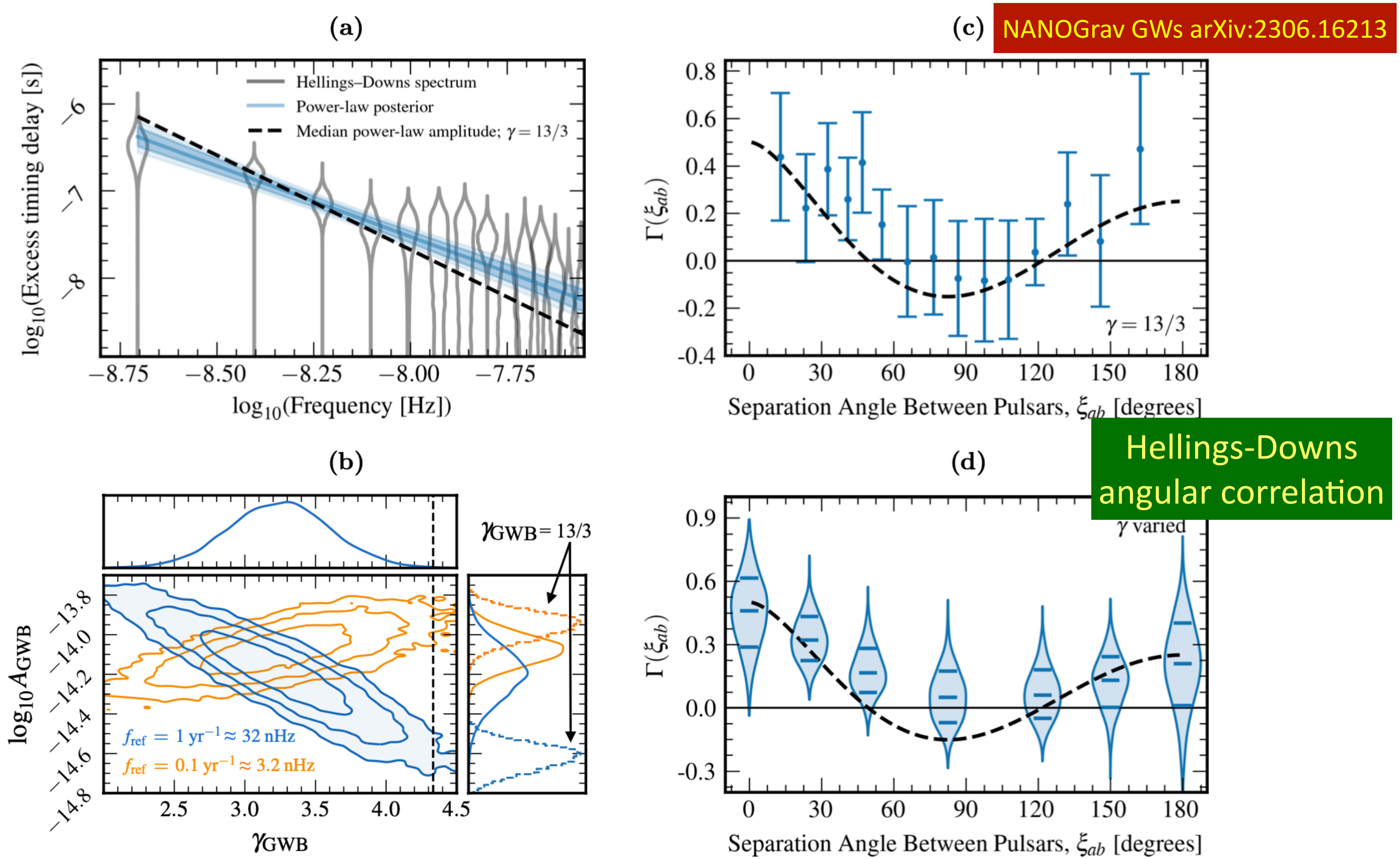
Mass ~ 6.5×10^9 solar masses

Pulsar Timing Arrays (PTAs)



NANOGrav
& other PTAs see
nanoHz GW signal

NANOGrav Pulsar Timing Array Data



Expect spectral index $\gamma = 13/3$ for SMBH binaries: not a good fit

Evidence for GWs: Hellings-Downs angular correlation Bayes factor ~ 200

BH Merger Rate Estimate

BH merger rate $R_{\rm BH}$

$$\frac{{\rm d}R_{\rm BH}}{{\rm d}m_1{\rm d}m_2} \approx p_{\rm BH}\frac{{\rm d}M_1}{{\rm d}m_1}\frac{{\rm d}M_2}{{\rm d}m_2}\frac{{\rm d}R_h}{{\rm d}M_1{\rm d}M_2}$$

where R_h is halo merger rate calculated using Extended Press-Schechter formalism,

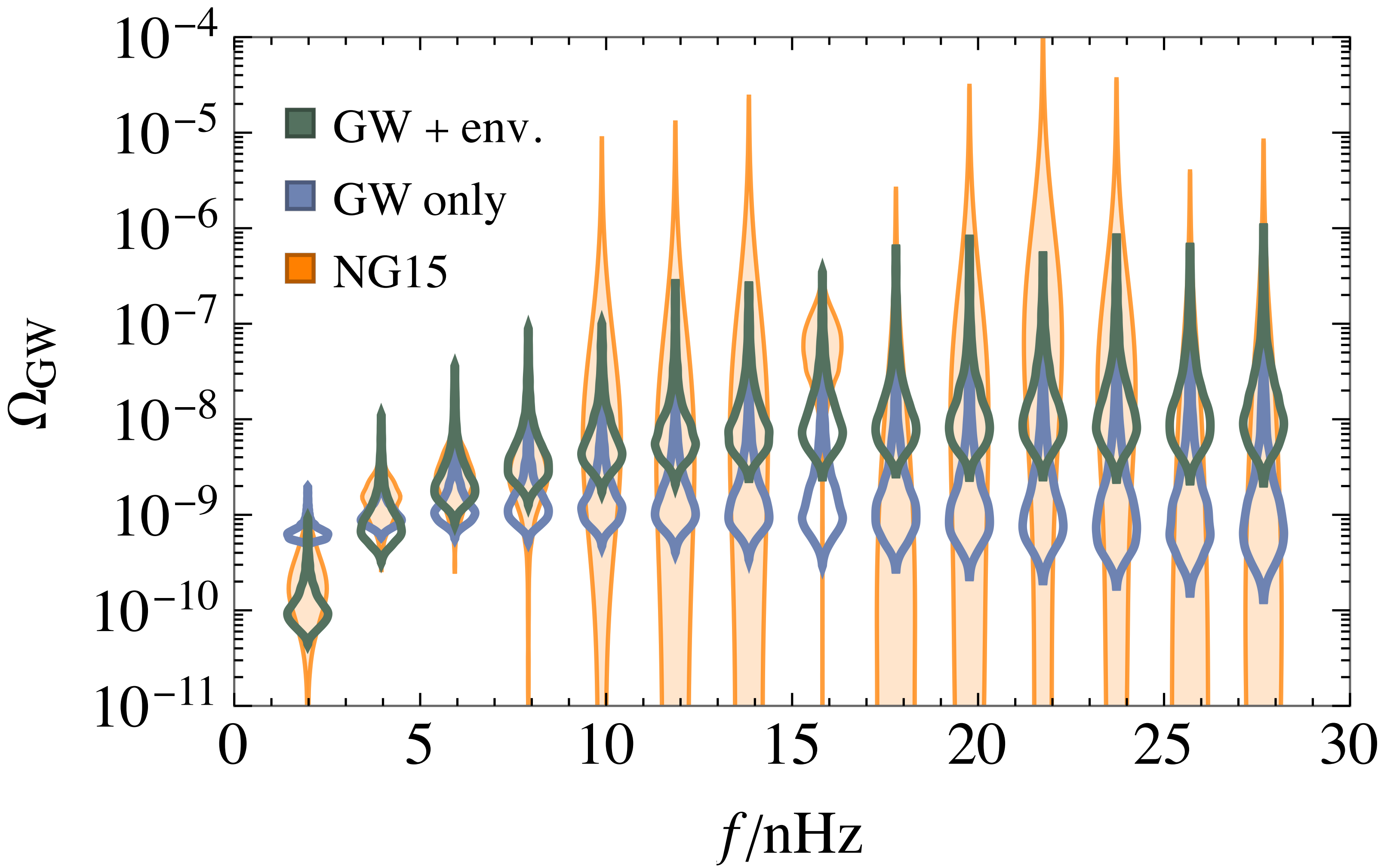
$$p_{\rm BH} \equiv p_{\rm occ}(m_1)p_{\rm occ}(m_2)p_{\rm merg}$$

is merger probability

Strength of PTA signal can be fitted by constant $p_{\rm BH}$

JE, Fairbairn, Hütsi, Raidal, Urrutia, Vaskonen & Veermäe: arXiv:2301.13854

Astrophysical Interpretations AION



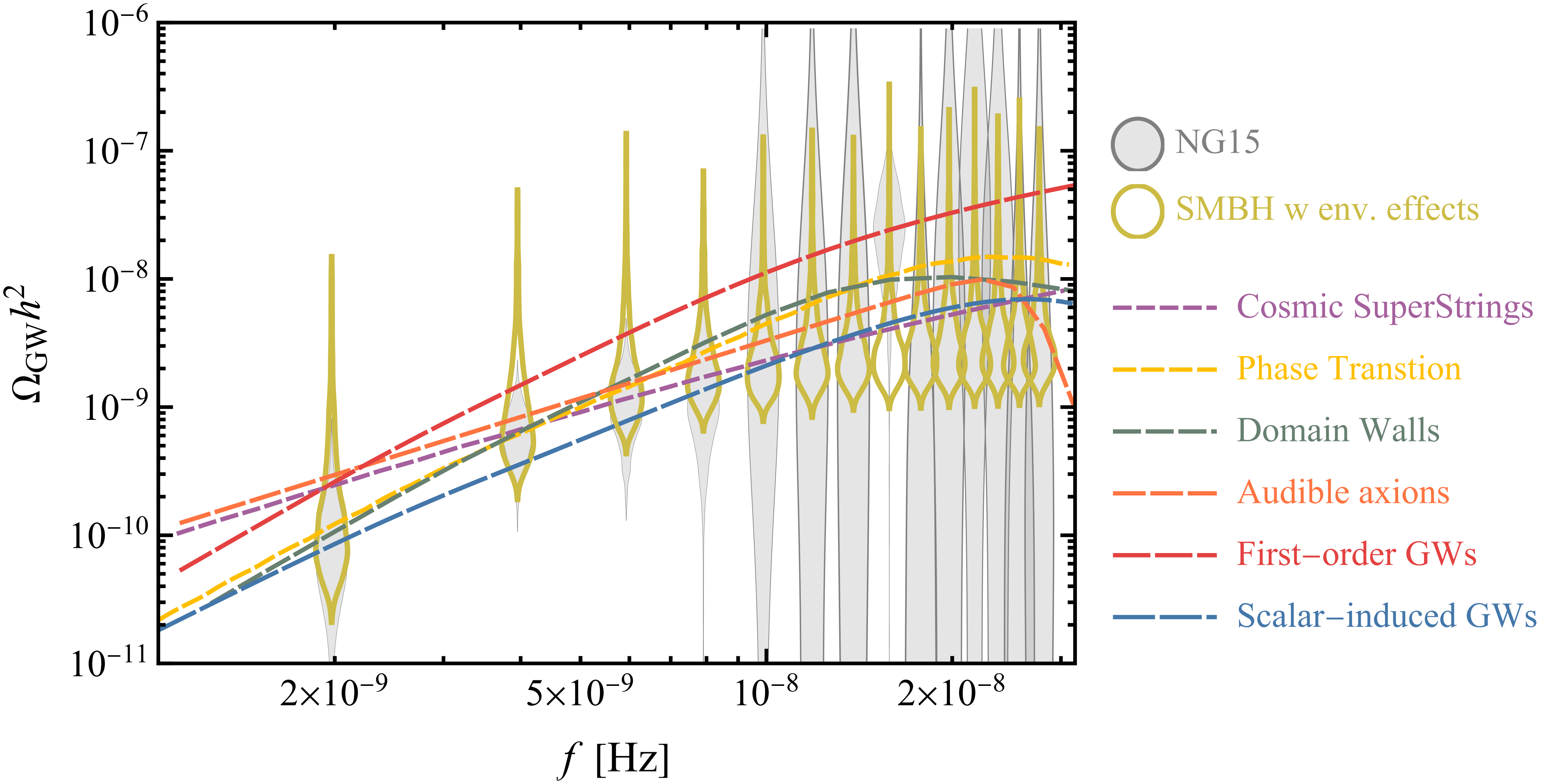
Fits use overlaps of data and model violins in each bin

NB: Fits go beyond simple power-law approximations

Better fit if evolution driven by halo environment & GWs - or BSM physics

JE, Fairbairn, Hütsi, Raidal', Urrutia, Vaskonen & Veermäe: arXiv:2306.17021

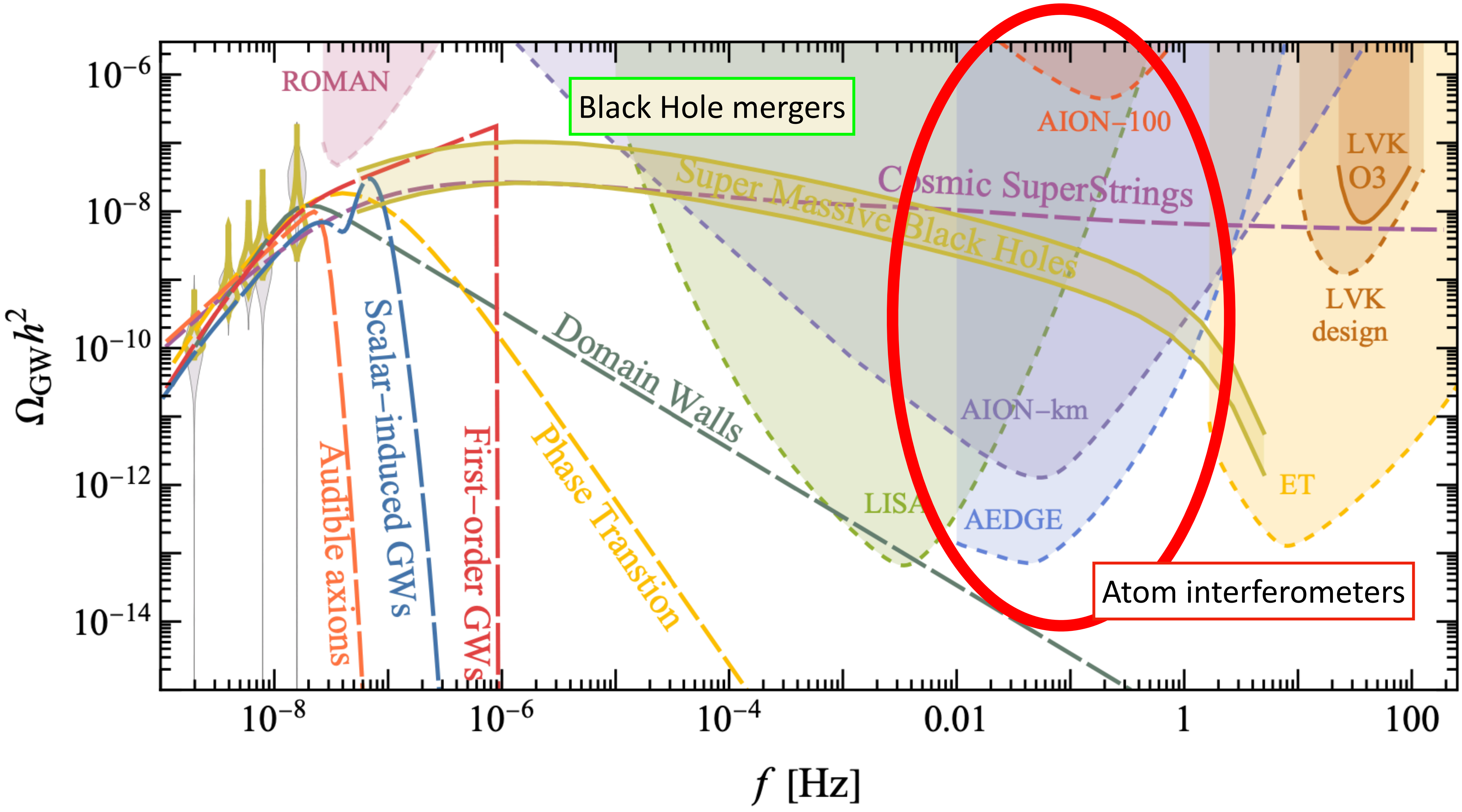
Fits to NANOGrav



JE, Fairbairn, Franciolini, Hütsi, Iovino, Lewicki, Raidal, Urrutia, Vaskonen & Veermäe, arXiv:2308.08546

