Atomic Interferometry: R&D and Science Targets

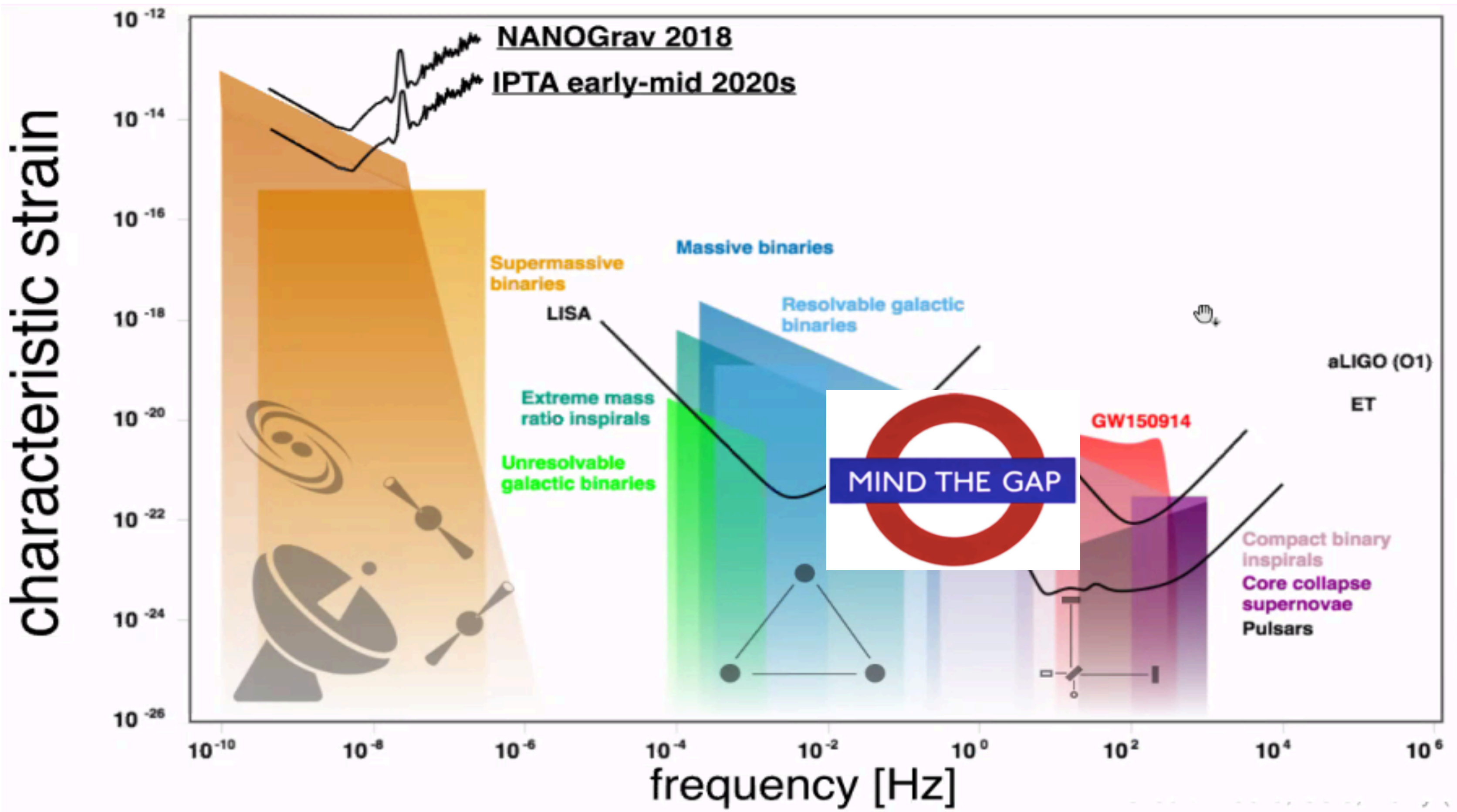
Concept of atom interferometry
AION project
R&D progress
Site plans & investigations
Mergers of Intermediate black holes
Interpretation and extrapolation of PTA data

AEDGE, arXiv:1908.00802,
AION, arXiv:1911.11755,
AION, arXiv:2305.20060,
JE, Schneider & Buchmueller, arXiv:2306.17726,
Terrestrial VLBAI, arXiv:2310.08183

John Ellis

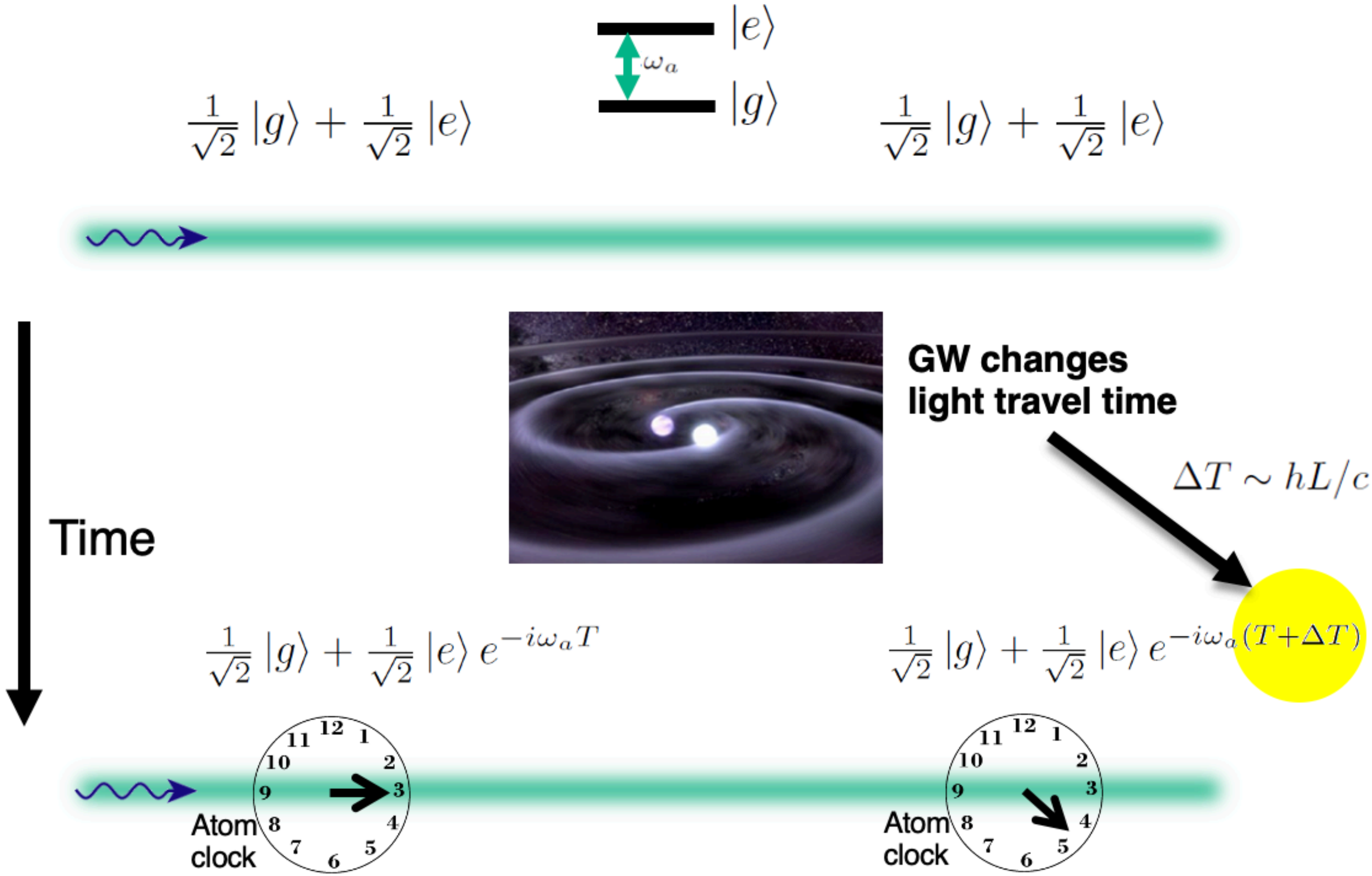
KING'S College LONDON

Gravitational Wave Spectrum

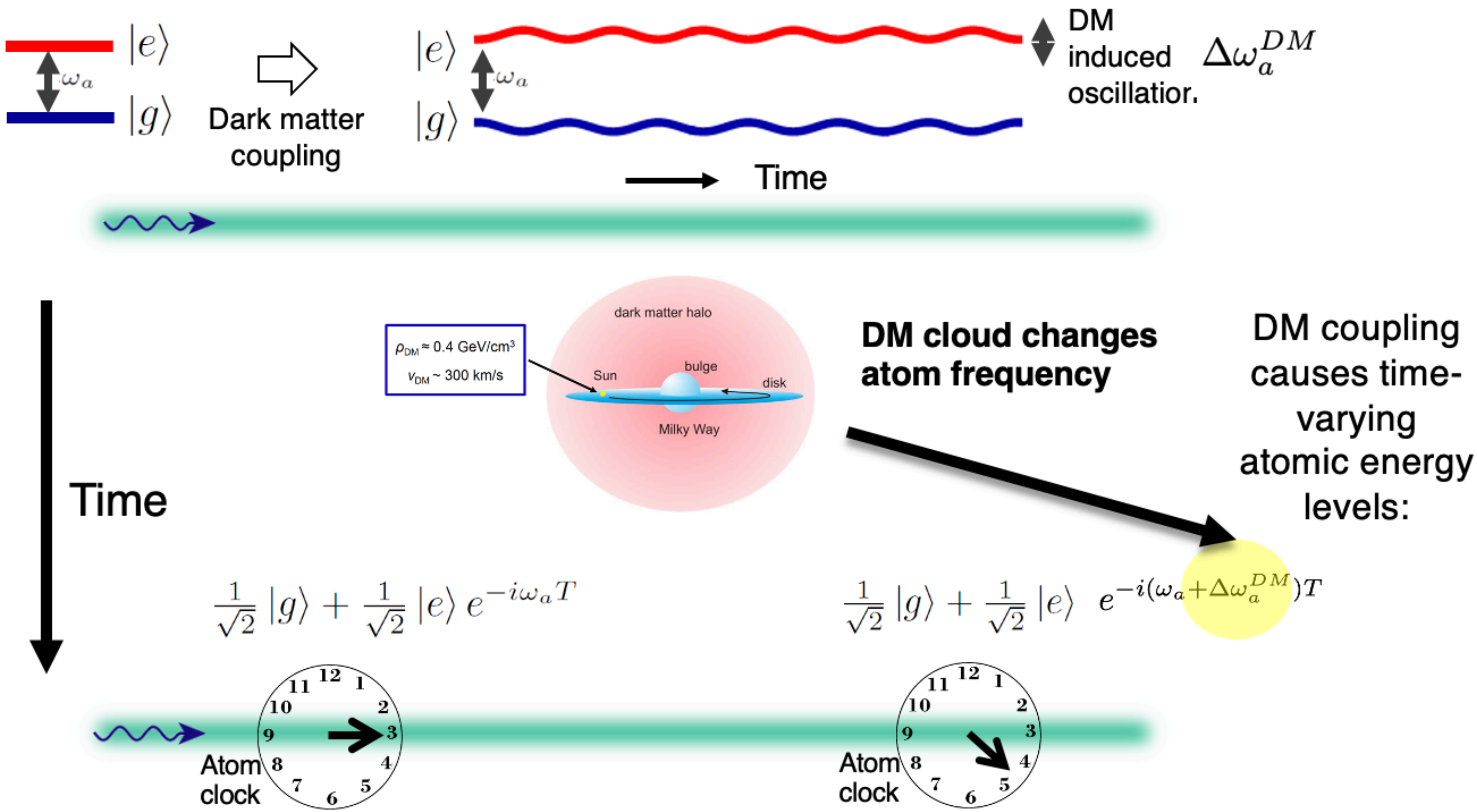


- Gap between ground-based optical interferometers & LISA
  - Formation of supermassive black holes (SMBHs)
  - Supernovae? Phase transitions? …
- **Atom interferometry?**

