Setting the Science Scene:

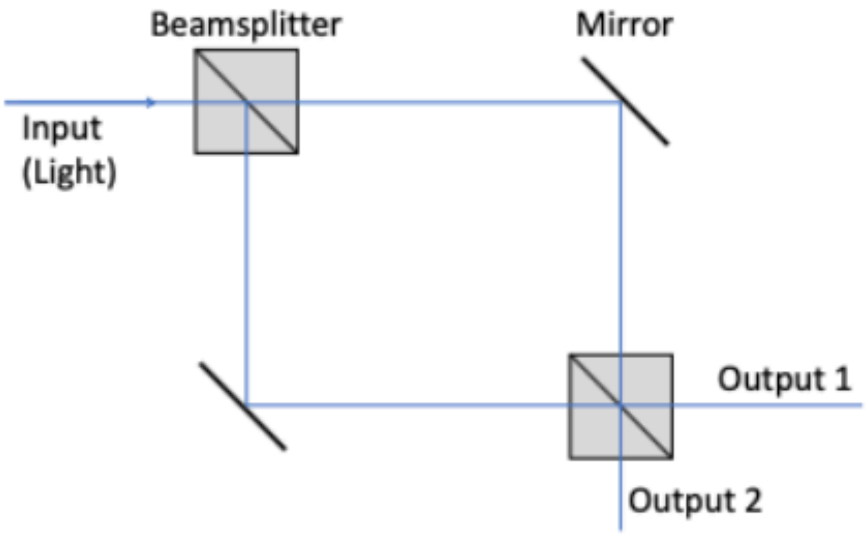
Ultralight Dark Matter & Gravitational Waves

