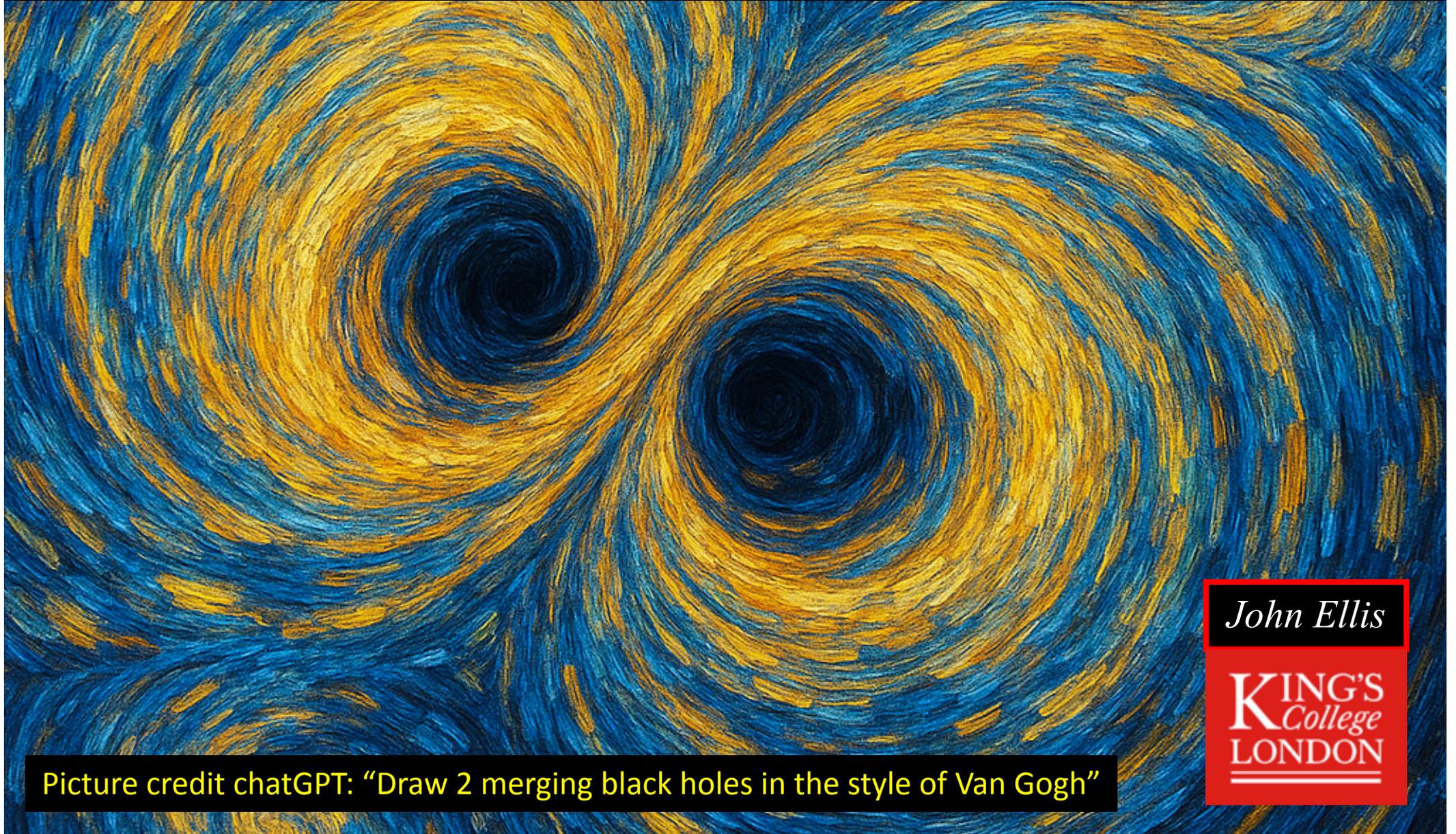


Chasing the Biggest Bangs since the Big Bang with Gravitational Waves

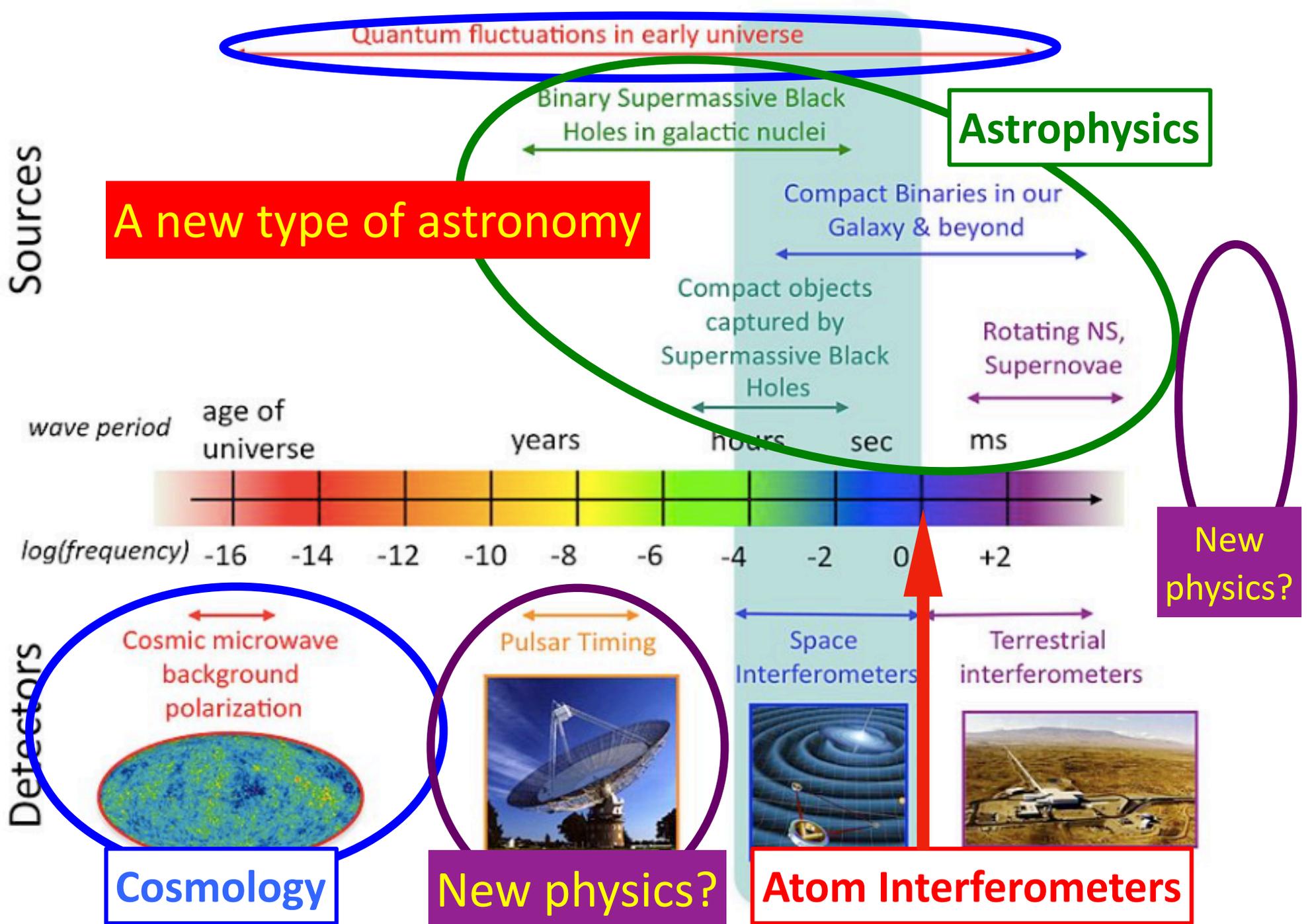


John Ellis

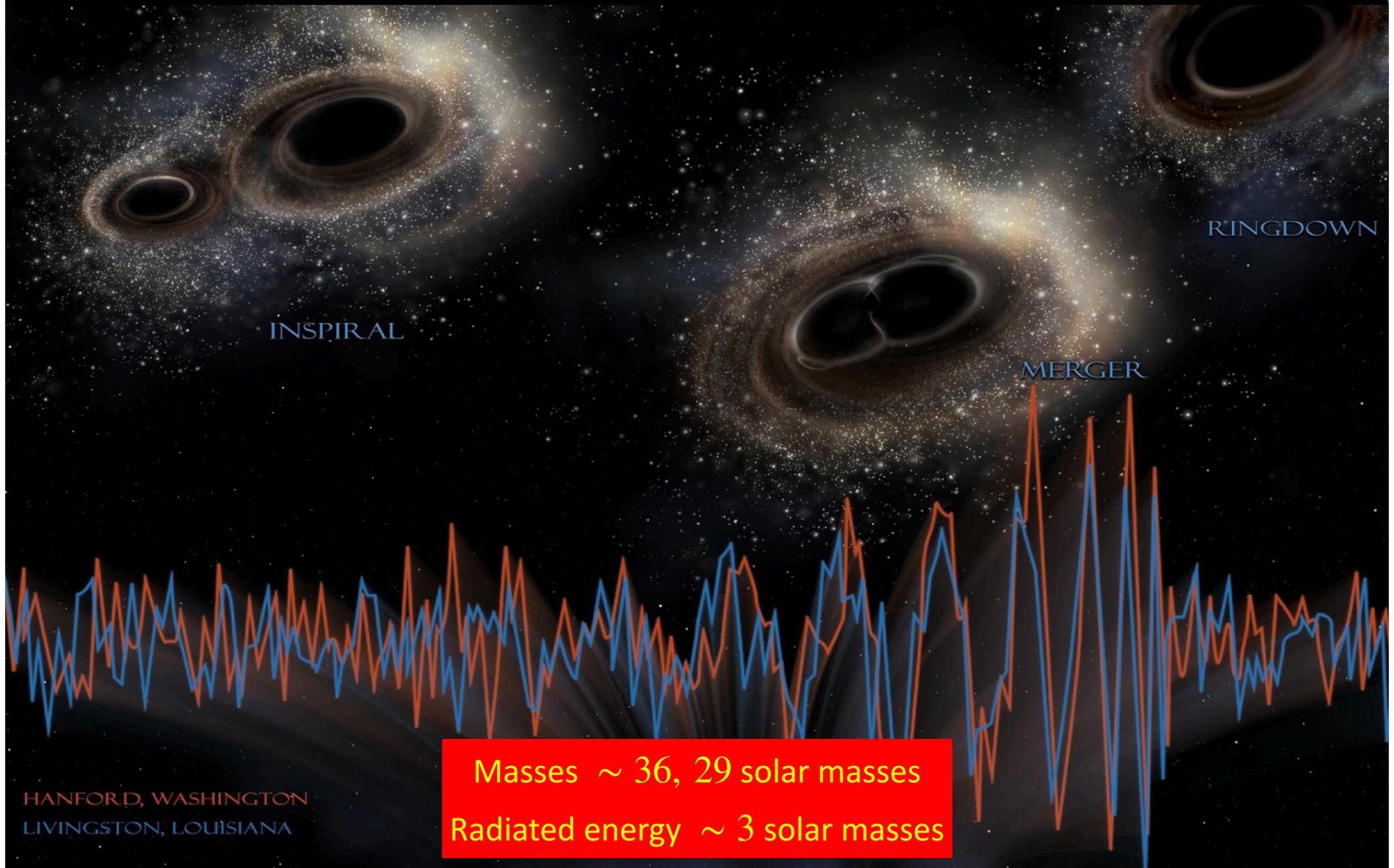
KING'S
College
LONDON

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

Gravitational Wave Spectrum



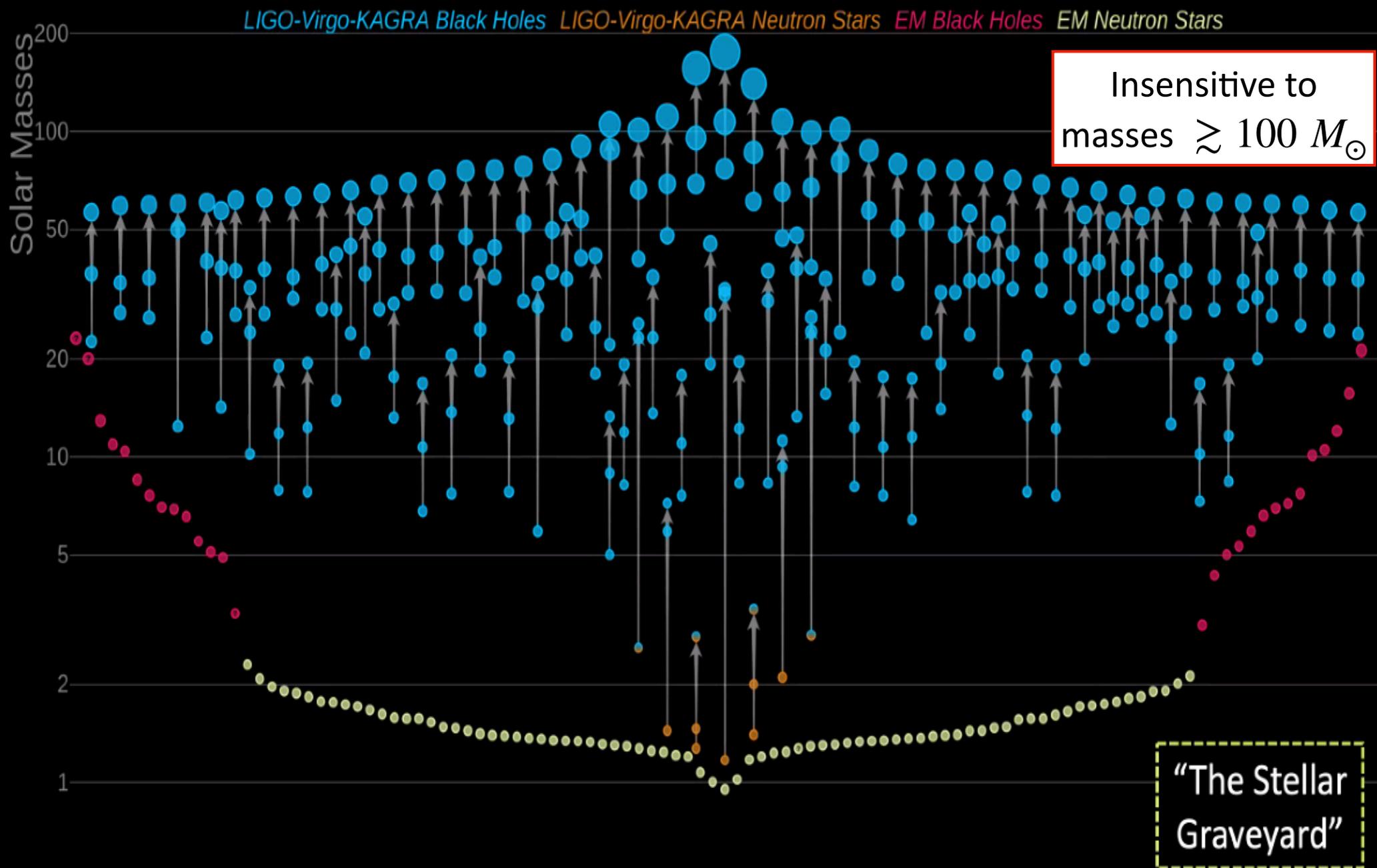
Discovery of Gravitational Waves from Merger of Black Holes (2016)



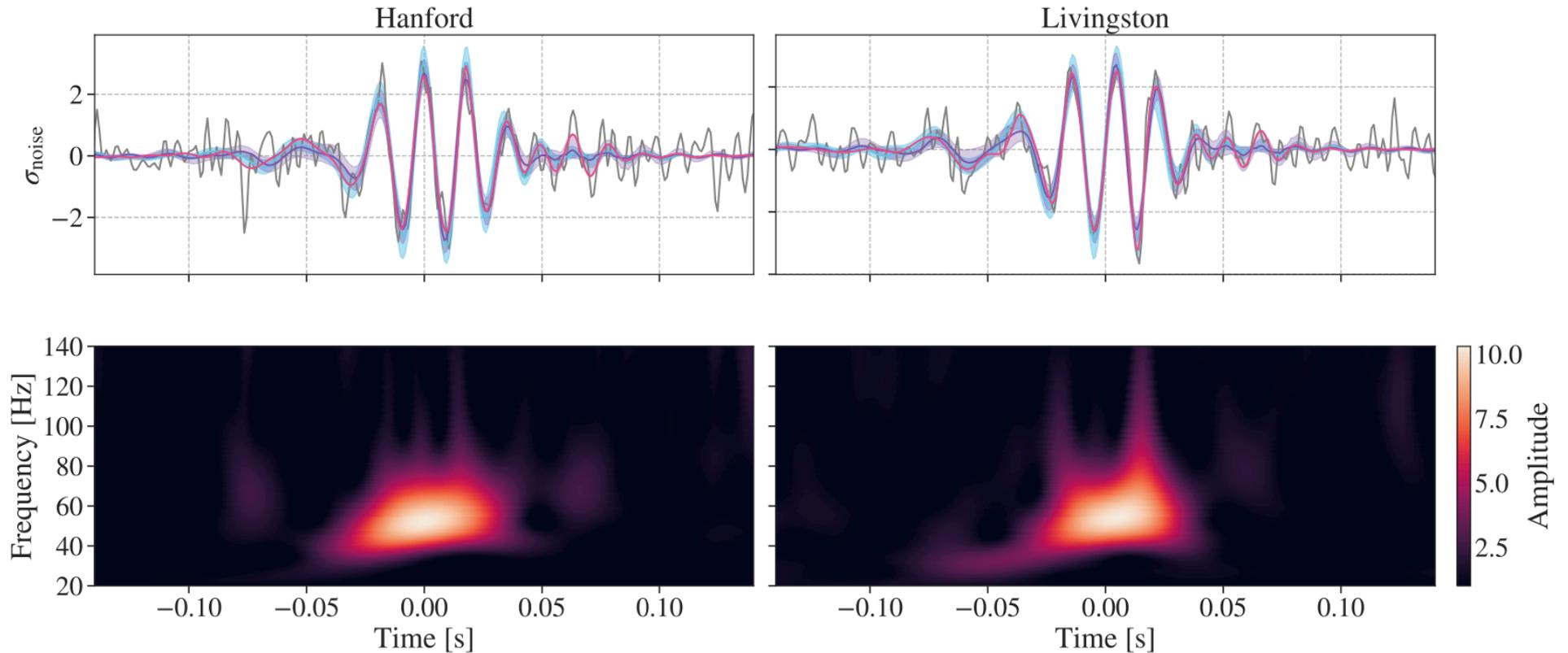
Masses $\sim 36, 29$ solar masses
Radiated energy ~ 3 solar masses