Effect of Gravitational Wave on Atom Interferometer

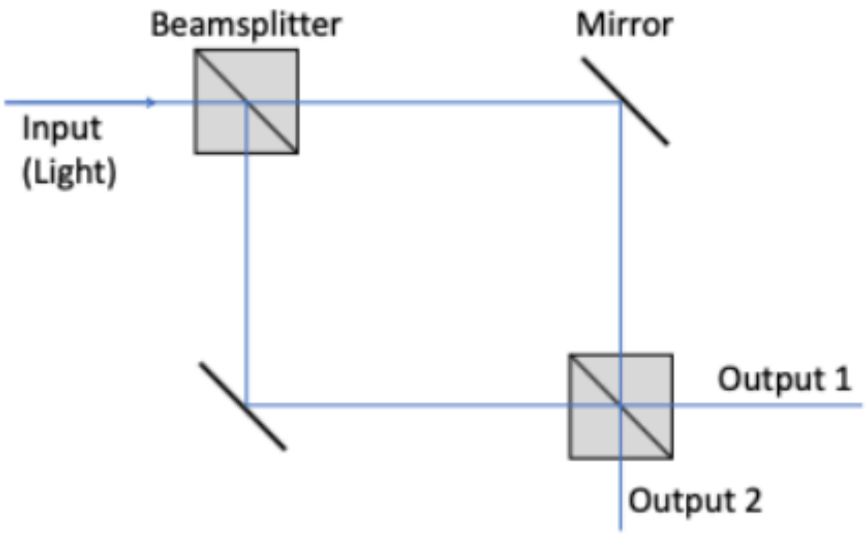


Effect of Dark Matter on Atom Interferometer

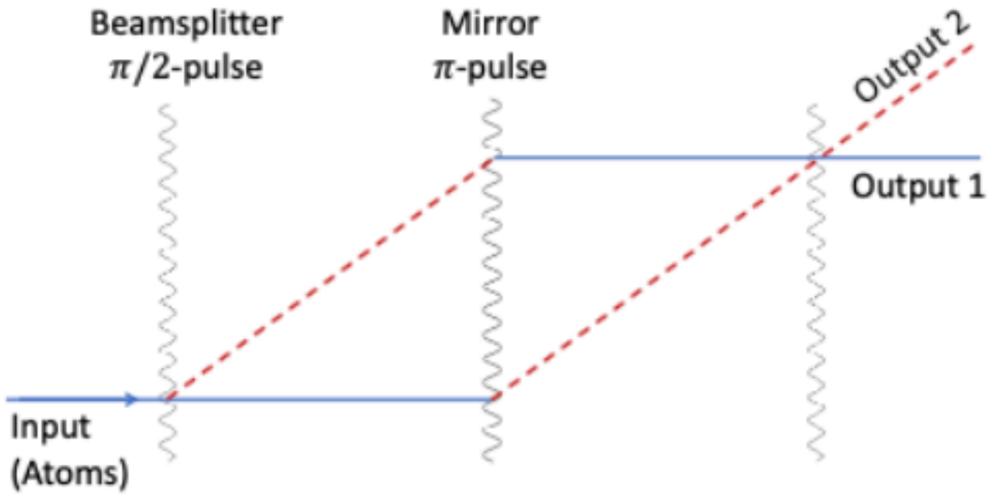


Principle of Atom Interferometry

Mach-Zehnder Laser Interferometer

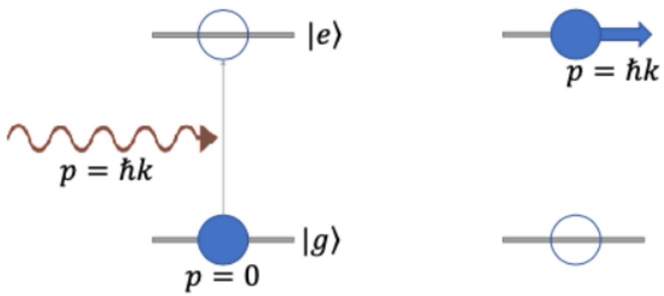


Atom Interferometer

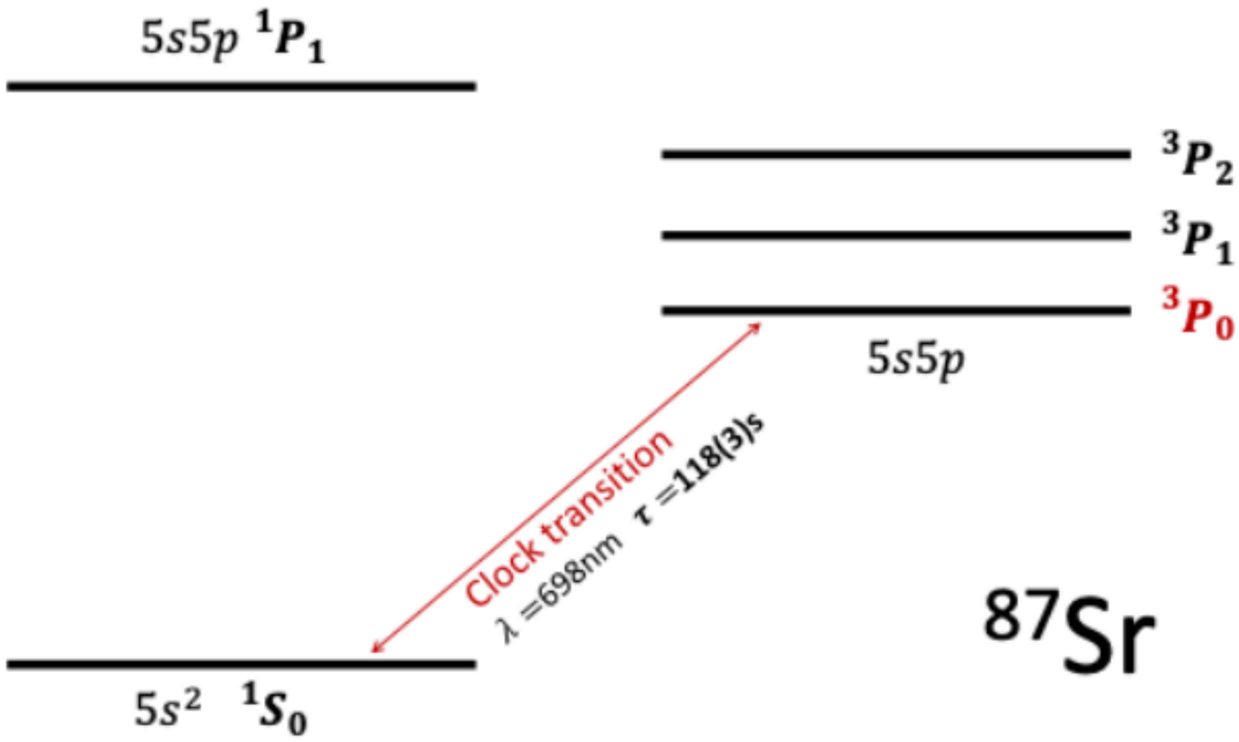


Laser excitation gives momentum kick to excited atom, which follows separated space-time path

Interference between atoms following different paths

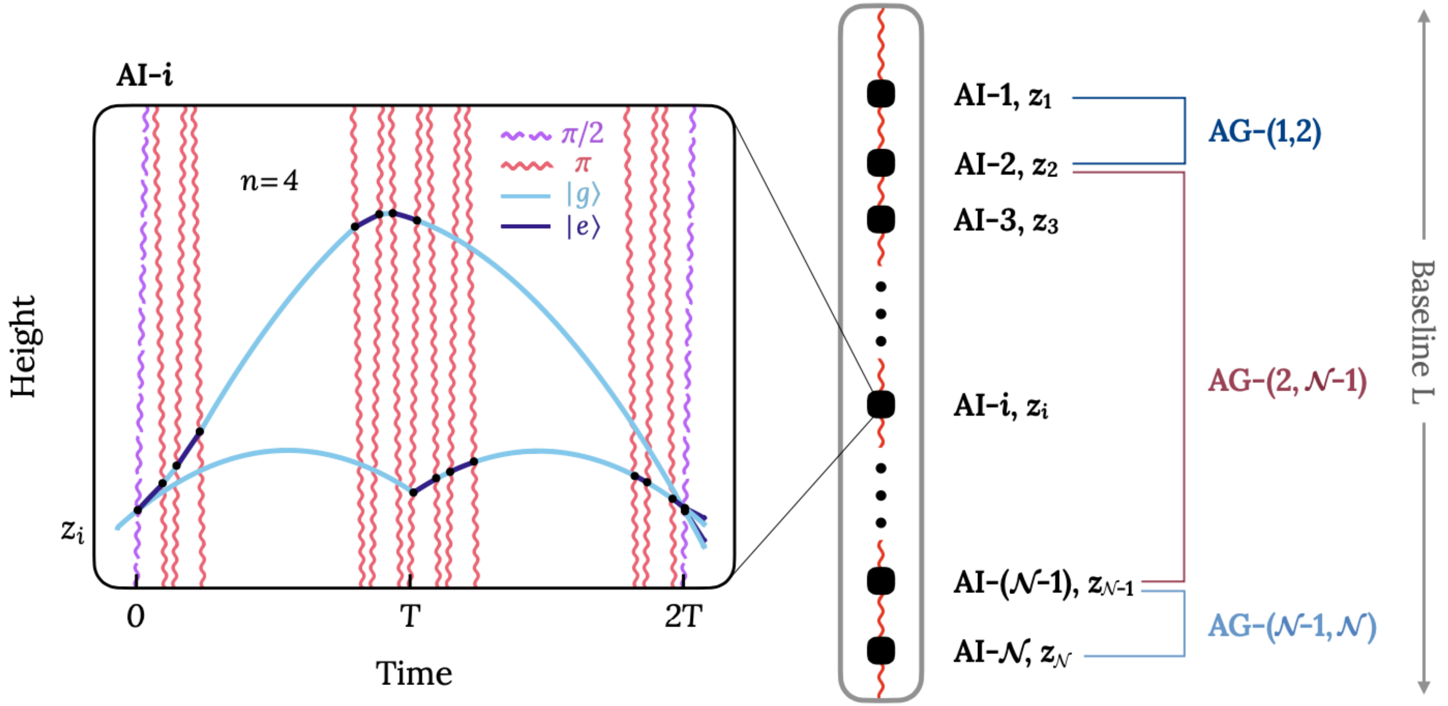


Clock Transition in ^{87}Sr



Long-lived state, can excite multiple times
Large momentum transfers, well-separated paths

Atomic Multi-Gradiometer



Multiple atomic interferometers in the same vertical shaft, manipulated with same laser beam:

Eliminate laser noise, minimize gravity gradient noise (direct effect on atoms of earth motion).

Many laser interactions to generate large momentum transfers

AION Collaboration

L. Badurina[1], S. Balashov[2], E. Bentine[3], D. Blas[1], J. Boehm[2], K. Bongs[4], A Beniwal[1]
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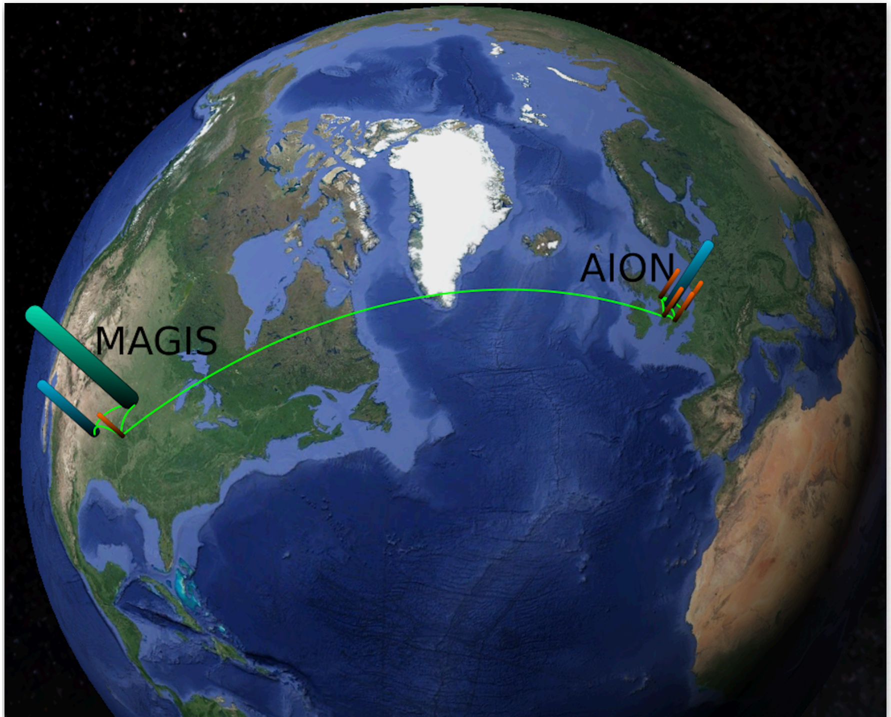


Network with MAGIS project in US

MAGIS Collaboration (Abe et al): arXiv:2104.02835

AION

AION – Staged Programme

AION

- AION-10: Stage 1 [year 1 to 3]
  - 1 & 10 m Interferometers & site investigation for 100m baseline

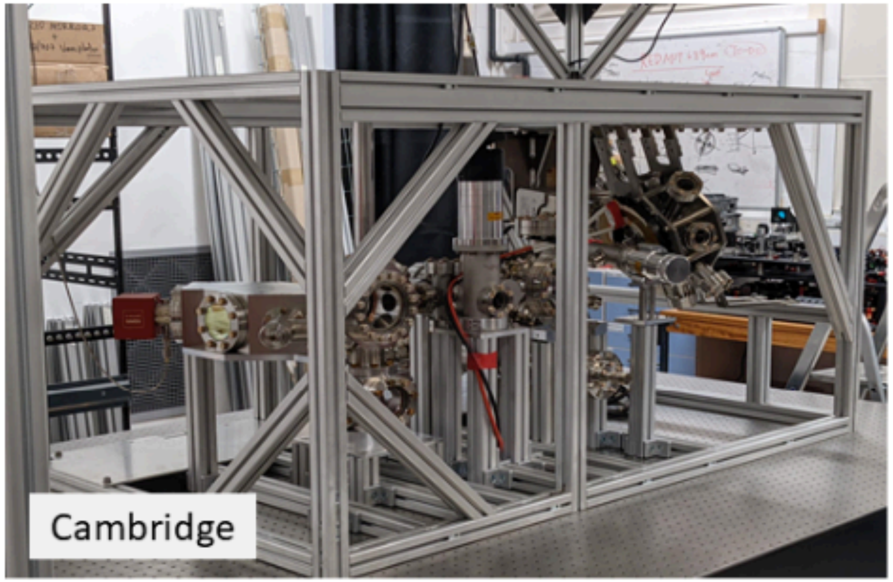
Initial funding from UK STFC

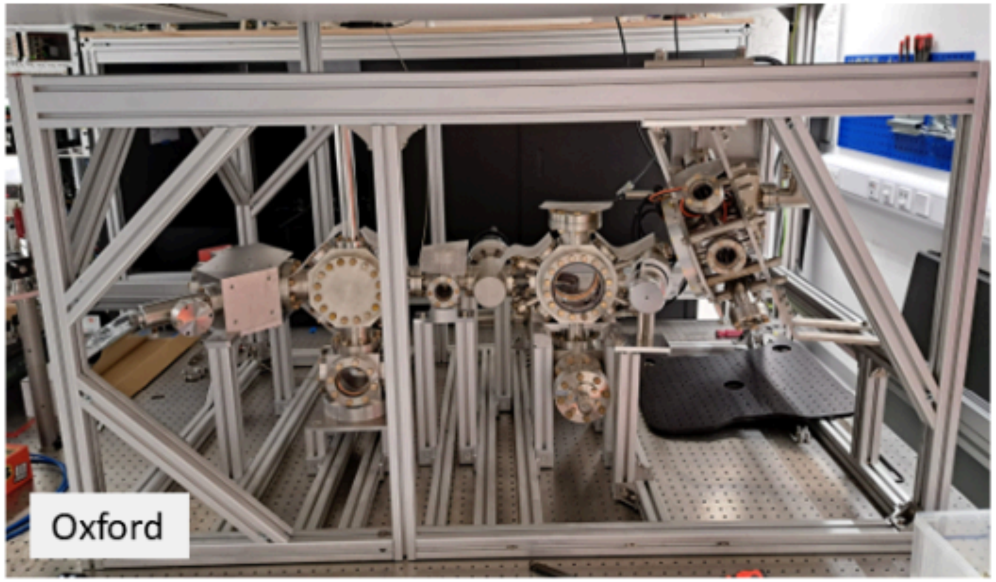
- AION-100: Stage 2 [year 3 to 6]
  - 100m Construction & commissioning
- AION-KM: Stage 3 [> year 6]
  - Operating AION-100, preparing 1 km & planning for beyond
- AION-SPACE (AEDGE): Stage 4 [after AION-km]
  - Space-based version

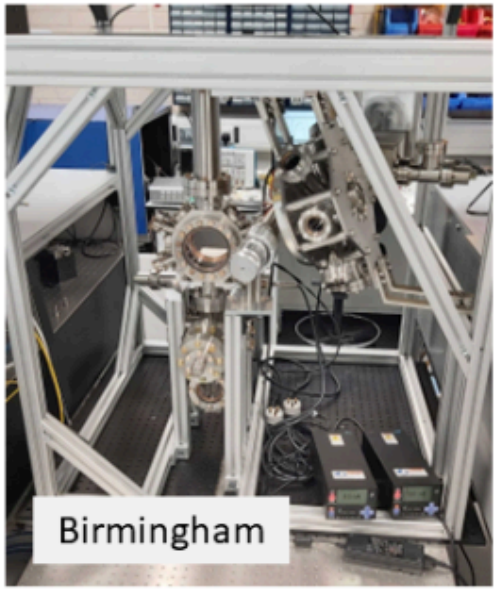
AION Collaboration (Badurina, ..., JE et al): arXiv:1911.11755