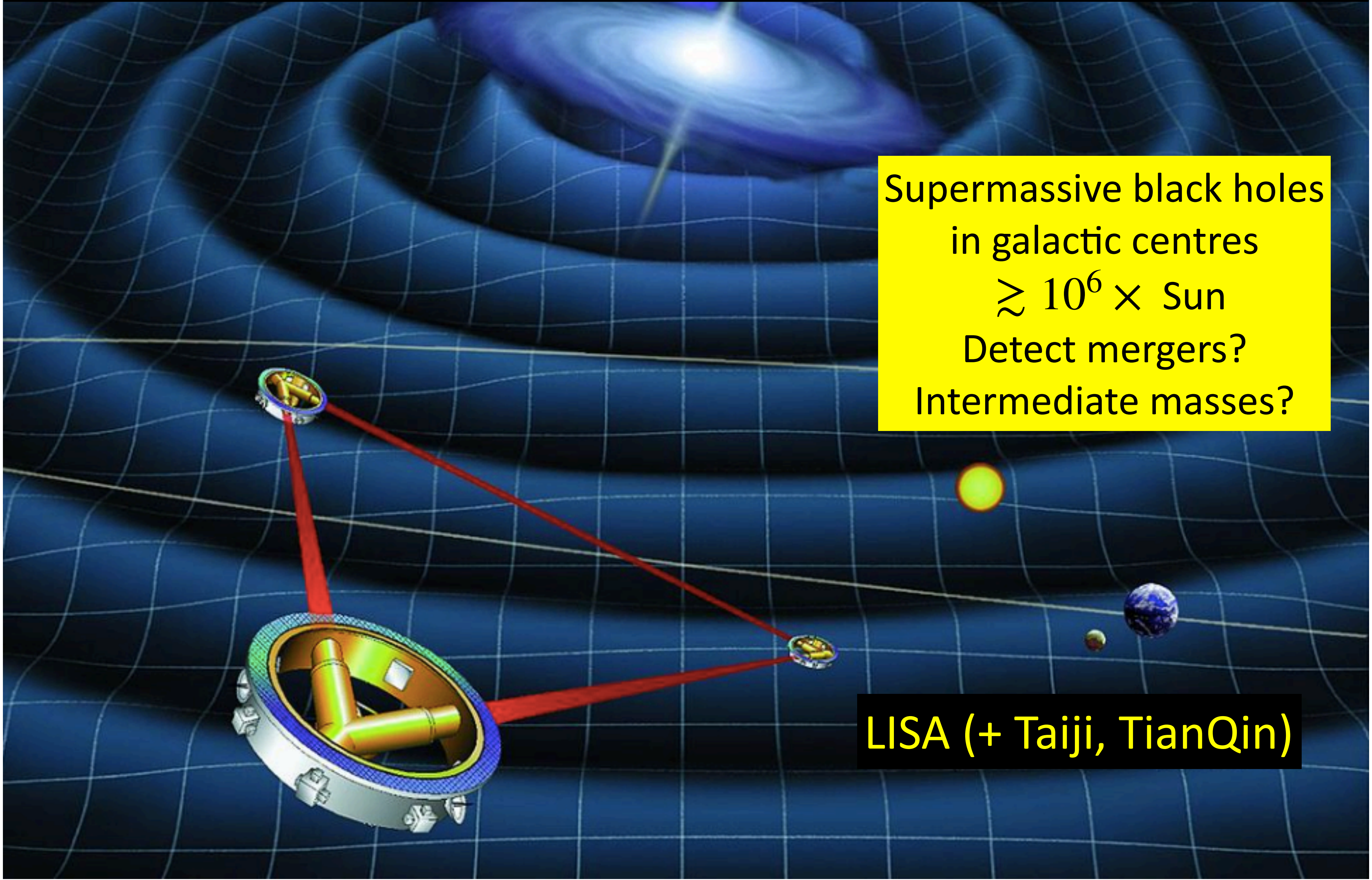
Extension of Fits to Higher Frequencies

AION

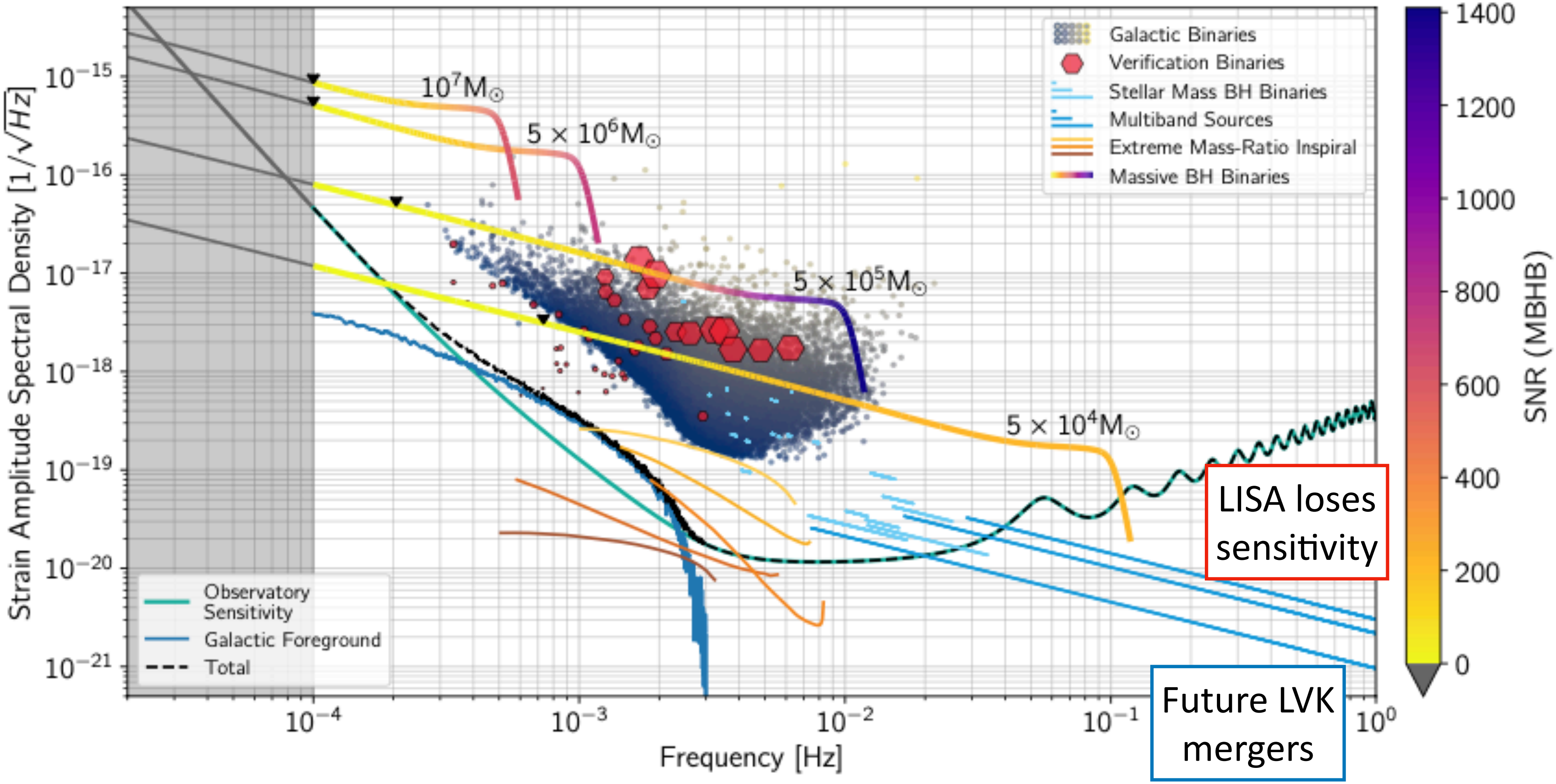


JE, Fairbairn, Franciolini, Hütsi, Iovino, Lewicki, Urrutia, Vaskonen & Veermäe, arXiv:2308.08546

Future Step: Interferometer in Space

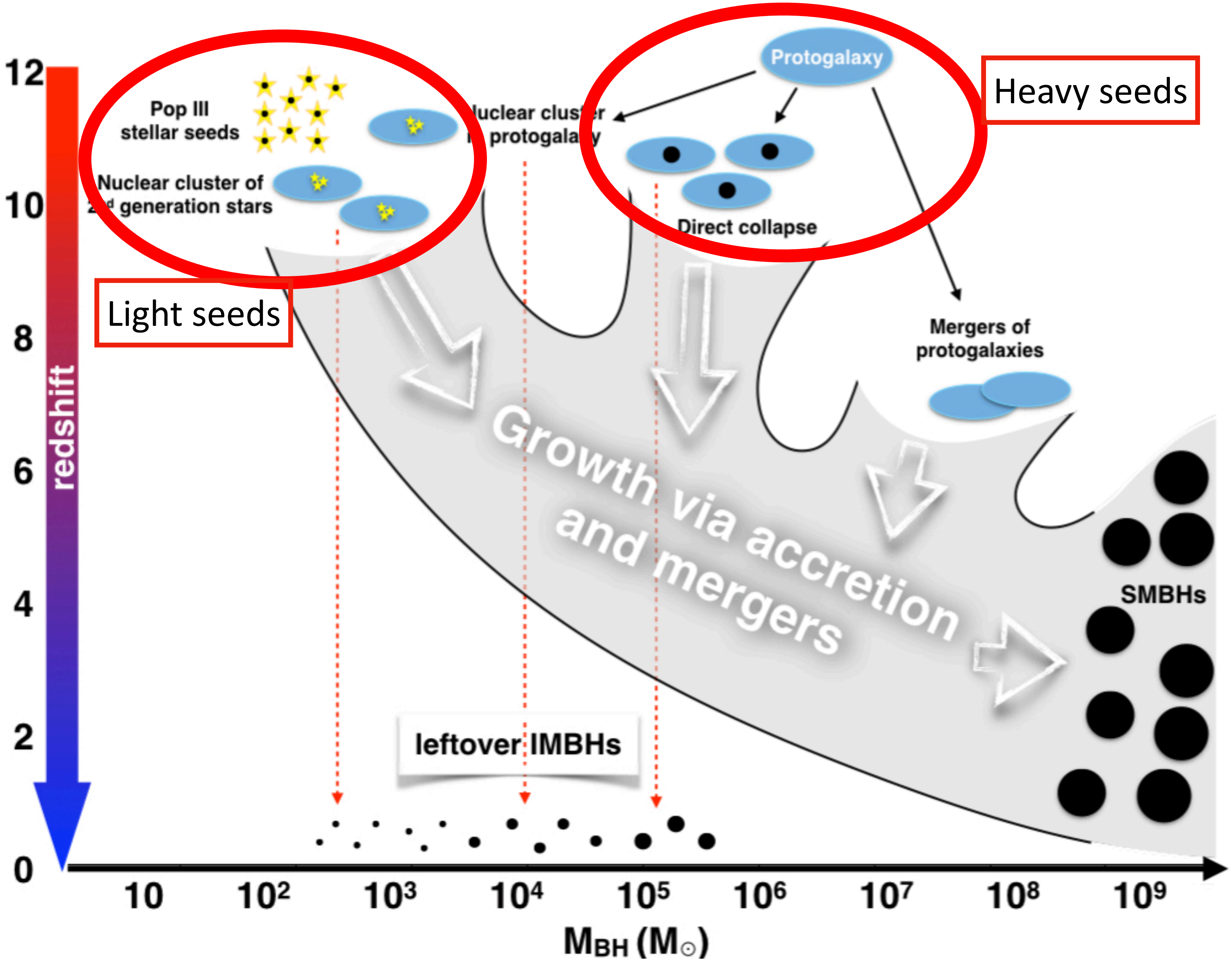


Possible LISA Observations



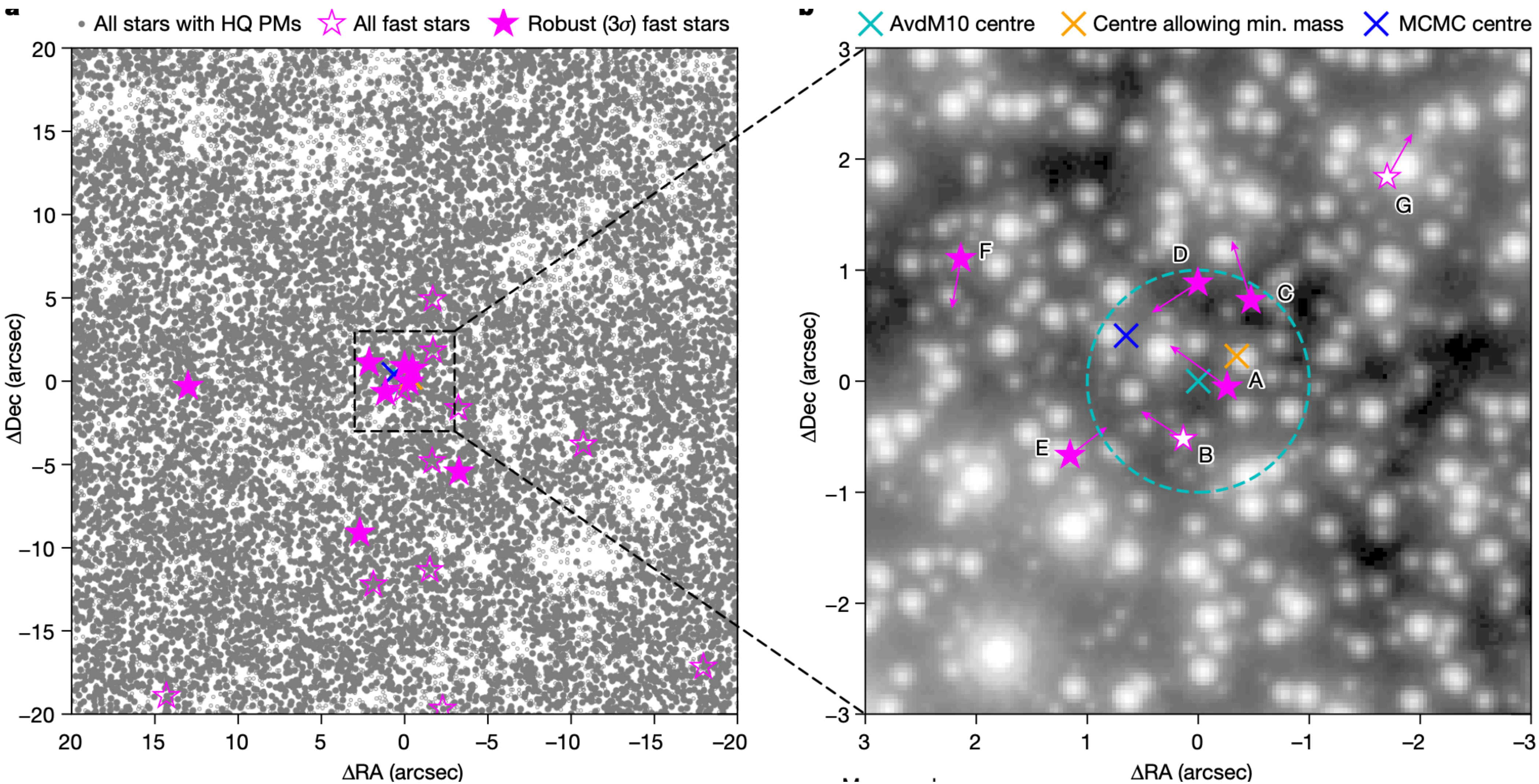
How to Make a Supermassive BH?

SMBHs from mergers of intermediate-mass BHs (IMBHs)?