HANFORD, WASHINGTON
LIVINGSTON, LOUISIANA

LIGO-Virgo-KAGRA Black Hole & Neutron Stars



Most Massive BH Merger so far



BH masses

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

LVK insensitive to higher masses

LVK: arXiv:2507.08219

Supermassive Black Holes in Active Galactic Nuclei: Image of M87

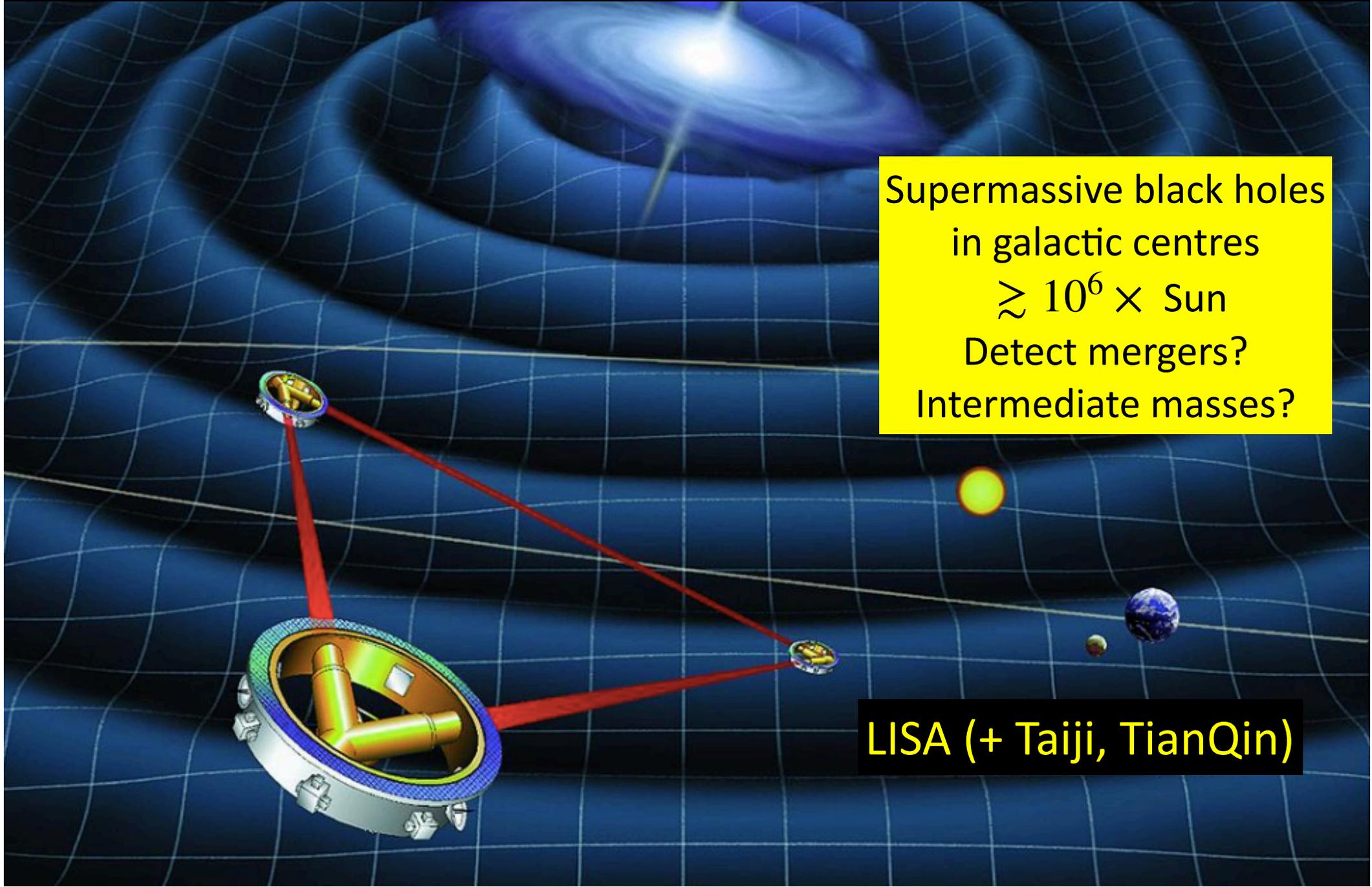


Mass $\sim 6.5 \times 10^9$ solar masses

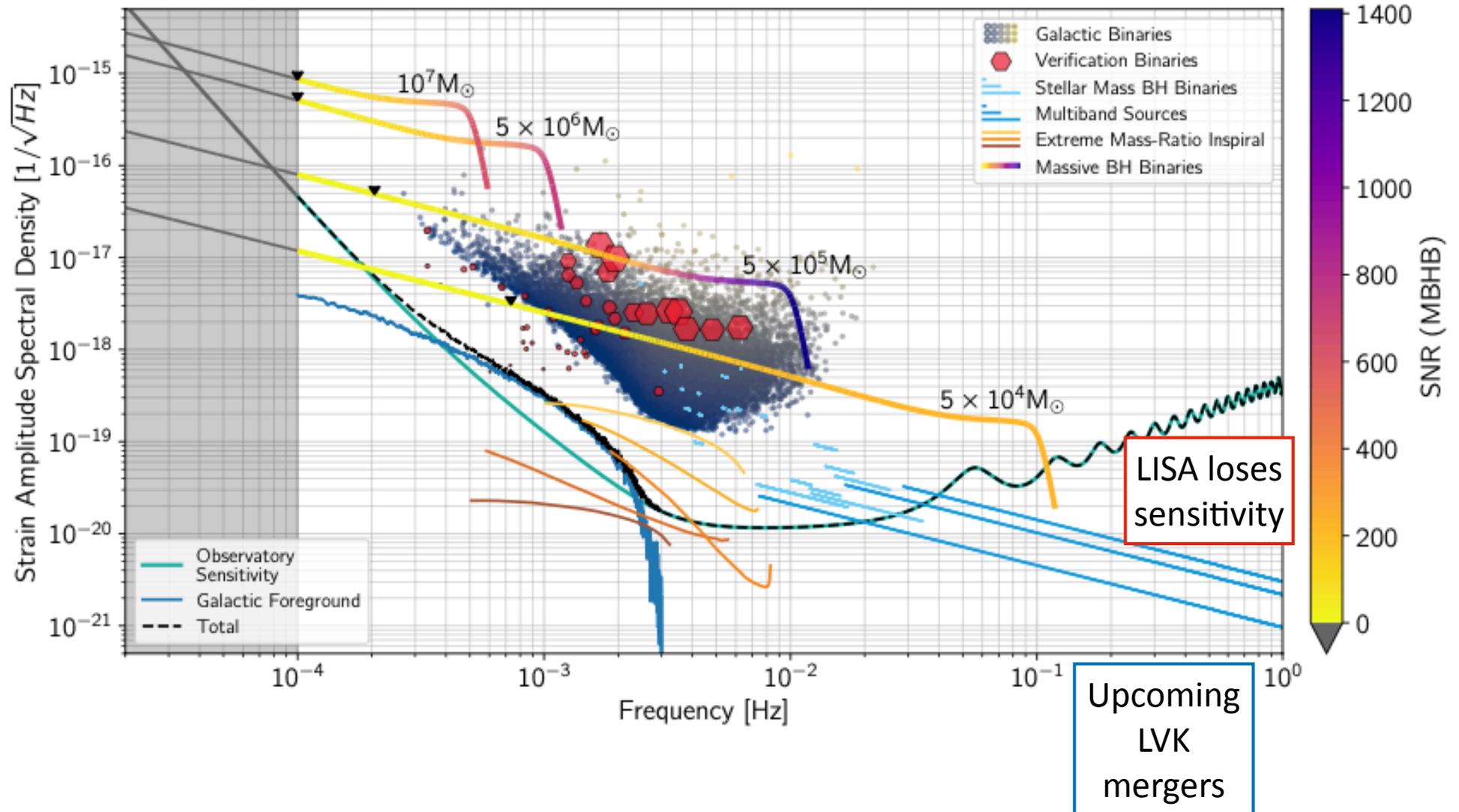
Future Step: Interferometer in Space

Supermassive black holes
in galactic centres
 $\gtrsim 10^6 \times \text{Sun}$
Detect mergers?
Intermediate masses?

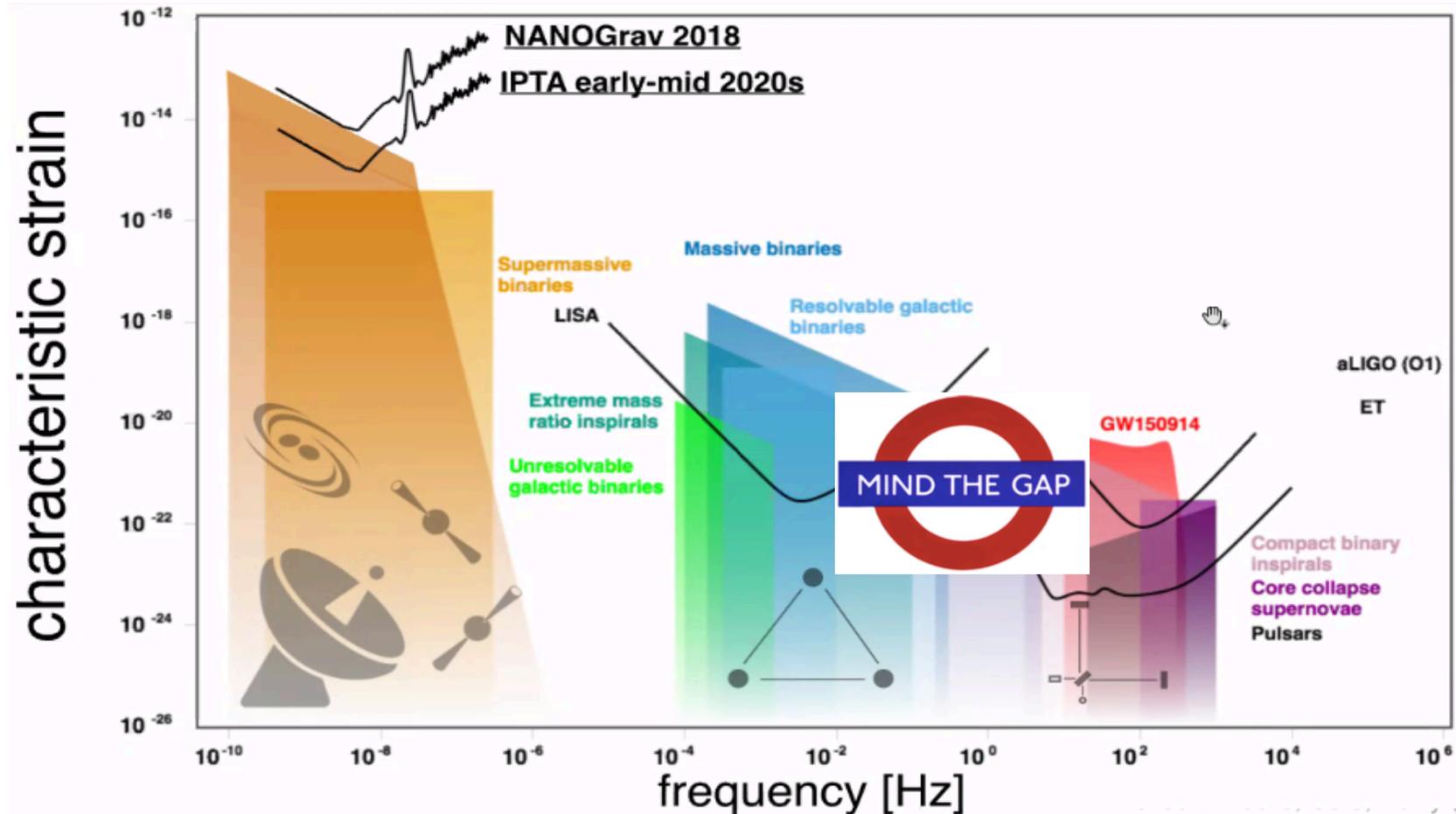
LISA (+ Taiji, TianQin)



Possible LISA Observations



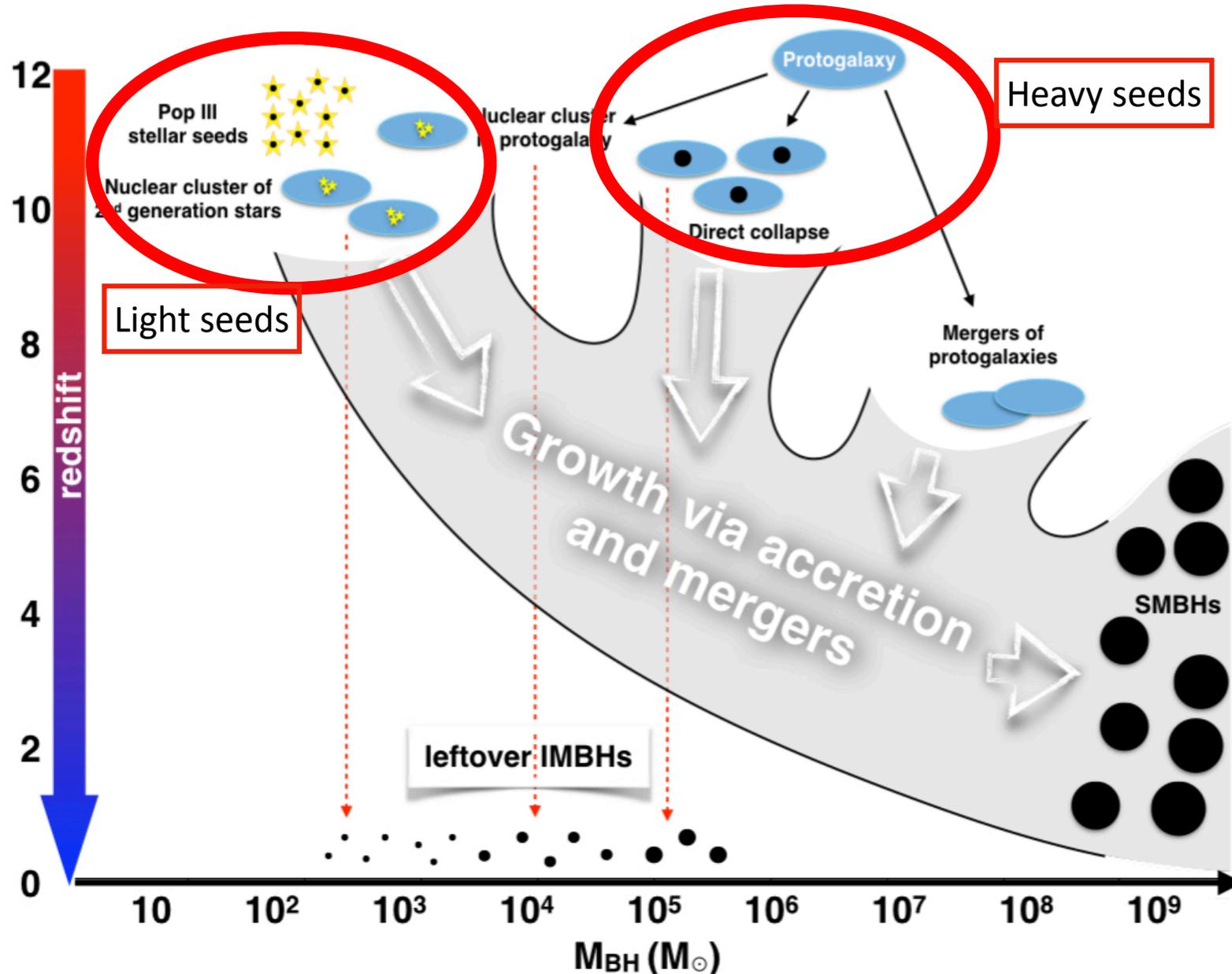
Gravitational Wave Spectrum



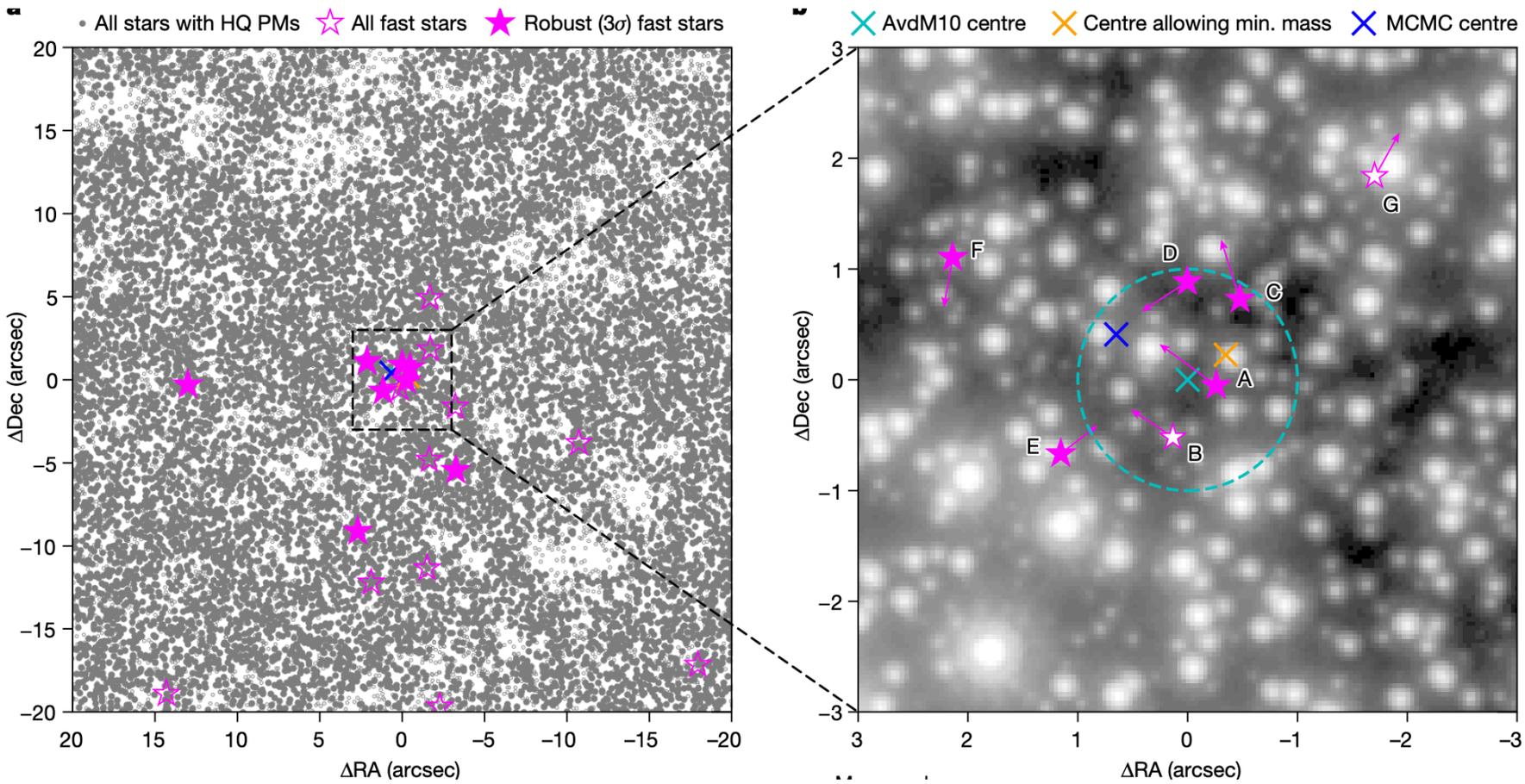
- Gap between ground-based optical interferometers & LISA
 - Formation of supermassive black holes (SMBHs) via mergers of intermediate-mass BHs (IMBHs)?
 - Electroweak phase transition? Cosmic strings?

How to Make a Supermassive BH?