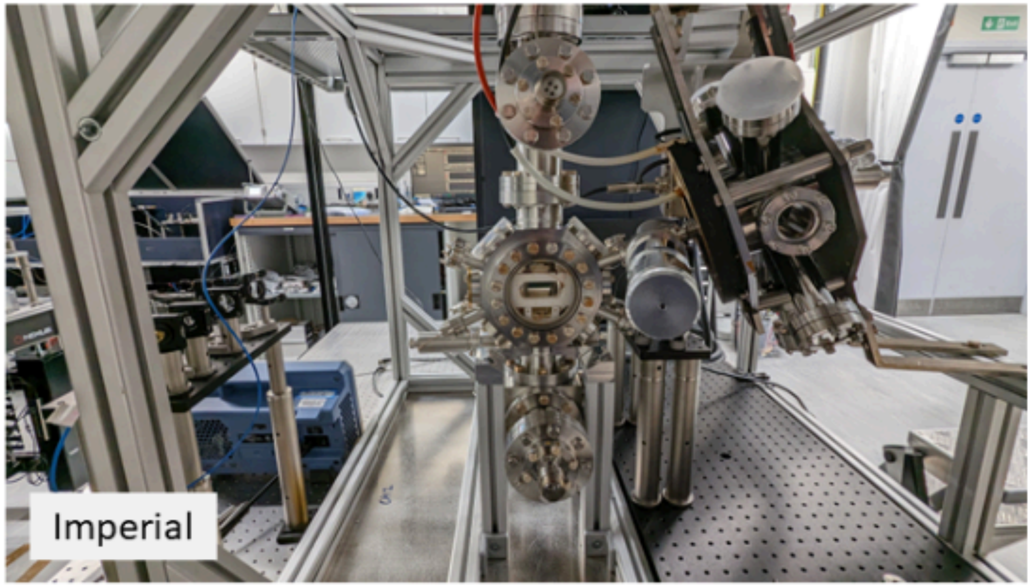
Laboratory Installations

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





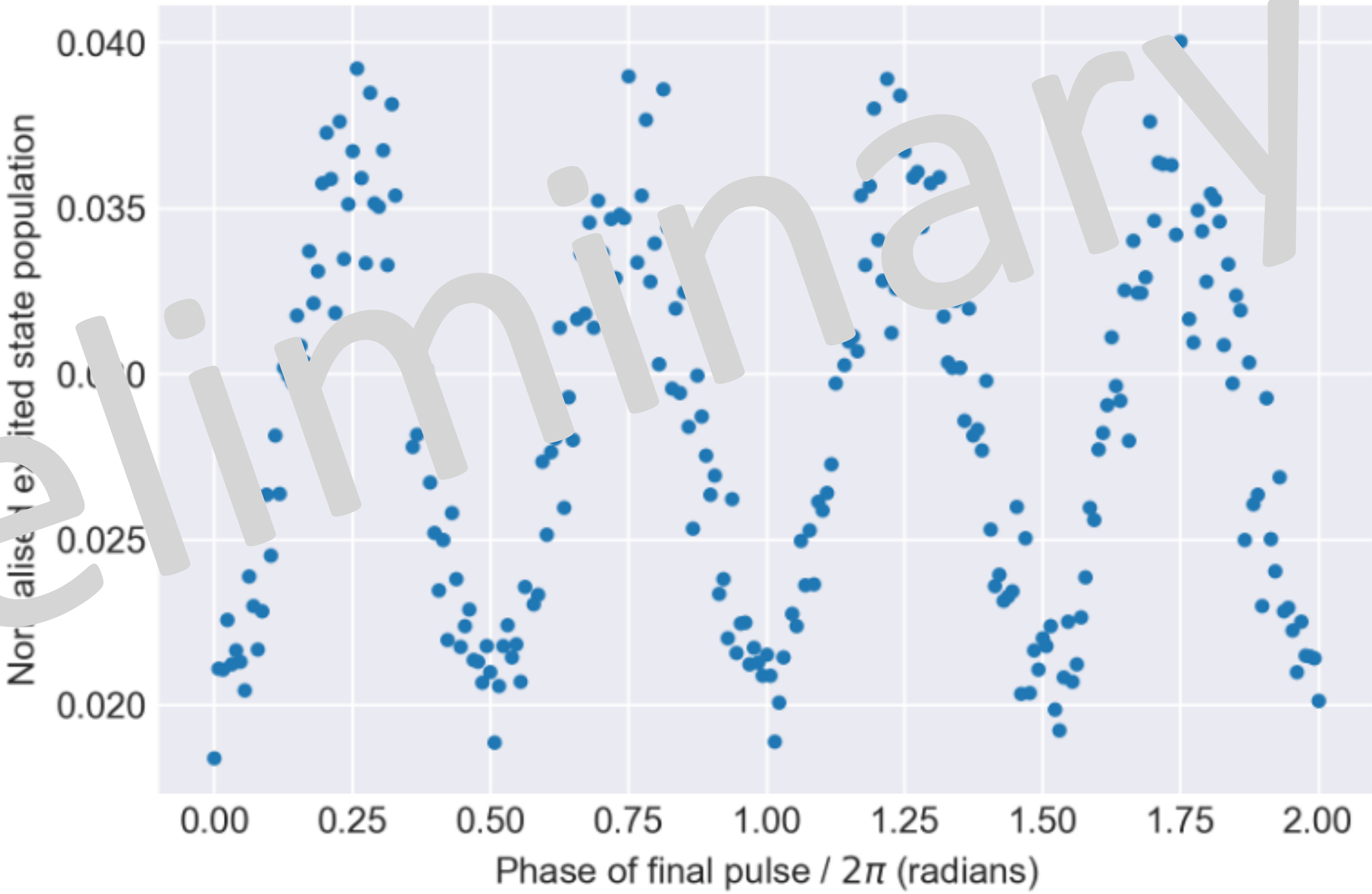




AION

Interference Fringes from Rabi Oscillations

Atomic analogue of Mach-Zehnder optical interferometer



Using 689 nm transition in Sr

AION Collaboration

Towards Large Momentum Transfers

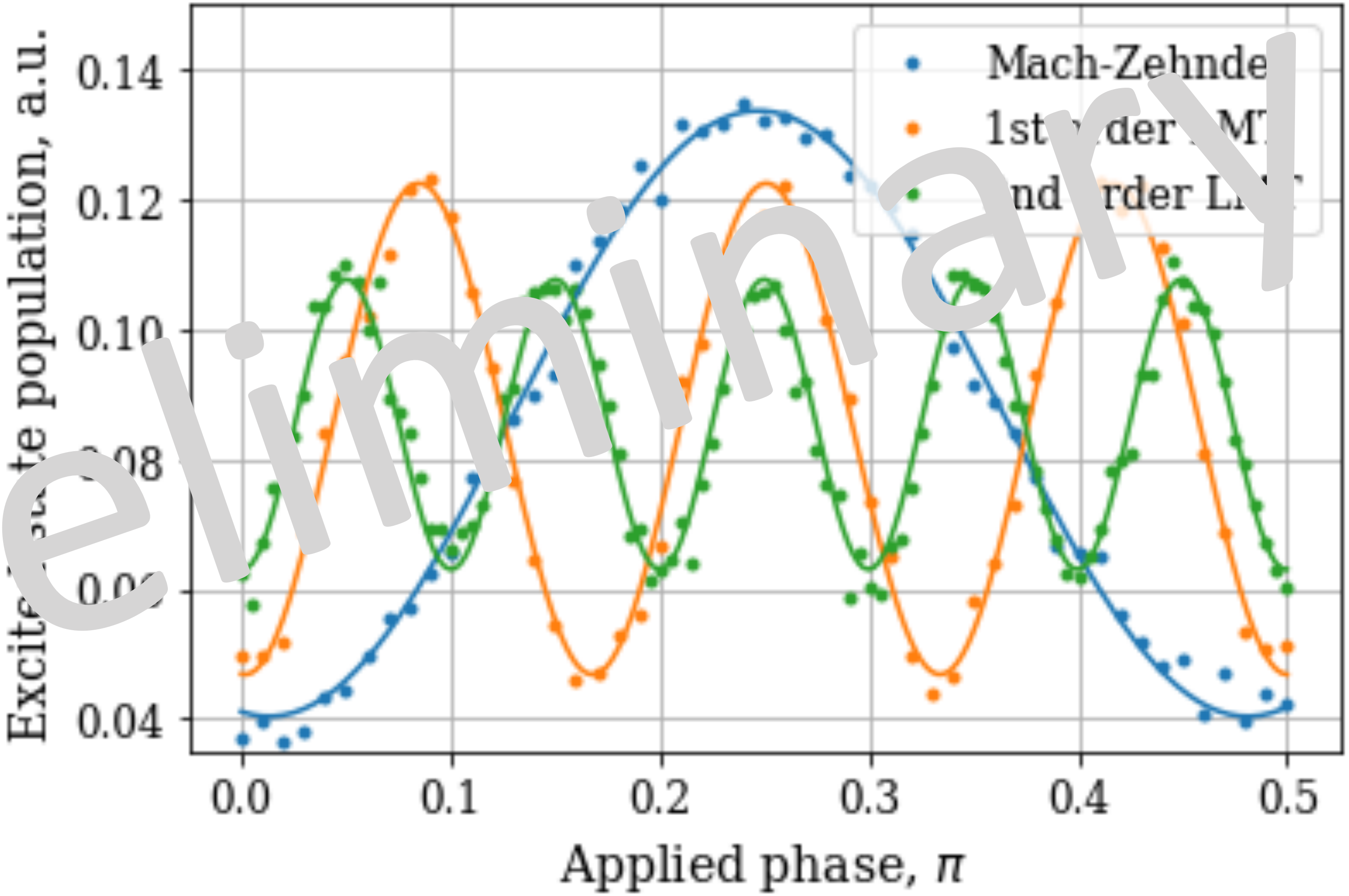
Interference fringes:

Mach-Zehnder

1st order

2nd order

momentum transfers



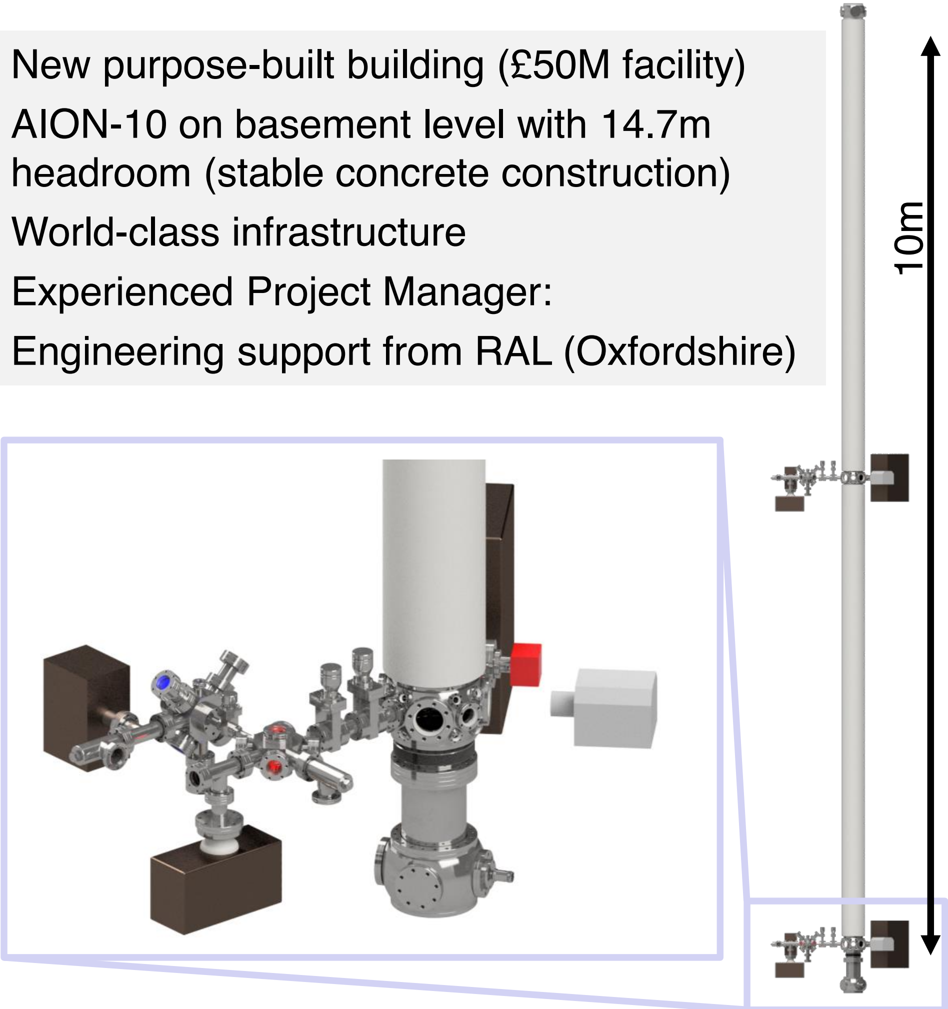
Using 689 nm transition in Sr

AION Collaboration

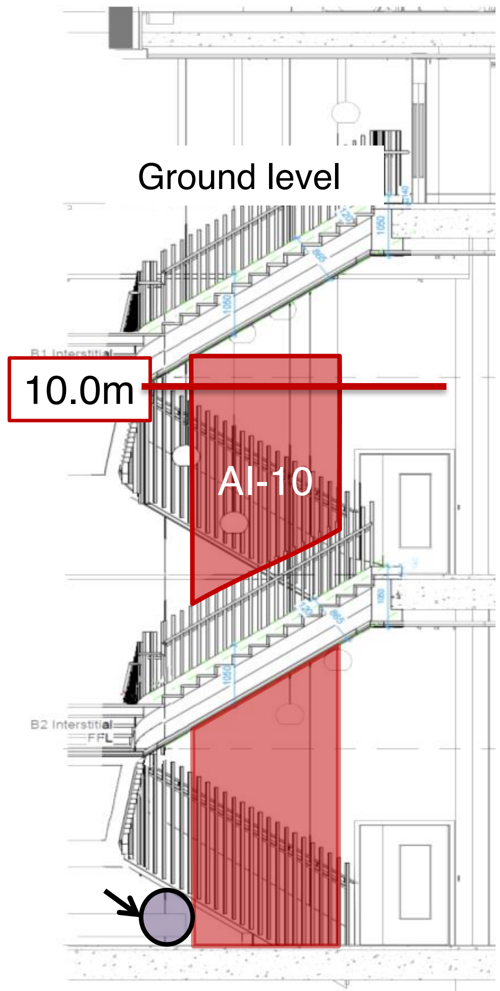
Planned Location of AION-10m

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



100m and 1km shafts @ Boulby

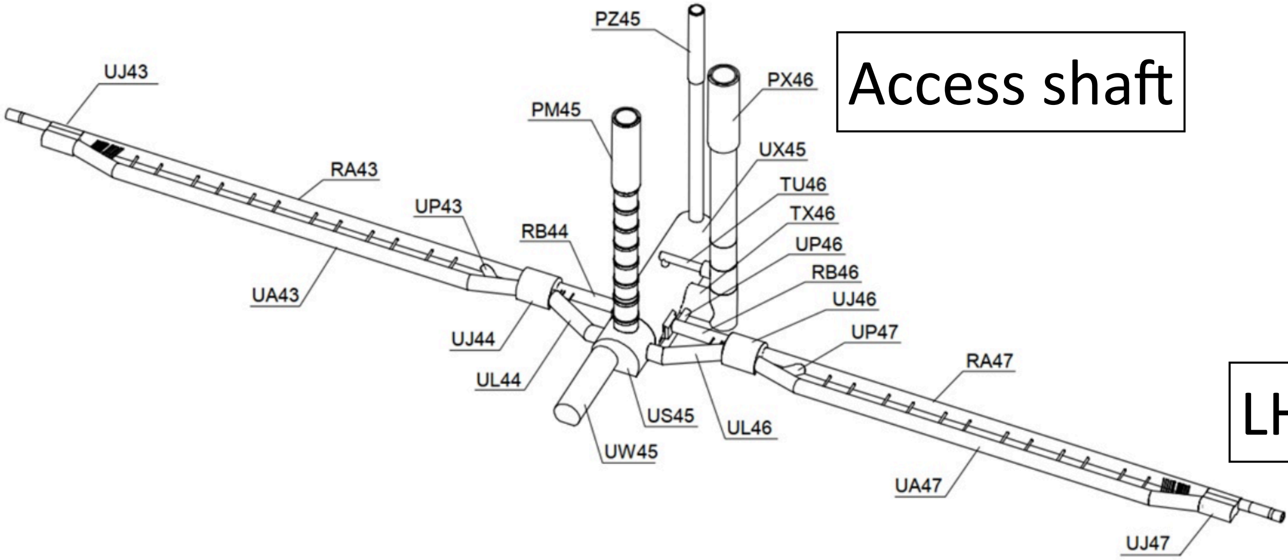
Shaft 3: 180m:

Space use in shaft?
Proximity to sea shore?
Water extraction tube?
Magnetic environment?