King's College London

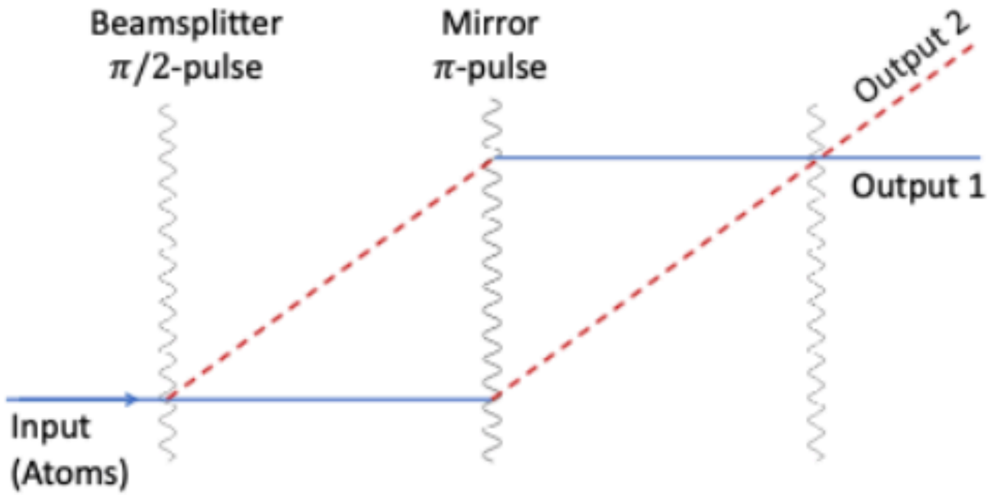
John Ellis

Principle of Atom Interferometry

Mach-Zehnder Laser Interferometer

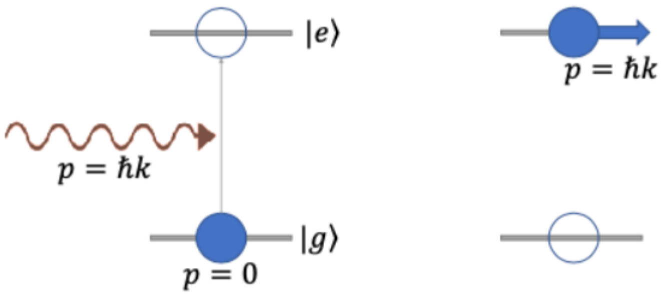


Atom Interferometer

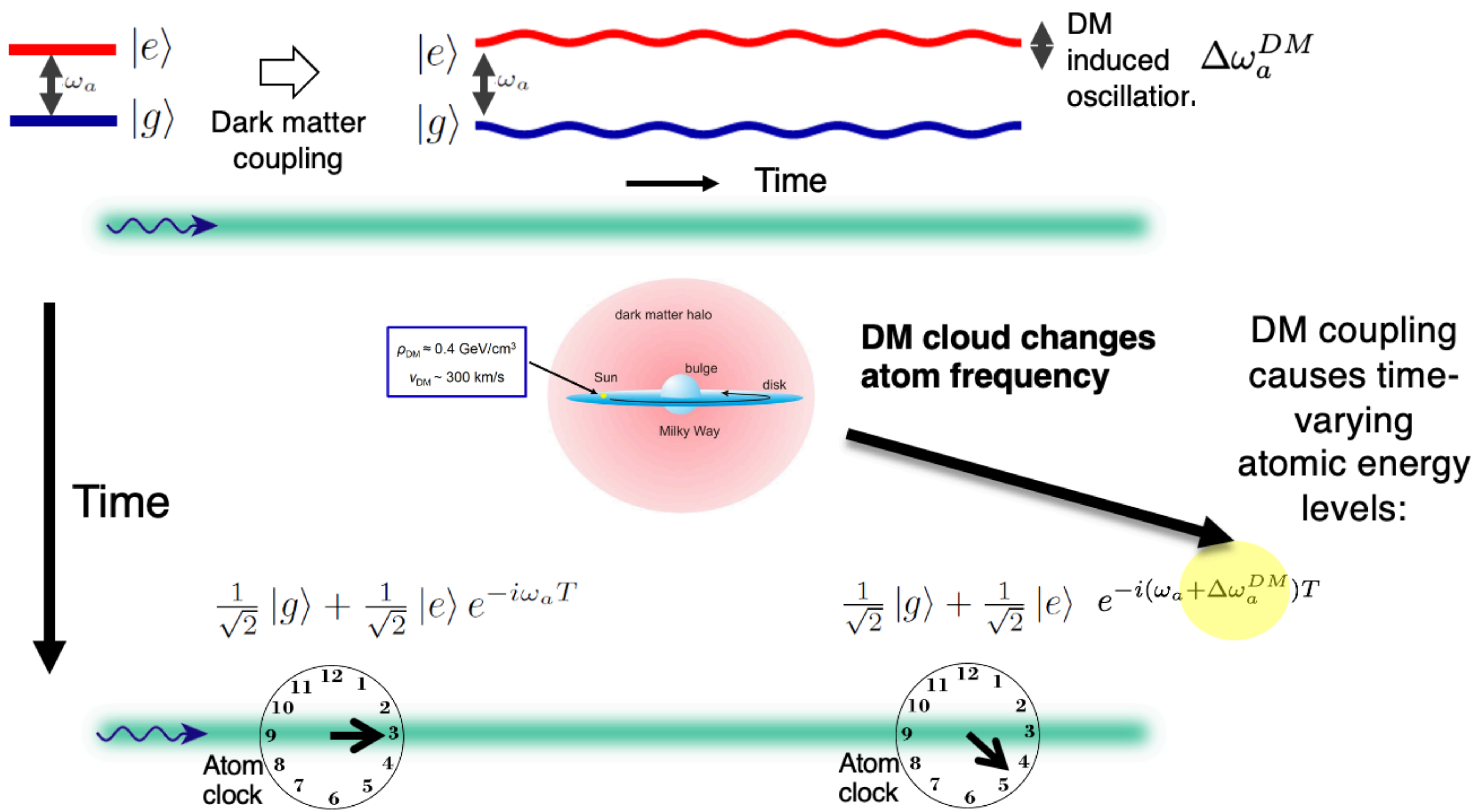


Laser excitation gives momentum kick to excited atom, which follows separated space-time path