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

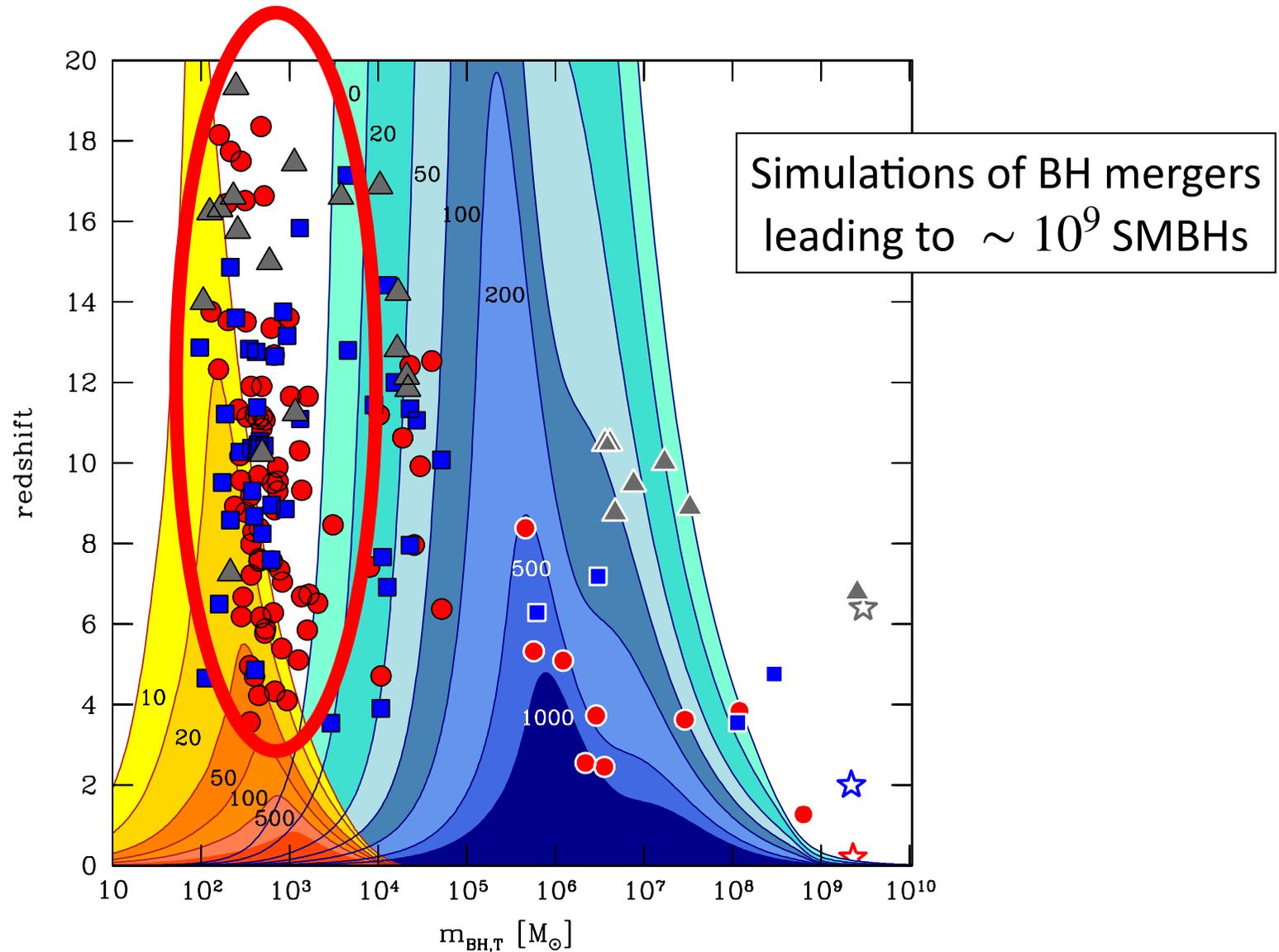


Intermediate-Mass Black Holes Exist



- Discovered through rapid motions of adjacent stars
- In our galaxy, constellation ω Centauri
- Distance 5.43 kpc, mass 8200 solar masses

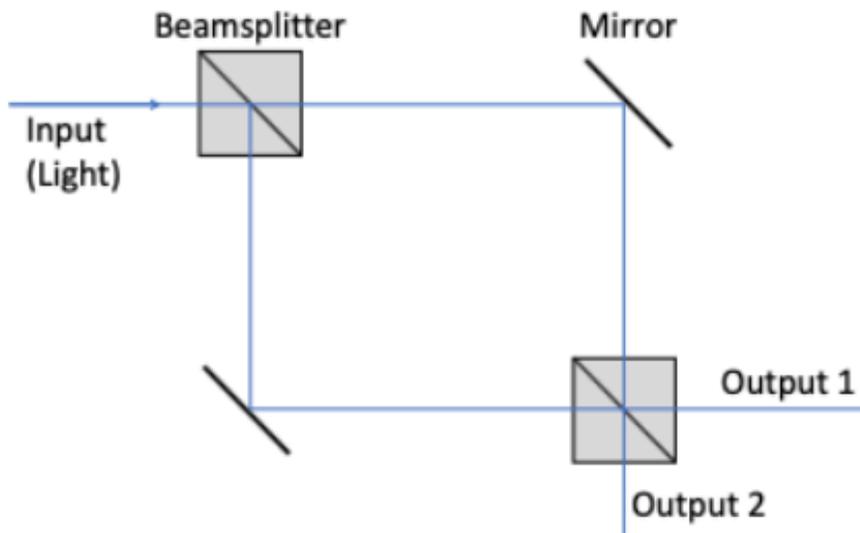
Complementarity to ET & LISA



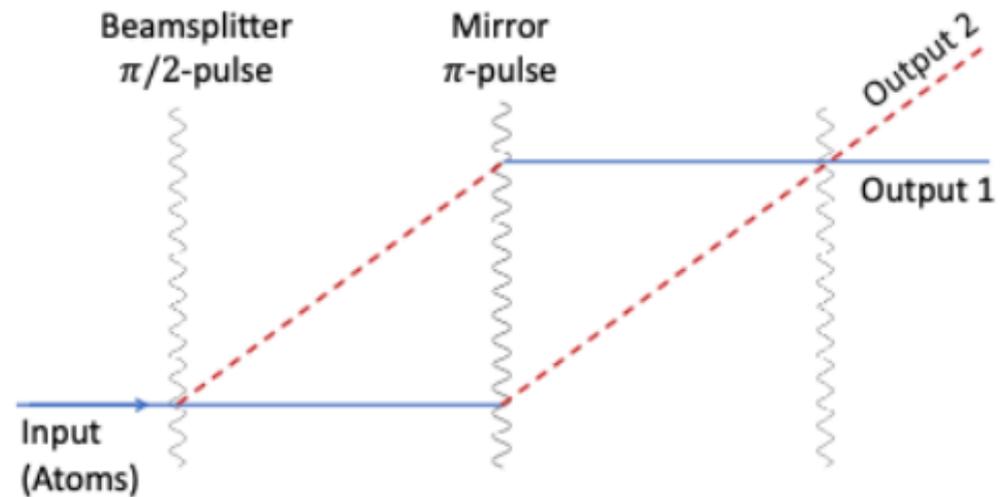
Opportunity in gap between ET & LISA

Principle of Atom Interferometry

Mach-Zehnder Laser Interferometer

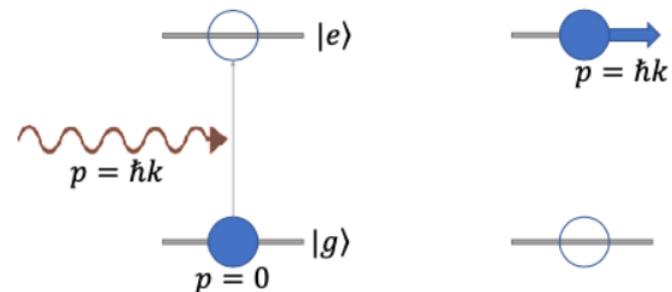


Atom Interferometer



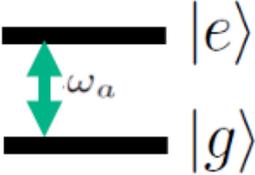
Laser excitation gives momentum kick to excited atom,
which follows separated space-time path

Interference between atoms following different paths



Effect of Gravitational Wave on Atom Interferometer

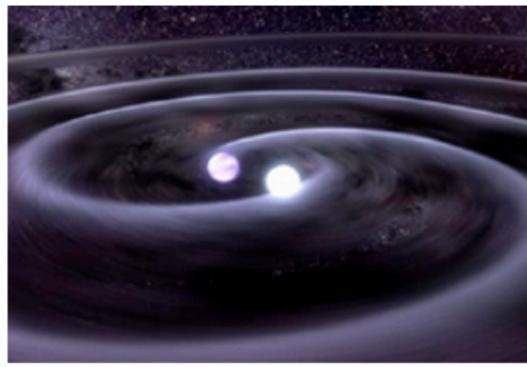
$$\frac{1}{\sqrt{2}} |g\rangle + \frac{1}{\sqrt{2}} |e\rangle$$



$$\frac{1}{\sqrt{2}} |g\rangle + \frac{1}{\sqrt{2}} |e\rangle$$



Time

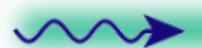
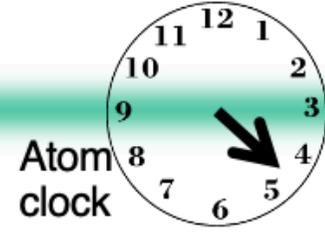
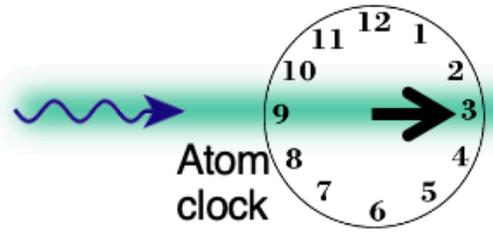


GW changes light travel time

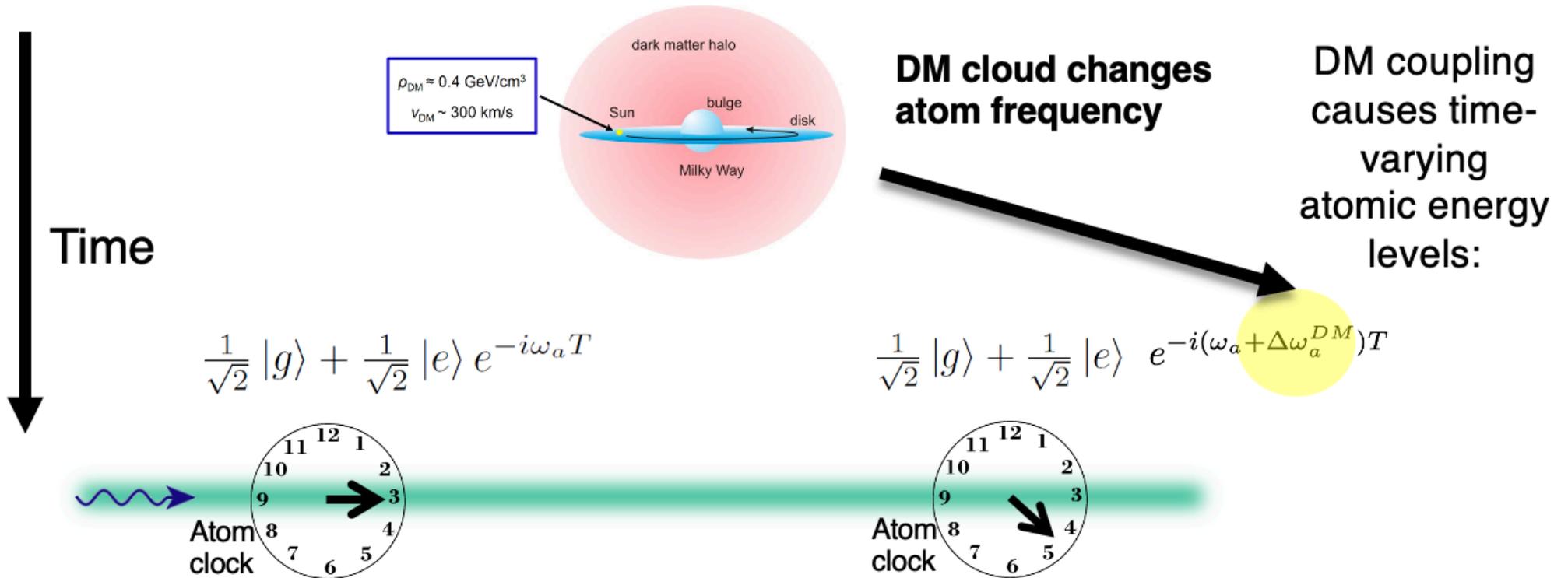
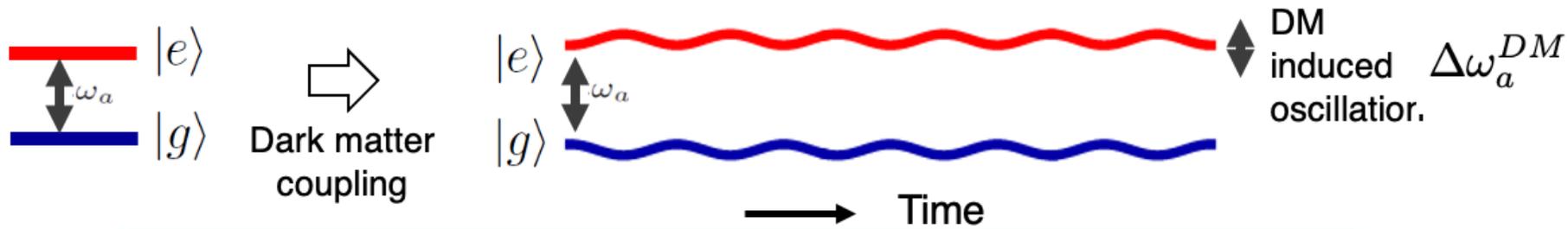
$$\Delta T \sim hL/c$$

$$\frac{1}{\sqrt{2}} |g\rangle + \frac{1}{\sqrt{2}} |e\rangle e^{-i\omega_a T}$$

$$\frac{1}{\sqrt{2}} |g\rangle + \frac{1}{\sqrt{2}} |e\rangle e^{-i\omega_a (T+\Delta T)}$$



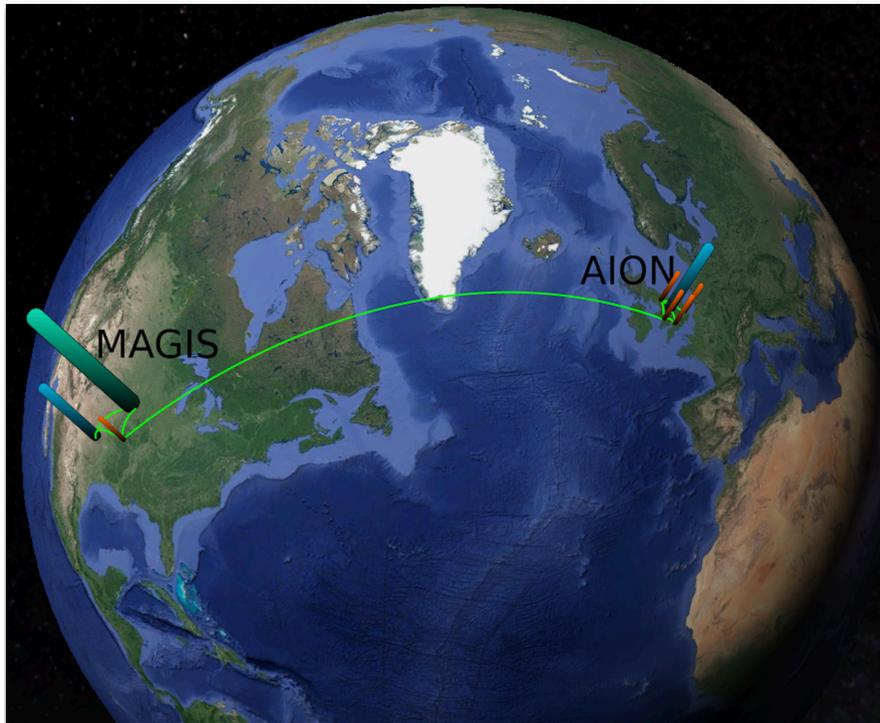
Effect of Dark Matter on Atom Interferometer



AION Collaboration

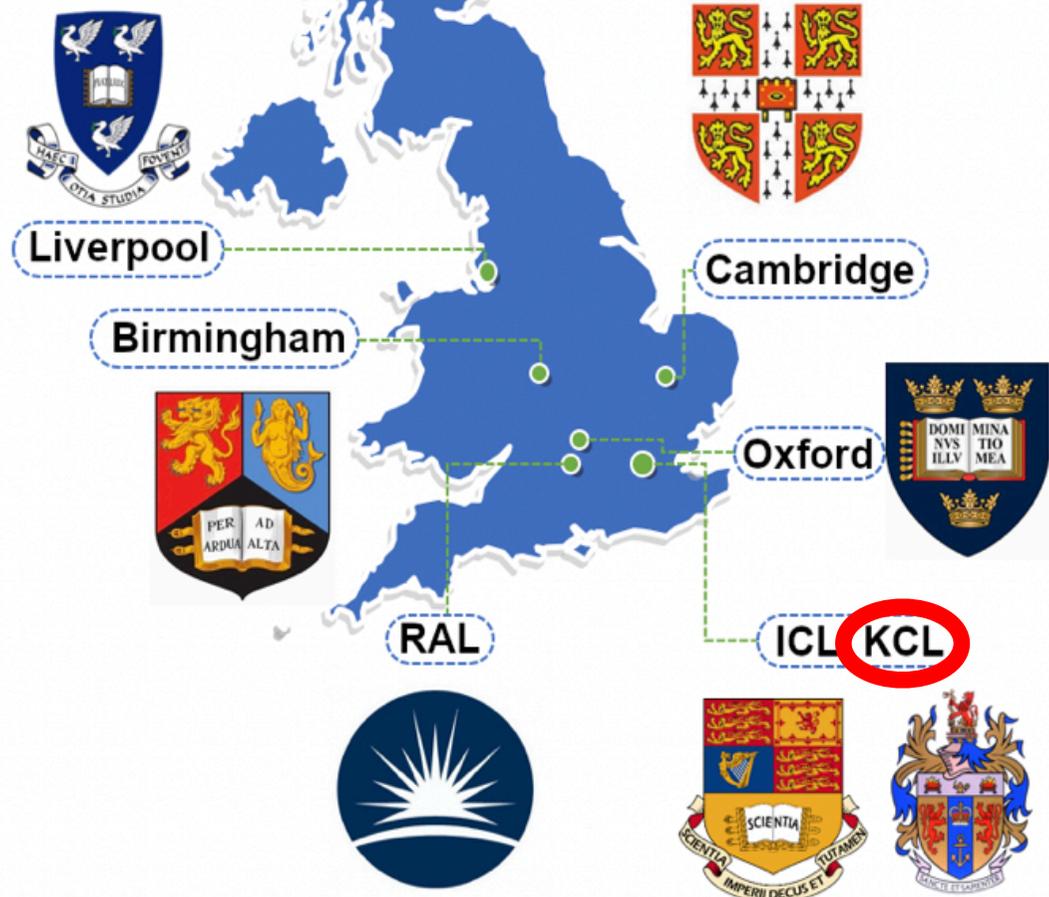
L. Badurina¹, S. Balashov², E. Bentine³, D. Blas¹, J. Boehm², K. Bongs⁶, A. Beniwal¹,
 D. Bortoletto⁶, J. Bowcock⁵, W. Bowden^{6,*}, C. Brew², O. Buchmueller⁶, J. Coleman⁶, J. Carlton¹,
 G. Elert¹, J. Ellis^{1,*}, C. Foot³, V. Gibson⁷, M. Haehnel⁷, T. Harte⁷, R. Hobson^{6,*},
 M. Holynski¹, A. Khazov², M. Langlois⁴, S. Lello⁴, Y.H. Lien⁴, R. Maiolino⁷,
 P. Majewski², S. Malik⁶, J. March-Russell¹, C. McCabe¹, D. Newbold², R. Preece³,
 B. Sauer⁶, U. Schneider⁷, I. Shipsey³, Y. Singh¹, M. Tarbutt⁶, M. A. Uchida⁷,
 T. V-Salazar², M. van der Grinten², J. Vosseveld⁴, D. Weatherill³, I. Wilmut⁷,
 J. Zielinska⁶