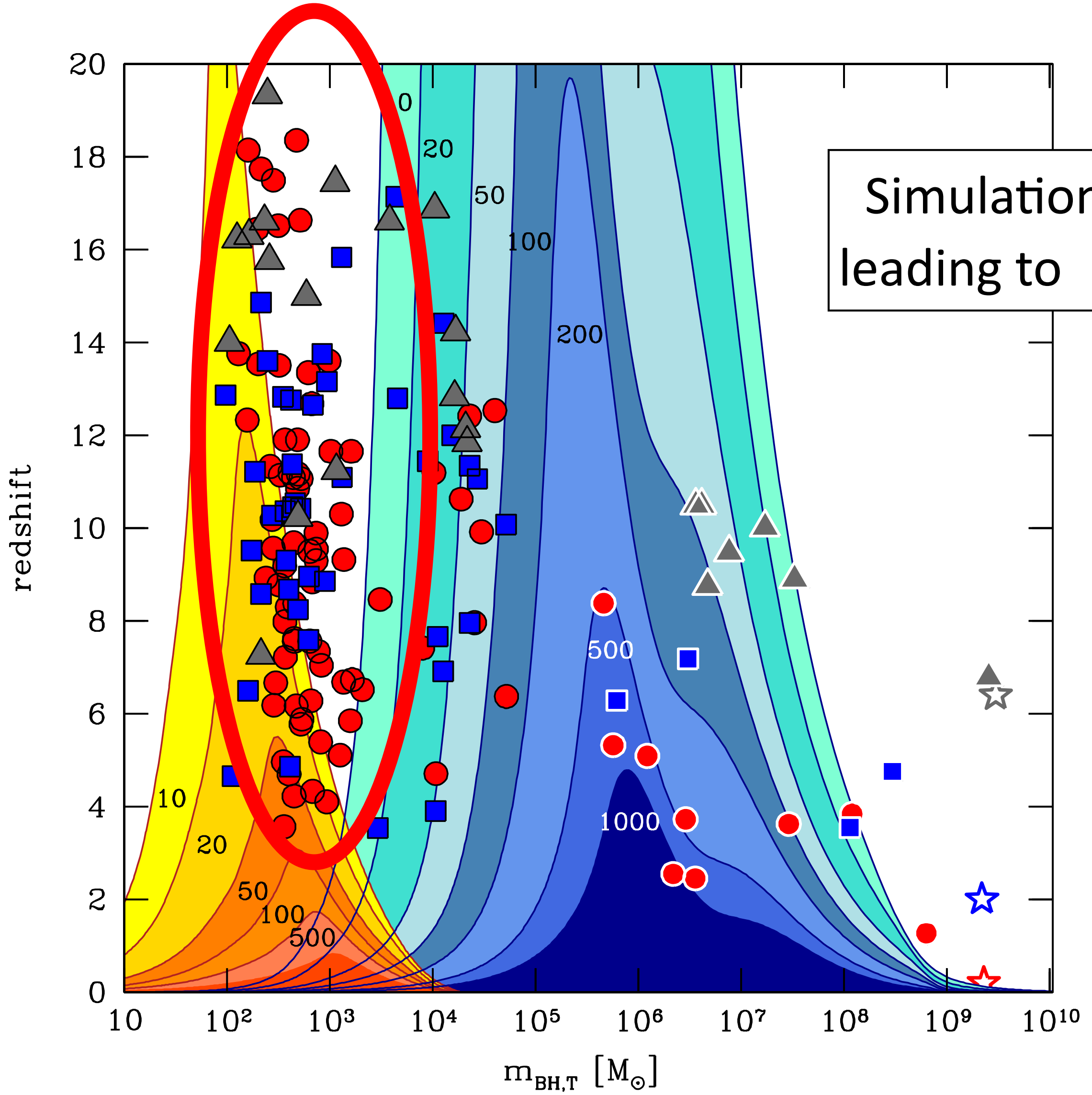
Häberle et al, Nature 631, 285 (2024)

Intermediate-Mass Black Holes Exist



Stellar **motions** evidence for BH weighing > 8000 solar masses in Milky Way

Gap between Einstein Telescope & LISA



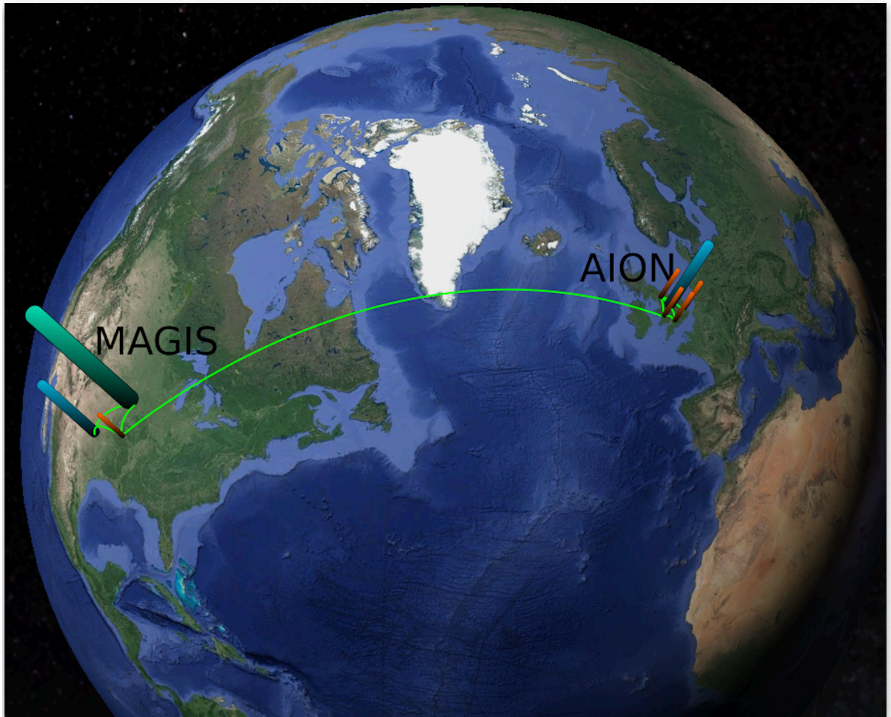
Simulations of BH mergers leading to $\sim 10^9 M_\odot$ SMBHs

GW opportunity at frequencies between ET & LISA

AION Collaboration

L. Badurina, S. Balashov[2], E. Bentine[3], D. Blas[1], J. Boehm[2], K. Bongs, A Beniwal[1], D. Bortoletto, Bowcock[5], W. Bowden[6,*], C. Brew[2], O. Buchmueller[6], J. Coleman, J. Carlton, G. Elertas, J. Ellis[1,&], C. Foot[3], V. Gibson[7], M. Haehnelt[7], T. Harte[7], R. Hobson[6,*], M. Holynski, A. Khazov[2], M. Langlois[4], S. Lellouch[4], Y.H. Lien[4], R. Maiolino[7], P. Majewski[2], S. Malik[6], J. March-Russell, C. McCabe, D. Newbold[2], R. Preece[3], B. Sauer[6], U. Schneider[7], I. Shipsey[3], Y. Singh, M. Tarbutt[6], M. A. Uchida[7], T. V-Salazar[2], M. van der Grinten[2], J. Vossebeld[4], D. Weatherill[3], I. Wilmut[7], J. Zielinska[6]

[1]Kings College London, [2]STFC Rutherford Appleton Laboratory, [3]University of Oxford, [4]University of Birmingham, [5]University of Liverpool, [6]Imperial College London, [7]University of Cambridge

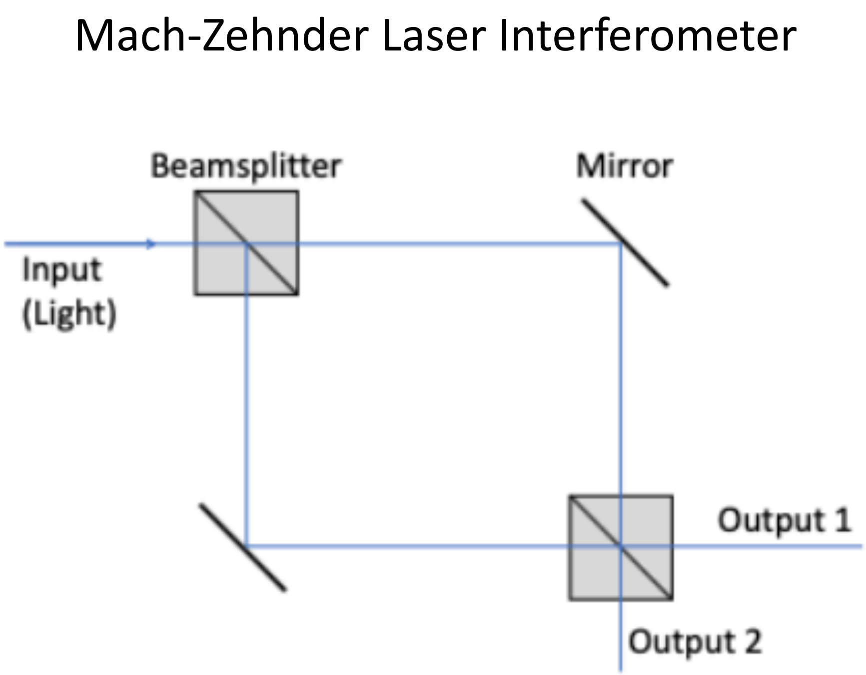


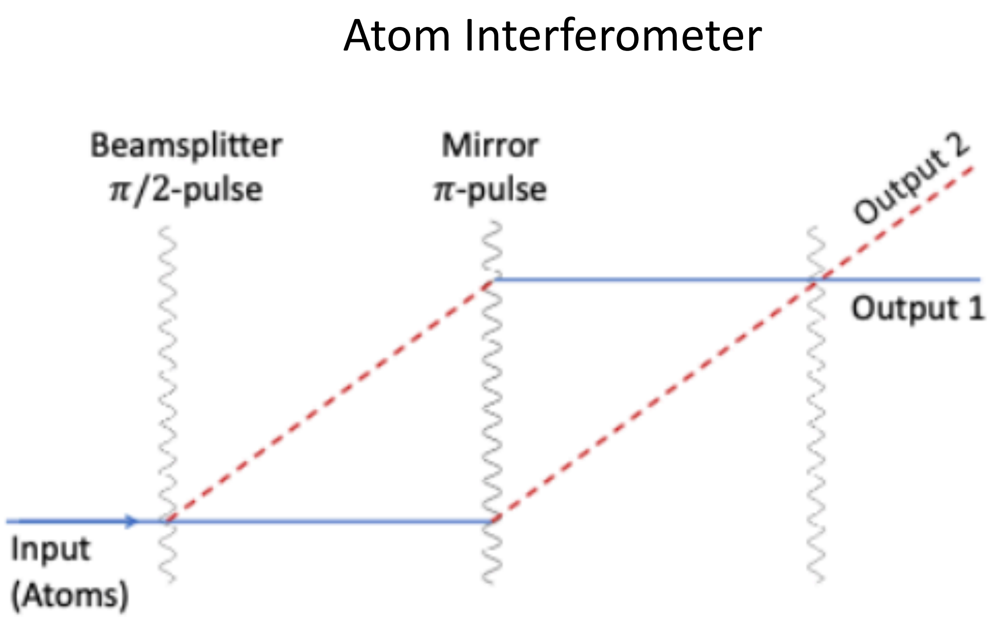
Network with MAGIS project in US

MAGIS Collaboration (Abe et al): arXiv:2104.02835

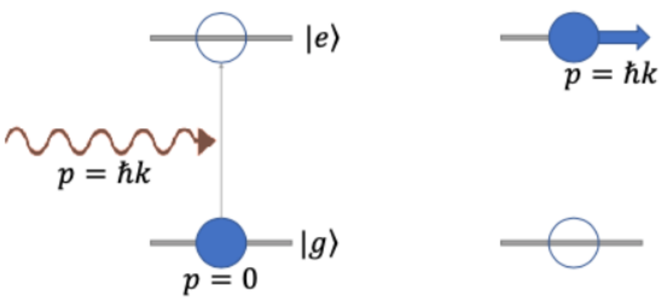
AION

Principle of Atom Interferometry



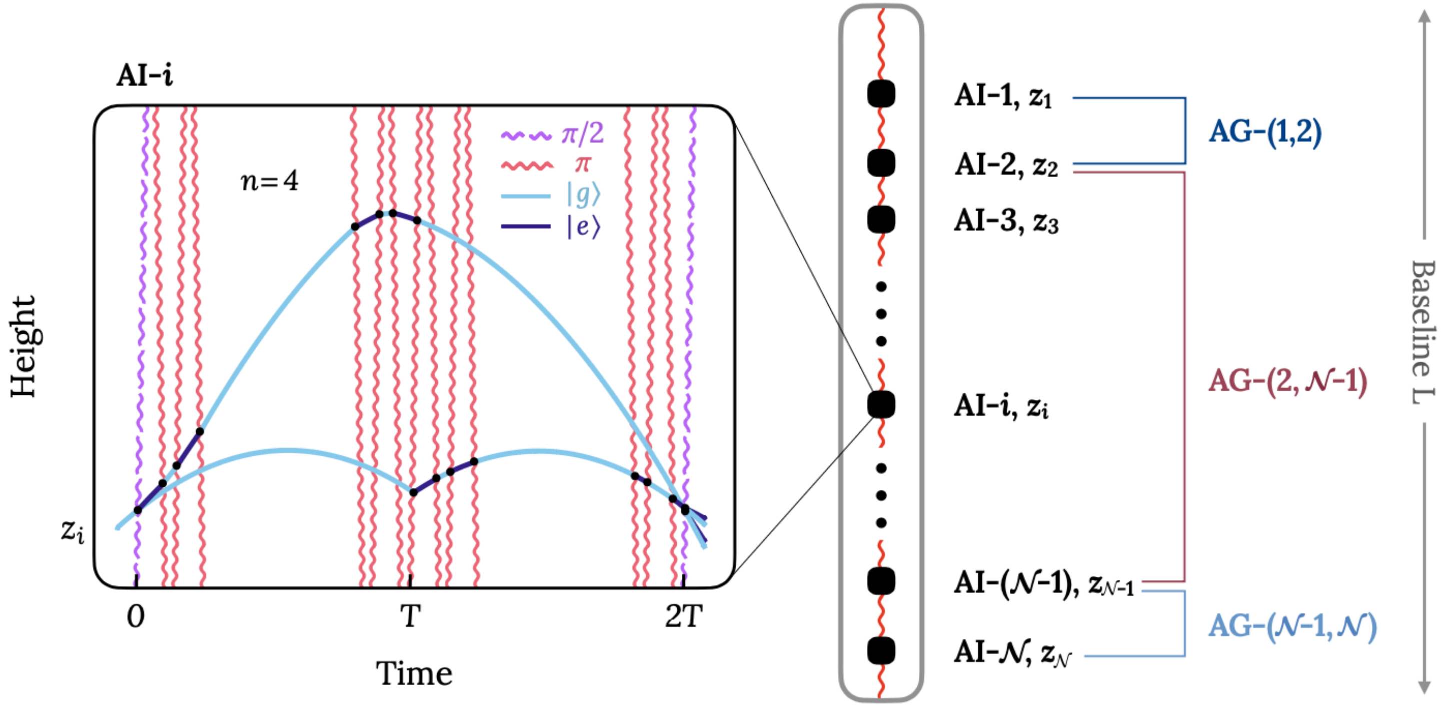


Laser excitation gives momentum kick to excited atom, which follows separated space-time path



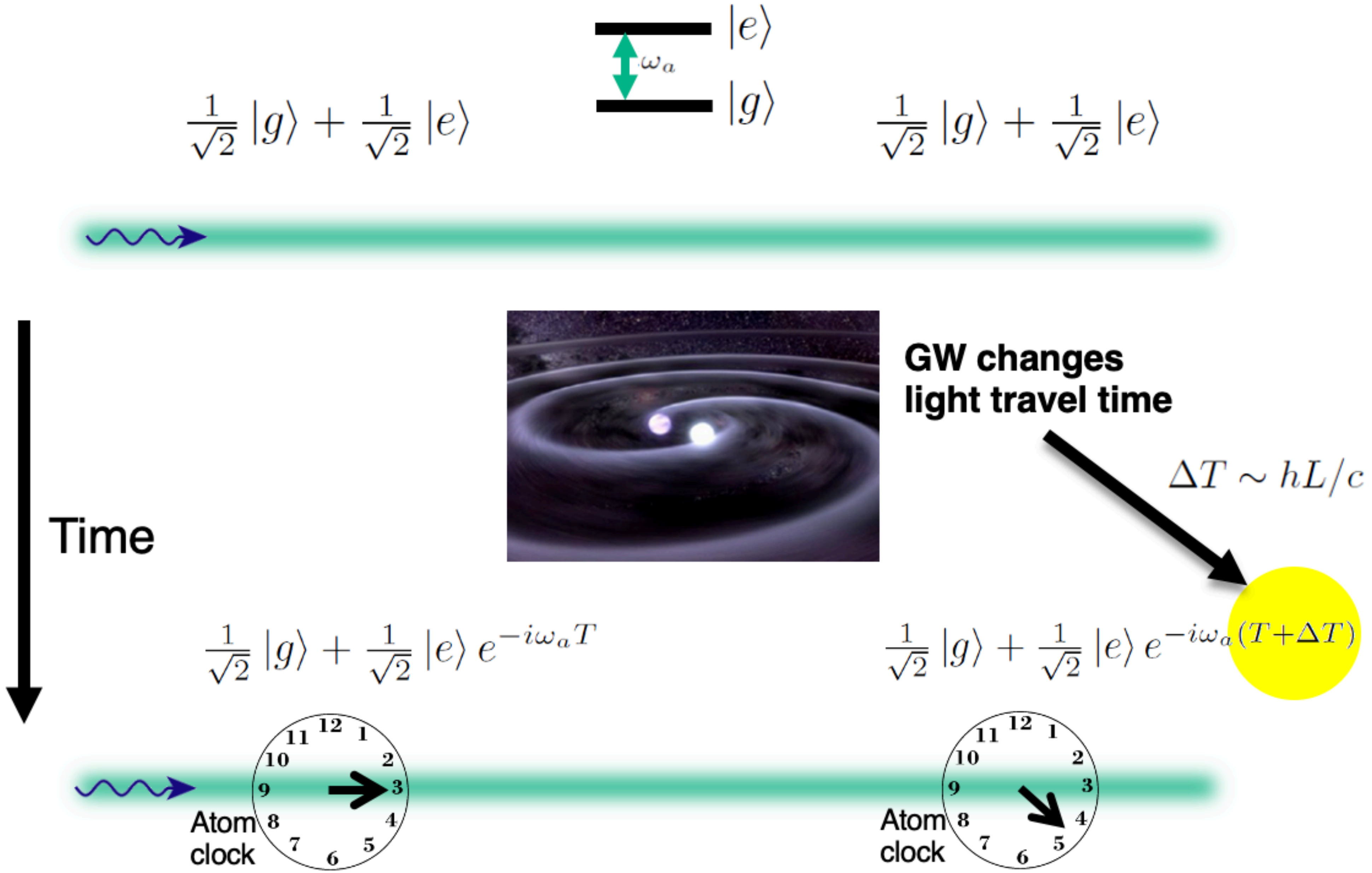
Interference between atoms following different paths