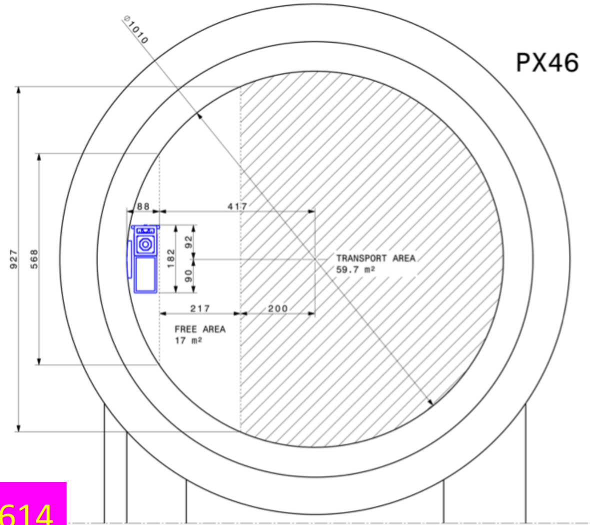
Shaft 1: 1.1km

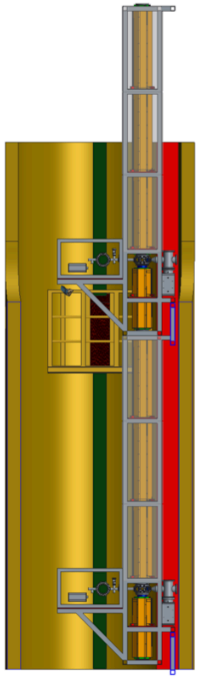
Operational access shaft
Space use in shaft?
Effects of physical activities?
Air flow?

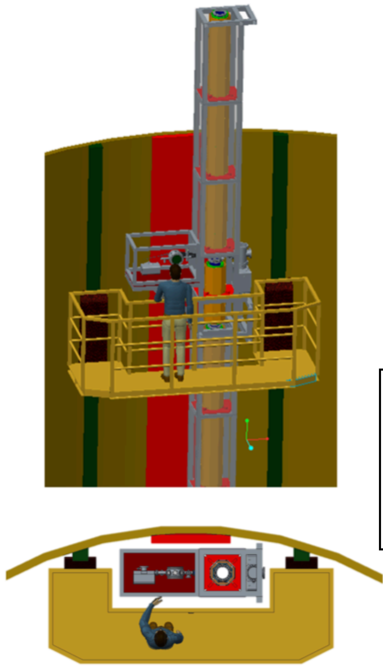
140m Access Shaft @ CERN



Cross-section of access shaft





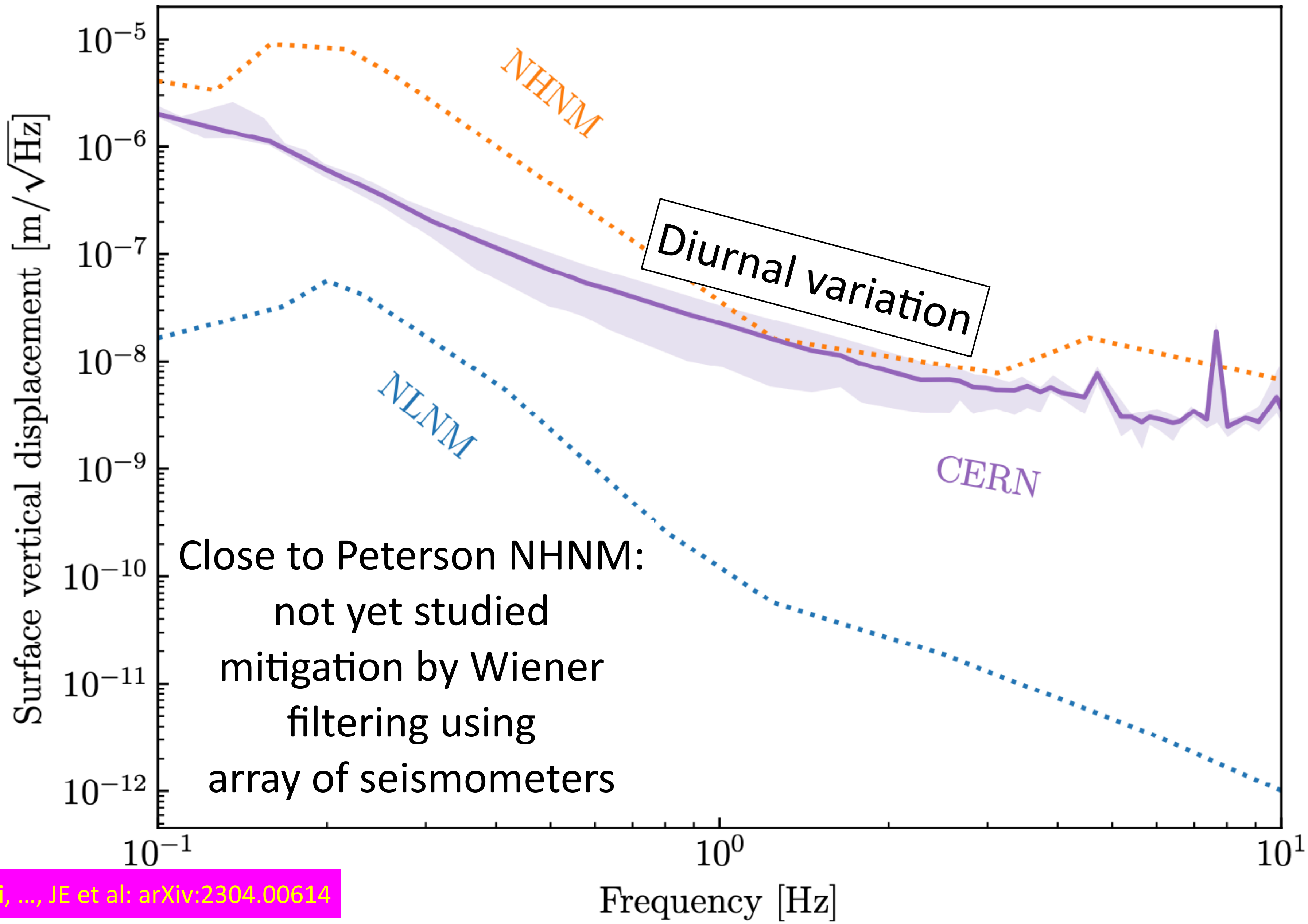


Layout of experiment

Arduini et al: arXiv:2304.00614

Gravity Gradient Noise @ CERN

AION

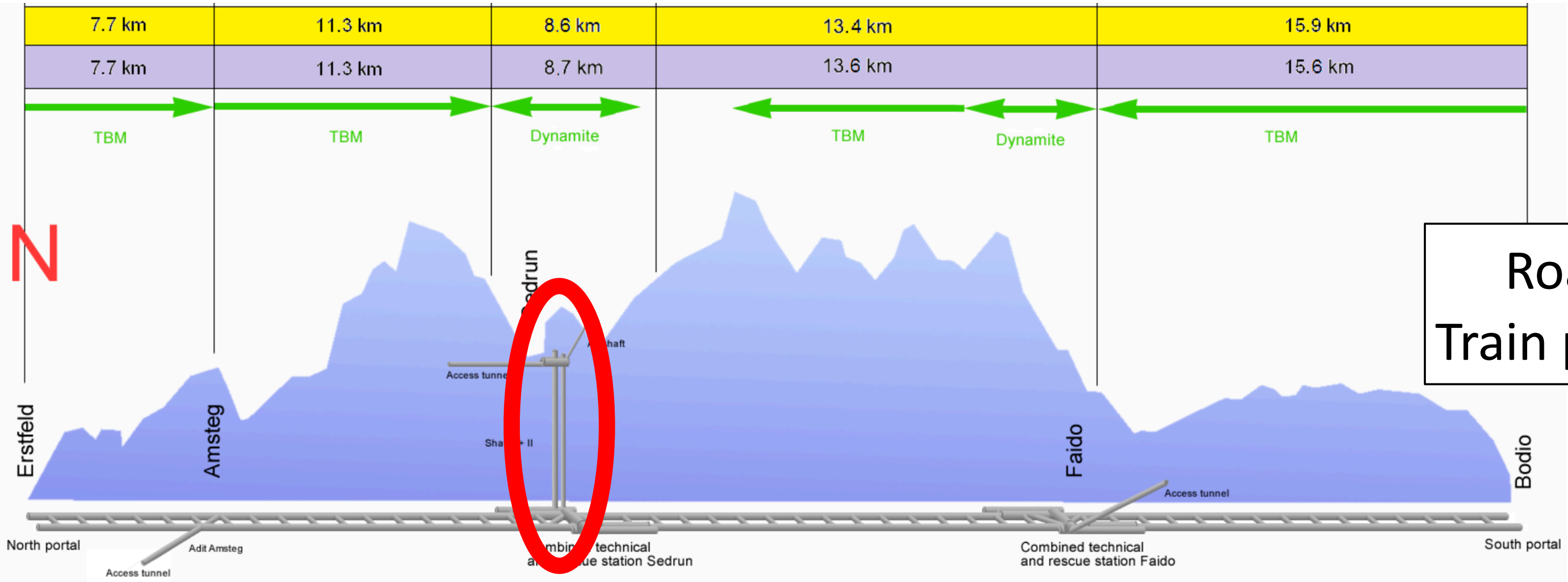


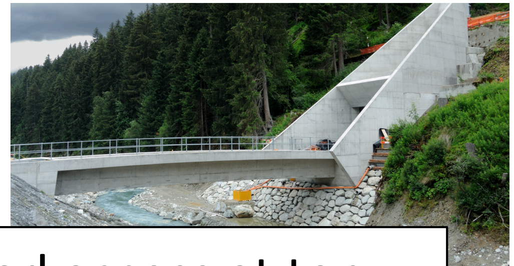
Arduini, …, JE et al: arXiv:2304.00614

Porta Alpina:

A possible site for a large terrestrial atom interferometer?

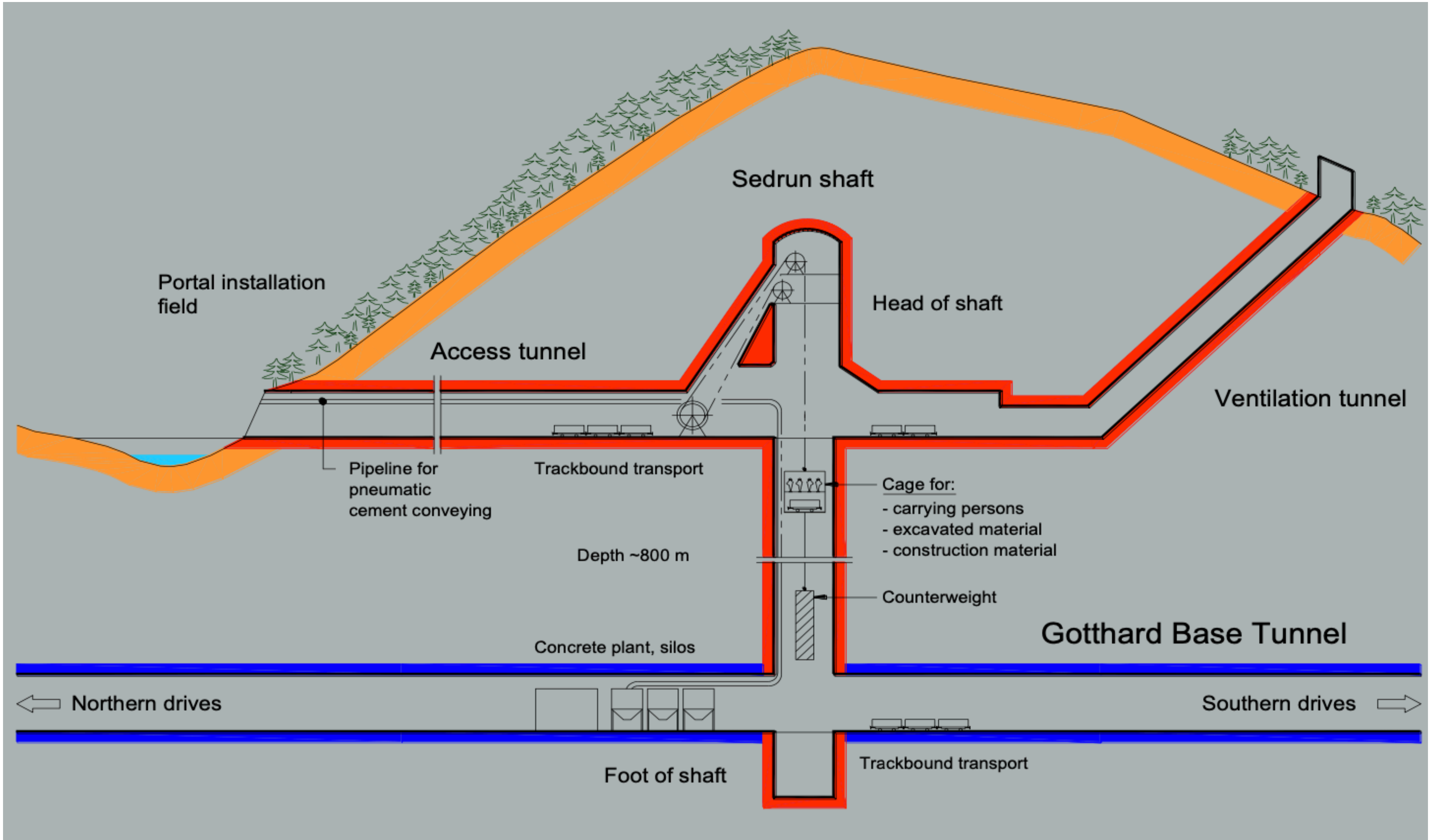
A pair of 800m vertical shafts down to the Gotthard base railway tunnel, with a 1km horizontal access tunnel