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



Network with MAGIS project in US

MAGIS Collaboration (Abe et al): arXiv:2104.02835



AION – Staged Programme

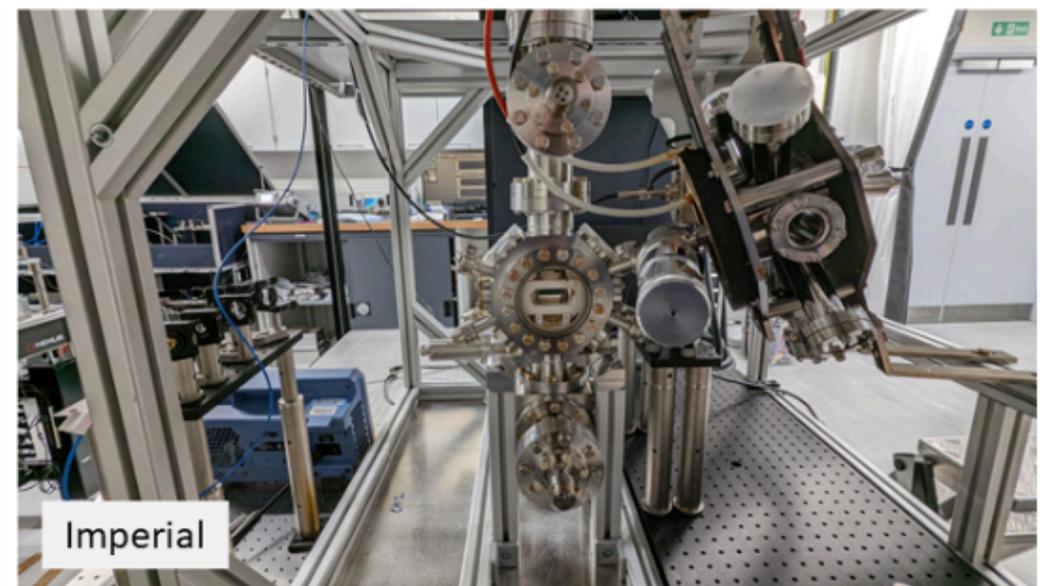
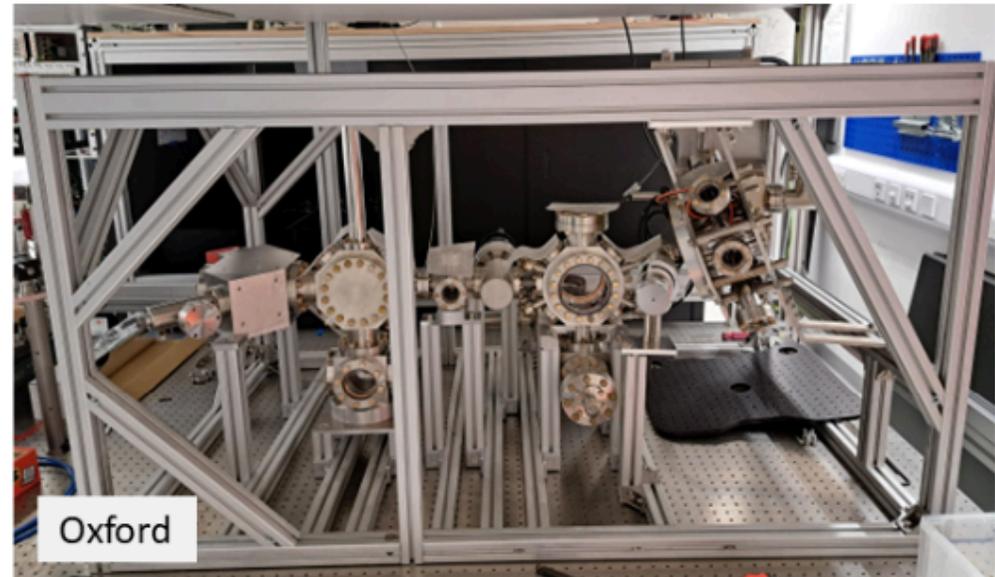
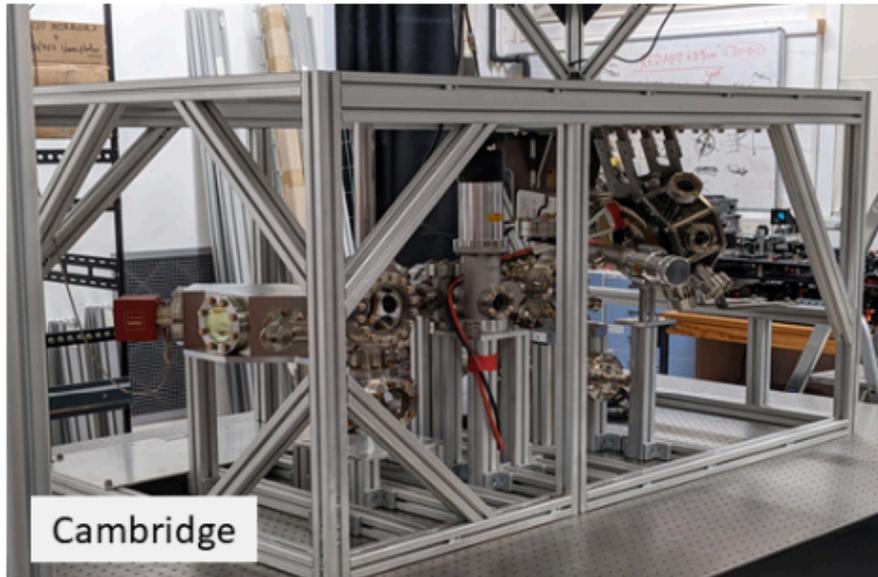
- AION-10:
 - 10 m Interferometer & site investigation for 100m baseline

Initial funding from UK STFC

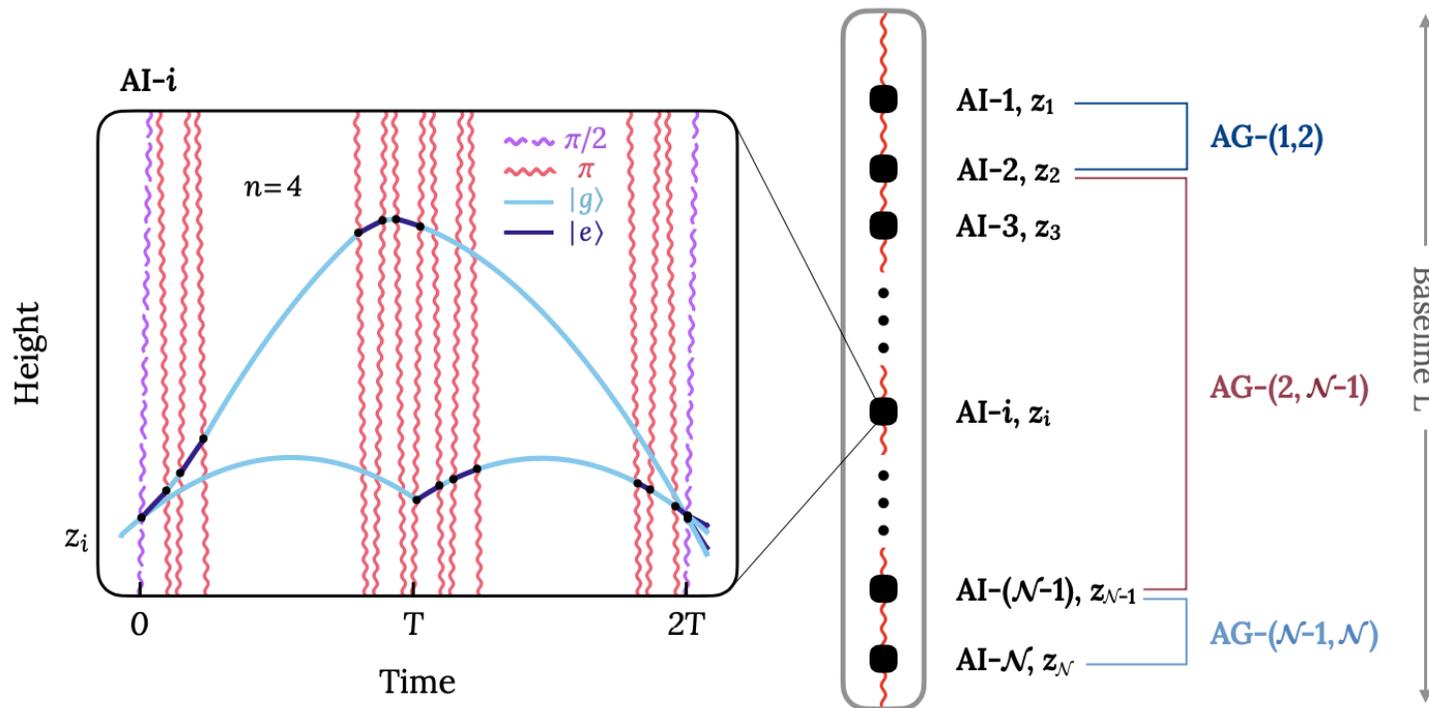
- AION-100: Stage 2
 - 100m Construction & commissioning
- AION-KM: Stage 3
 - 1 km construction & thinking beyond
- AION-SPACE (AEDGE): Stage 4
 - Space-based version

Laboratory Installations

AION Collaboration [Stray, ..., JE et al], arXiv:2305.20060



Atomic Multi-Gradiometer

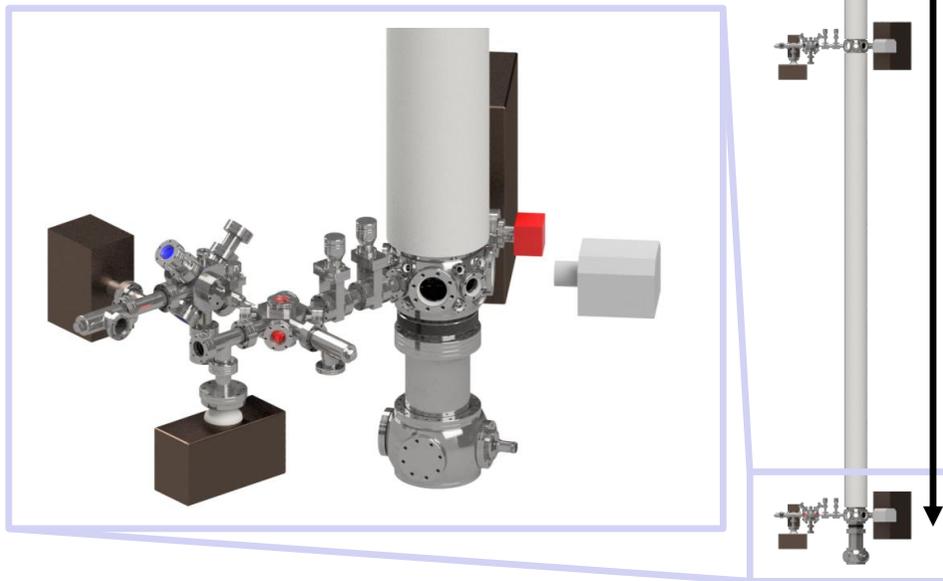


Multiple atomic interferometers in the same vertical shaft,
 manipulated with same laser beam.
 Eliminate laser noise, minimize gravity gradient noise.

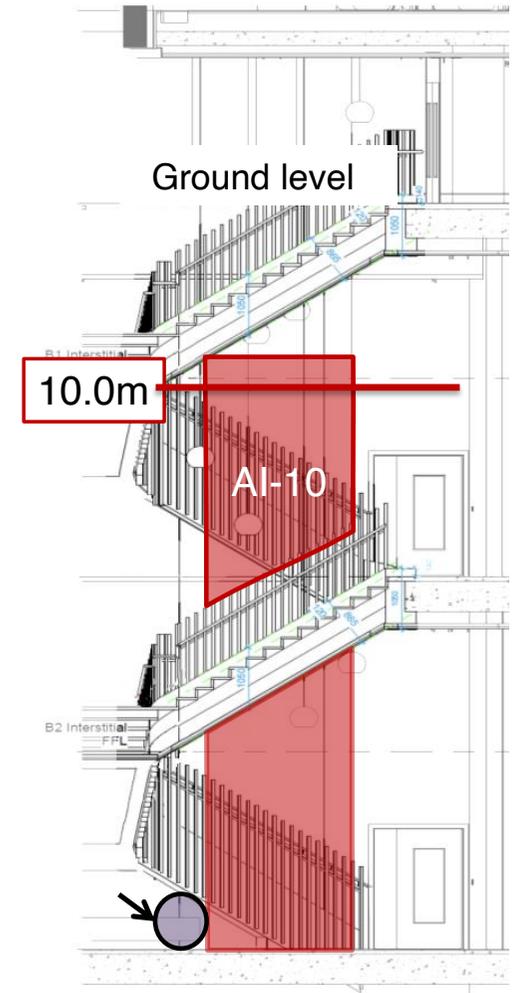
Possible Location of AION-10m

AION-10 @ Beecroft building, Oxford Physics

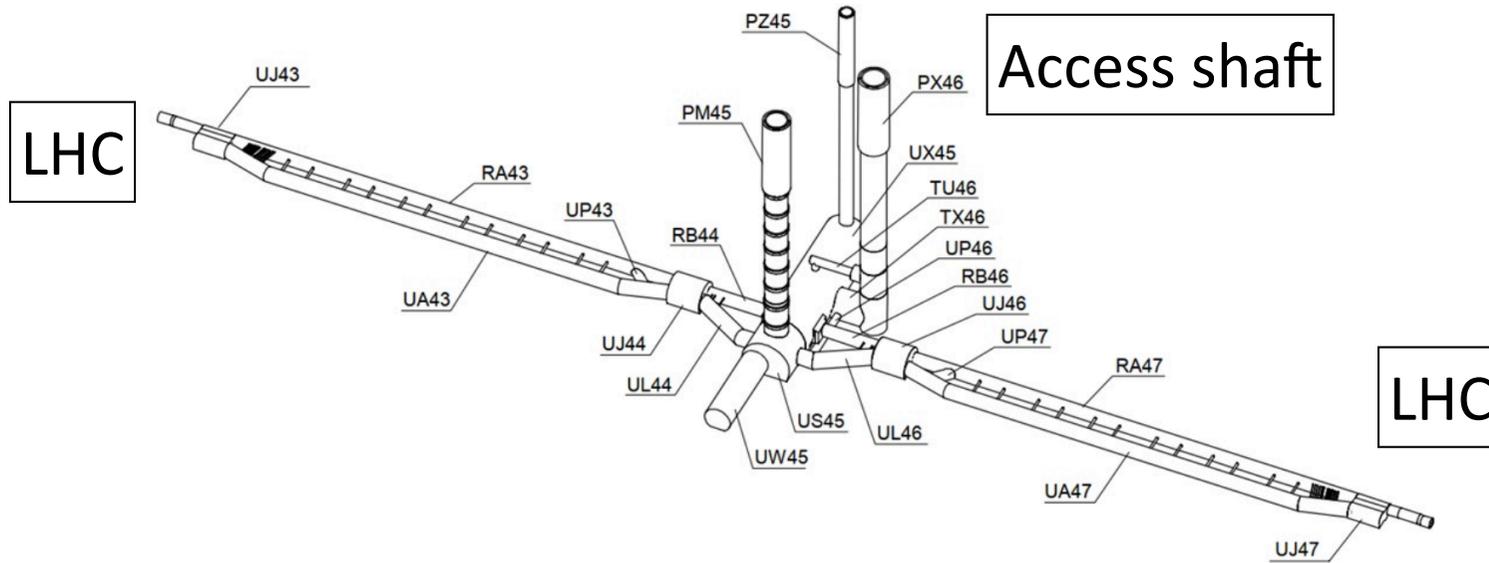
- New purpose-built building (£50M facility)
- AION-10 on basement level with 14.7m headroom (stable concrete construction)
- World-class infrastructure
- Experienced Project Manager:
- Engineering support from RAL (Oxfordshire)



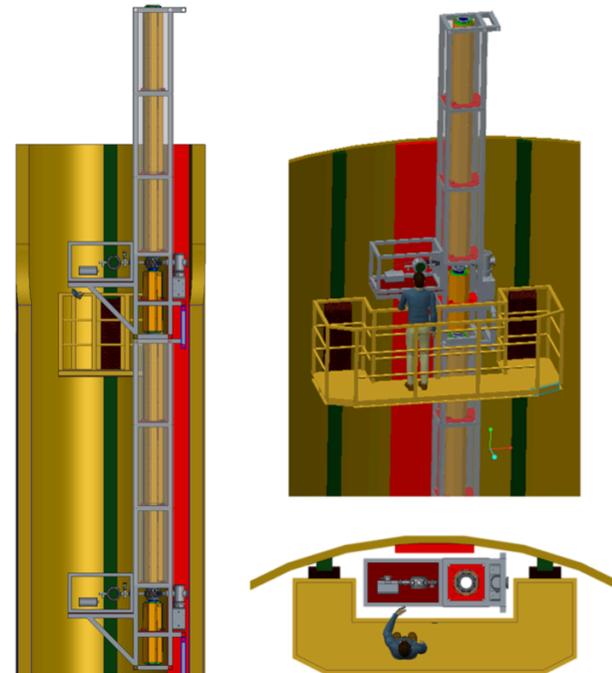
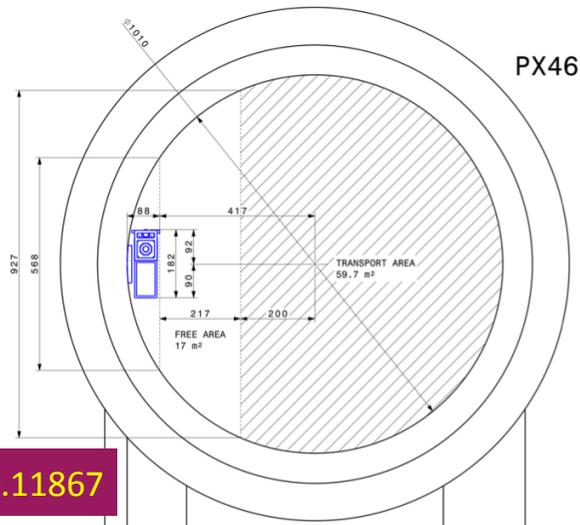
Laser lab for AION
vibration criterion, VC-G =
10nm@10Hz. Temperature
(22±0.1)° C



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



Cross-section of access shaft



*Baynham et al: arXiv:2509.11867

Letter of Intent:

AICE - Atom Interferometer CERN Experiment

Charles Baynham,¹ Andrea Bertoldi,² Diego Blas,³ Oliver Buchmueller*,^{1,4} Sergio Calatroni,⁵ Vassilis Charmandaris,⁶ Maria Luisa (Marilù) Chiofalo,⁷ Pierre Cladé,⁸ Jonathon Coleman,⁹ Fabio Di Pumpo,¹⁰ John Ellis*,¹¹ Naceur Gaaloul,¹² Saïda Guellati-Khelifa,⁸ Tiffany Harte,¹³ Richard Hobson,¹ Michael Holynski,¹⁴ Samuel Lellouch,^{14,15} Lucas Lombriser,^{16,17} Elias Lopez Asamar,¹⁸ Michele Maggiore,^{17,19} Christopher McCabe,¹¹ Jeremiah Mitchell,¹³ Ernst M. Rasel,¹² Federico Sanchez Nieto,^{17,19} Wolfgang Schleich,²⁰ Dennis Schlippert,¹² Ulrich Schneider,¹³ Steven Schramm,^{17,19} Marcelle Soares-Santos,²¹ Guglielmo M. Tino,²² Jonathan N. Tinsley,⁹ Tristan Valenzuela,²³ Maurits van der Grinten,²⁴ Wolf von Klitzing,²⁵

¹*High Energy Physics Group, Blackett Laboratory, Imperial College, Prince Consort Road, London, SW7 2AZ, UK*

²*IOGS, LP2N, Université Bordeaux, CNRS, UMR 5298, F-33400 Talence, France*

³*Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, 08193 Bellaterra (Barcelona), Spain; Institució Catalana de Recerca i Estudis Avançats (ICREA), Passeig Lluís Companys 23, 08010 Barcelona, Spain*

⁴*University of Oxford, South Parks Road, Oxford OX1 3PU, UK*

⁵*CERN, 1211 Geneva 23, Switzerland*

⁶*Chairman, Board of Directors, Foundation for Research and Technology – Hellas (FORTH), Vassilika Vouton, 70013 Heraklion, Crete, Greece*

⁷*Department of Physics, University of Pisa, Largo Bruno Pontecorvo 3 56126 Pisa, Italy; INFN-Pisa, Largo Bruno Pontecorvo 3 56126 Pisa, Italy*

⁸*Laboratoire Kastler Brossel, Sorbonne Université PSL, Collège de France, 75005 Paris, France*

⁹*Department of Physics, University of Liverpool, Merseyside, L69 7ZE, UK*

¹⁰*Institut für Quantenphysik and Center for Integrated Quantum Science and Technology (IQST), Universität Ulm, Albert-Einstein-Allee 11, 89081 Ulm, Germany*

¹¹*Physics Department, King's College London, Strand, London, WC2R 2LS, UK*

¹²*Leibniz Universität Hannover, Institut für Quantenoptik, Welfengarten 1, 30167 Hannover, Germany*

¹³*Cavendish Laboratory, University of Cambridge, J J Thomson Avenue, Cambridge, CB3 0US, UK*