Atomic Multi-Gradiometer

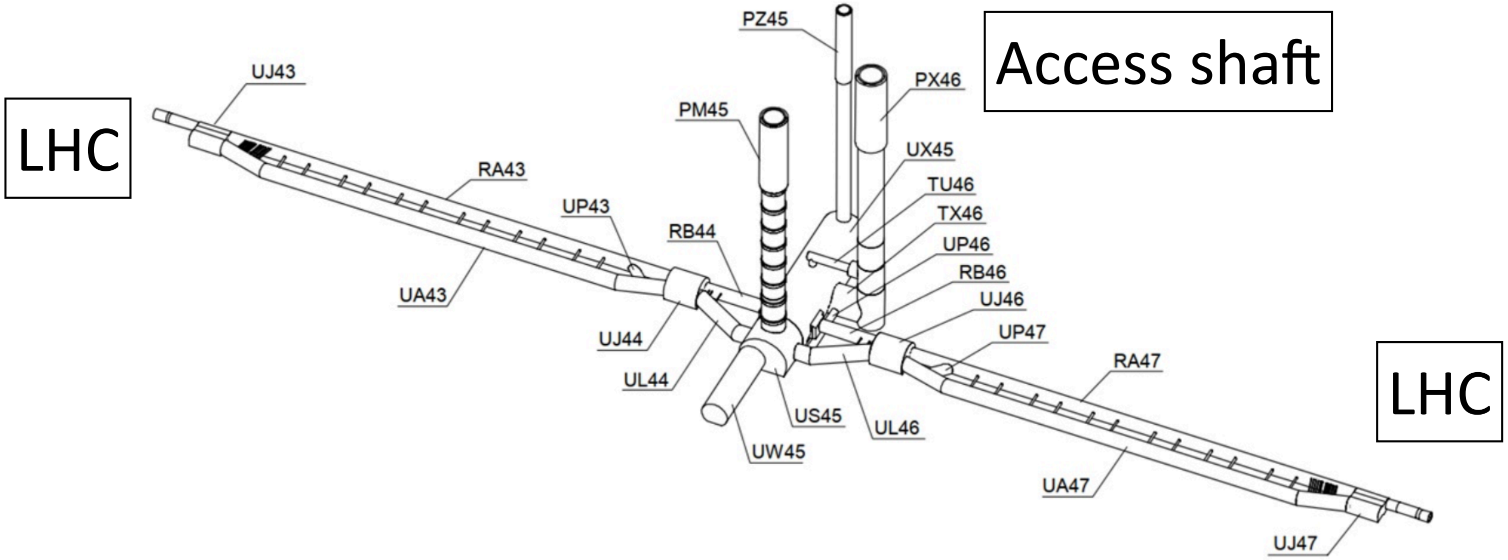


Multiple atomic interferometers in the same vertical shaft, manipulated with same laser beam.
Eliminate laser noise, minimize gravity gradient noise.

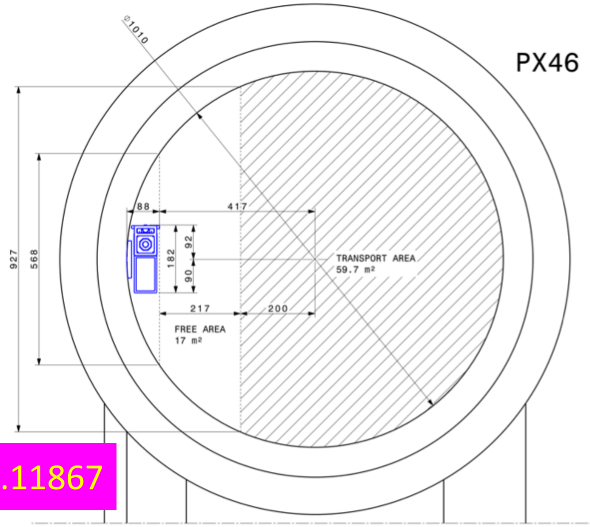
Effect of Gravitational Wave on Atom Interferometer

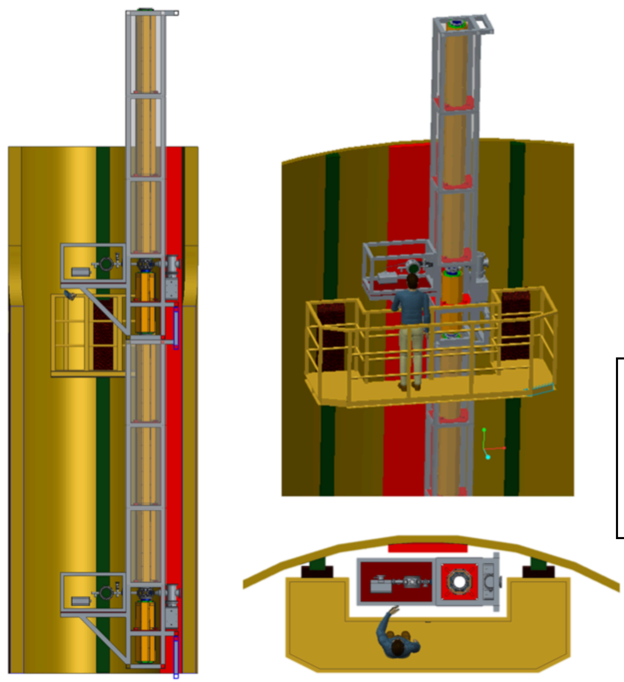


Possible CERN Location of 100m Atom Interferometer Experiment (AICE*)



Cross-section of access shaft





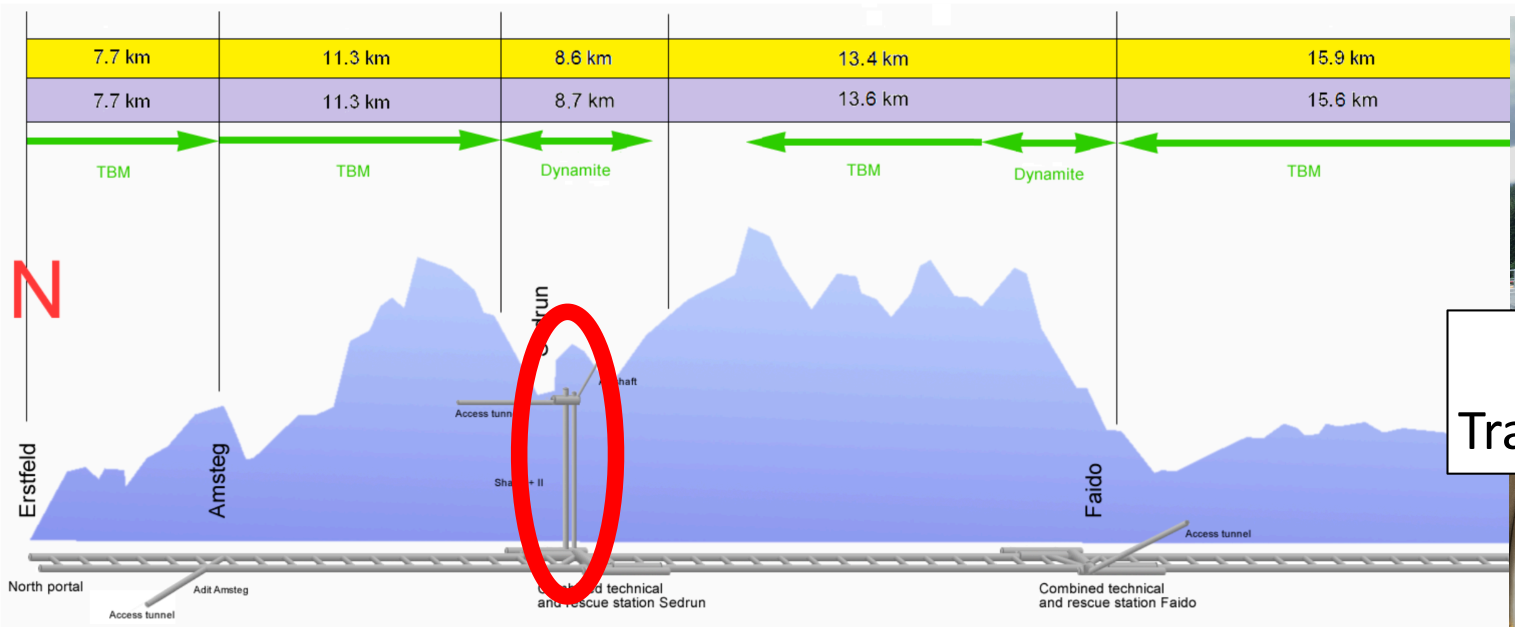
Layout of experiment

*Baynham et al: arXiv:2509.11867

Porta Alpina:

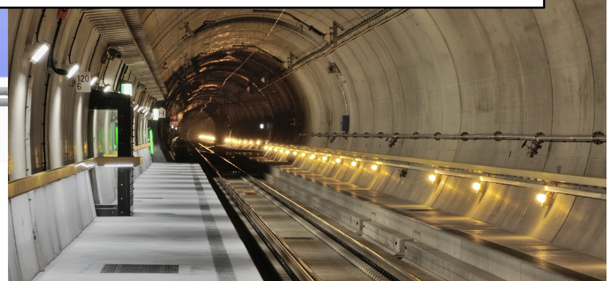
A possible site for a large terrestrial atom interferometer experiment (AIGE)?

A pair of 800m vertical shafts down to the Gotthard base railway tunnel, with a 1km horizontal access tunnel



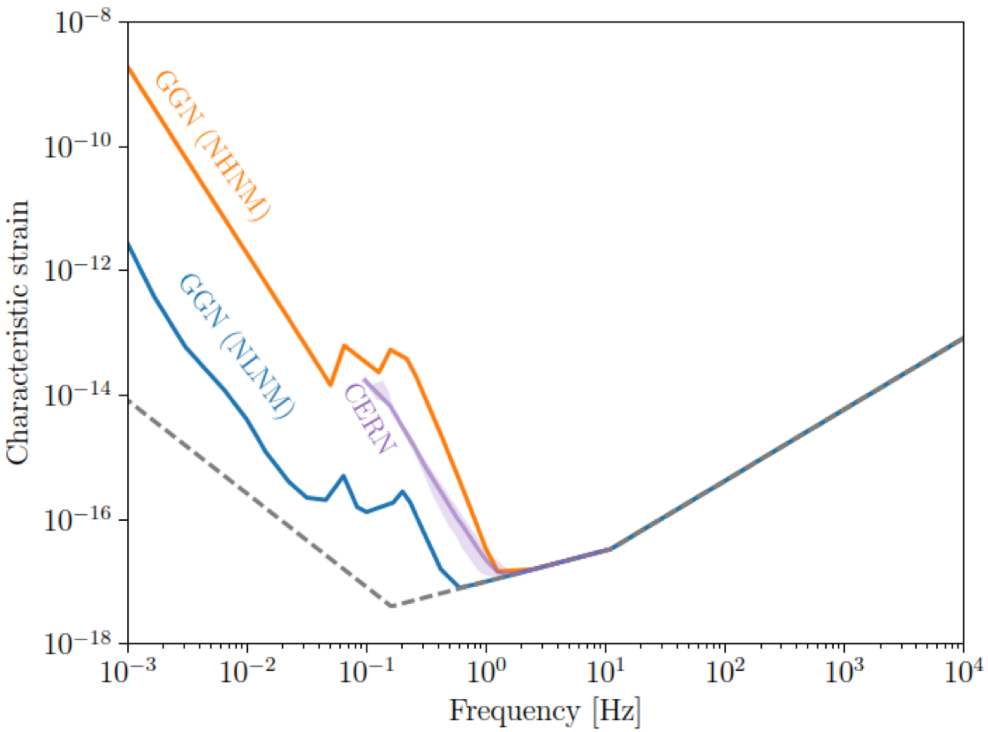
Road access at top

Train platform at bottom

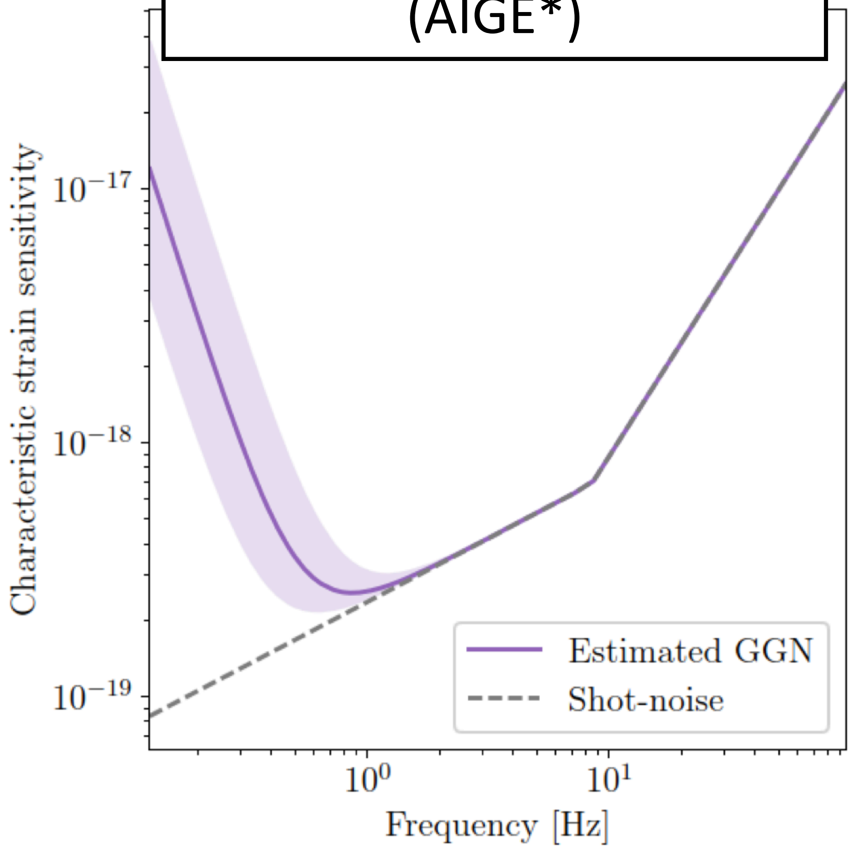


Sensitivities to Gravitational Waves

100-m detector at CERN
(AICE*)



800-m Port Alpina detector
(AIGE*)