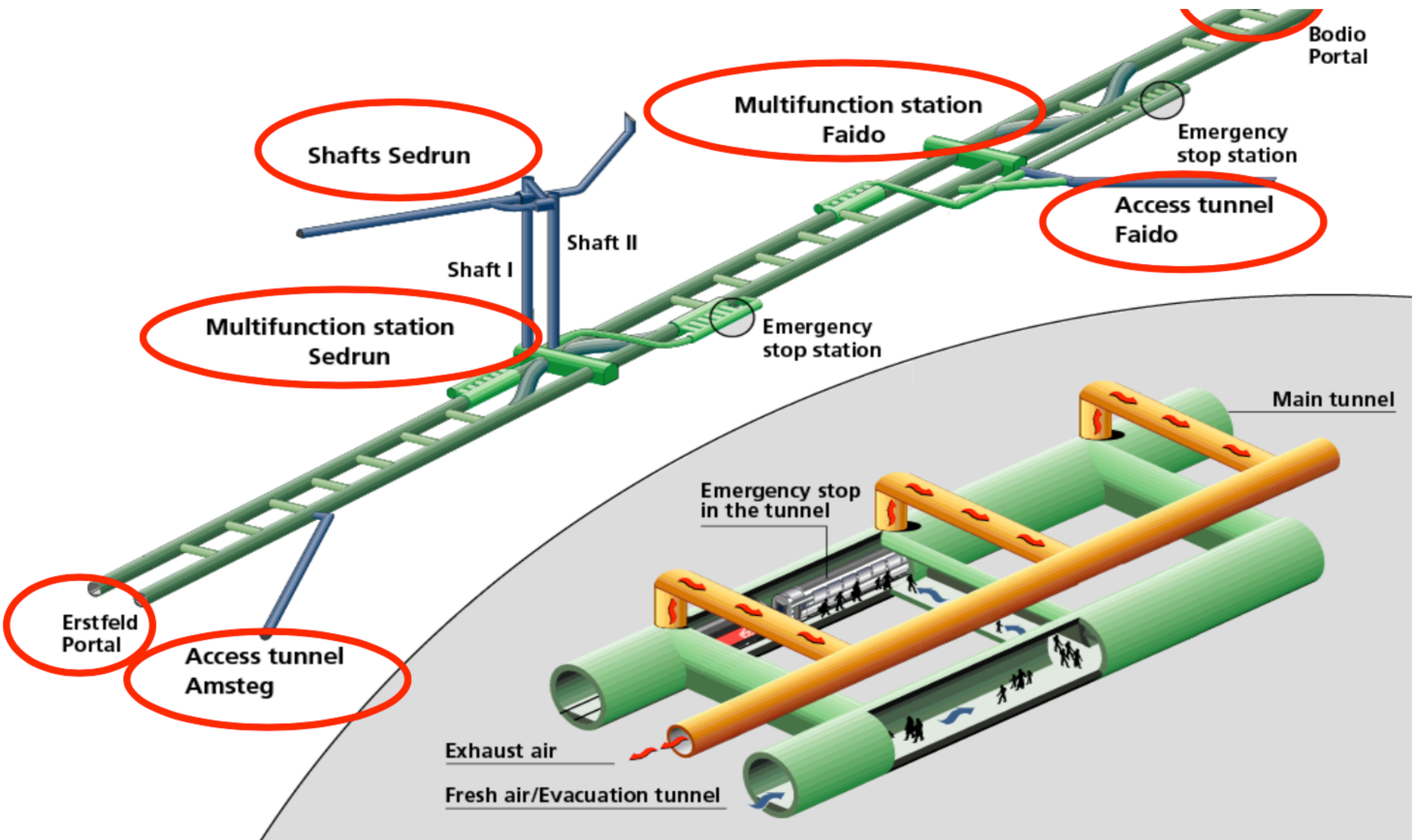


Road access at top
Train platform at bottom

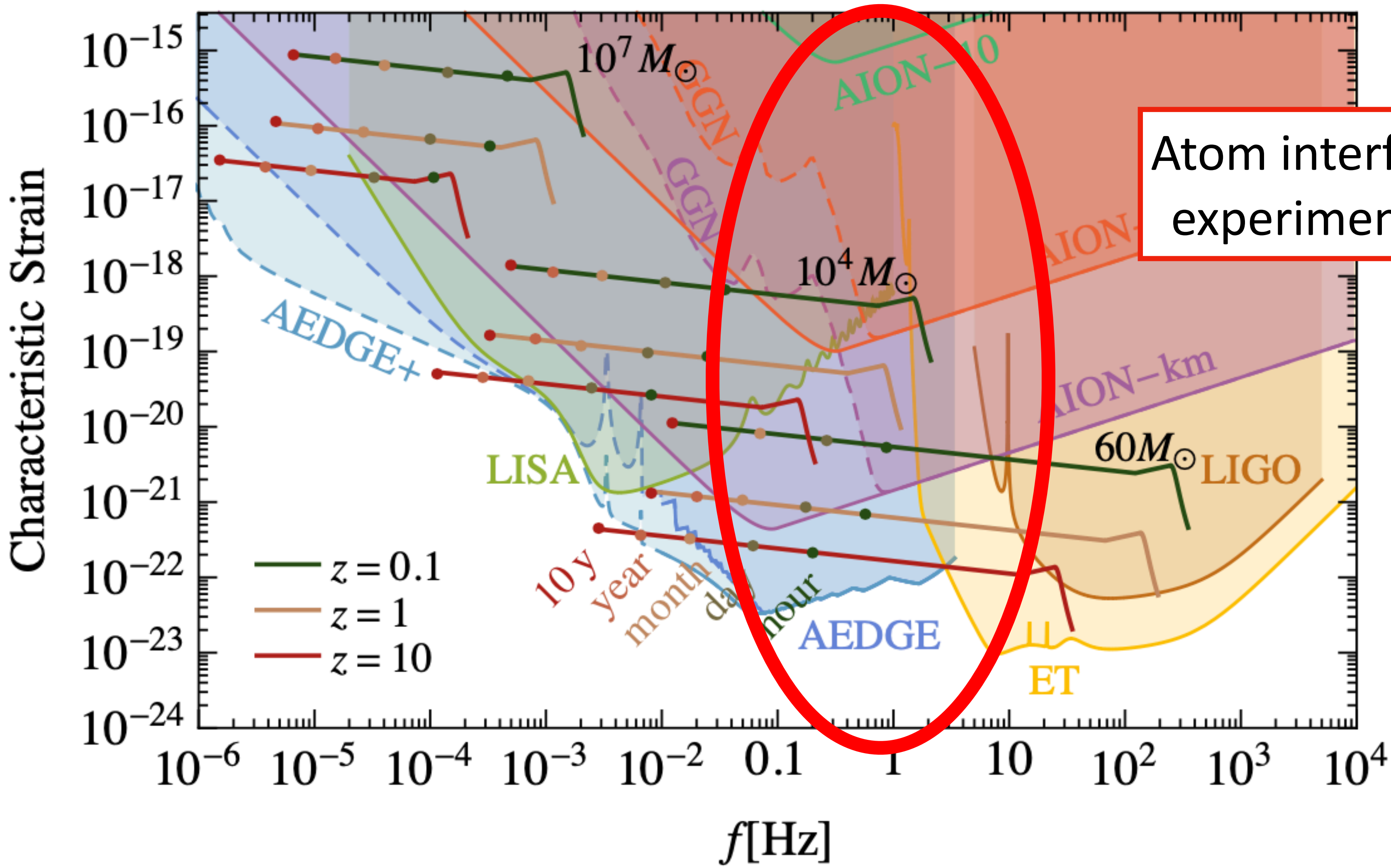
Gotthard Access Shafts



Gotthard Tunnel Layout



Gravitational Waves from IMBH Mergers



Atom interferometer experiments: AION

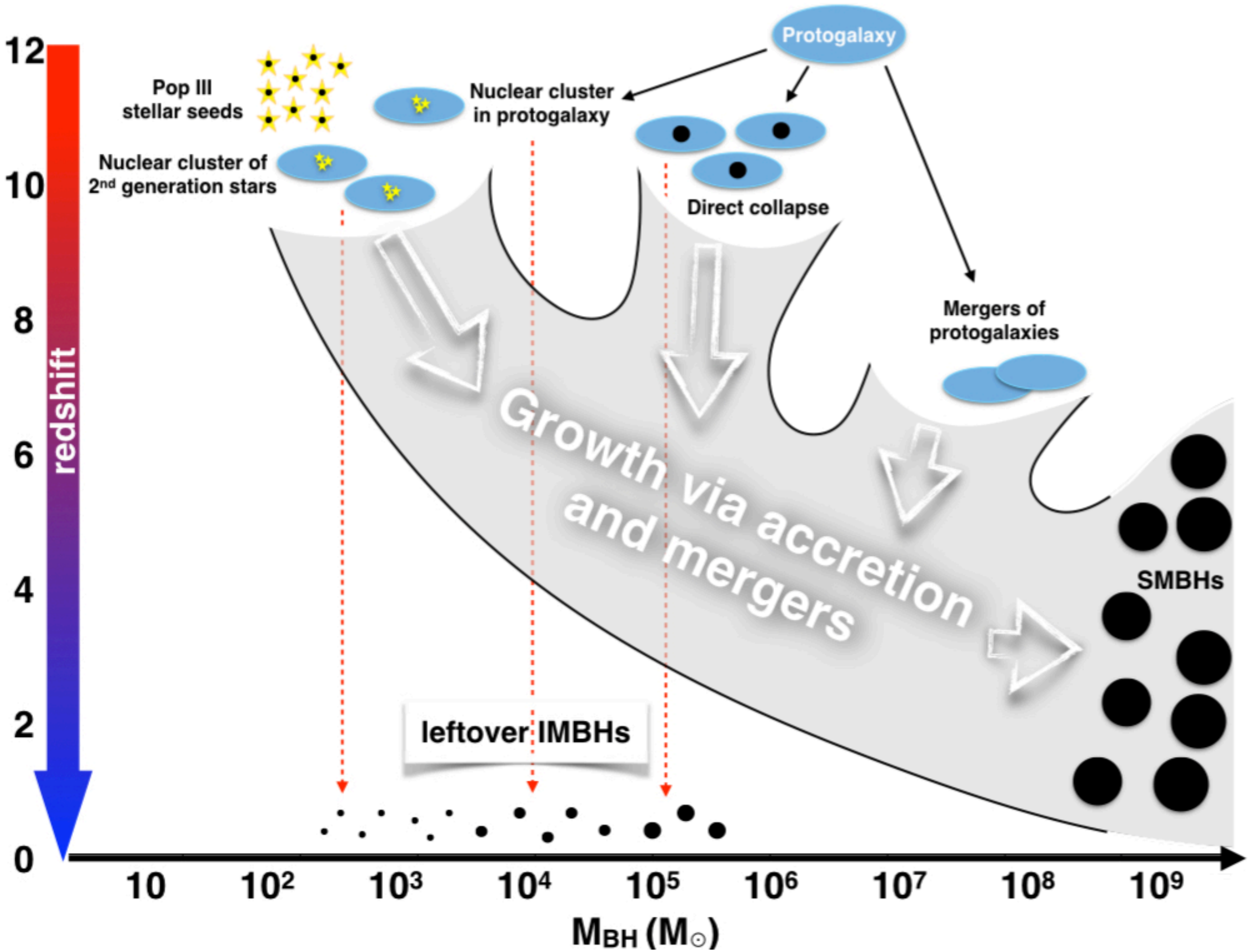
Probe formation of SMBHs

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

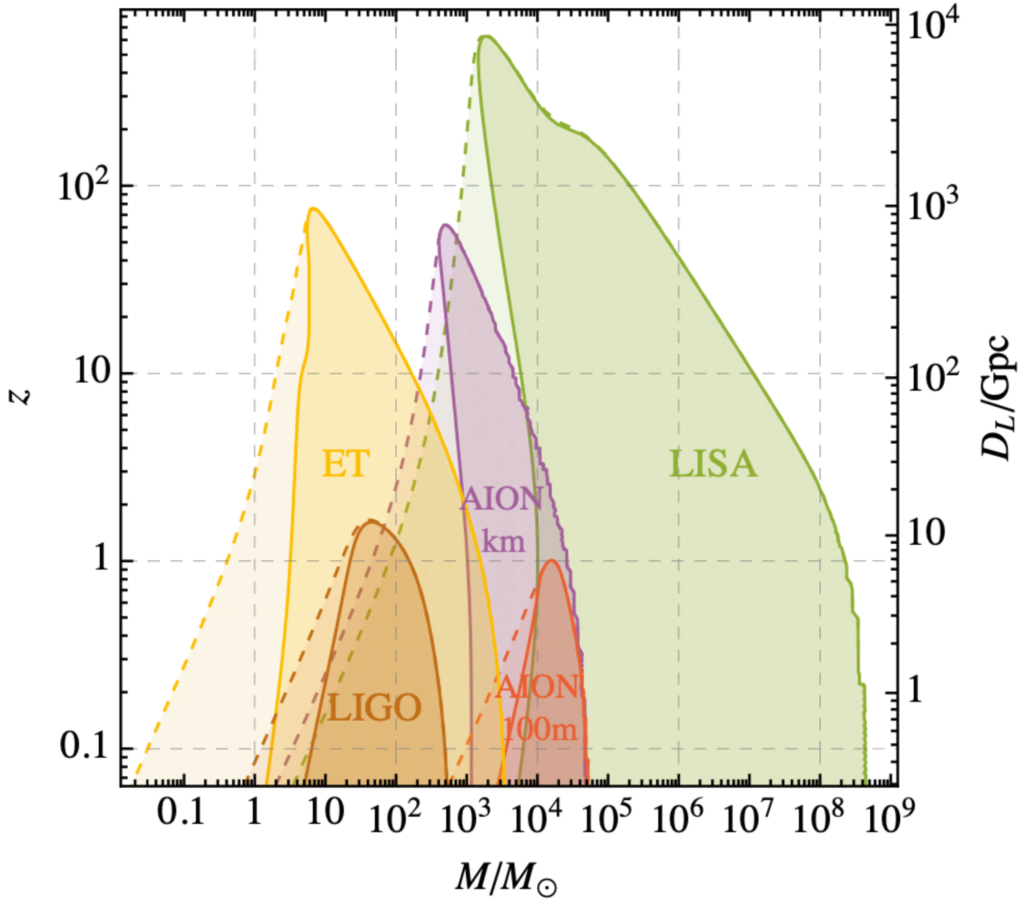
Badurina, Buchmueller, JE, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

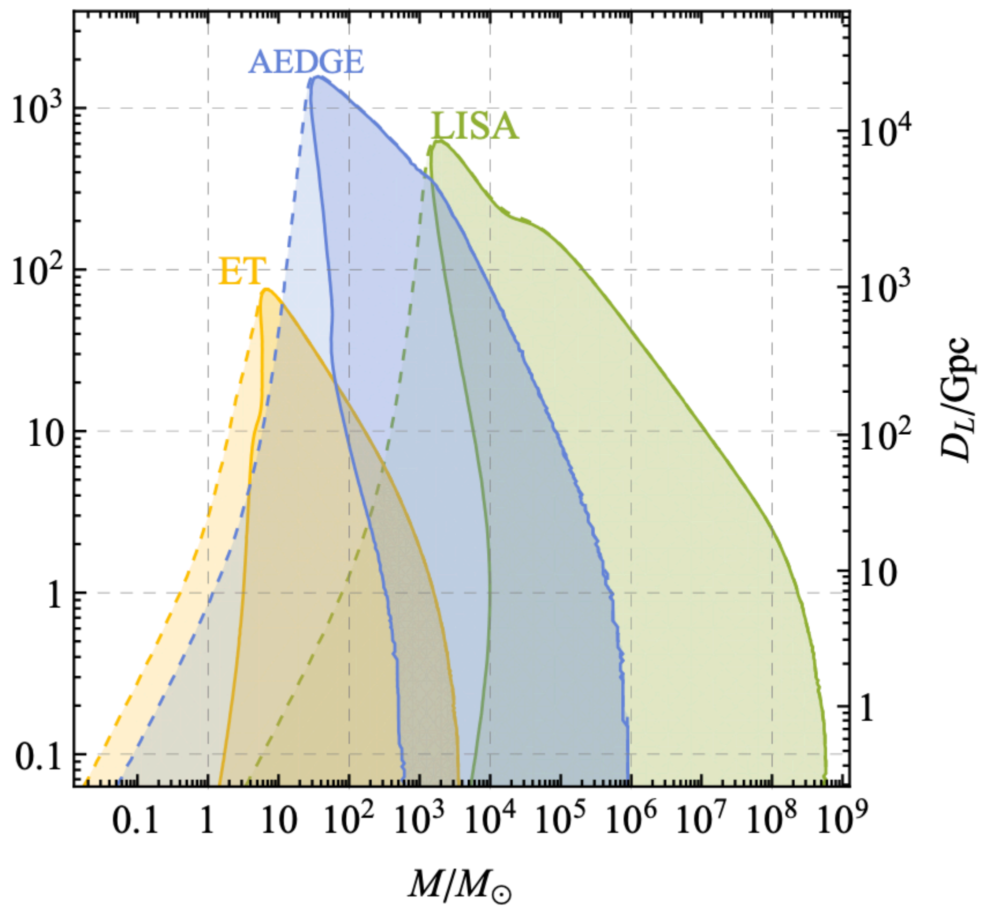
How to Make a Supermassive BH?