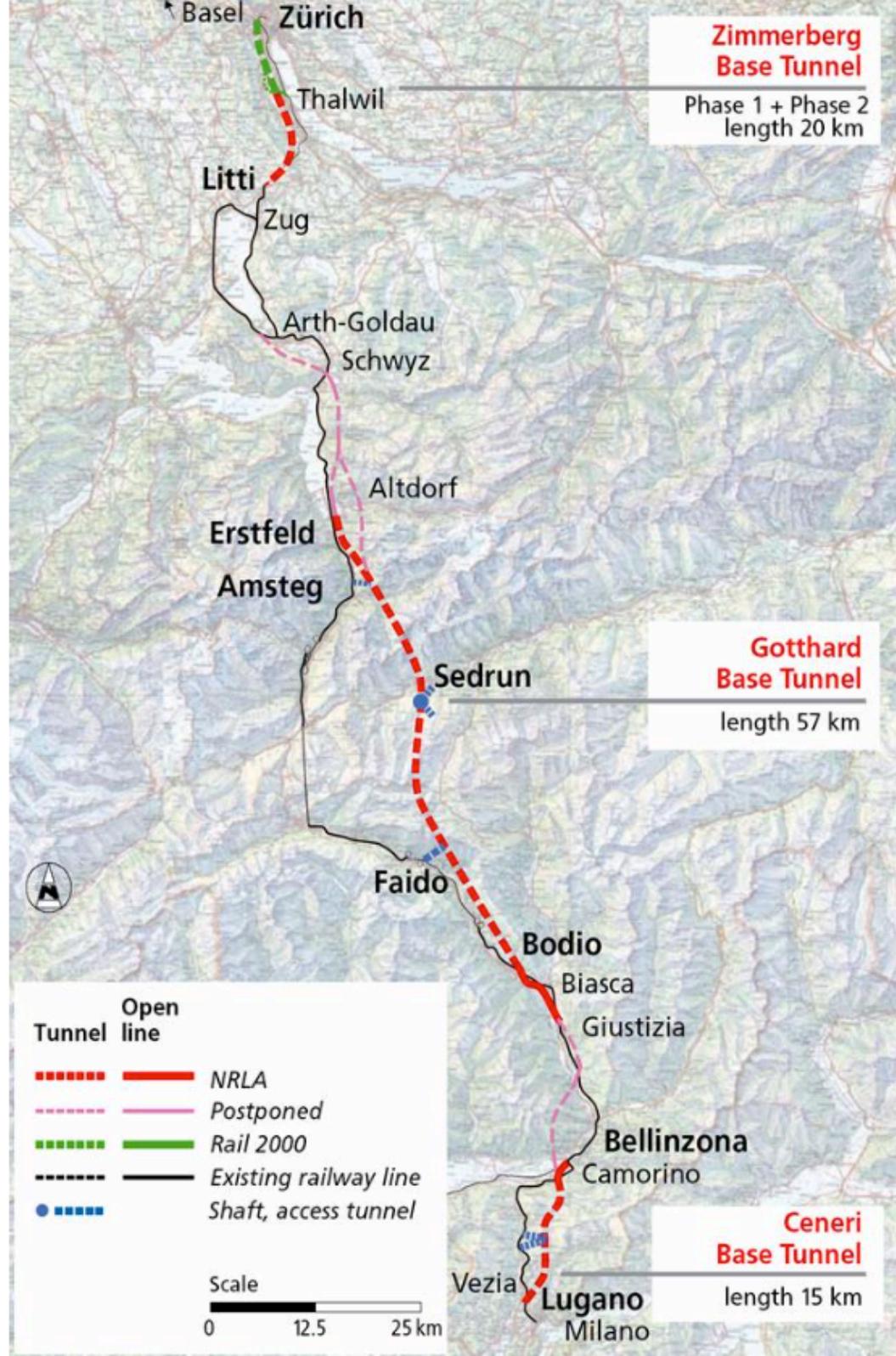
¹⁴*School of Physics and Astronomy, University of Birmingham, B152TT Edgbaston, UK*

¹⁴*School of Engineering, University of Birmingham, B152TT Edgbaston, UK*

¹⁶*Department of Applied Future Technologies, University of Applied Sciences of the Grisons, Pulvermühlestrasse 57, 7000 Chur, Switzerland*

Gotthard Base Tunnel

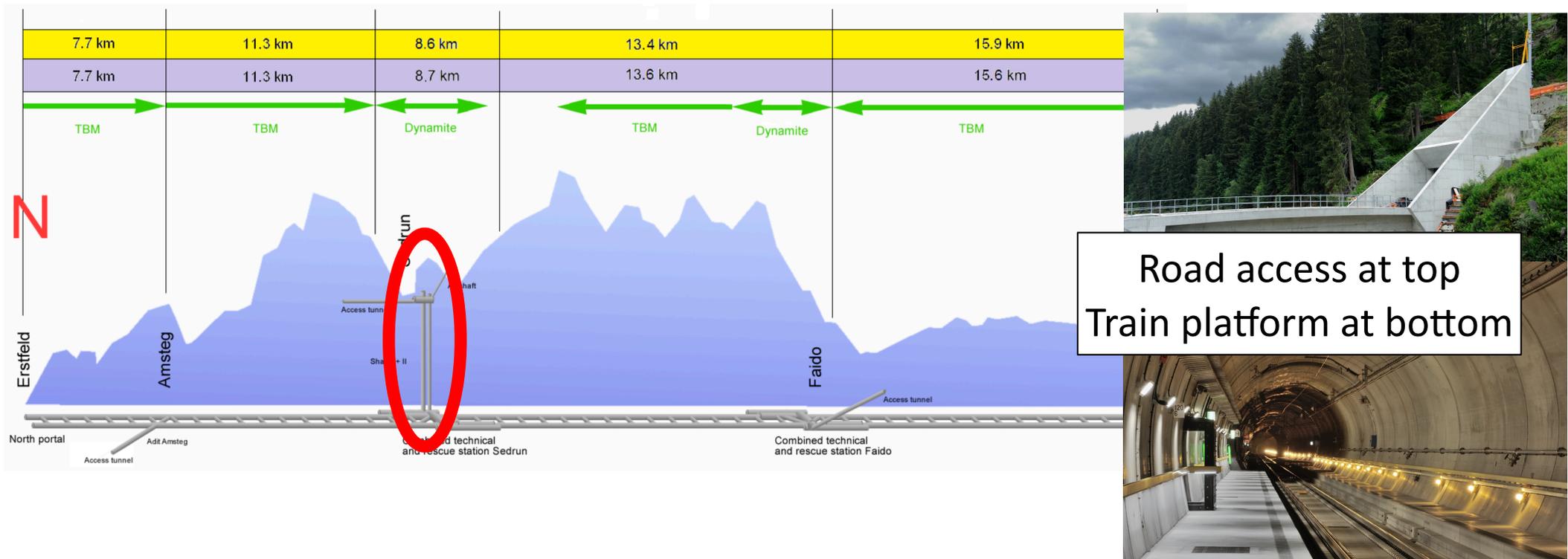
Longest operational railway tunnel in Europe
Length 57.1km
Opened for traffic in 2016
200 to 300 trains per day



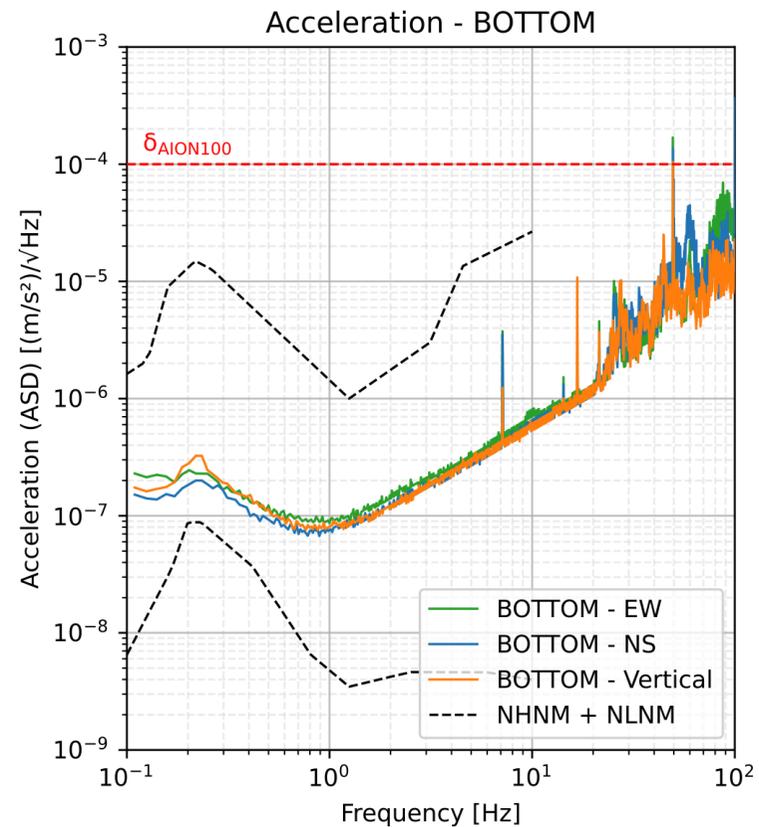
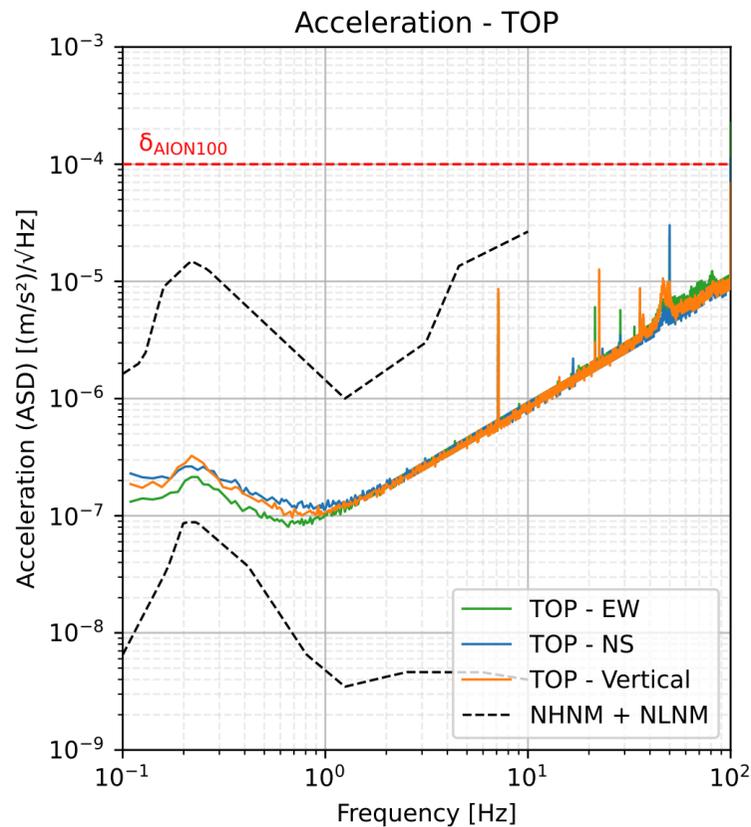
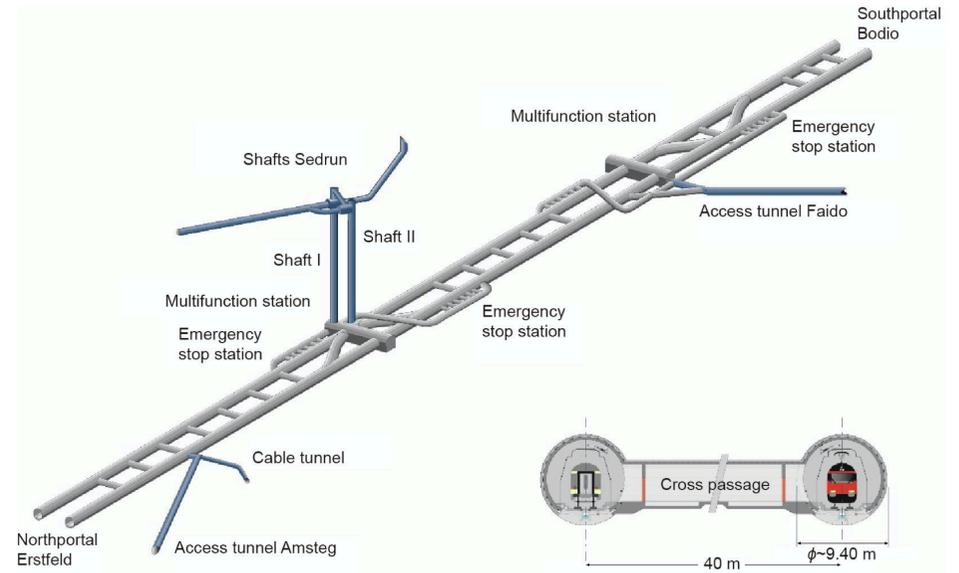
Porta Alpina:

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

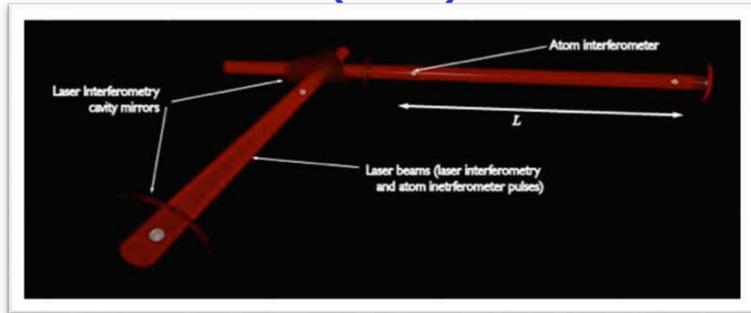


Environmental Measurements at Porta Alpina

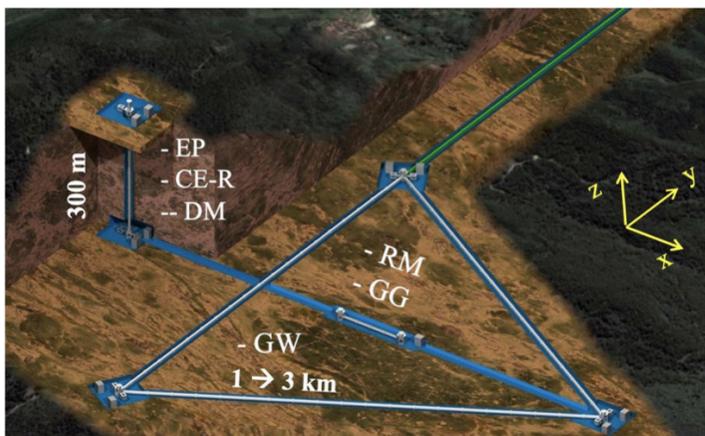


Atom Interferometer Projects around World

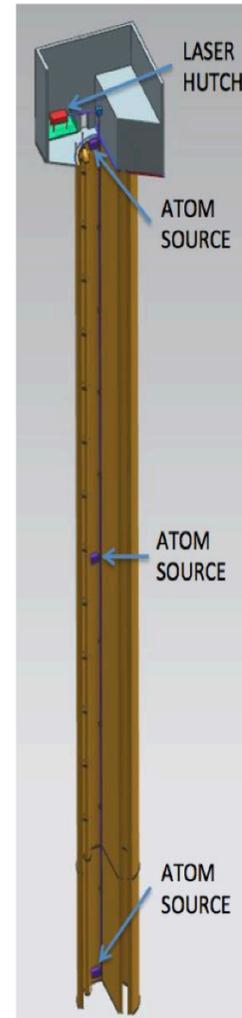
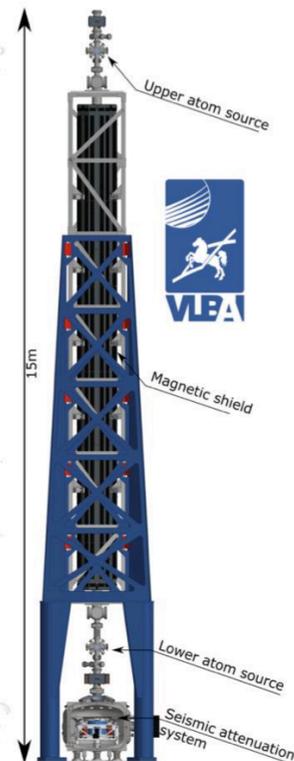
MIGA: Terrestrial detector using atom interferometer at O(100m)
(France)



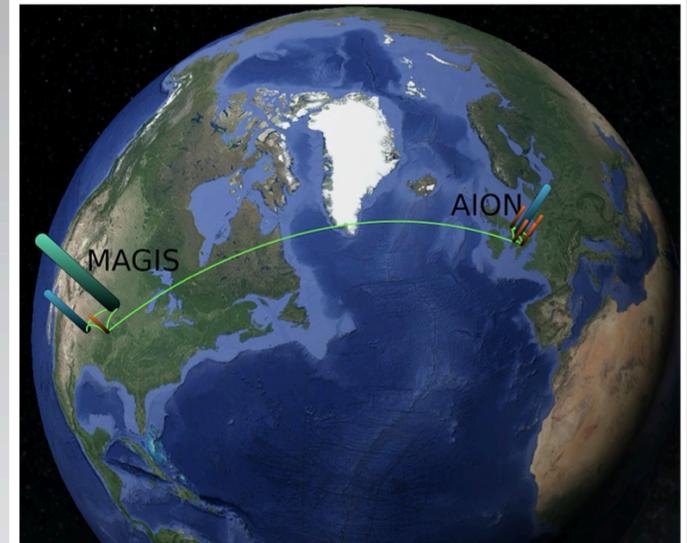
ZAIGA: Terrestrial detector for large scale atomic interferometers, gyros and clocks at O(100m)
(China)



VLBAI: Terrestrial tower using atom interferometer O(10m)
(Germany)



AION: Terrestrial shaft detector using atom interferometer at 10m – O(100m) planned
(UK)



MAGIS: Terrestrial shaft detector using atom interferometer at O(100m)
(US)

Planned network operation

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)

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)

Observers (Under Evaluation)

Germany

- German Aerospace Center (DLR)

Iran

- Isfahan University of Technology

United States

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

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

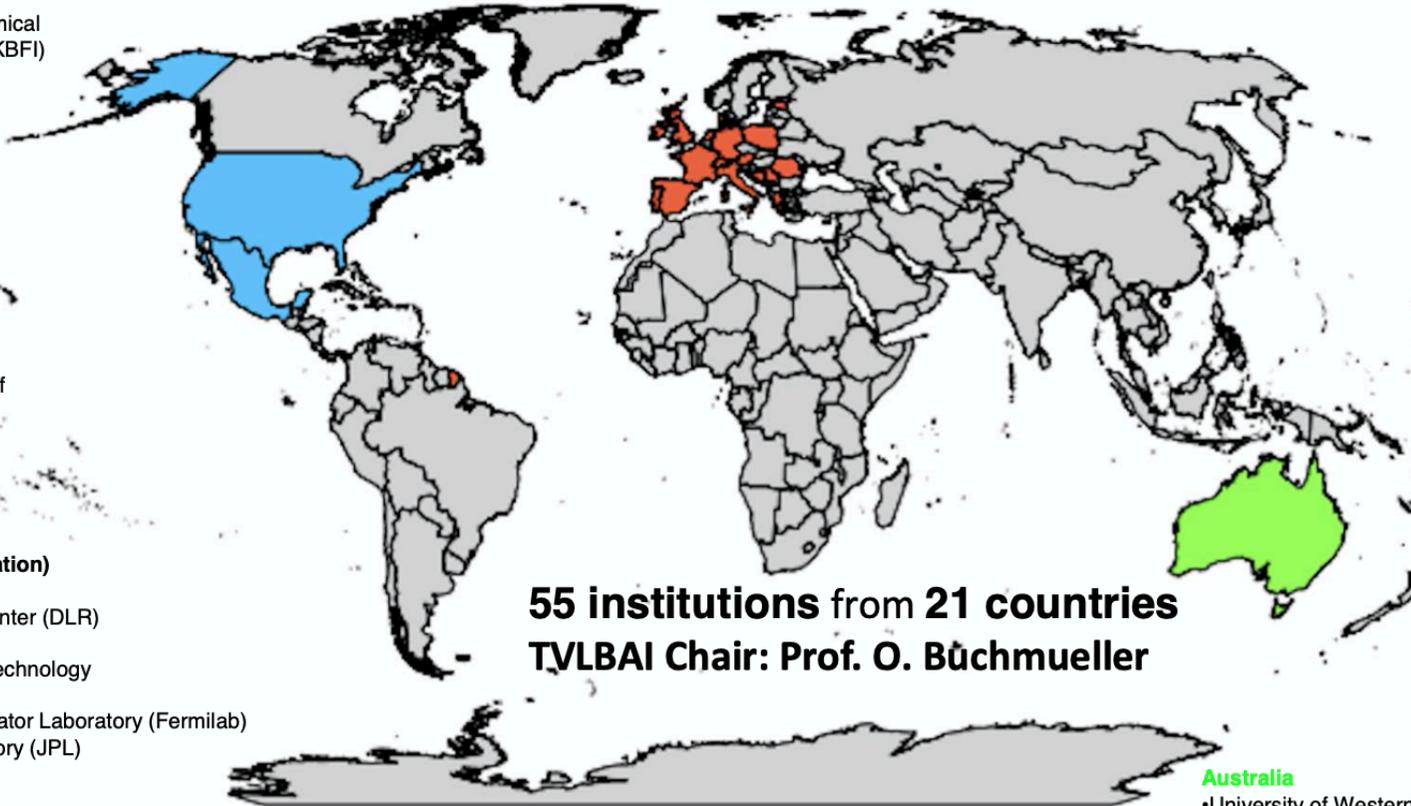
- University of Geneva
- CERN
- University of Neuchâtel
- University of Zurich
- Fachhochschule Graubünden