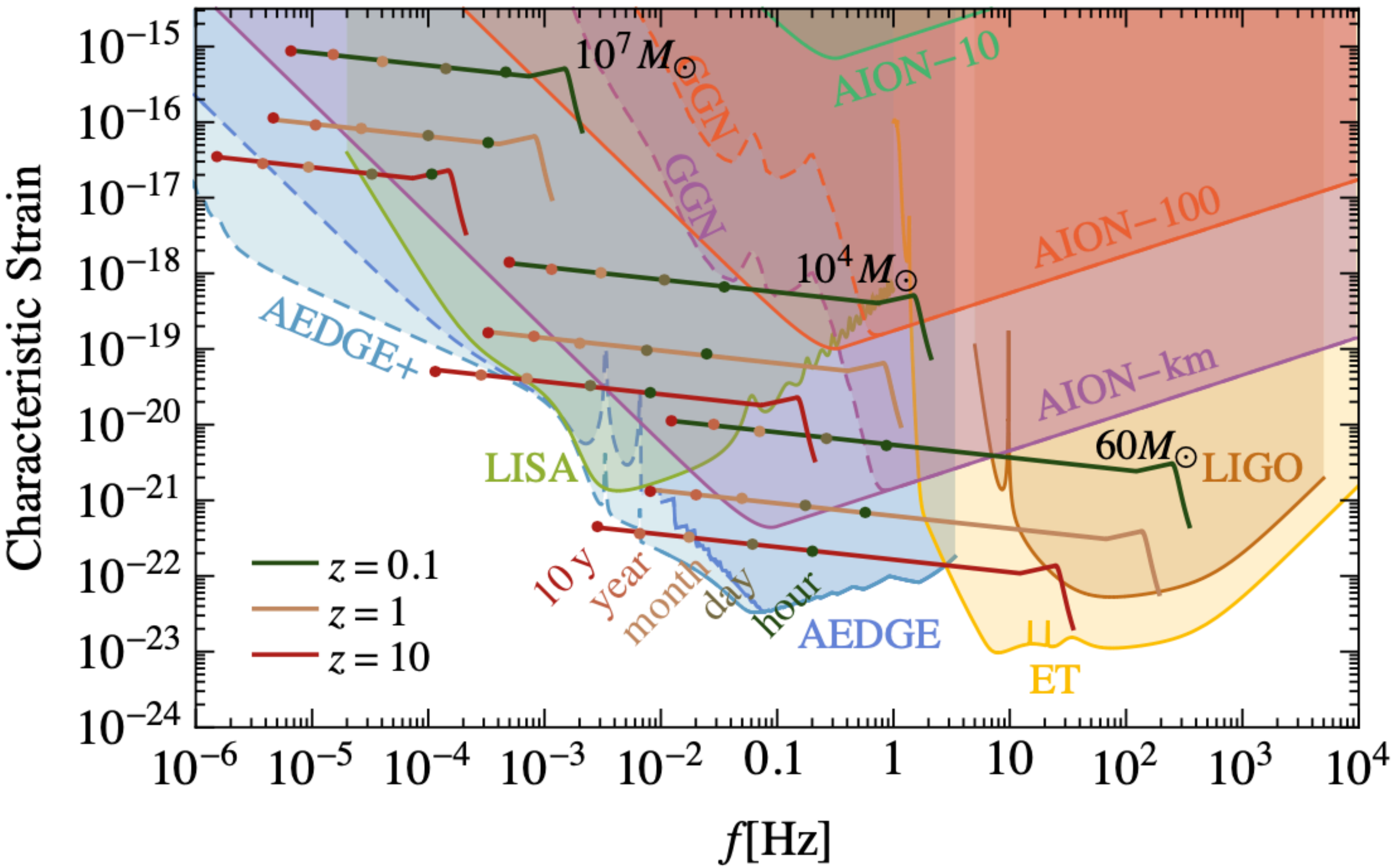


*AICE = Atom Interferometer CERN Experiment

*AIGE = Atom Interferometer Gotthard/Grisons/Graubünden Experiment

AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755

Searching for Gravitational Waves

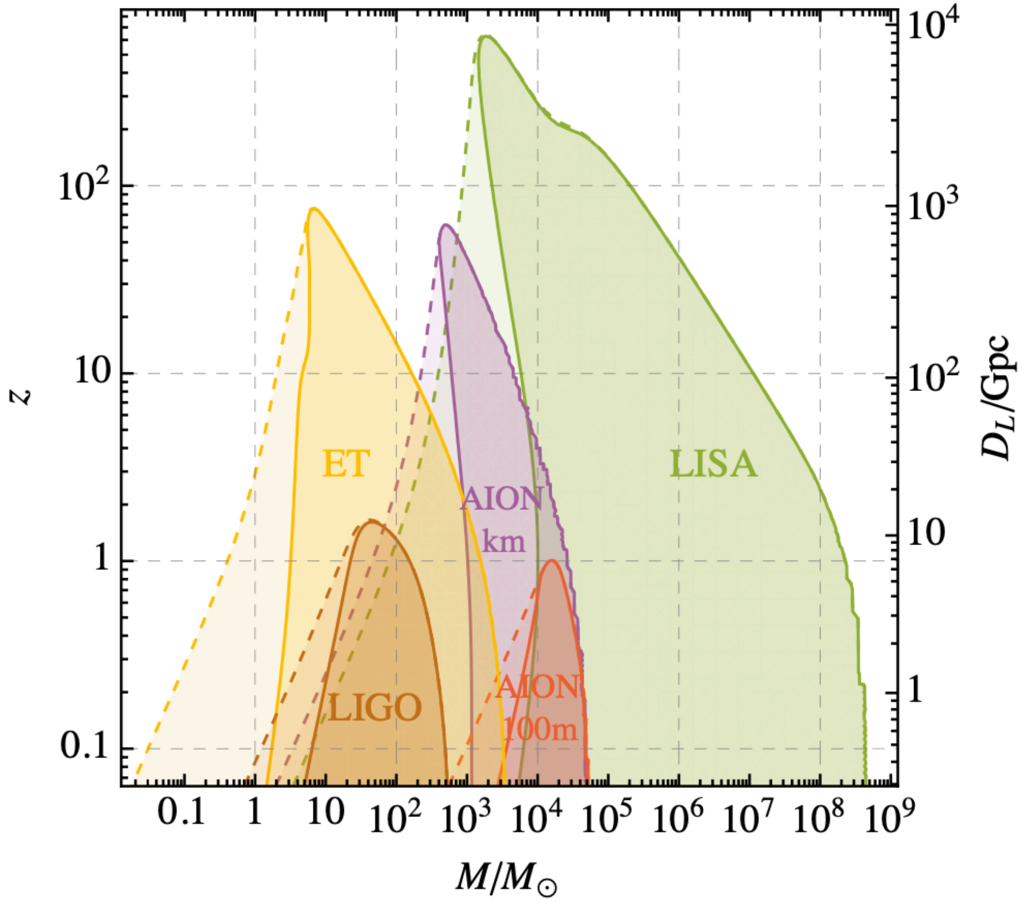


Probe formation of SMBHs

Synergies with other GW experiments (LIGO, LISA), test GR

Badurina, Buchmueller, JE, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

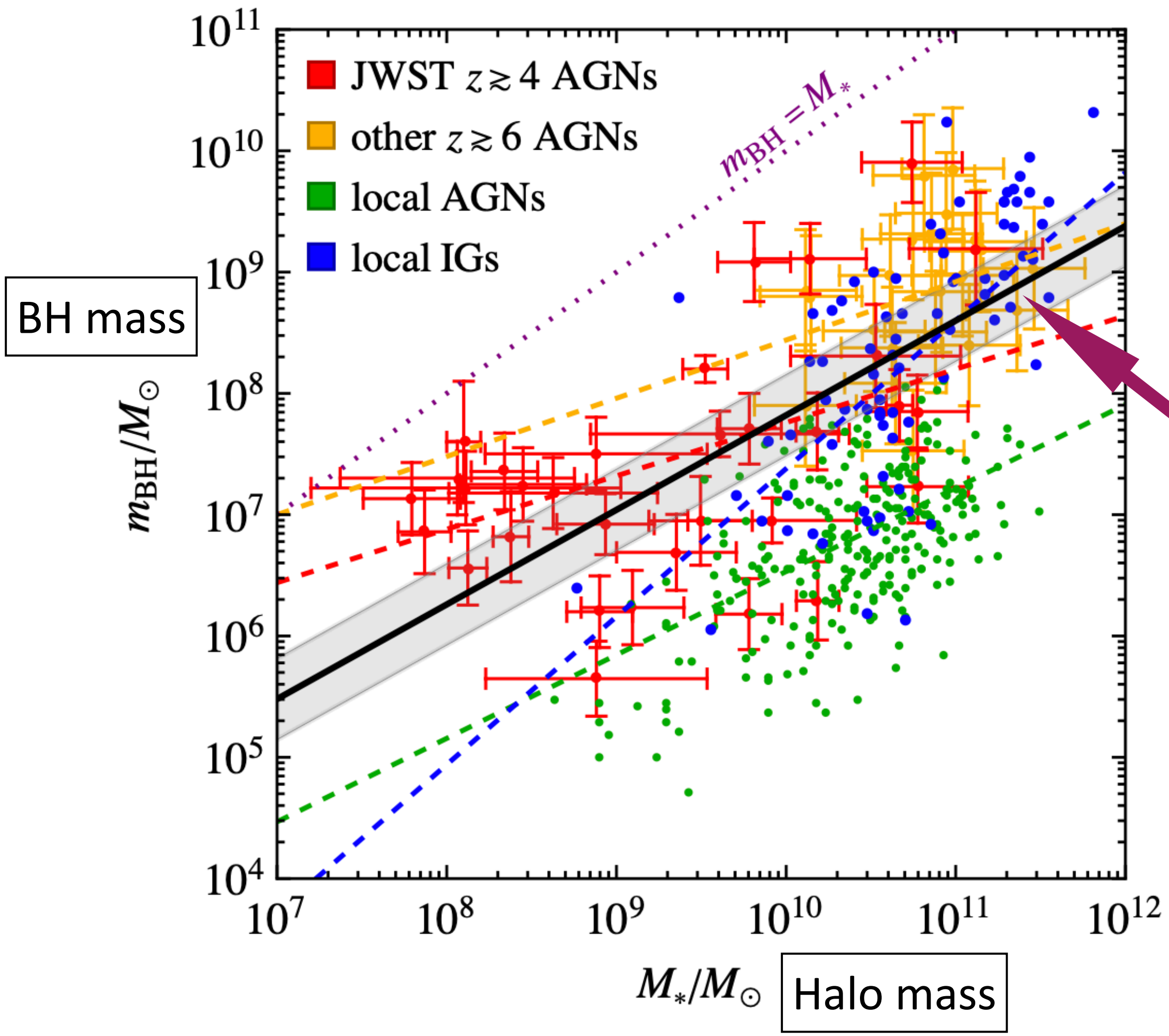
SNR = 8 Sensitivities to GWs from Mergers



In the lighter regions between the dashed and solid lines the corresponding detector observes only the inspiral phase: Synergies and complementarity of atom interferometers

AION, arXiv:1911.11755

High-z SMBHs seen with JWST

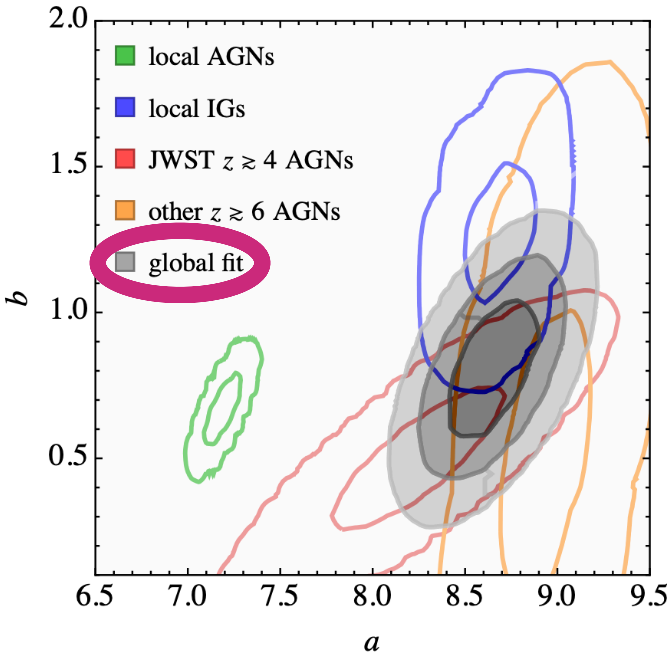


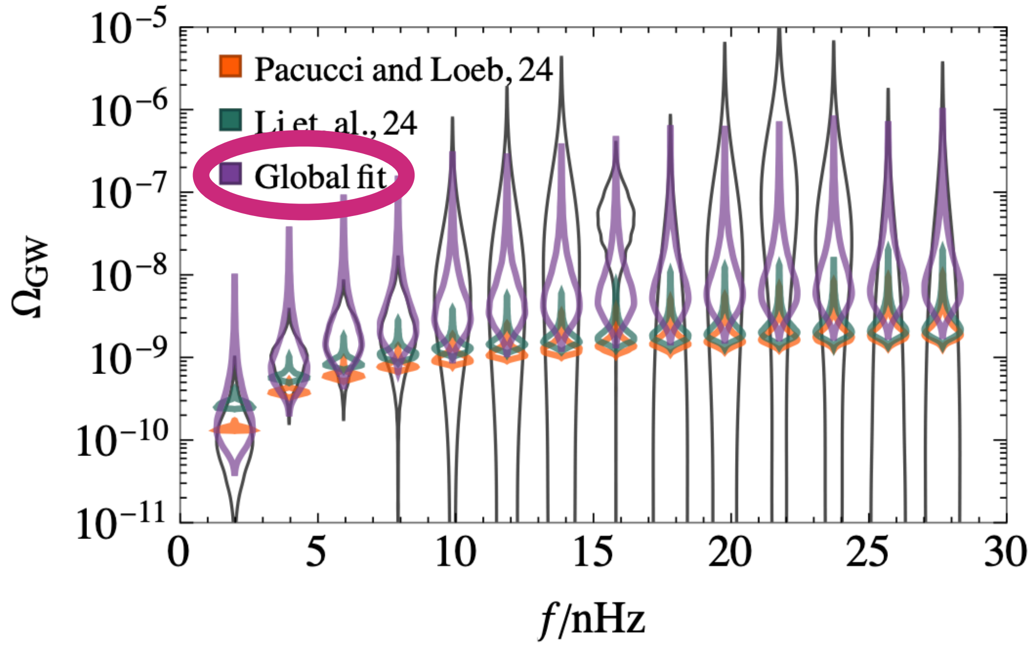
- **"Surprisingly many"**
- **Also other observations**
- **Match inactive galaxies**
- **Global fit**
- Also dual systems
- **Good news for GWs**
- Consistent with PTAs

JE, Fairbairn, Hütsi, Urrutia, Vaskonen & Veermäe: arXiv:2403.19650, A&A 690, A270

Consistent with NANOGrav

Fits to BH-halo mass relation $\frac{\mathrm{d}P(m|M_*,\boldsymbol{\theta})}{\mathrm{d}\log_{10}m} = \mathcal{N}\left(\log_{10}\frac{m}{M_\odot}\middle|a + b\log_{10}\frac{M_*}{10^{11}M_\odot},\sigma\right)$



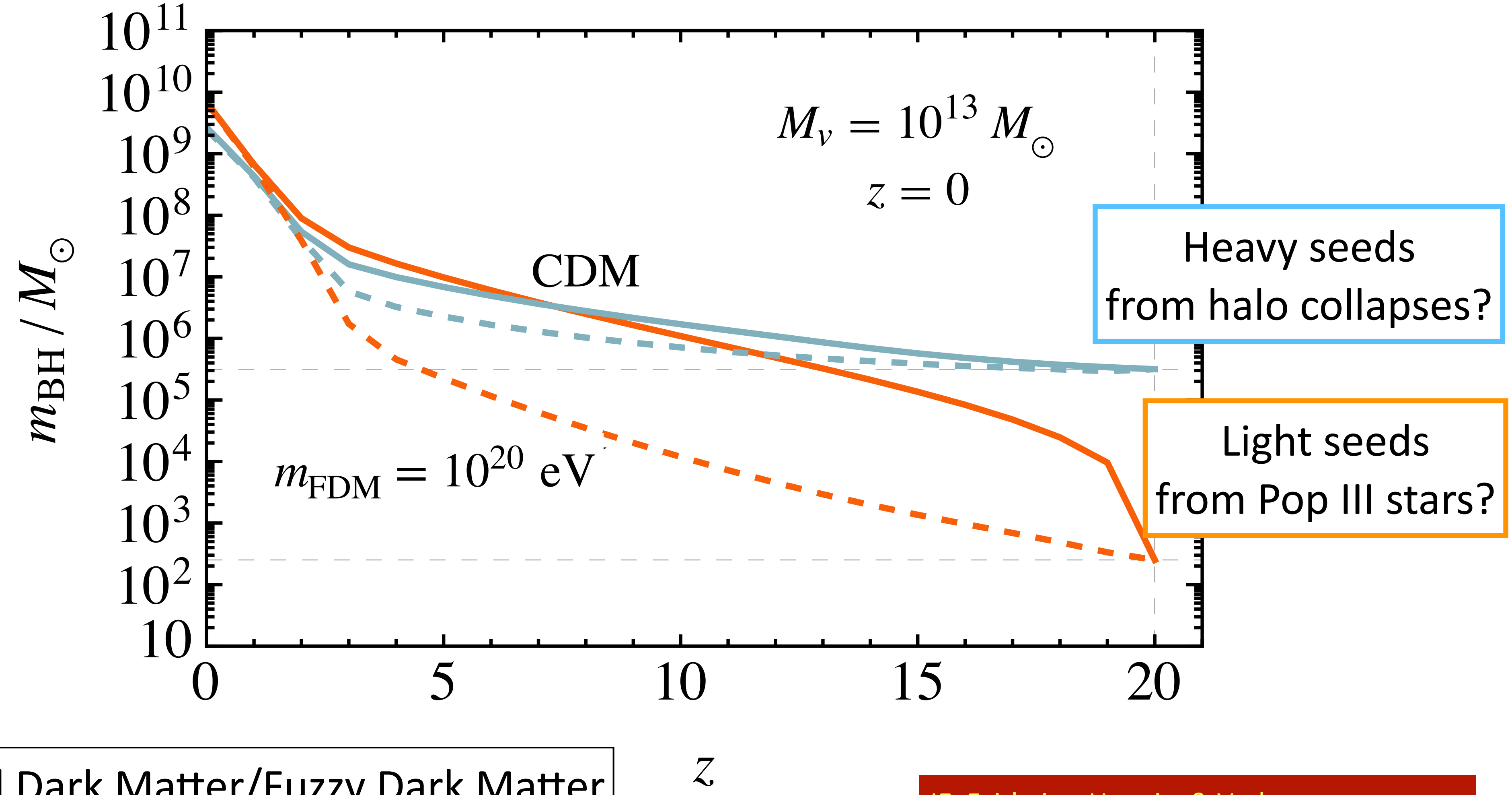


- Local AGNs underestimate SMBH masses
- Probably many SMBHs unseen in inactive galaxies
- **Our global fit** preferred over other JWST/NANOGrav scenarios

JE, Fairbairn, Hütsi, Urrutia, Vaskonen & Veermäe: arXiv:2403.19650, A&A 690, A270