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



SNR = 8 Sensitivities to GWs from Mergers



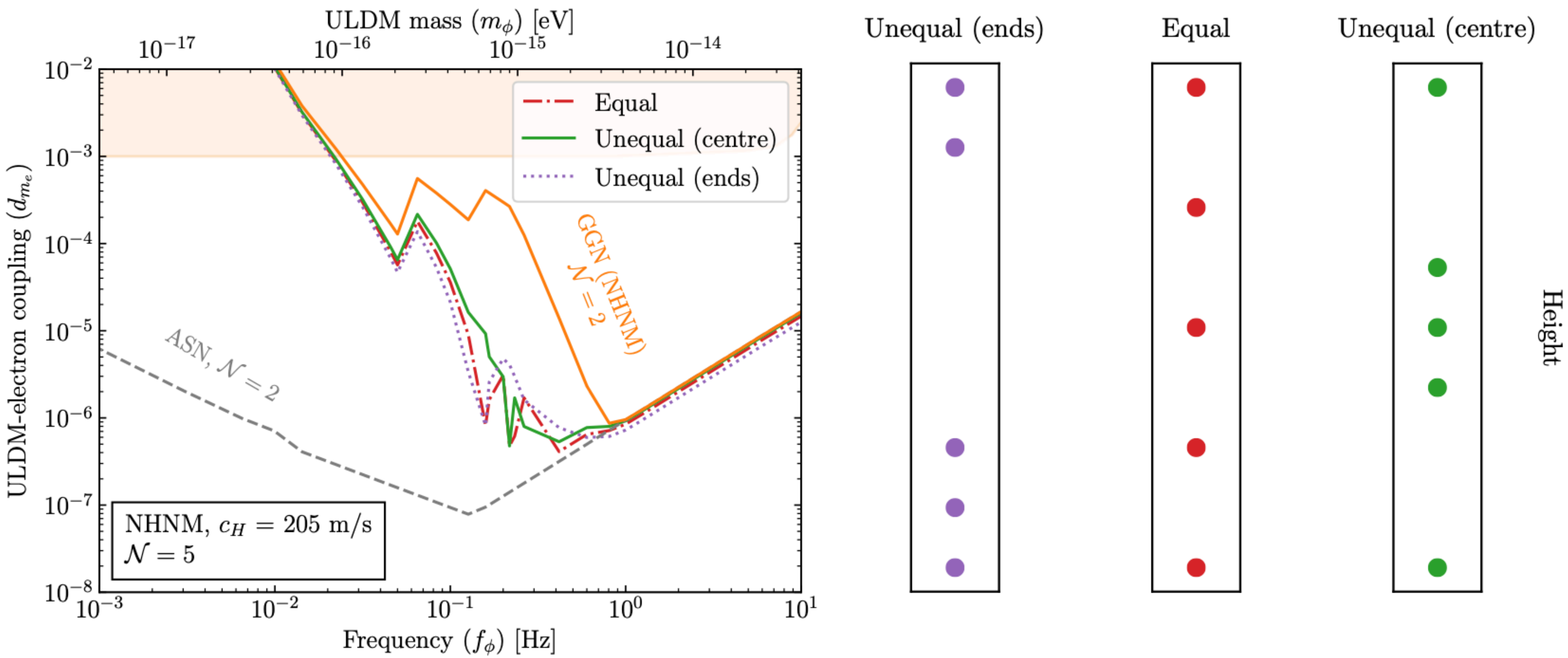


In the lighter regions between the dashed and solid lines the corresponding detector observes only the inspiral phase.

AION, arXiv:1911.11755

AEDGE, arXiv:1908.00802

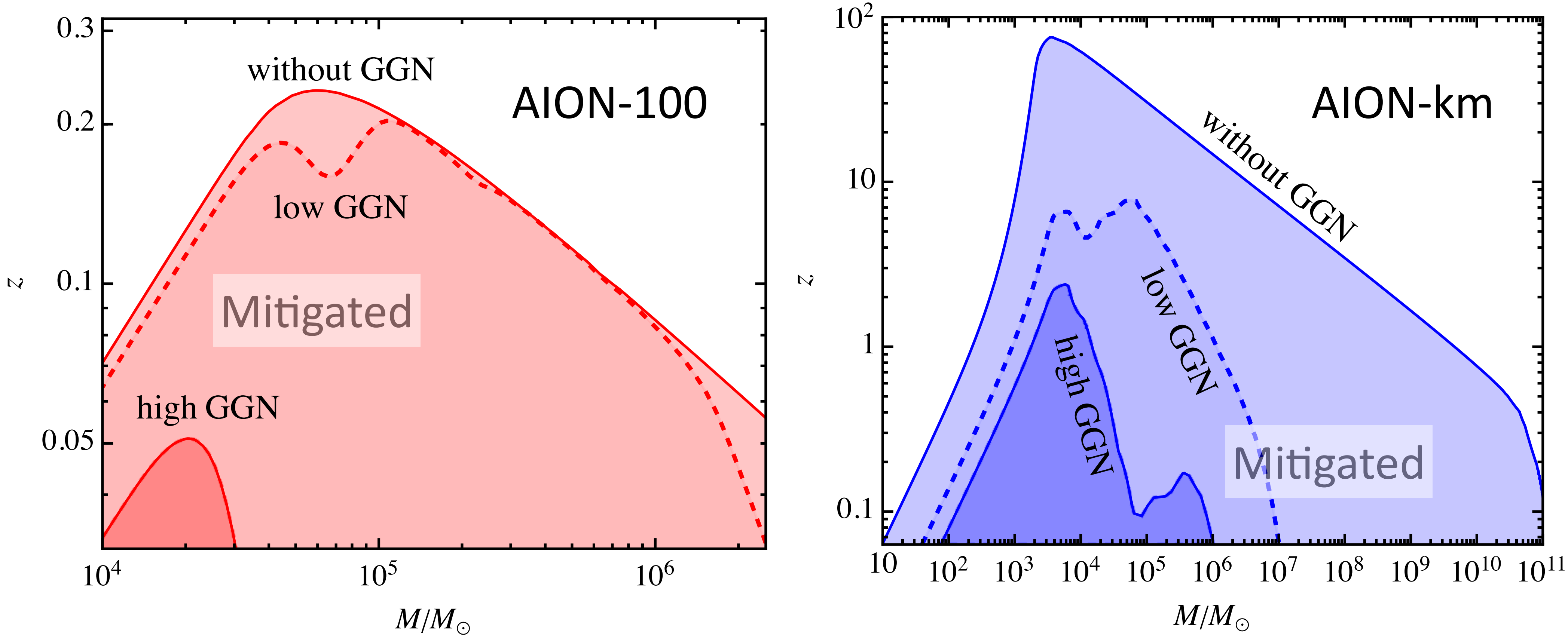
GGN Mitigation for AION-km



Assuming GGN level and rock properties similar to CERN studies for AION-100

Badurina, Gibson, McCabe & Mitchell, arXiv:2211.0854

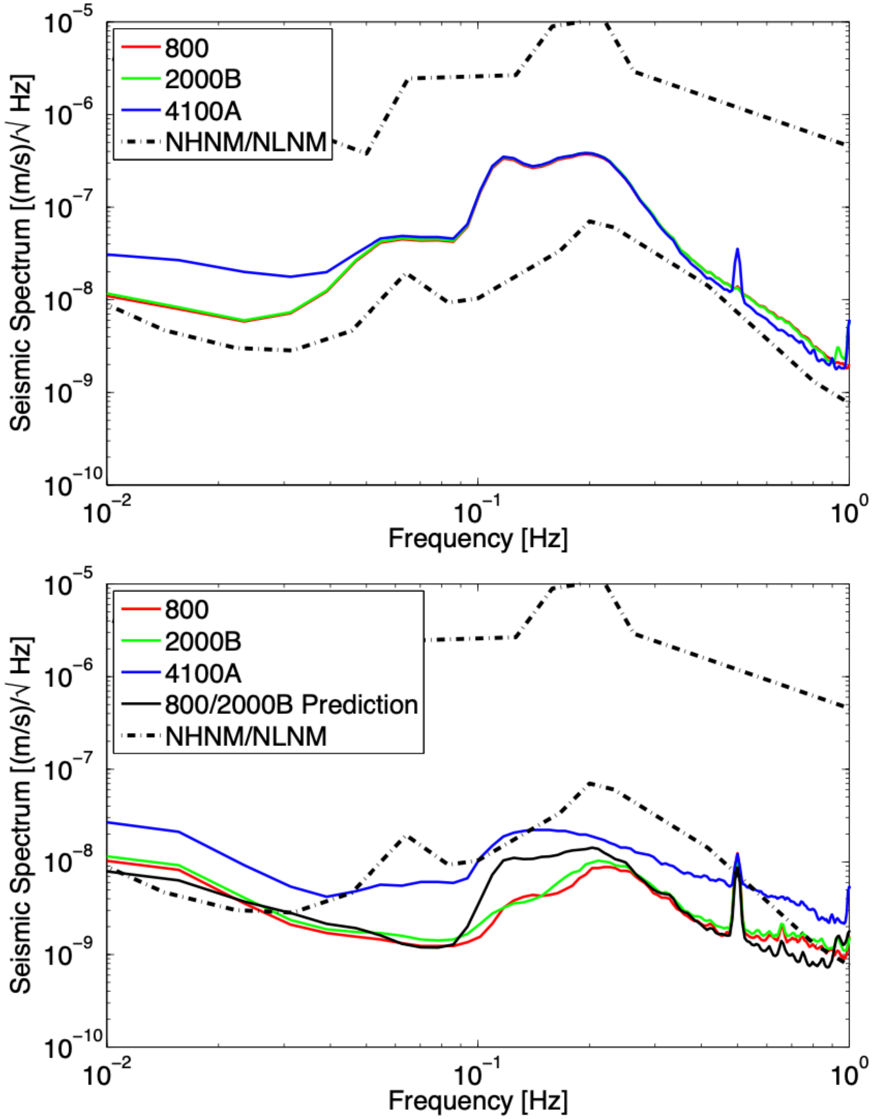
Searching for IMBH Mergers



GGN mitigated using multiple interferometers;
further mitigation possible with external seismometer network,
to be studied

Vaskonen, AION Collaboration

Gravity Gradient Noise Deep Underground

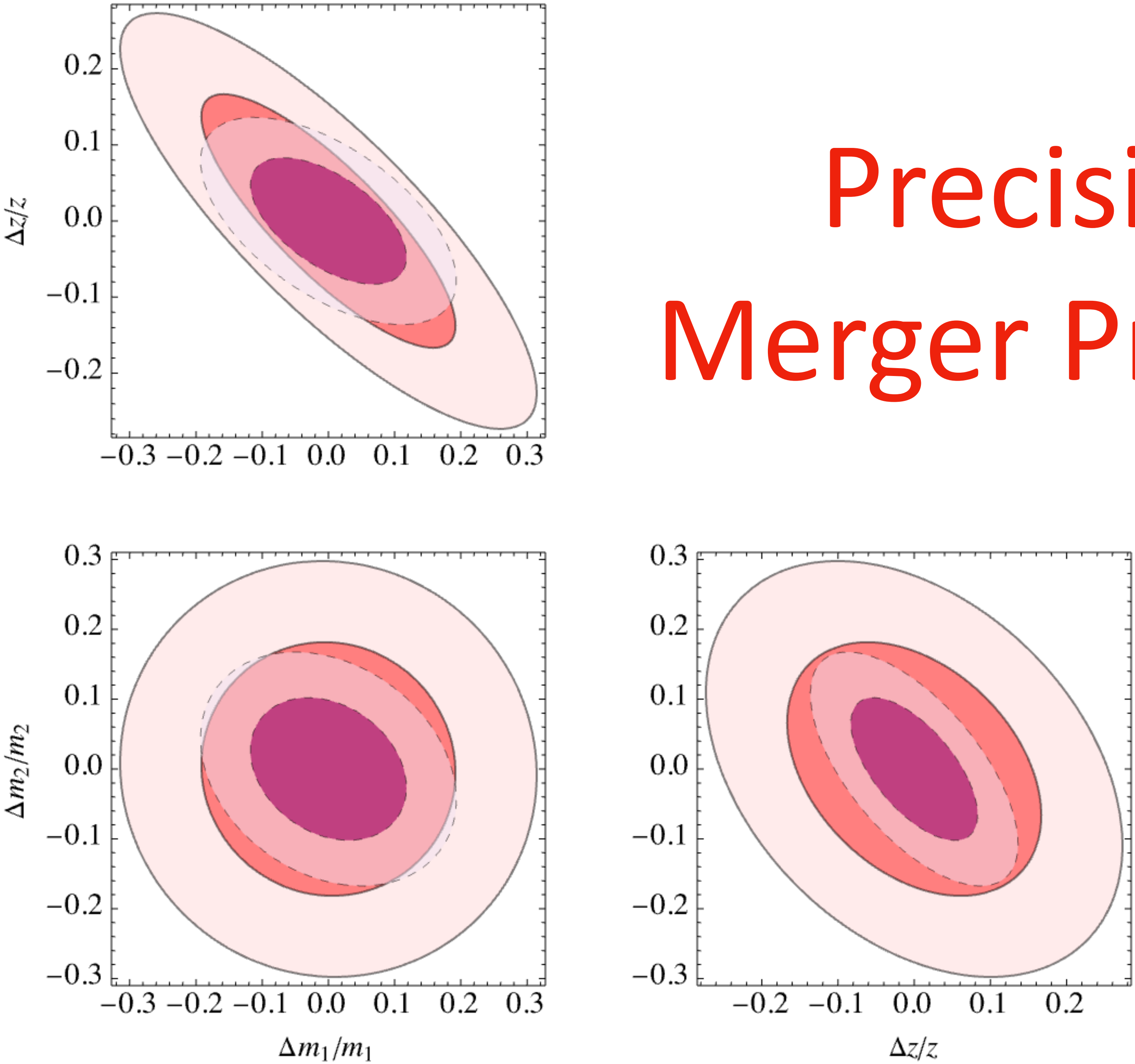


SURF measurements close to Peterson NLNM

Can mitigate by Wiener filtering using array of seismometers

Coughlin, Harms, Christensen, Dergachev, DeSalvo, Kandhasamy & Mandic: arXiv:1403.7756