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

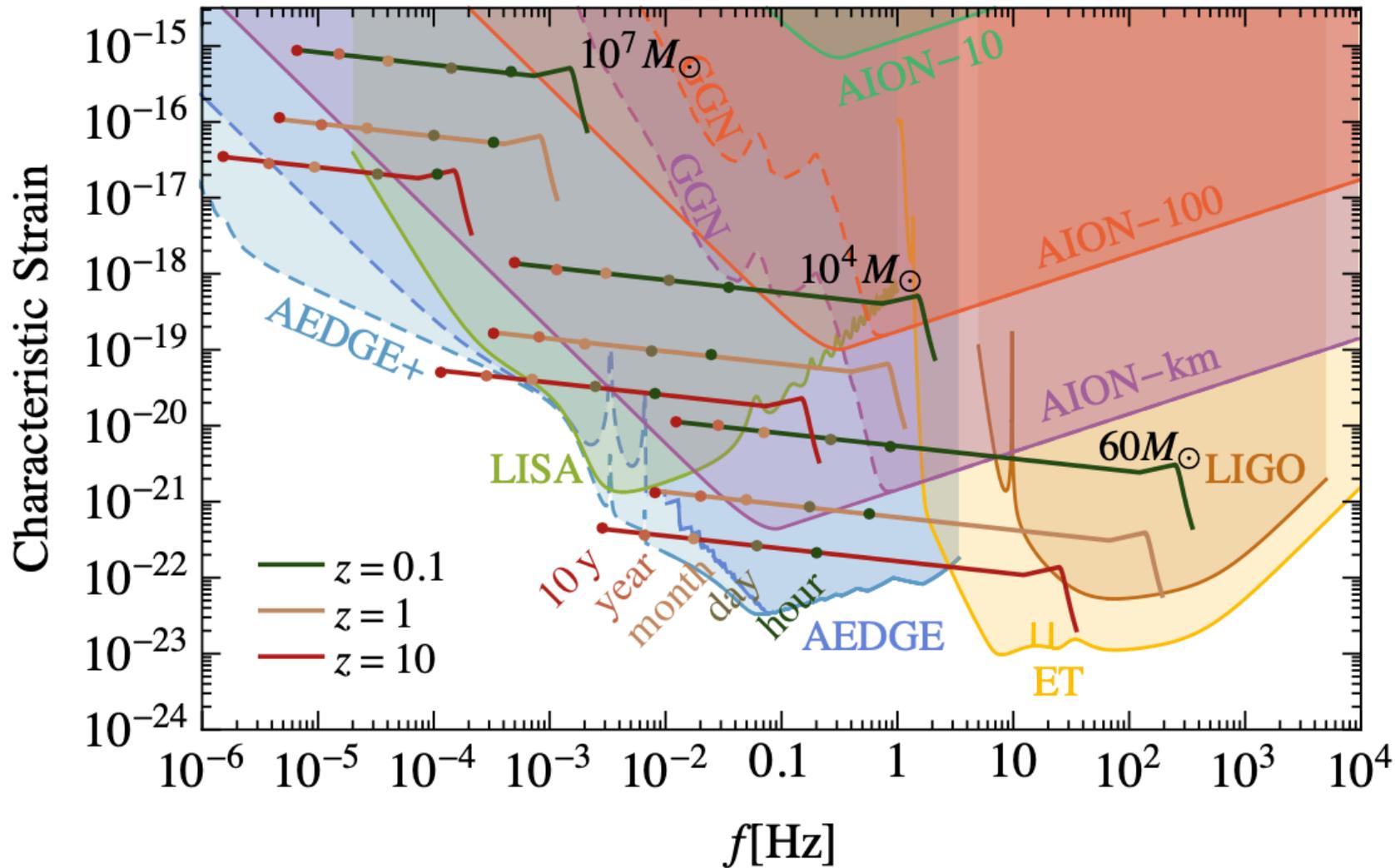
Australia

- University of Western Australia



55 institutions from 21 countries
TVLBAI Chair: Prof. O. Büchmueller

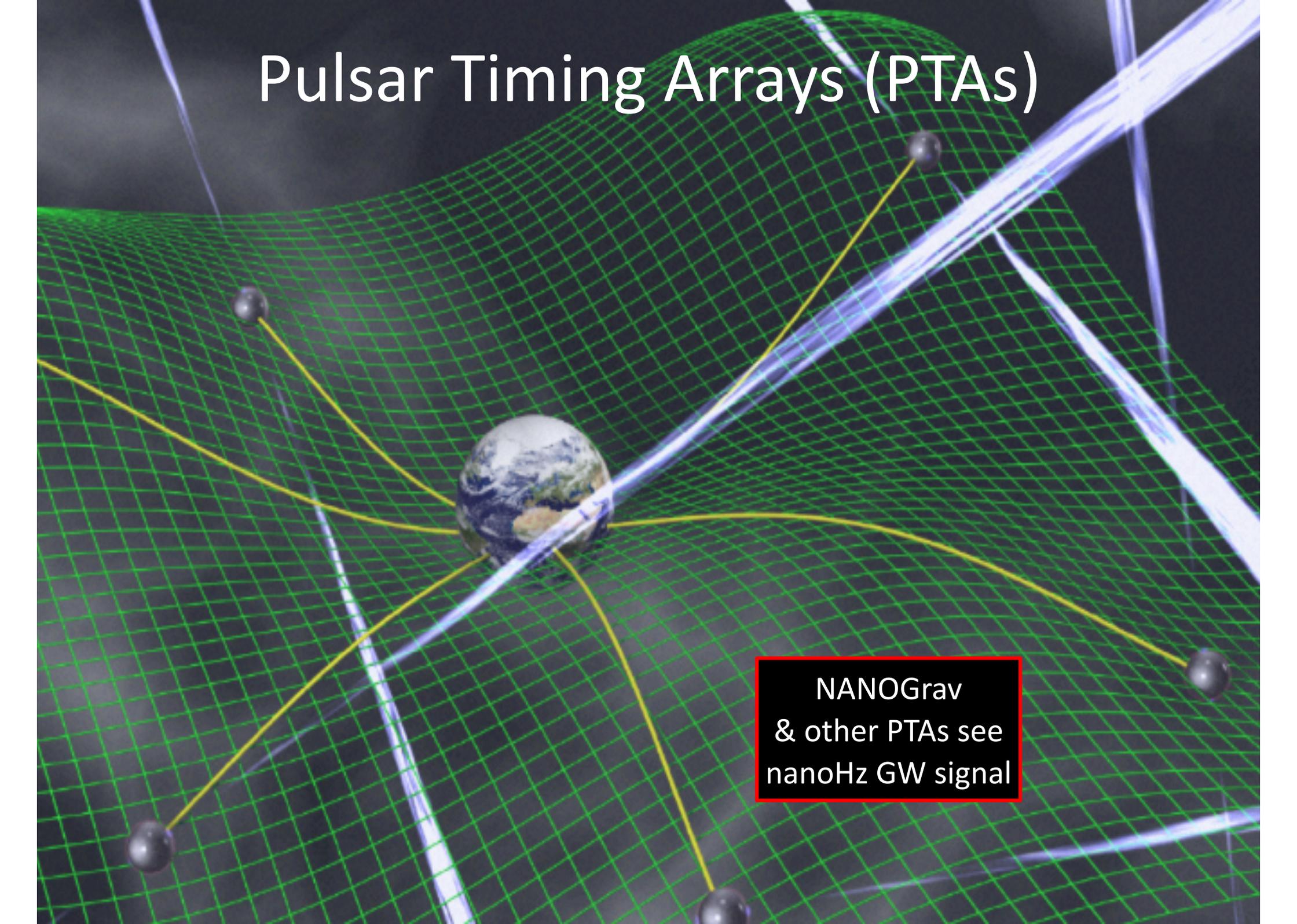
Searching for Gravitational Waves



Probe formation of SMBHs

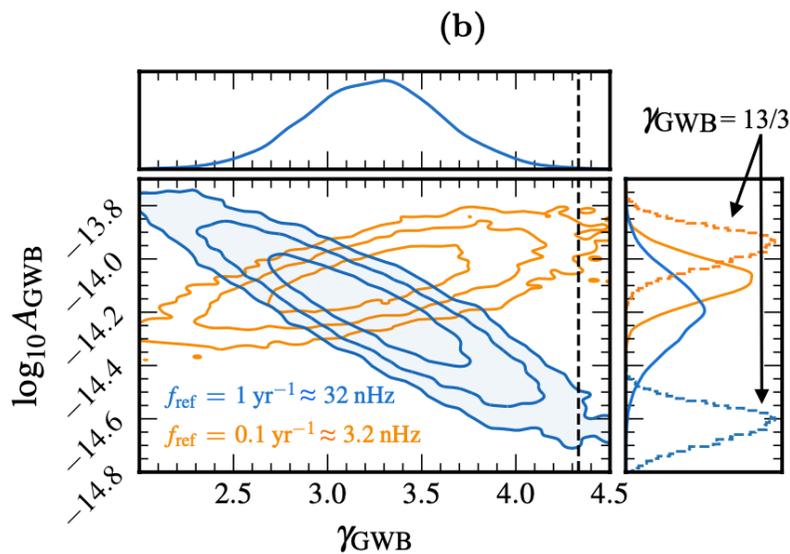
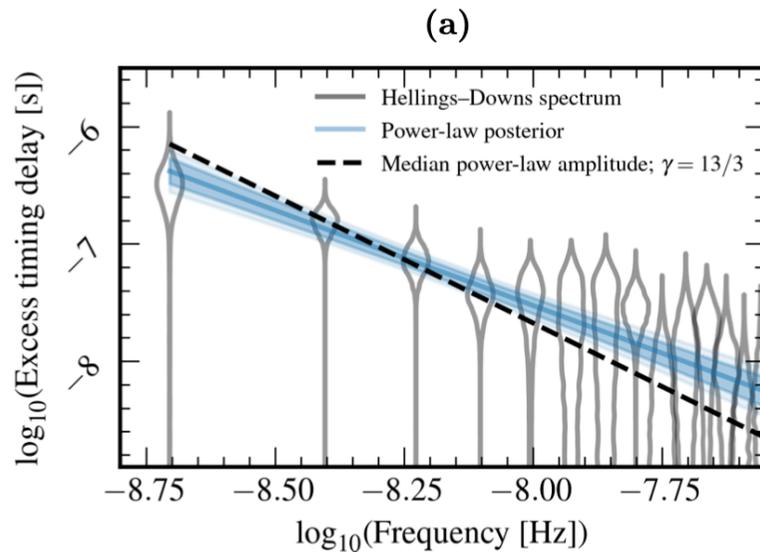
Synergies with other GW experiments (LIGO, LISA), test GR

Pulsar Timing Arrays (PTAs)

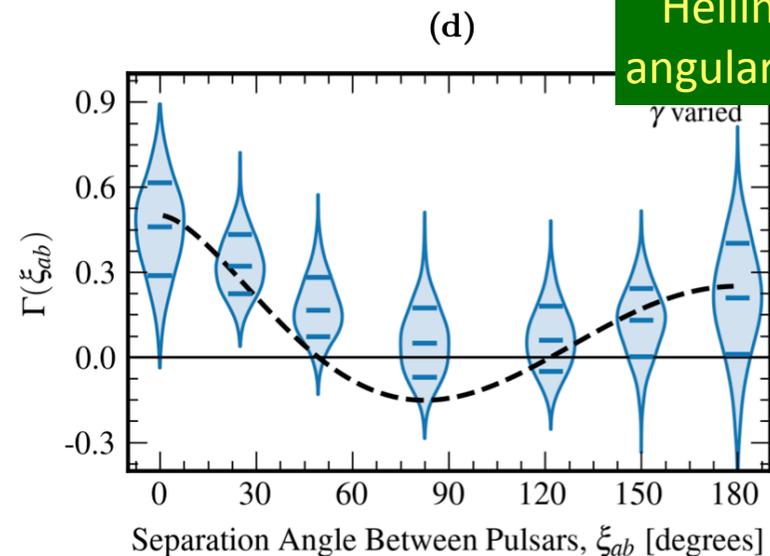
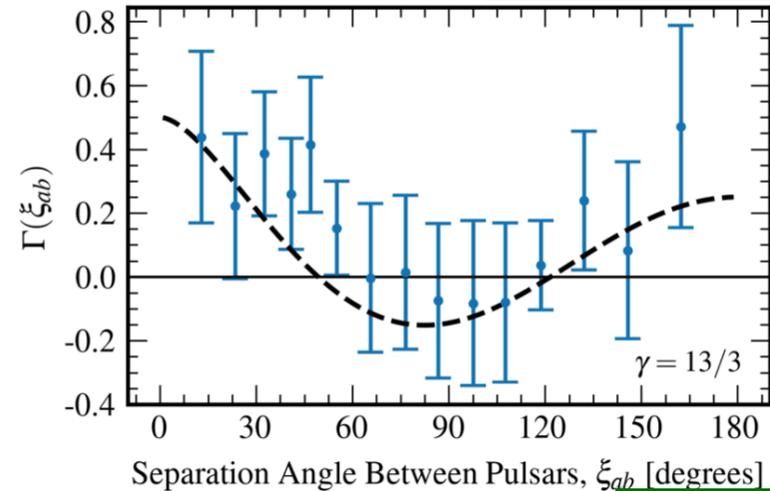


NANOGrav
& other PTAs see
nanoHz GW signal

NANOGrav Pulsar Timing Array Data



(c) NANOGrav GWs arXiv:2306.16213



Hellings-Downs
angular correlation

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_{BH}

$$\frac{dR_{\text{BH}}}{dm_1 dm_2} \approx p_{\text{BH}} \frac{dM_1}{dm_1} \frac{dM_2}{dm_2} \frac{dR_h}{dM_1 dM_2}$$

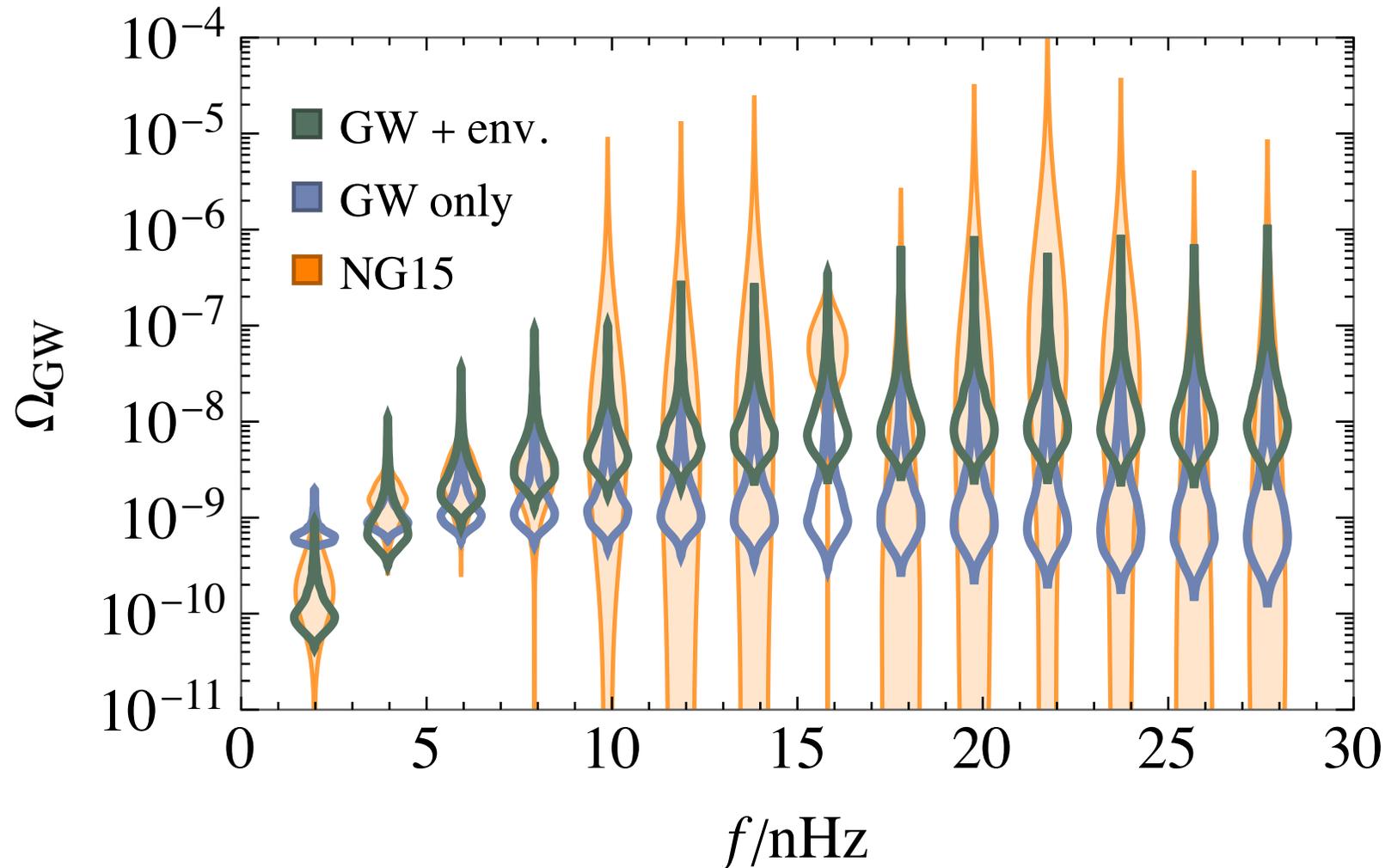
where R_h is halo merger rate calculated using Extended Press-Schechter formalism,