Growth of SMBH in CDM/FDM*
with Light/Heavy Seeds

BH mass can grow by mergers or accretion

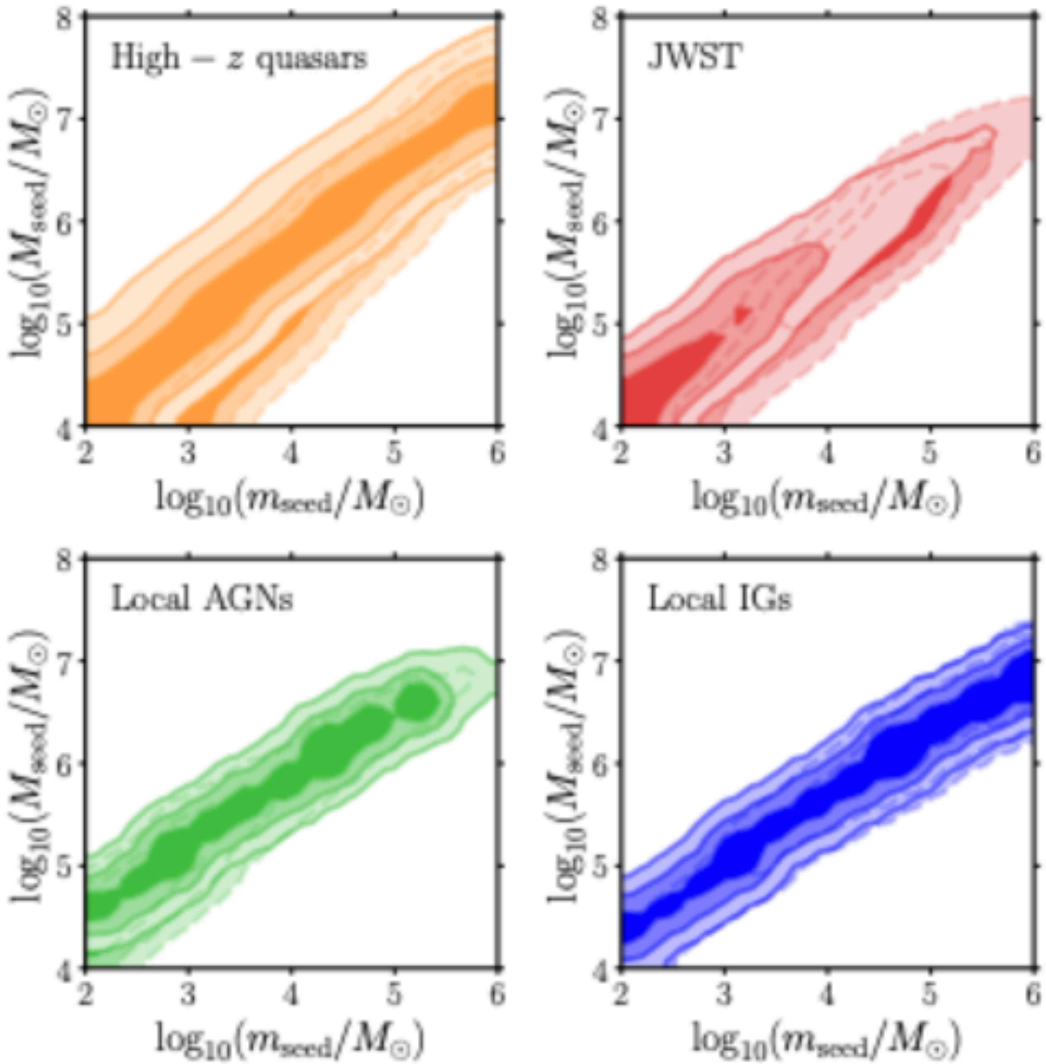


*Cold Dark Matter/Fuzzy Dark Matter

JE, Fairbairn, Urrutia, & Vaskonen: *to appear*

Fits to Seed BH Masses

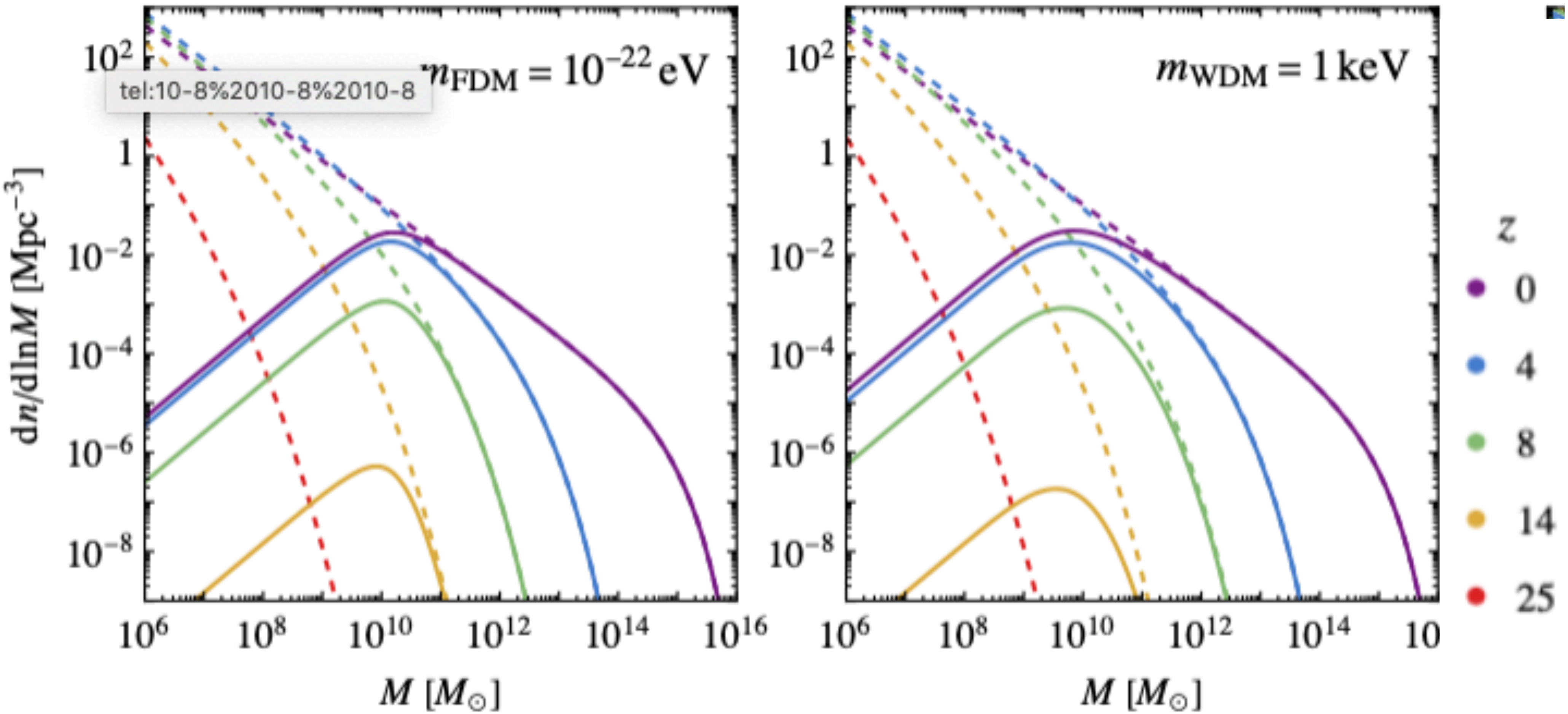
- Model parameters:
  Seed BH mass $m_{\rm seed}$
  Host galaxy mass $M_{\rm seed}$
  Initial redshift $z_{\rm seed}$
  Probability of BH merger $p_{\rm BH}$
- Results insensitive to $z_{\rm seed}$, use $z_{\rm seed} = 20$
- Strong ($m_{\rm seed}$, $M_{\rm seed}$) correlation
- Consistency between all data



Solid lines: $p_{\rm BH} = 1$, dashed lines $p_{\rm BH} = 0.1$

JE, Fairbairn, Juan Urrutia, Ville Vaskonen, arXiv:2410.24224, to appear in A&A

Halo Mass Function in CDM, FDM, WDM*



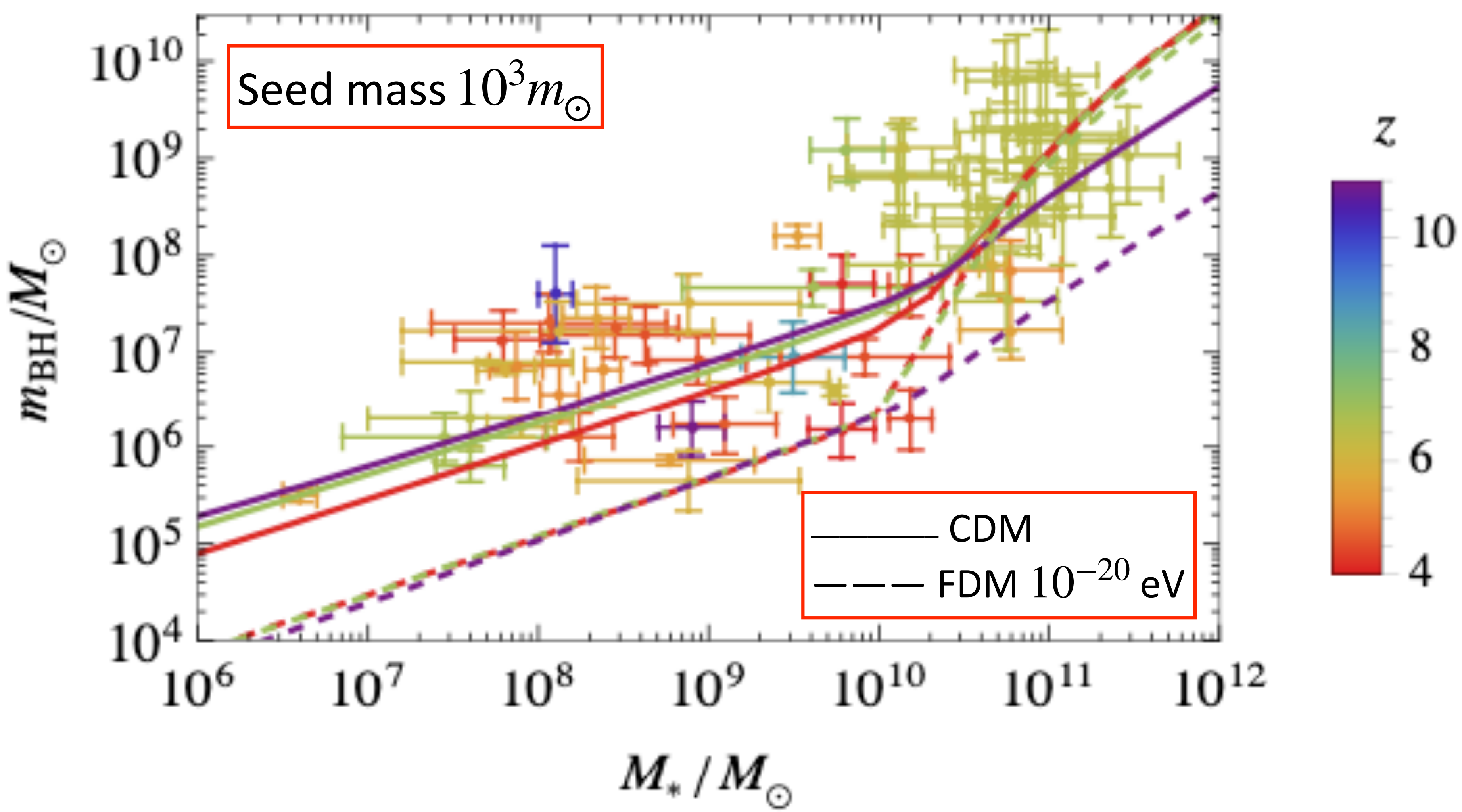
FDM and WDM show larger differences from CDM at high z

Novel way to probe FDM & CDM

*Warm Dark Matter

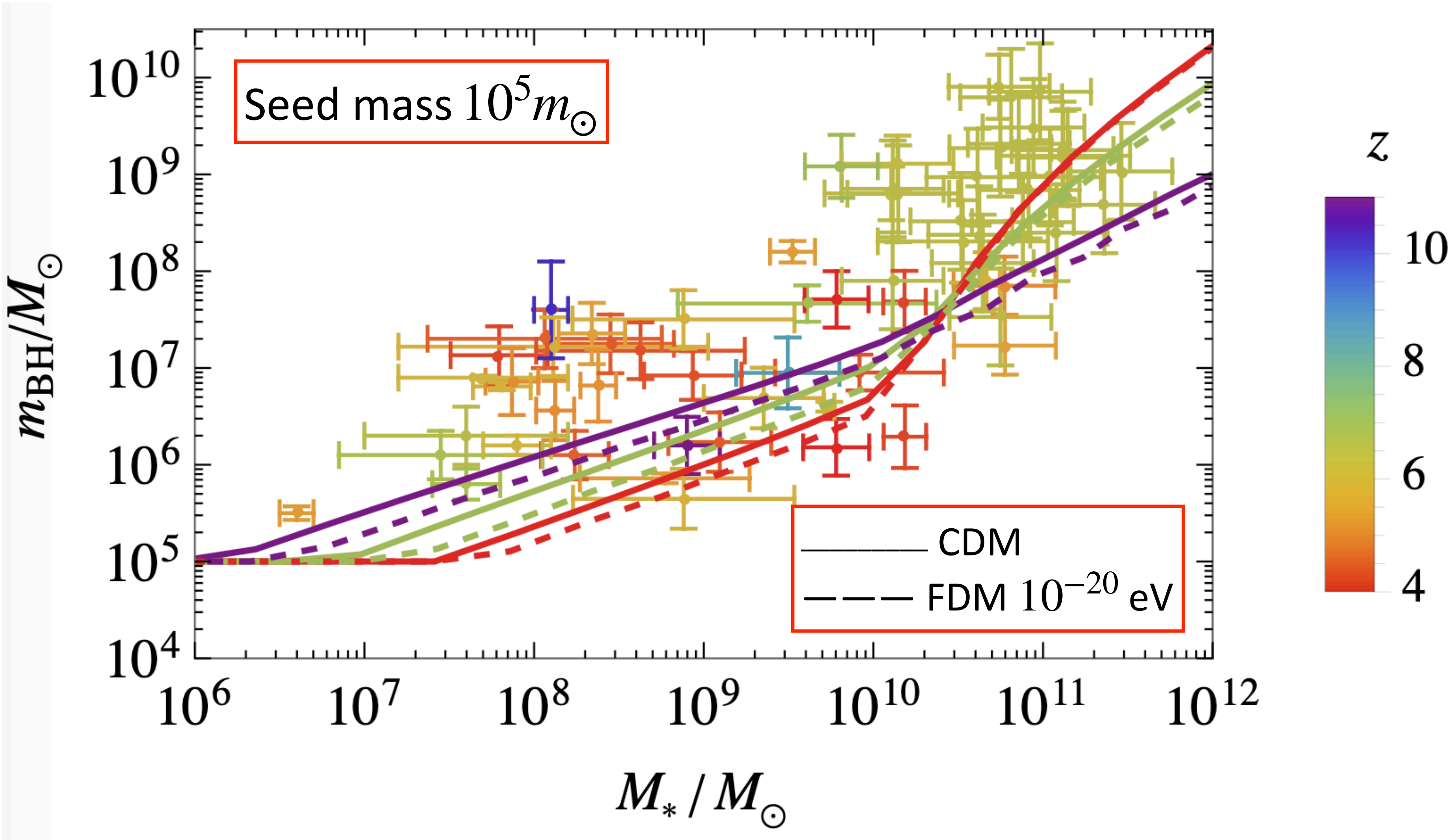
JE, Fairbairn, Juan Urrutia, Ville Vaskonen, arXiv:2504.20043, to appear in A&A