Precision of Merger Prediction



AION-km

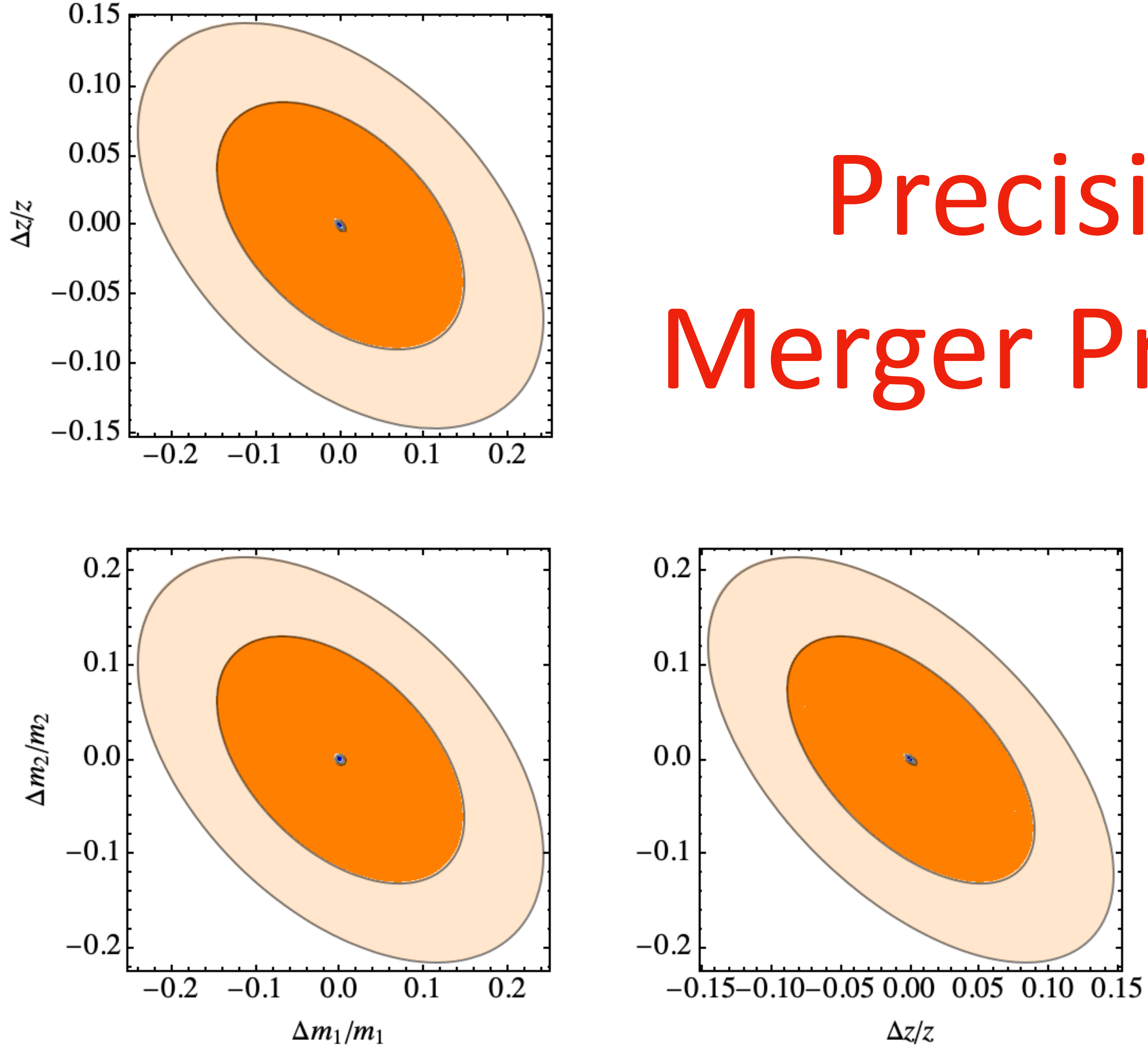
more precise than

LISA

(200, 800) solar masses at z = 4

JE, Fairbairn, Urrutia & Vaskonen *in preparation*

Precision of Merger Prediction



AEDGE

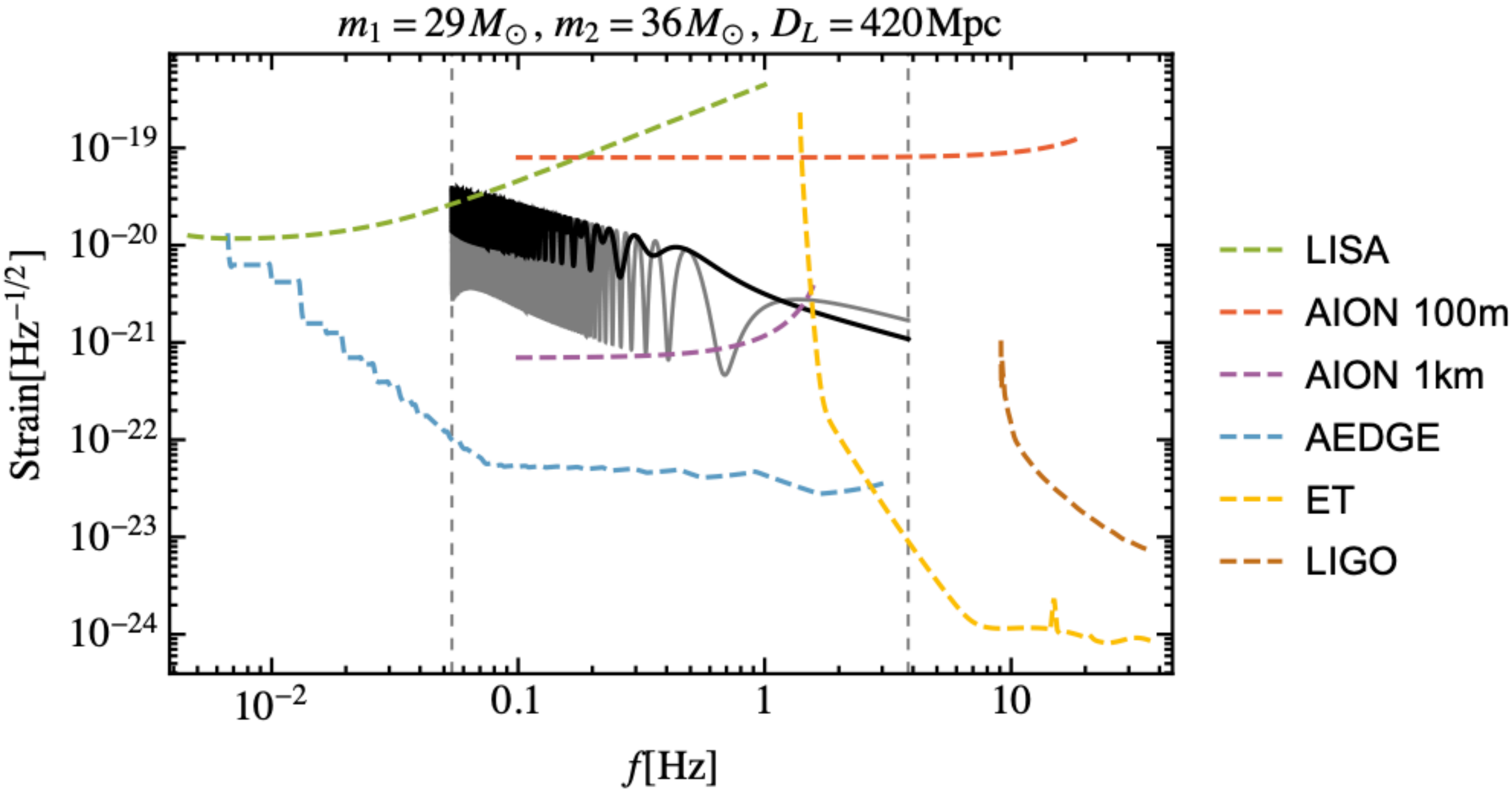
more precise than

LISA

(200, 800) solar masses at z = 4

JE, Fairbairn, Urrutia & Vaskonen *in preparation*

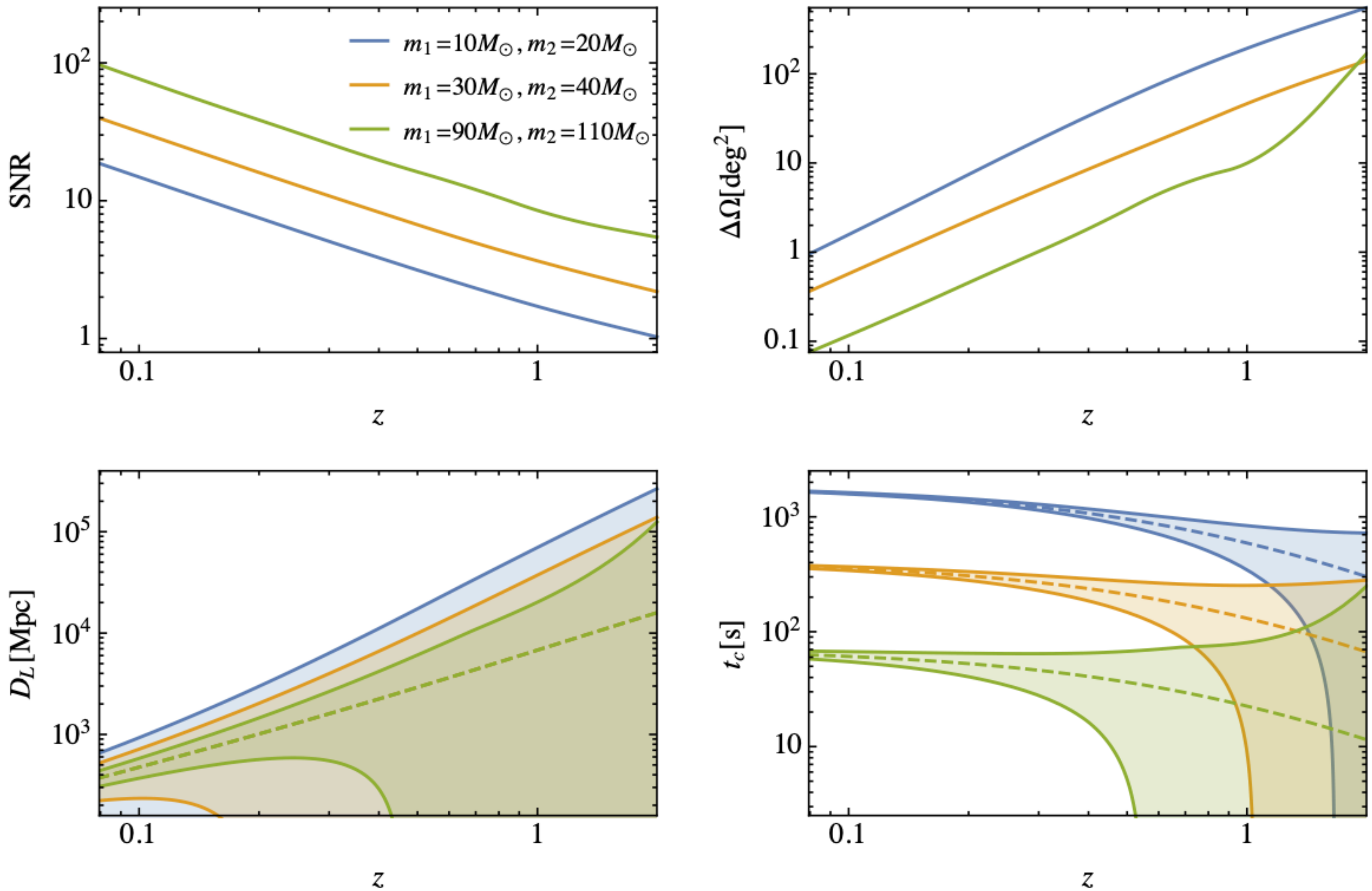
Synergies with Higher-Frequency Experiments



Inspiral waveforms for **ground**-/space-based detectors

JE & Vaskonen: arXiv:2003.13480

Synergies with Higher-Frequency Experiments



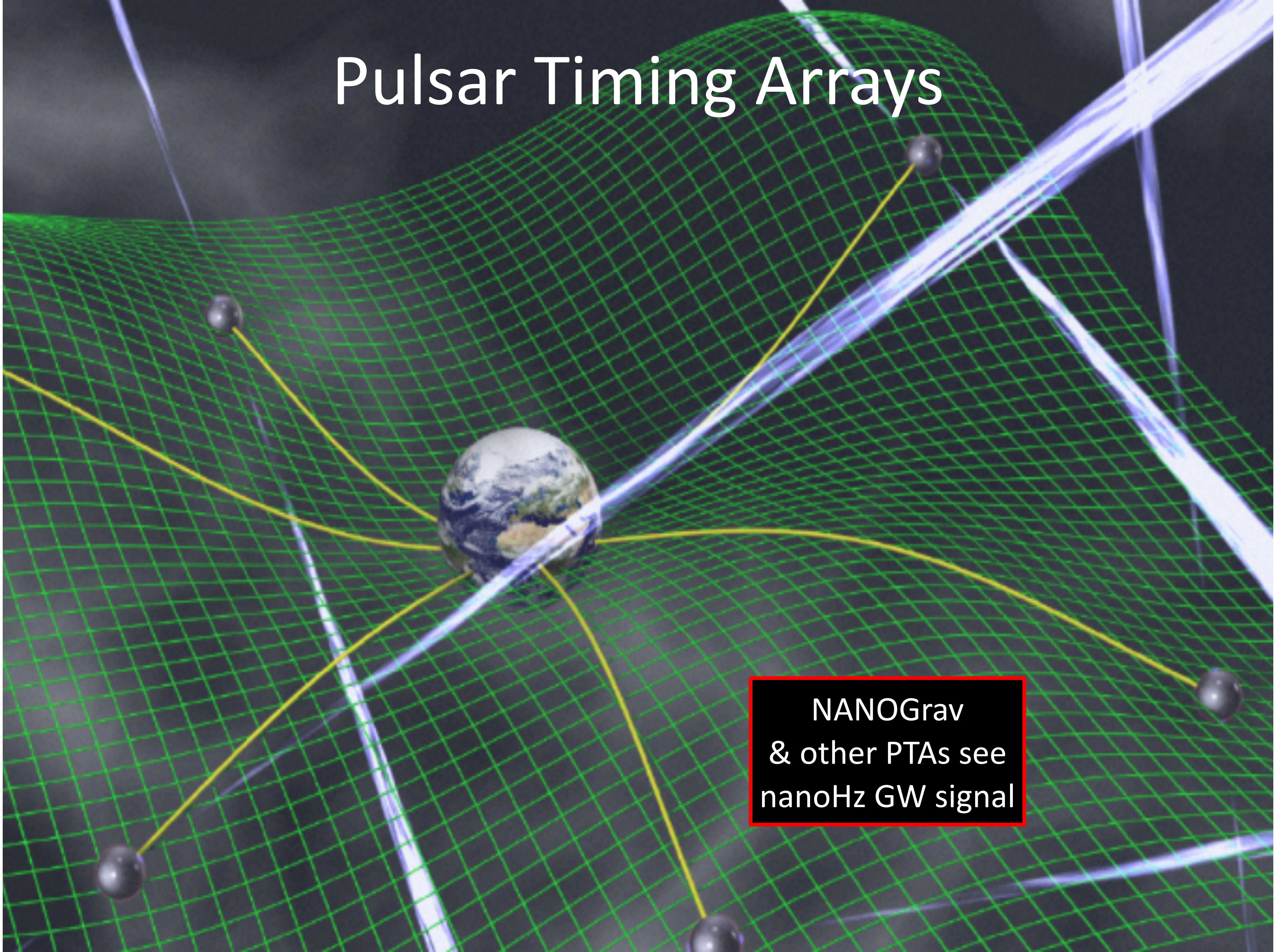
Predictions for future LVK/ET/CE measurements:

Direction, distance, time of merger

Prepare for multi-messenger observations

JE & Vaskonen: arXiv:2003.13480

Pulsar Timing Arrays



The Biggest Bangs since the Big Bang?