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

is merger probability, and

strength of PTA signal can be fitted by constant $p_{\text{BH}} \gtrsim 0.1$

Astrophysical Interpretations

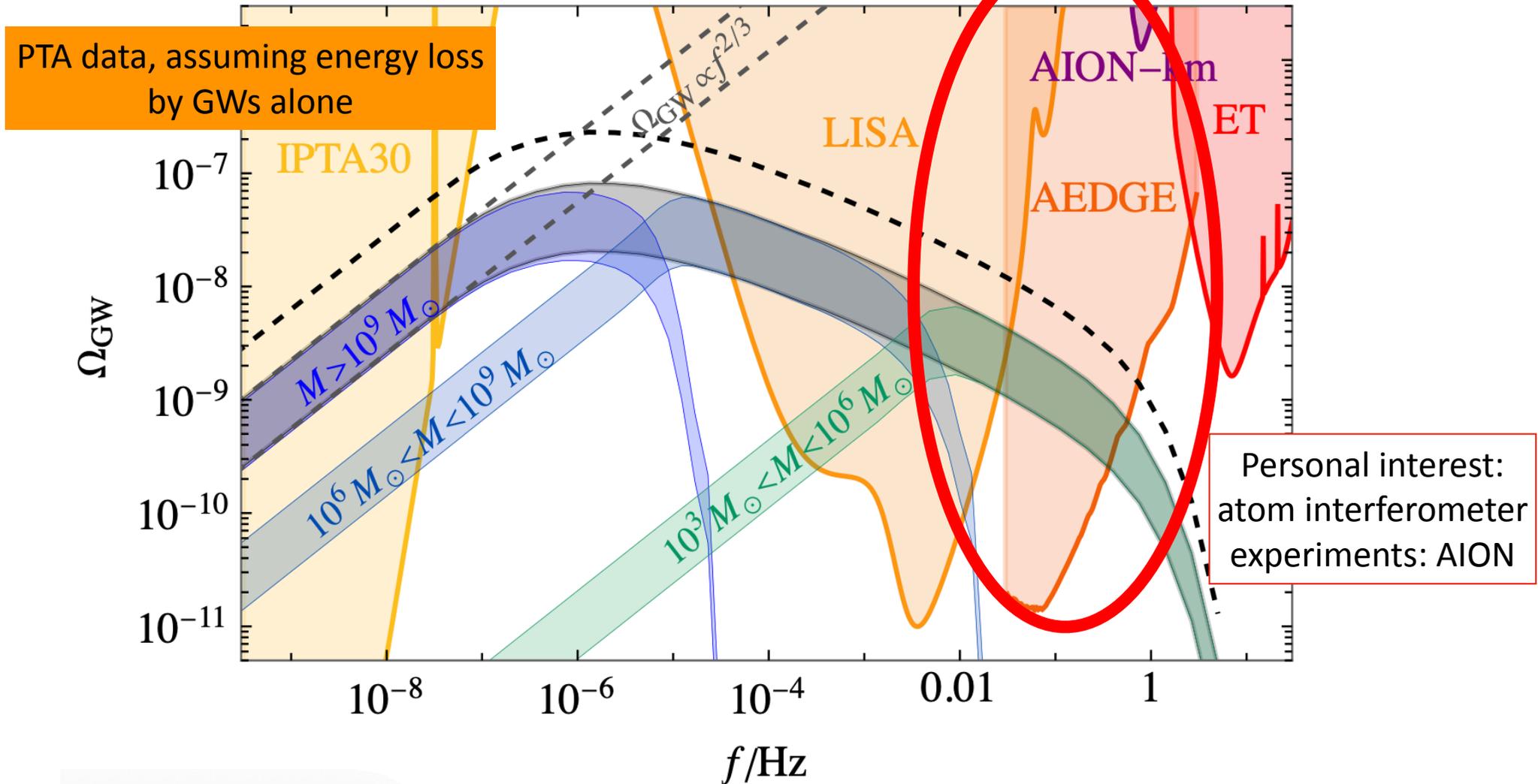


Fits use overlaps of data and model violins in each bin

NB: Fits go beyond simple power-law approximations

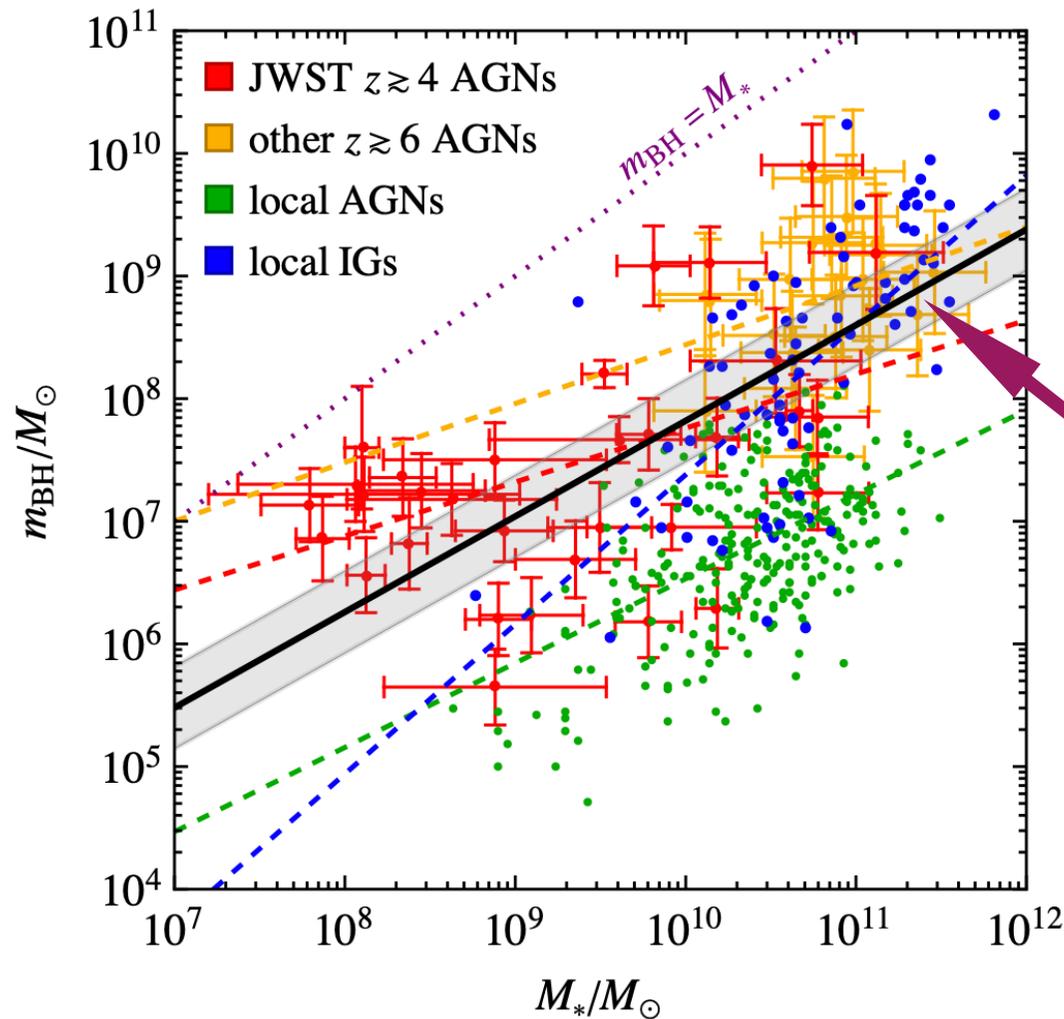
Better fit to spectrum if evolution driven by halo environment + GWs

Stochastic GW Background from BH Mergers



Black dashed line is maximum possible Ω_{GW} , i.e., $p_{\text{BH}} = 1$

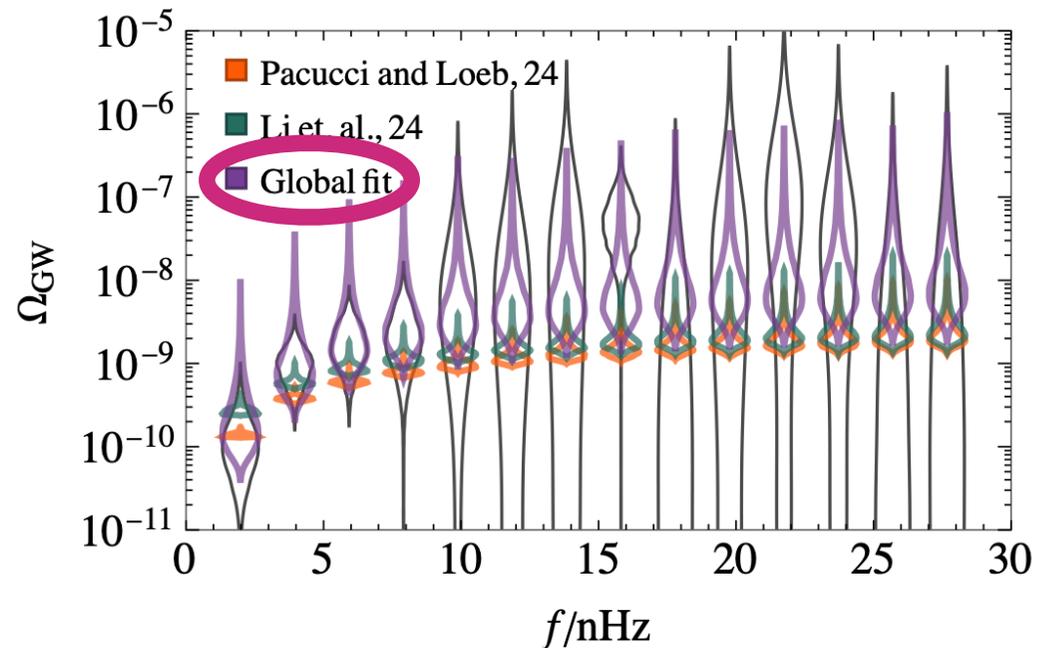
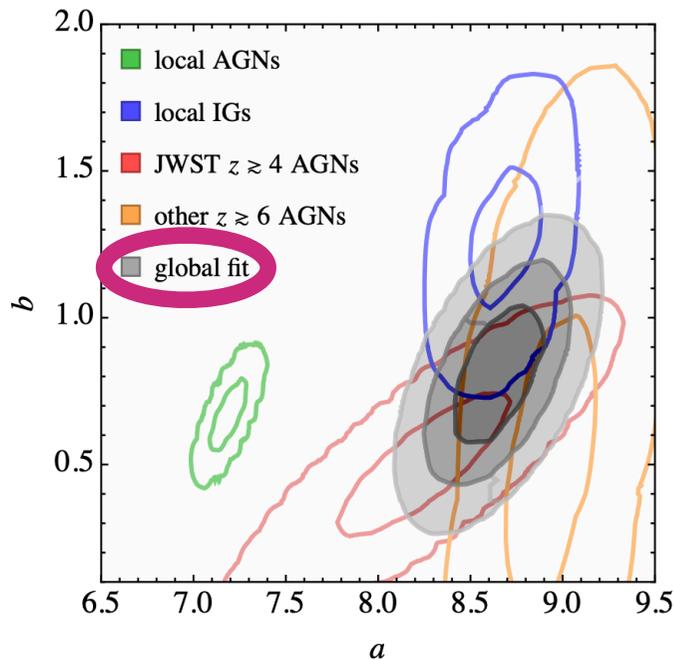
High- z SMBHs seen with JWST



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

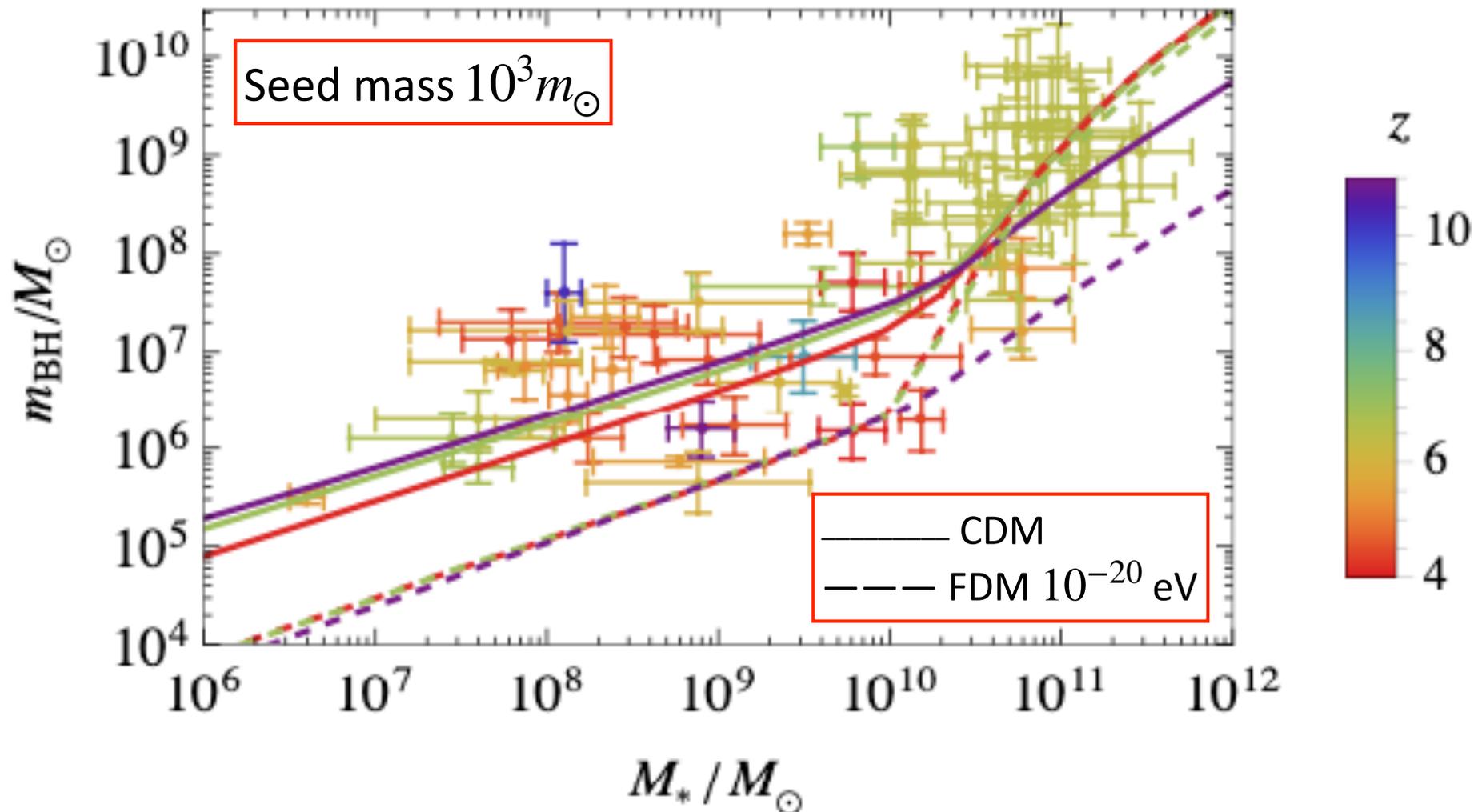
Consistent with NANOGrav

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



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

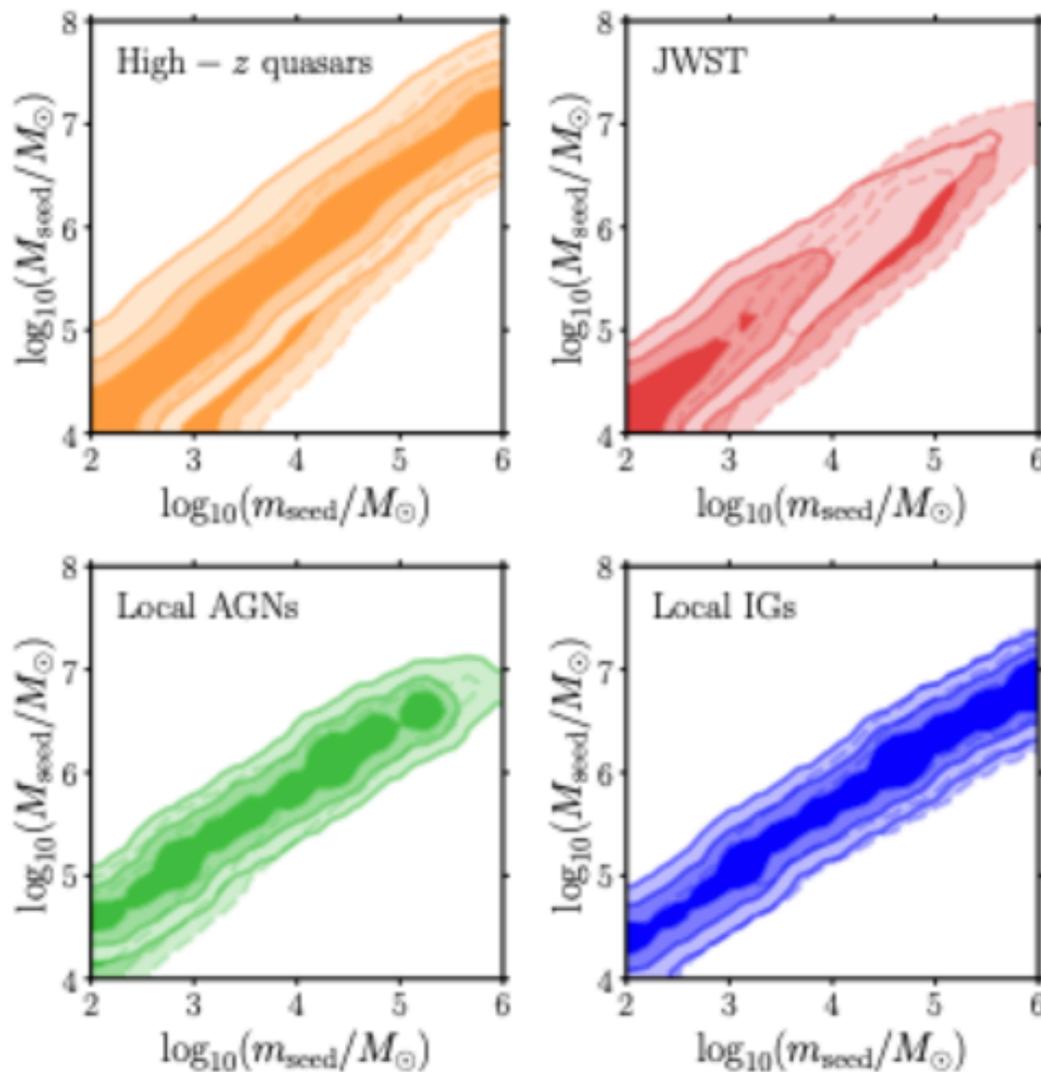
Modelling Population of High- z SMBHs in CDM, FDM, WDM*



*Cold Dark Matter/Fuzzy Dark Matter

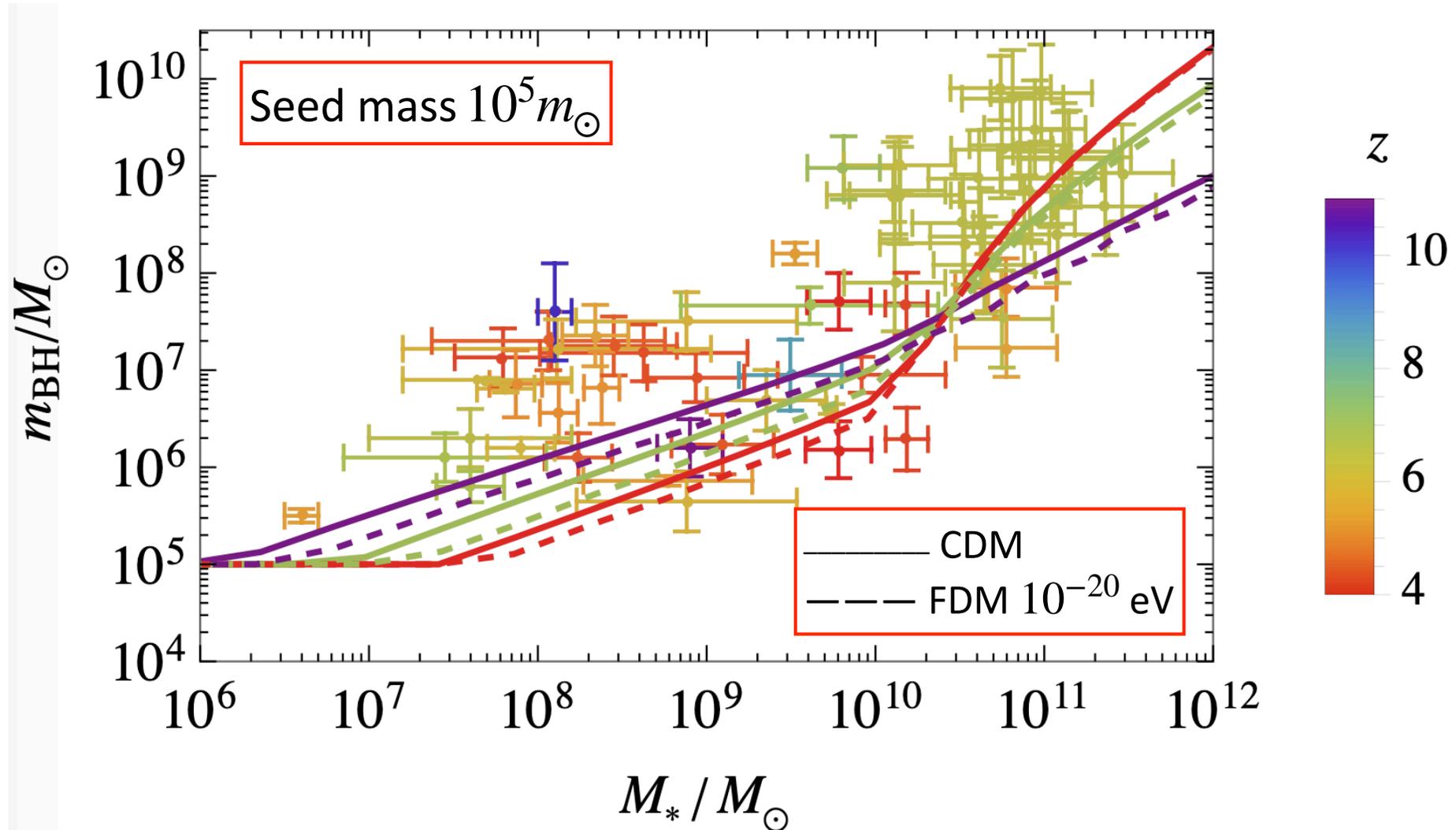
CDM Fits to Seed BH Masses

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



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

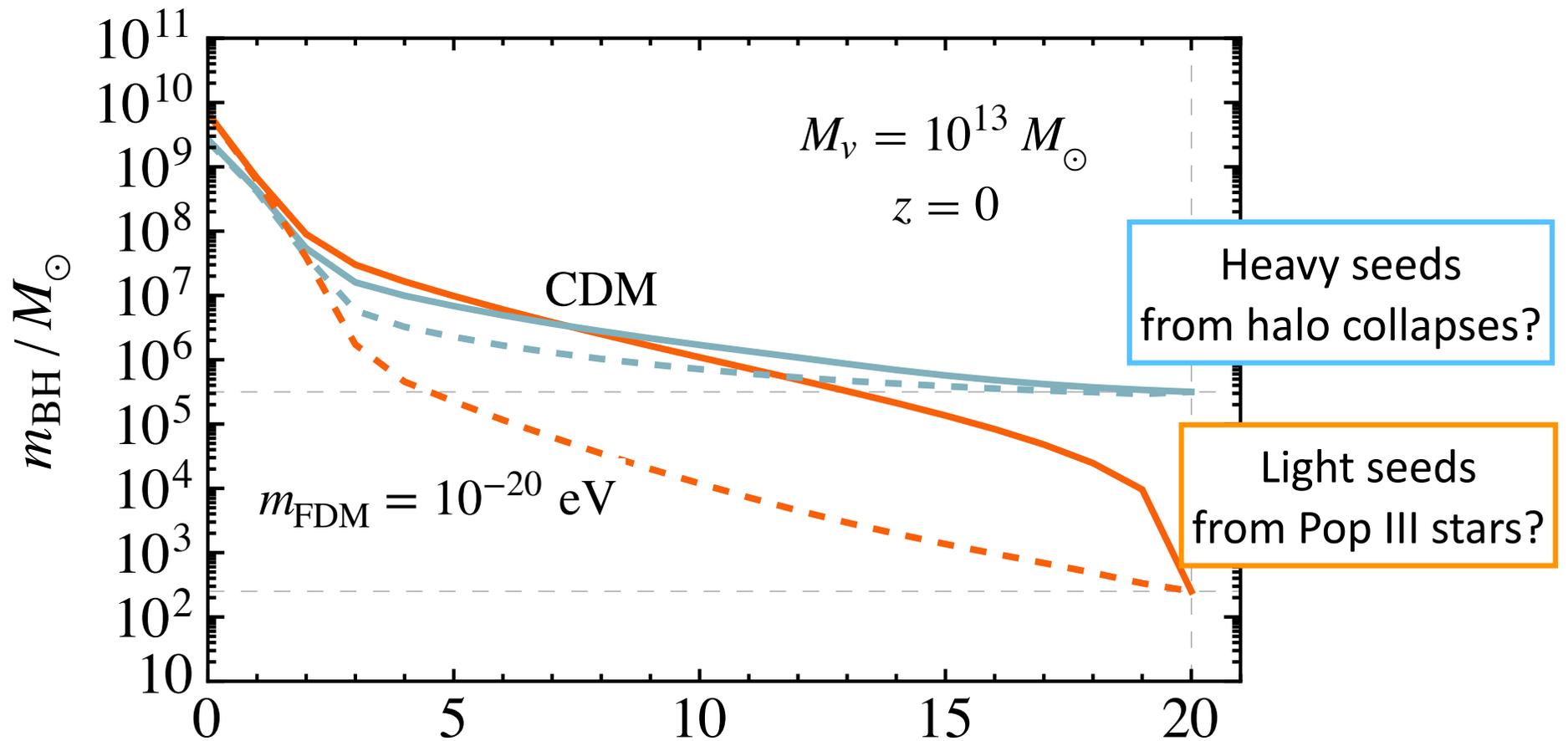
Modelling Population of High- z SMBHs in CDM, FDM, WDM*