Population of High-z SMBHs vs CDM, FDM, WDM



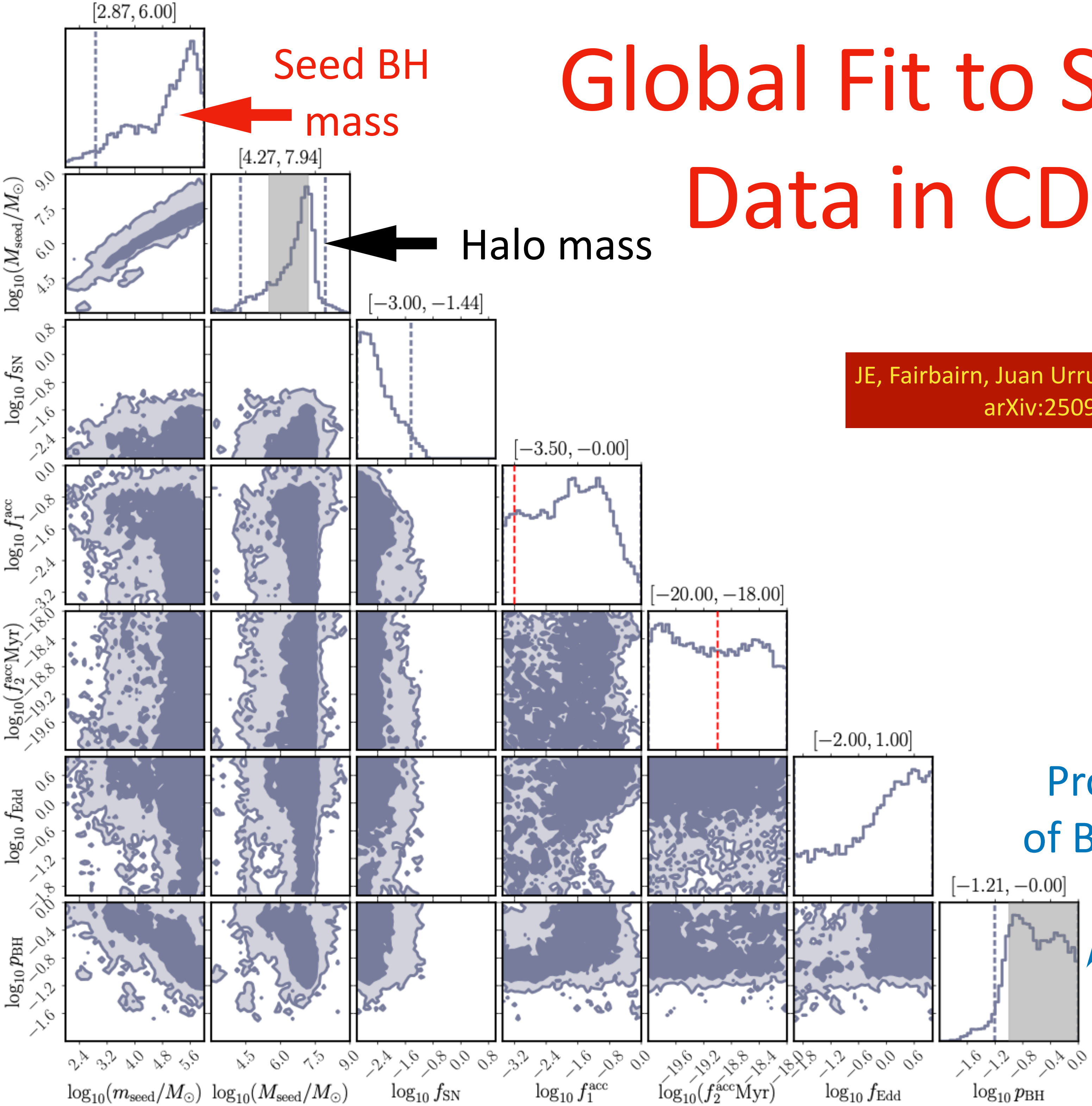
JE, Fairbairn, Juan Urrutia, Ville Vaskonen, arXiv:2509.06955

Population of High-z SMBHs vs CDM, FDM, WDM



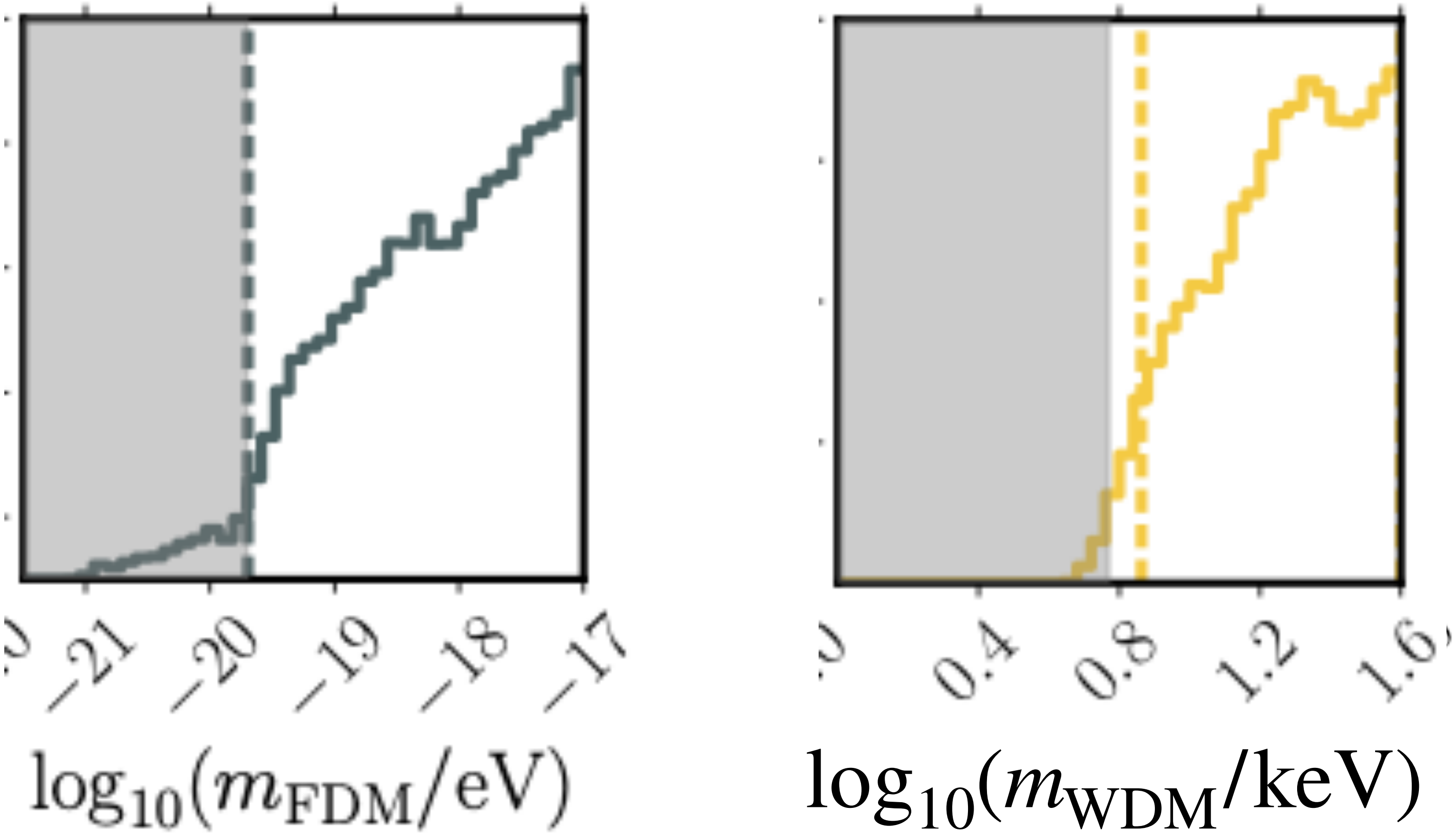
JE, Fairbairn, Juan Urrutia, Ville Vaskonen, arXiv:2509.06955

Global Fit to SMBH Data in CDM



JE, Fairbairn, Juan Urrutia, Ville Vaskonen,
arXiv:2509.06955

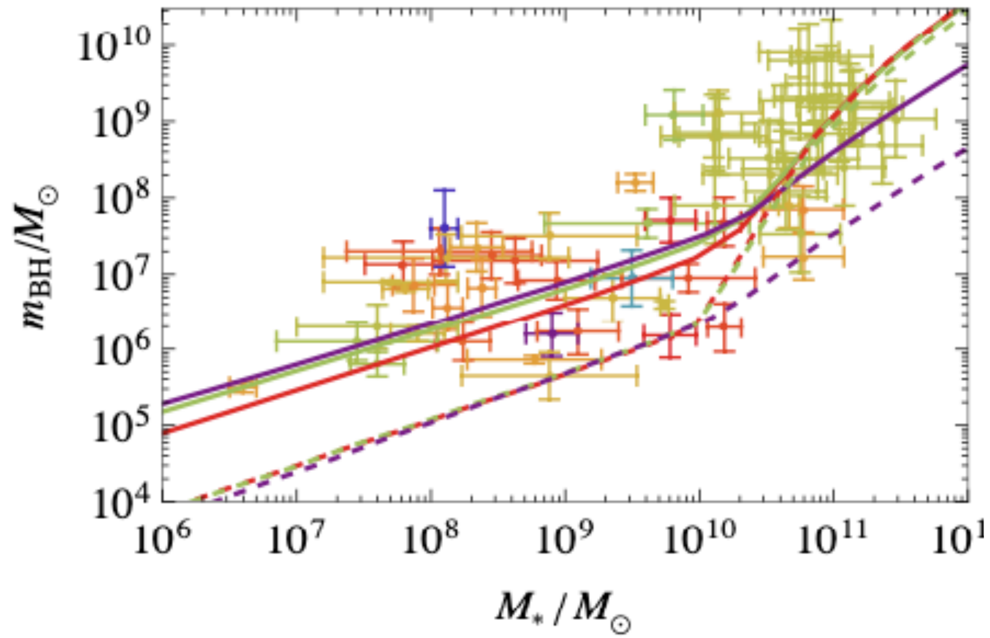
Posterior Density Functions from SMBH Mass Analysis



SMBH data constrain $m_{\rm FDM} > 2 \times 10^{-20}$ eV, $m_{\rm WDM} > 7.2$ keV

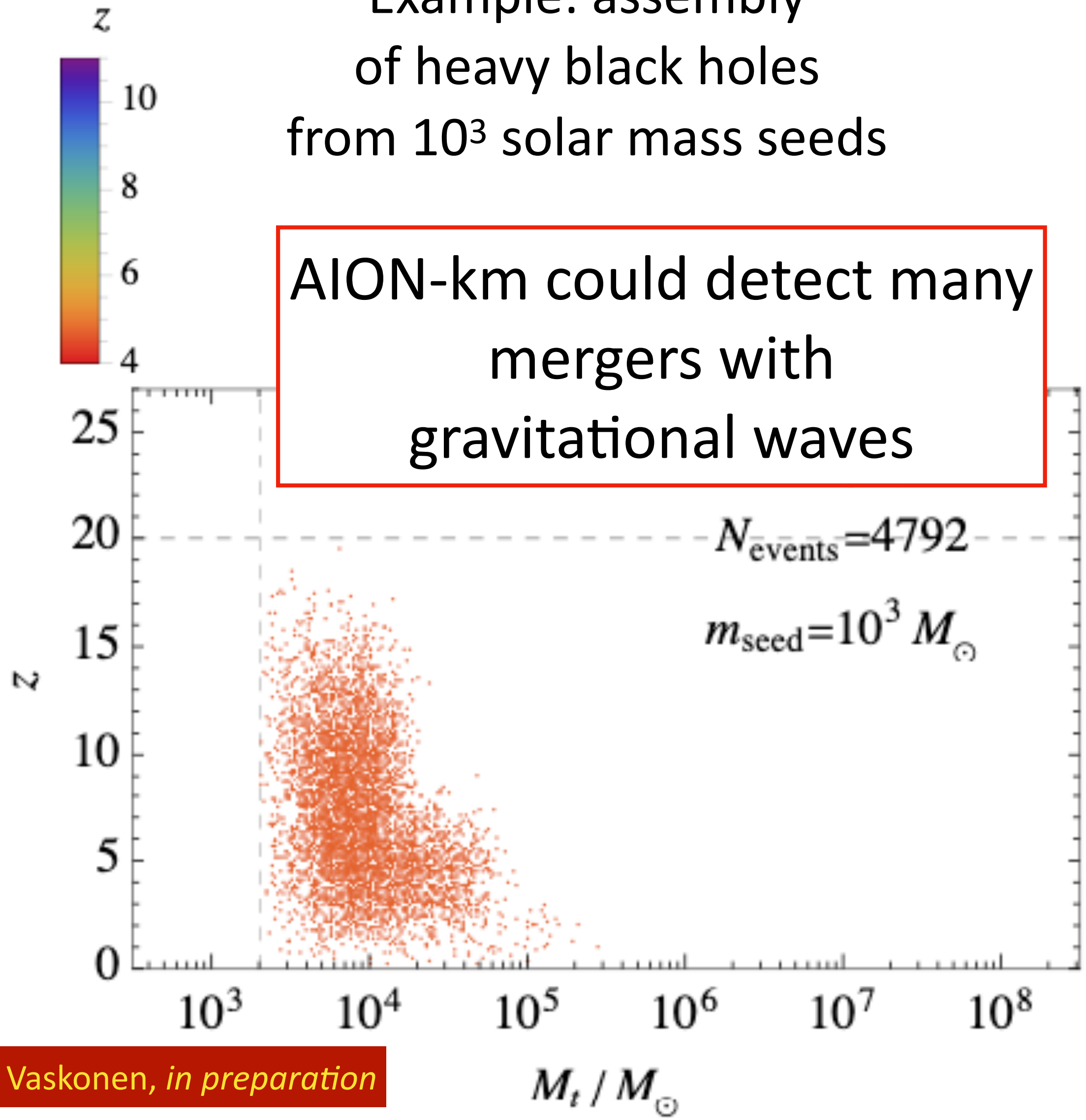
JE, Fairbairn, Juan Urrutia, Ville Vaskonen, arXiv:2509.06955

Probing Origin of Supermassive Black Holes with Gravitational Waves



Example: assembly of heavy black holes from 10^3 solar mass seeds

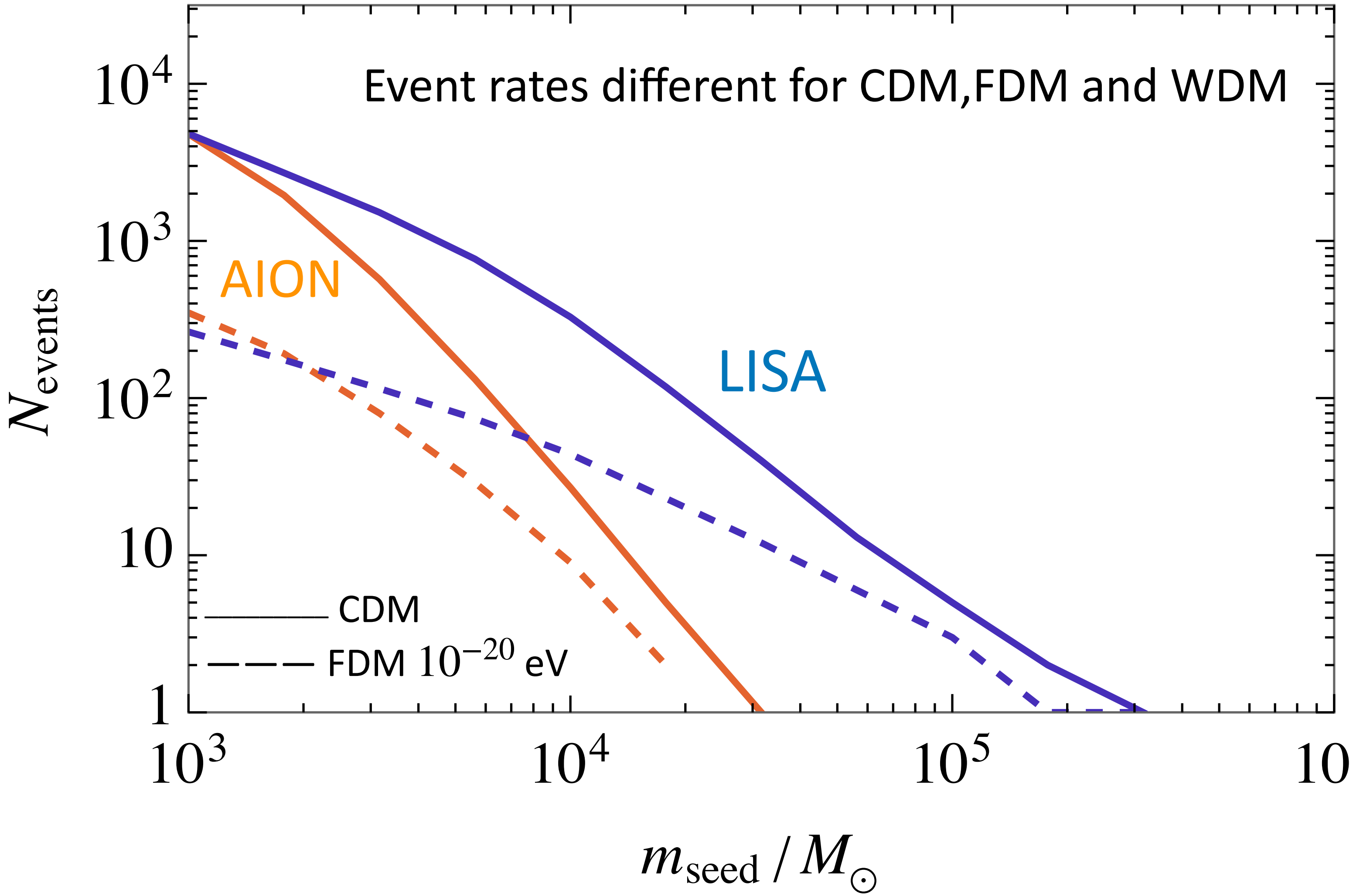
AION-km could detect many mergers with gravitational waves