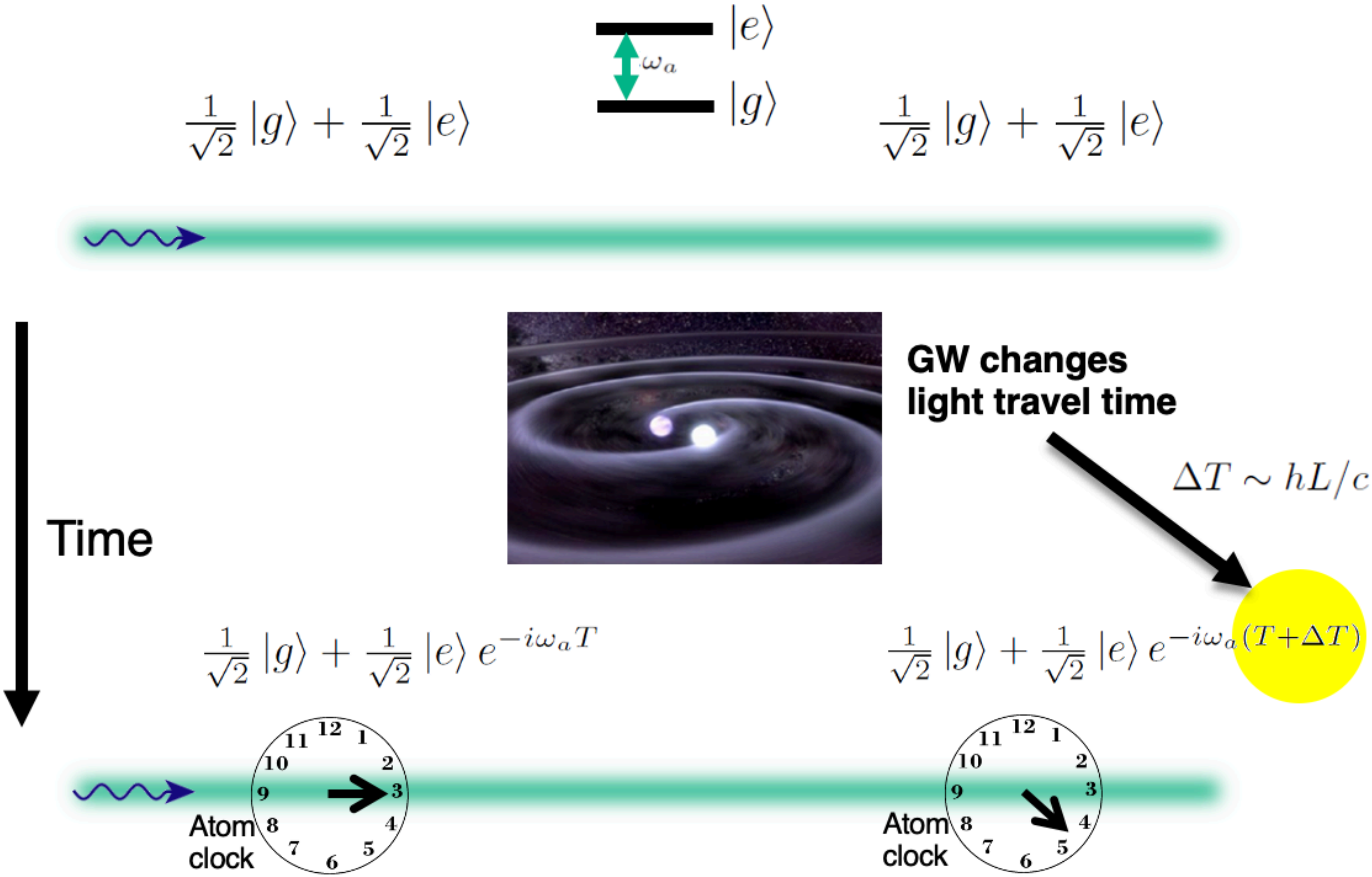
Interference between atoms following different paths