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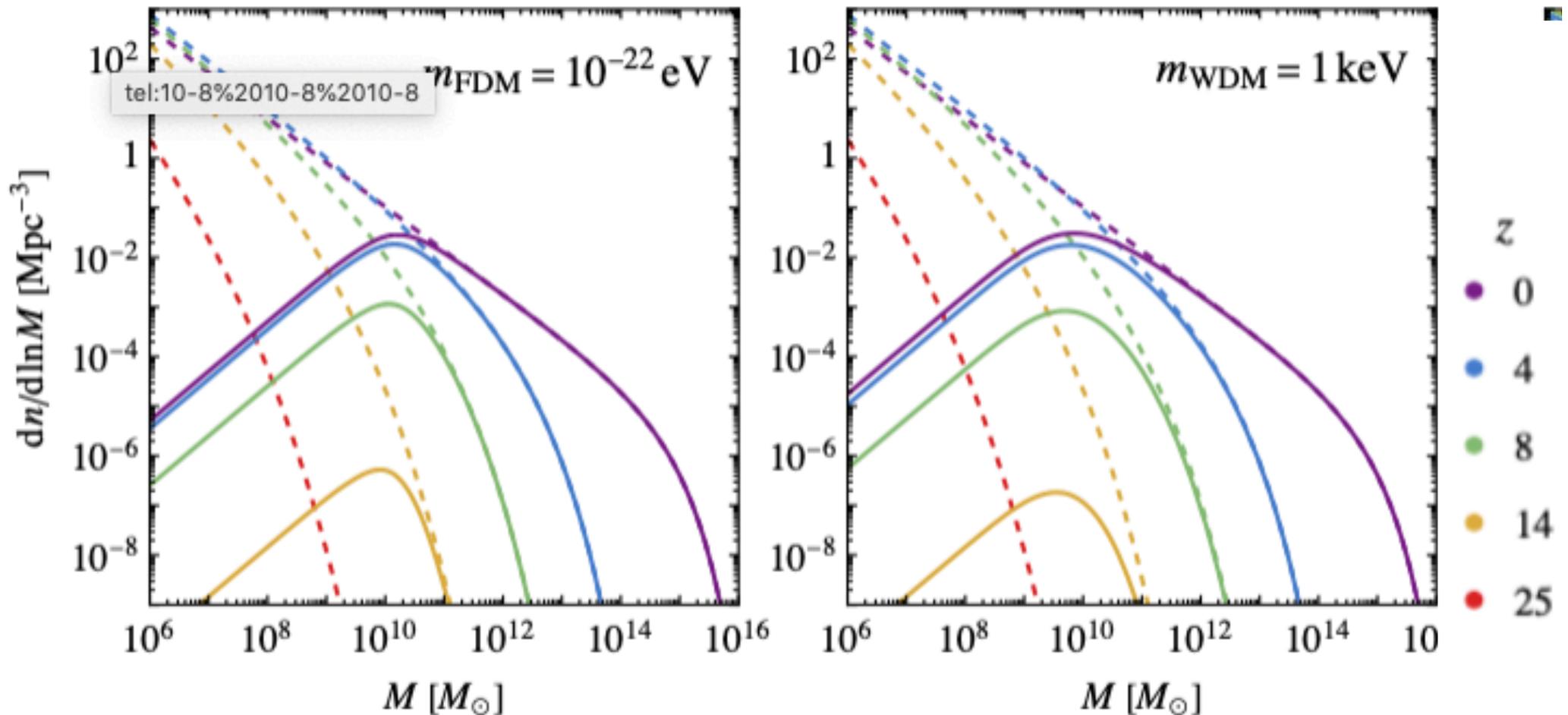
Growth of SMBH in CDM/FDM* with Light/Heavy Seeds

BH mass can grow by mergers or accretion



*Cold Dark Matter/Fuzzy Dark Matter

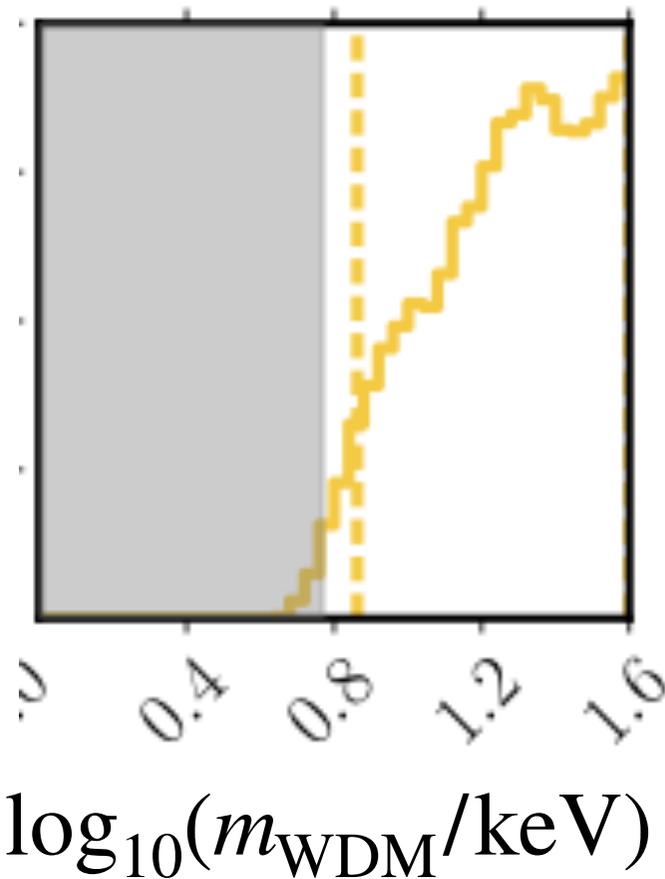
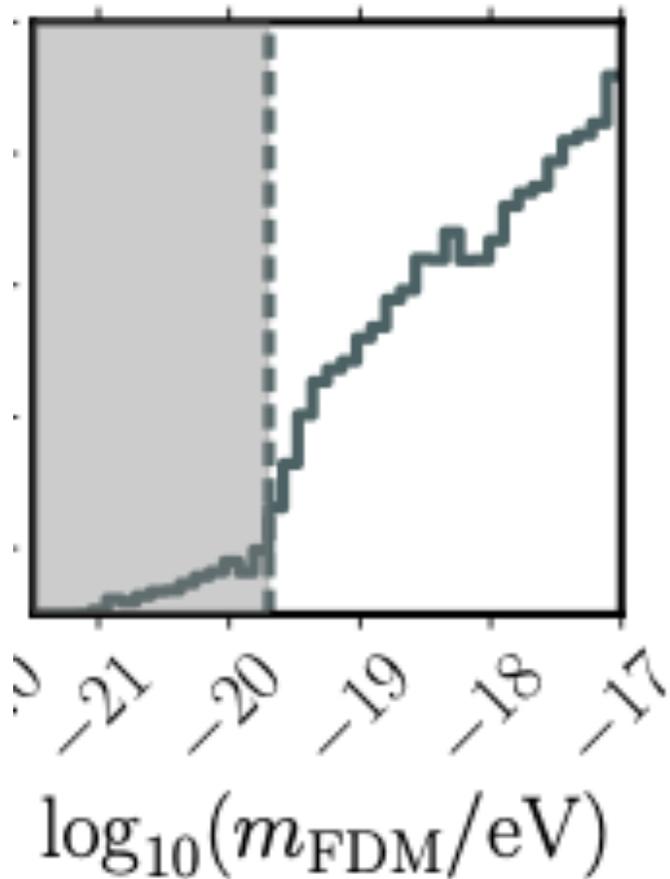
Halo Mass Function in CDM, FDM, WDM*



FDM and WDM show larger differences from CDM at high z

Novel way to probe FDM & CDM

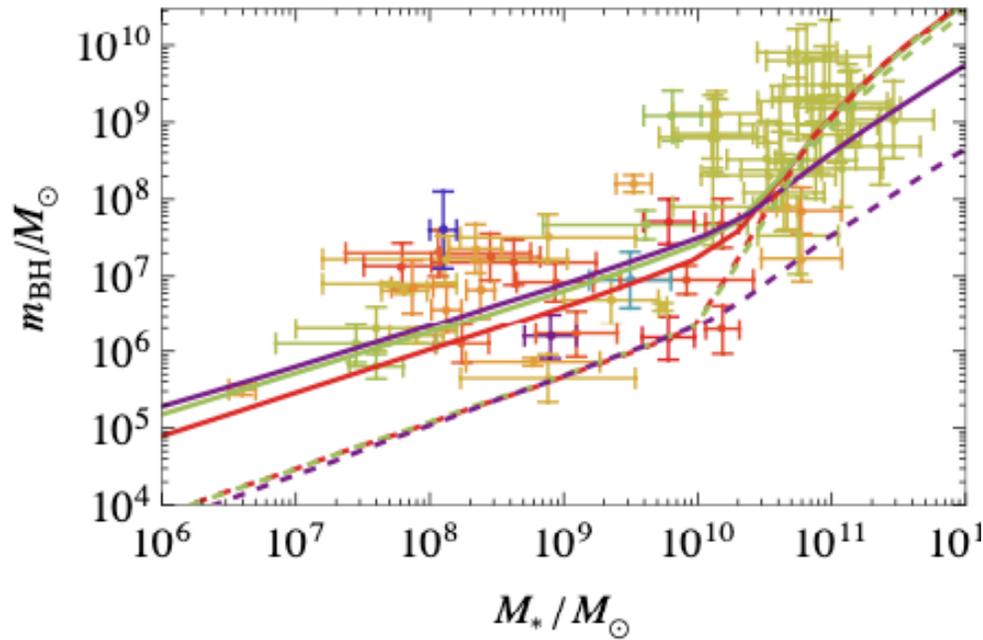
Posterior Density Functions from SMBH Mass Analysis



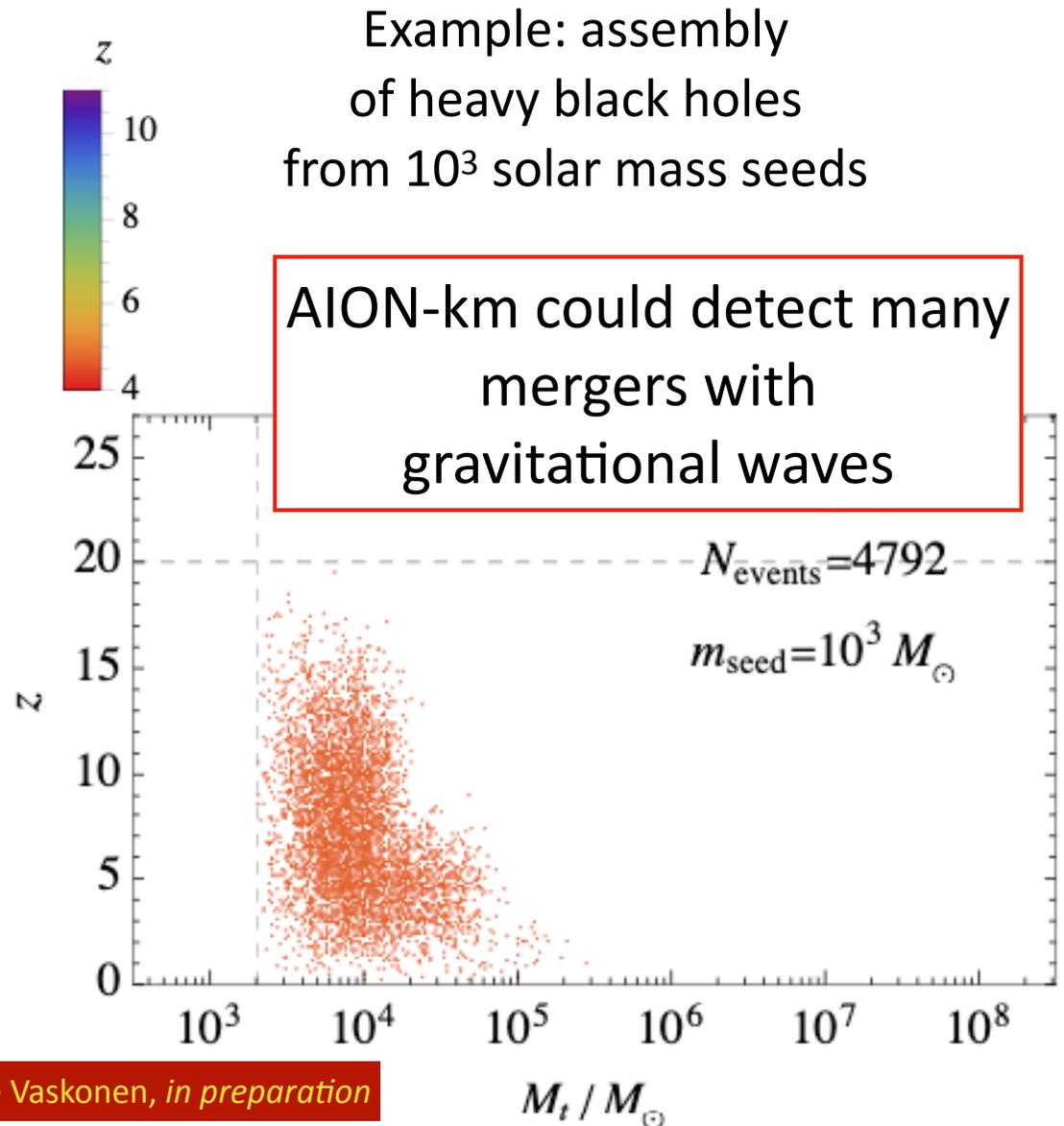
SMBH data constrain $m_{\text{FDM}} > 2 \times 10^{-20}$ eV, $m_{\text{WDM}} > 7.2$ keV

Shading: previous limits from Ly- α et al.

Probing Origin of Supermassive Black Holes with Gravitational Waves



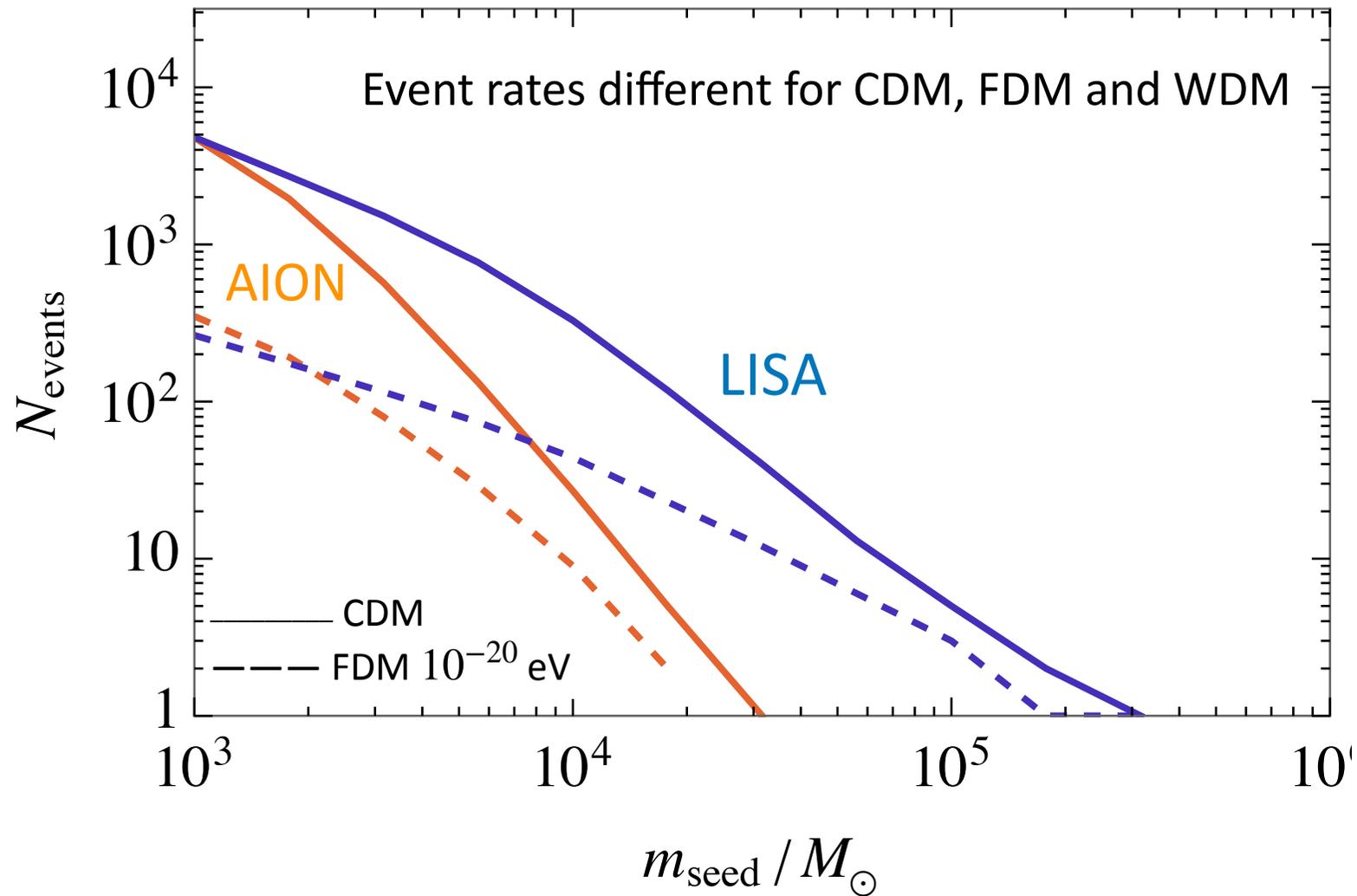
CDM model fits data on supermassive black holes at high & low redshifts



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

AION-km could detect many mergers with gravitational waves

GW Event Rates in AION-km & LISA



Summary

- GWs provide new window on astrophysical black holes
- Atom interferometry (AI) promising technique for detecting GWs in frequency band between LIGO/Virgo/KAGRA/ET and LISA (and DM)
 - AION is staged UK project: also others (MAGIS, MIGA, CERN?)
- AI could detect mergers of intermediate mass BHs forming SMBHs
- PTA and JWST data constrain models of SMBH formation, models of dark matter
- Future AI GW observations could strengthen these constraints