Model fits data on supermassive black holes at high & low redshifts

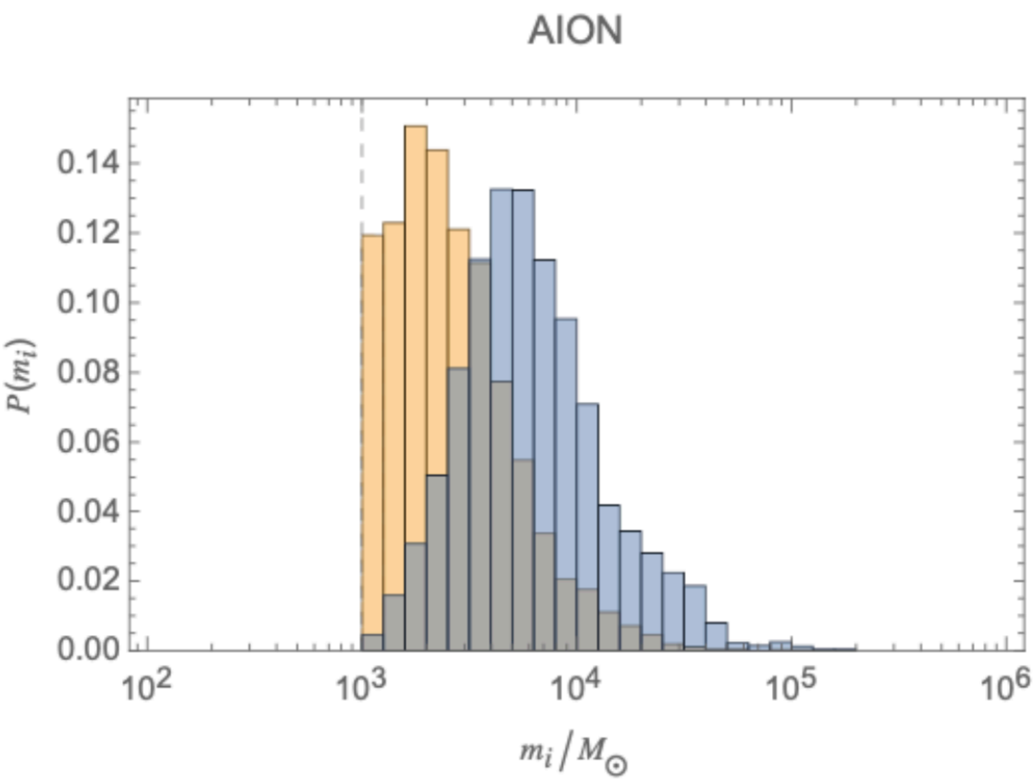
JE, Fairbairn, Juan Urrutia, Ville Vaskonen, *in preparation*

GW Event Rates in AION-km & LISA

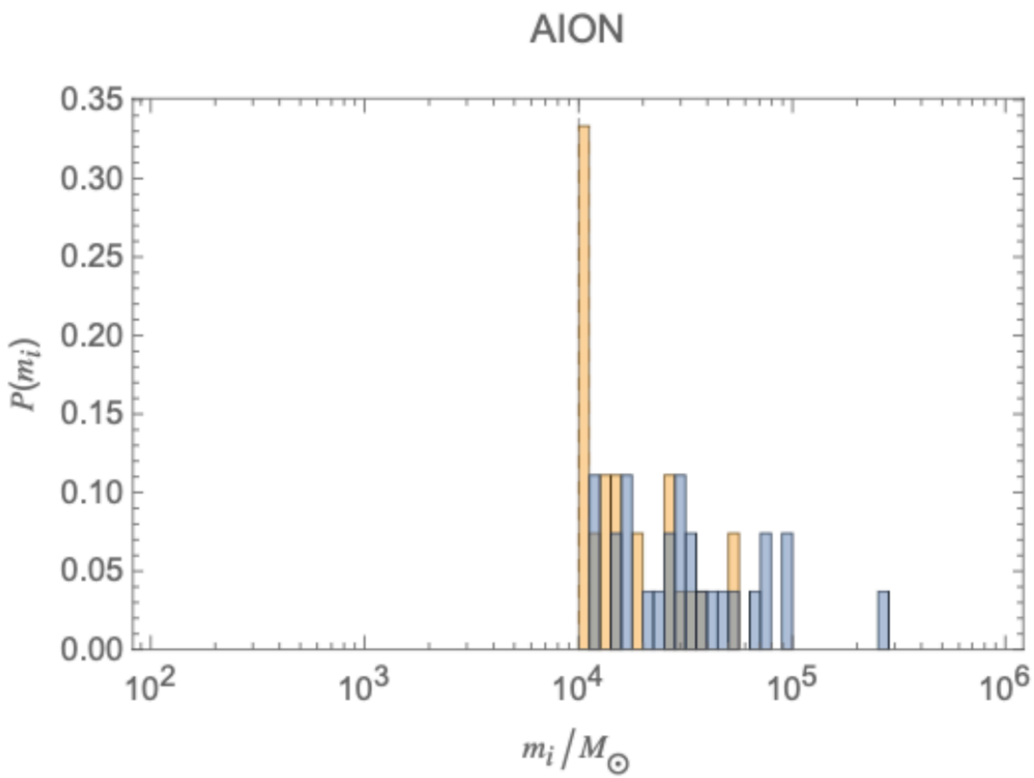


JE, Fairbairn, Juan Urrutia, Ville Vaskonen, *in preparation*

Masses of Merging BHs



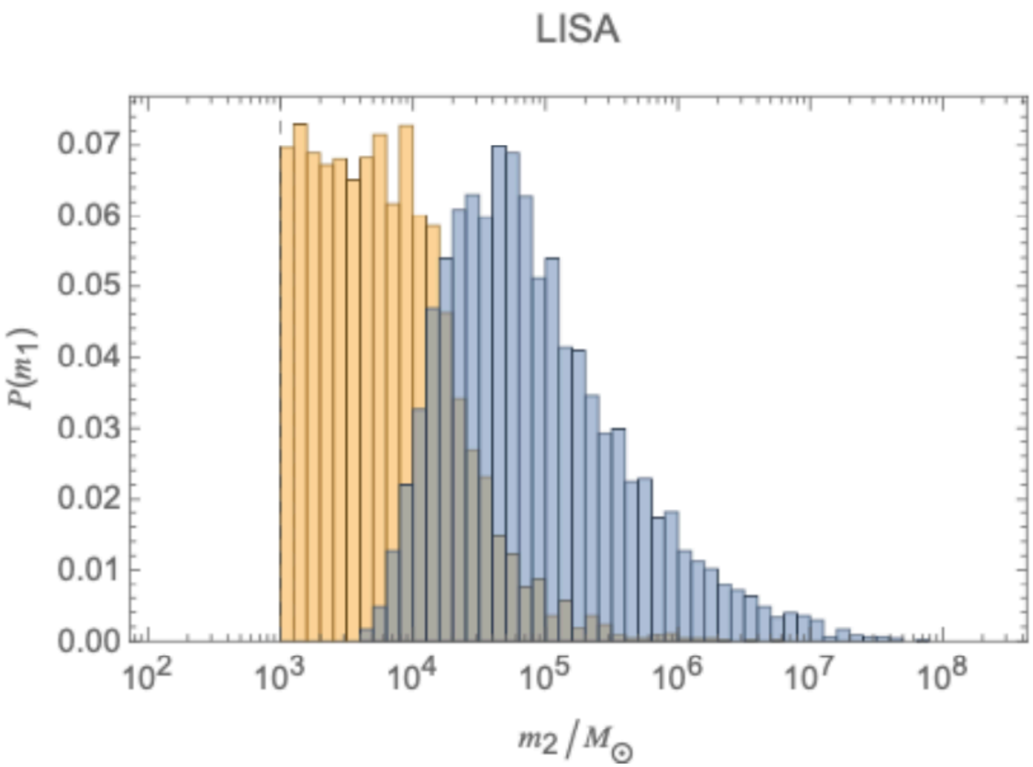
10^3 solar mass seeds



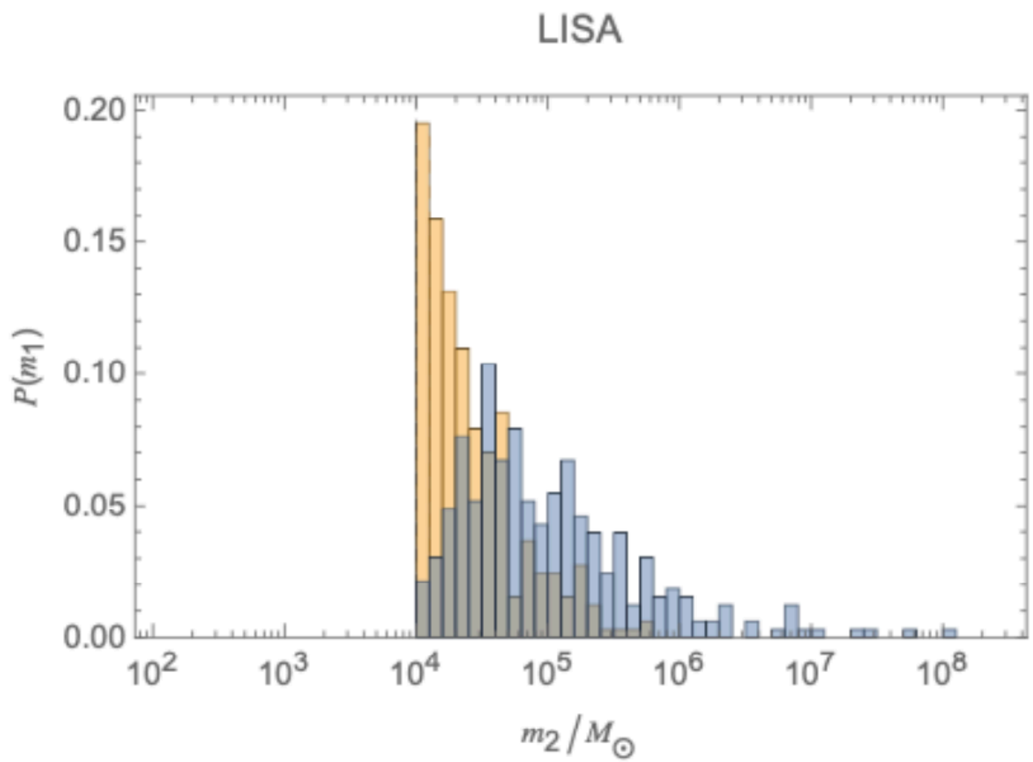
10^4 solar mass seeds

GW observations can measure seed mass

Masses of Merging BHs



10^3 solar mass seeds



10^4 solar mass seeds

GW observations can measure seed mass

Proto-Collaboration Interested in Large Atom Interferometer Experiments

Austria
•Institute of Science and Technology Austria
Bosnia and Herzegovina
•University of Sarajevo - Faculty of Science
Denmark
•Aarhus University - Department of Physics and Astronomy
Estonia
•National Institute of Chemical Physics and Biophysics (KBFI)

France
•University of Toulouse III – Paul Sabatier
•École Normale Supérieure
Germany
•Technische Universität Darmstadt
•Leibniz University Hannover
•Ulm University

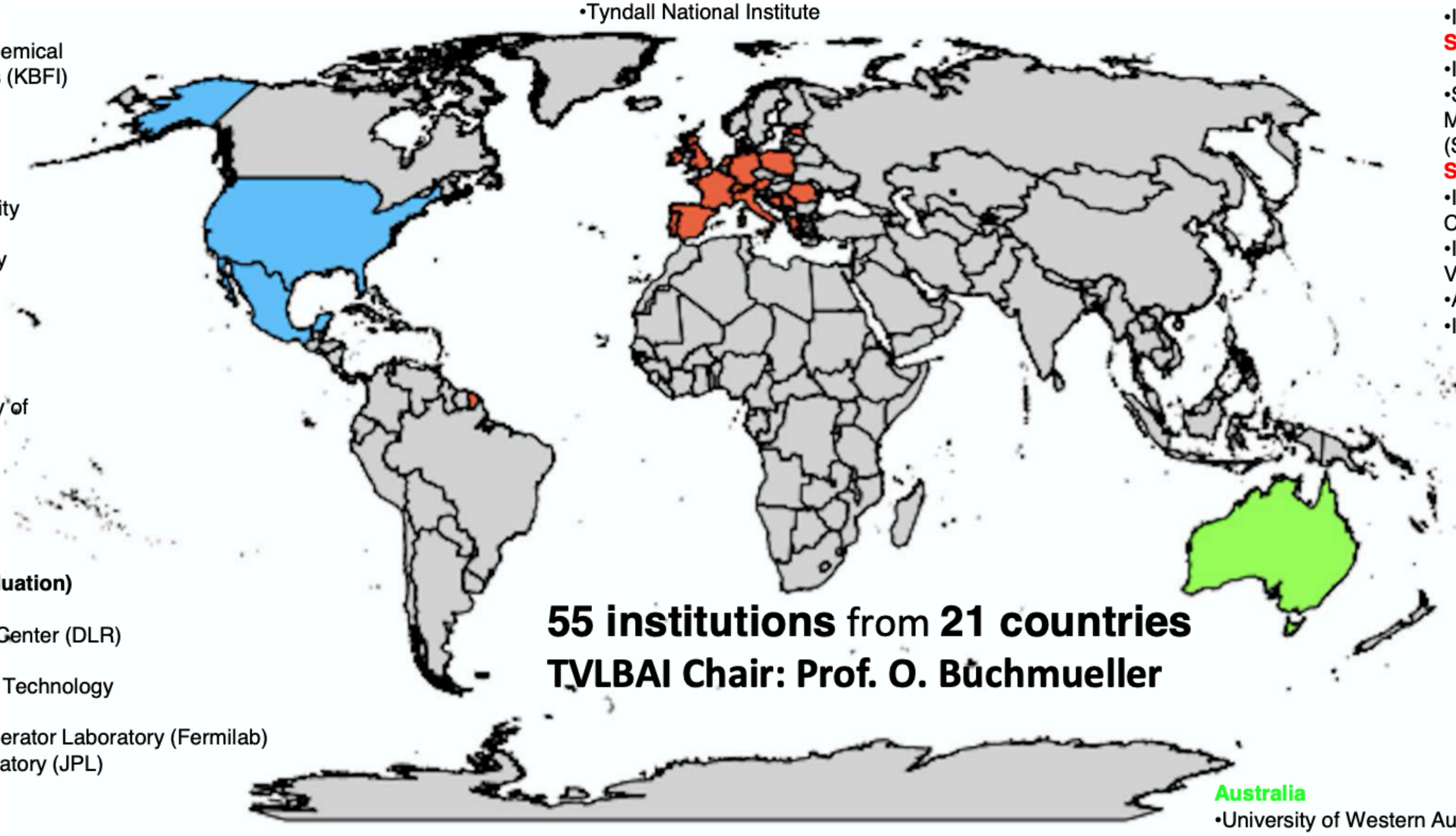
Greece
•Laboratory of Theoretical and Computational Physics, National Technical University of Athens (LThCP)
•Foundation for Research and Technology – Hellas (FORTH)
•Laboratory of Astronomy, Aristotle University of Thessaloniki (AUTH)
Ireland
•Tyndall National Institute

Italy
•University of Florence – DFA
•LENS Laboratory
•University of Pisa
Malta
•University of Malta
Netherlands
•University of Amsterdam

Poland
•Space Technology Centre, AGH University of Science and Technology, Krakow
•Center for Theoretical Physics, Polish Academy of Sciences (CTP PAS)
•University of Warsaw
Portugal
•Instituto de Telecomunicações
Romania
•Institute of Space Science
Serbia
•Institute of Physics Belgrade (IPB)
•South East European Network for Mathematical and Theoretical Physics (SEENET-MTP) Centre
Spain
•Institute of Theoretical Physics (IFT UAM-CSIC)
•Institute of Corpuscular Physics (IFIC), Valencia
•Autonomous University of Madrid (UAM)
•Institut de Fisica d'Altes Energies (IFAE)
Switzerland
•University of Geneva
•CERN
•University of Neuchâtel
•University of Zurich
•Fachhochschule Graubünden
United Kingdom
•Imperial College London
•King's College London
•University College London (UCL)
•University of Birmingham
•University of Cambridge
•University of Liverpool
•University of Manchester
•University of Oxford
•University of Southampton
•University of Sussex
•University of Warwick
•UKRI-STFC RAL

United States
•University of Arizona
•Johns Hopkins University
•Stanford University
•Northwestern University
•University of Delaware
•University of Kentucky
•Bates College, Maine

Mexico
•Autonomous University of Aguascalientes (UAA)



55 institutions from **21 countries**
TVLBAI Chair: Prof. O. Buchmueller

Australia
•University of Western Australia

Observers (Under Evaluation)
Germany
- German Aerospace Center (DLR)

Iran
- Isfahan University of Technology

United States
- Fermi National Accelerator Laboratory (Fermilab)
- Jet Propulsion Laboratory (JPL)

Summary & Conclusions

- (Not so)(surprisingly many) high-z (not so)(surprisingly heavy) Supermassive Black Holes
- Challenge for models of SMBH assembly
  - **Hierarchical mergers** from seed BHs and/or **accretion**
    - **Light seeds**: relics of Pop-III stars? Masses ~ 10^2 - 10^3 Sun?
    - **Heavy seeds**: collapses of halos of first galaxies? Masses ~ 10^5 - 10^6 Sun?
- **Both consistent with the high-z SMBH data**
- **Constraints on FDM, WDM from high-z SMBHs:**

SMBH data constrain $m_{\rm FDM} > 2 \times 10^{-20}$ eV, $m_{\rm WDM} > 7.2$ keV

- **Possible future constraints from GW observations**