AION

BH Merger Rate Estimate

BH merger rate $R_{\rm BH}$

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

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

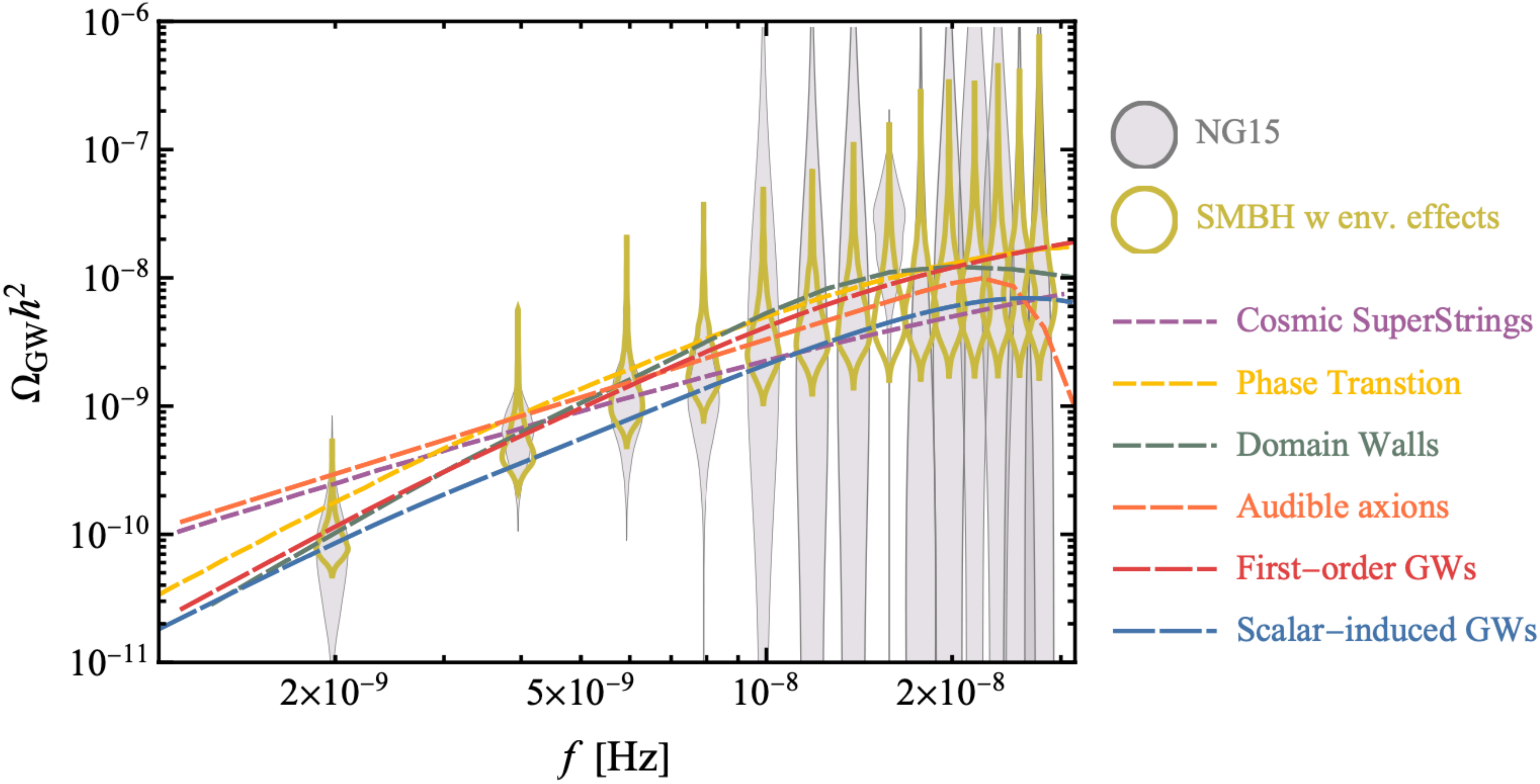
$$p_{\rm BH} \equiv p_{\rm occ}(m_1)p_{\rm occ}(m_2)p_{\rm merg}$$

is merger probability, and

strength of IPTA signal can be fitted by constant $p_{\rm BH}$

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

Fits to NANOGrav

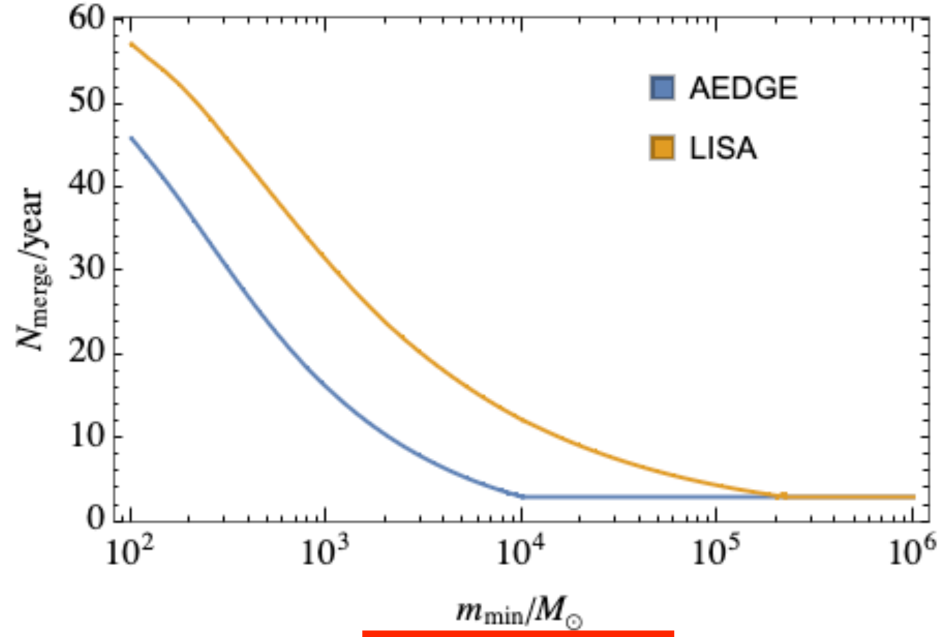


JE, Fairbairn, Franciolini, Hütsi, Iovino, Lewicki, Urrutia, Vaskonen & Veermäe, arXiv:2308.08546

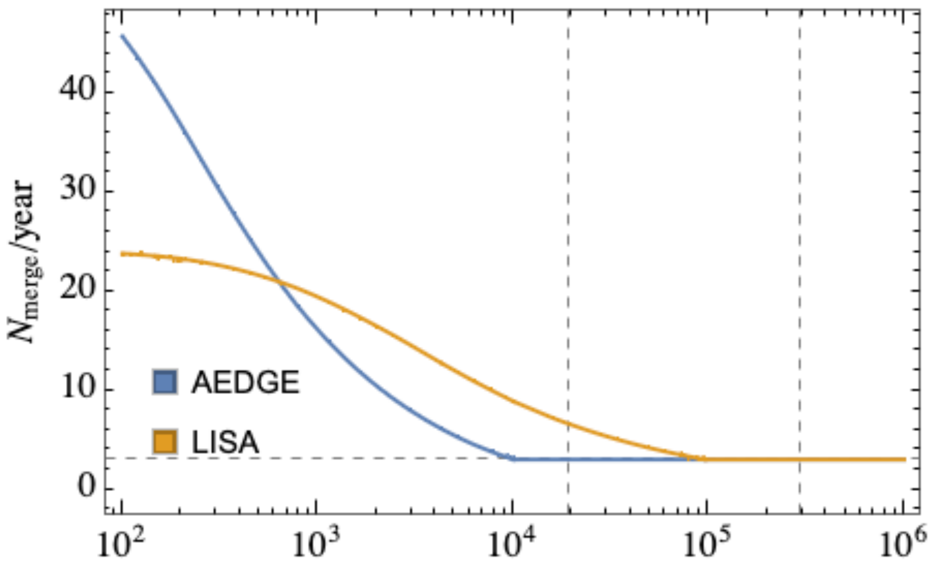
Rates in Model with 10^3 Solar Mass Seeds

LISA loses events before merger

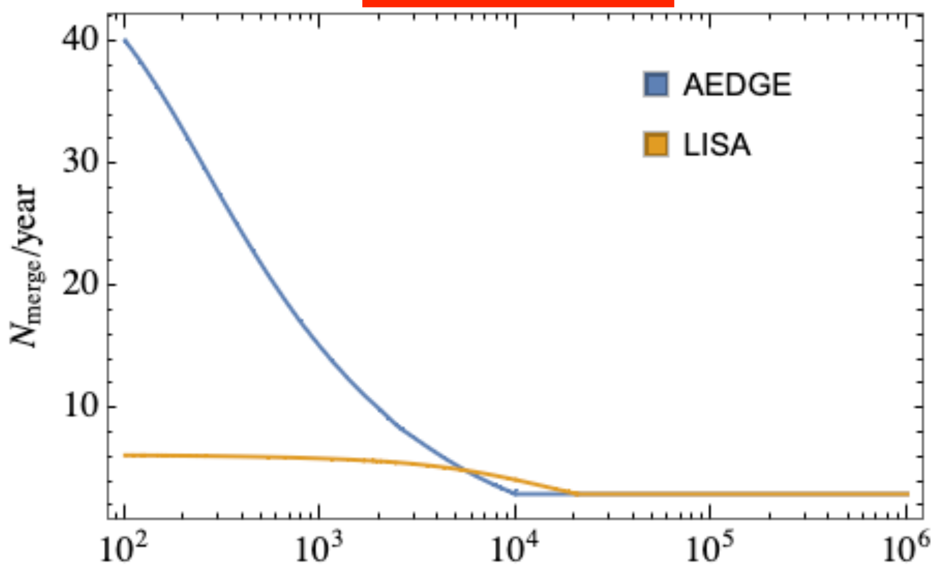
1 *year* to merge



1 *h* to merge

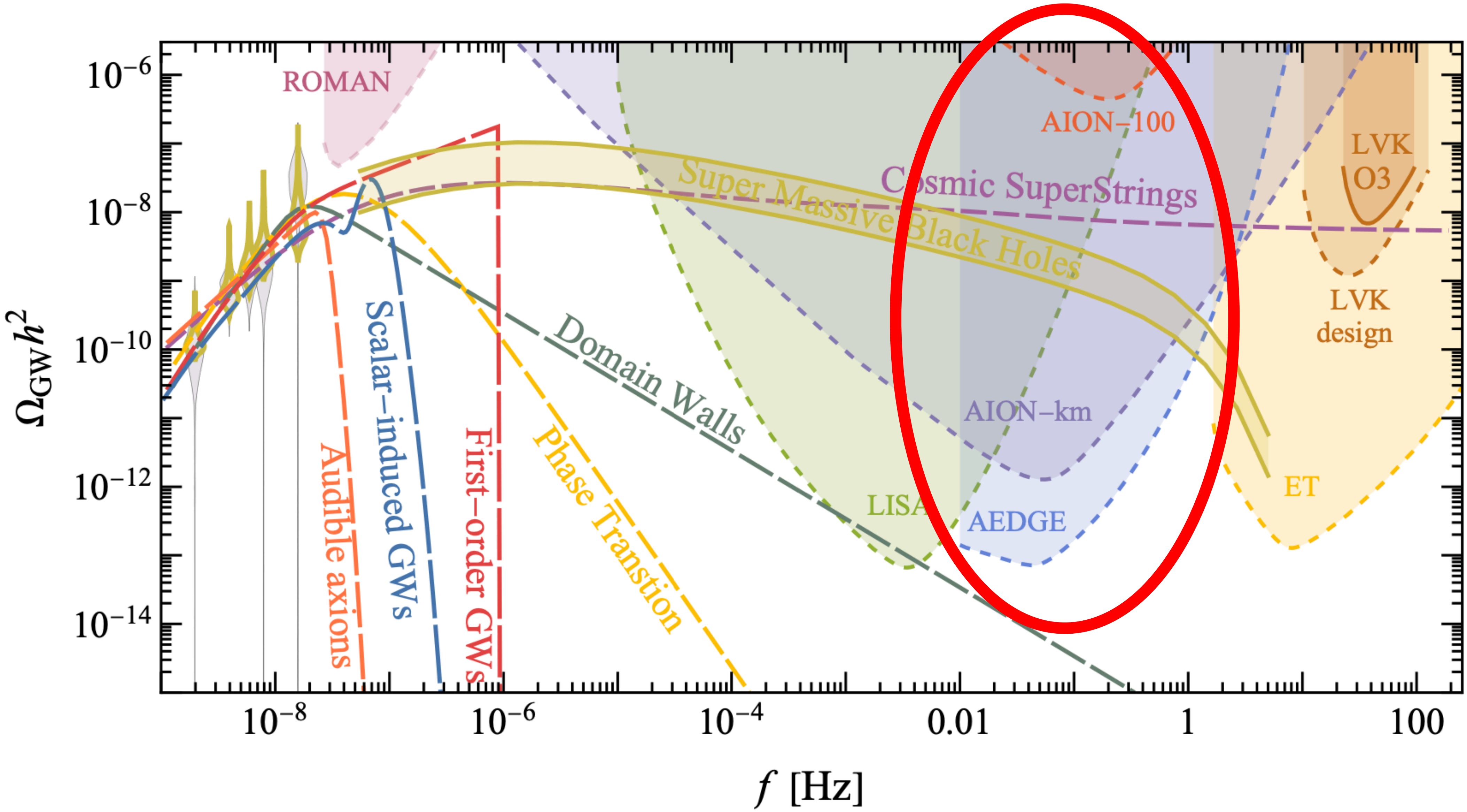


1 *min* to merge



JE, Fairbairn, Urrutia & Vaskonen *in preparation*

Extension of Fits to Higher Frequencies AION



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

Summary

- Atom interferometry is a promising new technology
- AION Collaboration making progress with R&D
- Advanced plans for 10-m prototype detector @ Oxford, sites for 100-m and km including Boulby, CERN & Switzerland being investigated
- Exploring sensitivity including effects of (mitigated) GGN
- Atom interferometers have interesting stand-alone science, also potential synergies with laser interferometers
- PTA data evidence for a SGWB that is potentially observable by atom interferometers

AEDGE, arXiv:1908.00802,
AION, arXiv:1911.11755,
AION, arXiv:2305.20060,
JE, Schneider & Buchmueller, arXiv:2306.17726,
Terrestrial VLBAI, arXiv:2310.08183