Effect of Dark Matter on Atom Interferometer

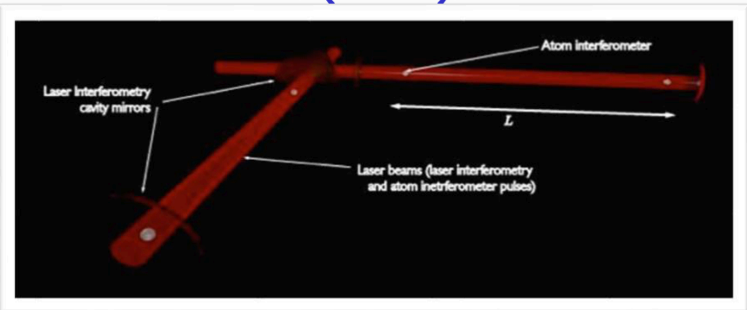


Effect of Gravitational Wave on Atom Interferometer

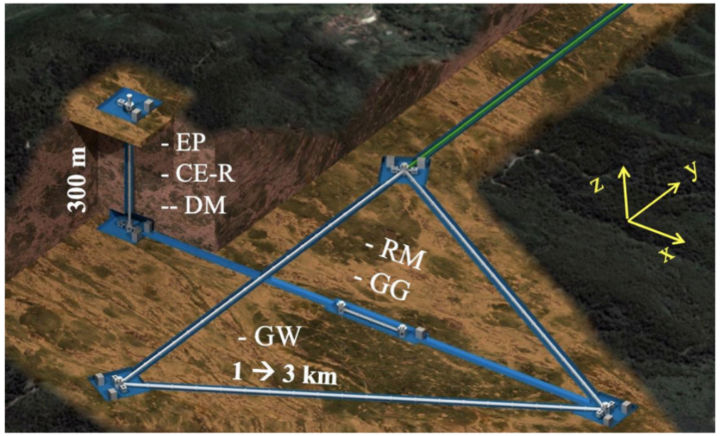


100m Projects around World

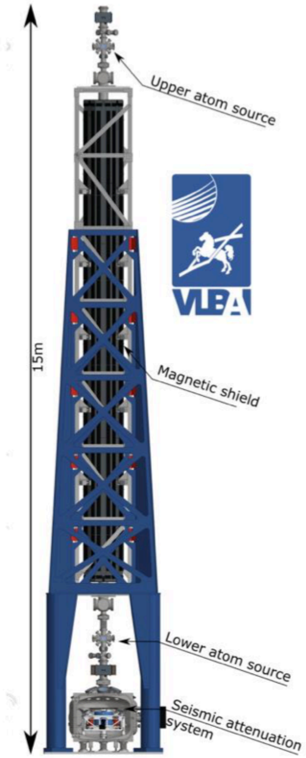
MIGA: Terrestrial detector using atom interferometer at O(100m)
(France)

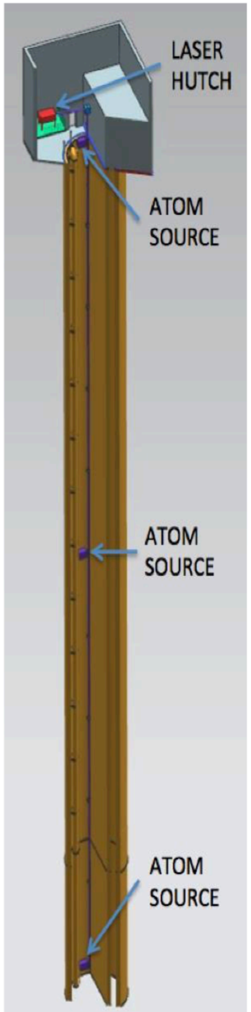


ZAIGA: Terrestrial detector for large scale atomic interferometers, gyros and clocks at O(100m)
(China)

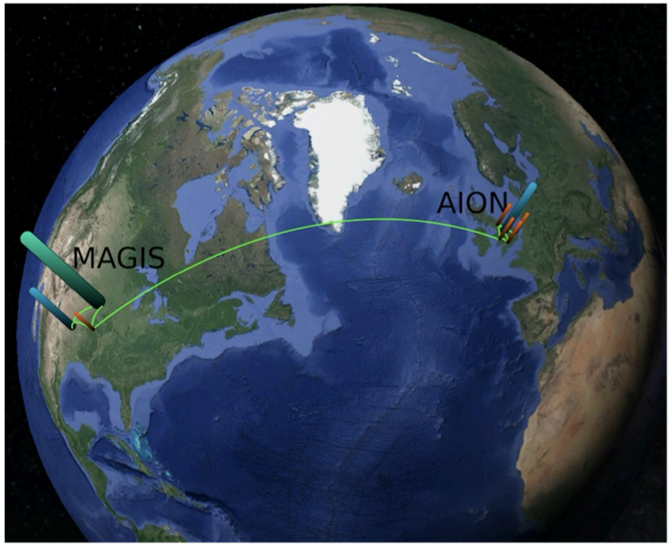


VLBAI: Terrestrial tower using atom interferometer O(10m)
(Germany)





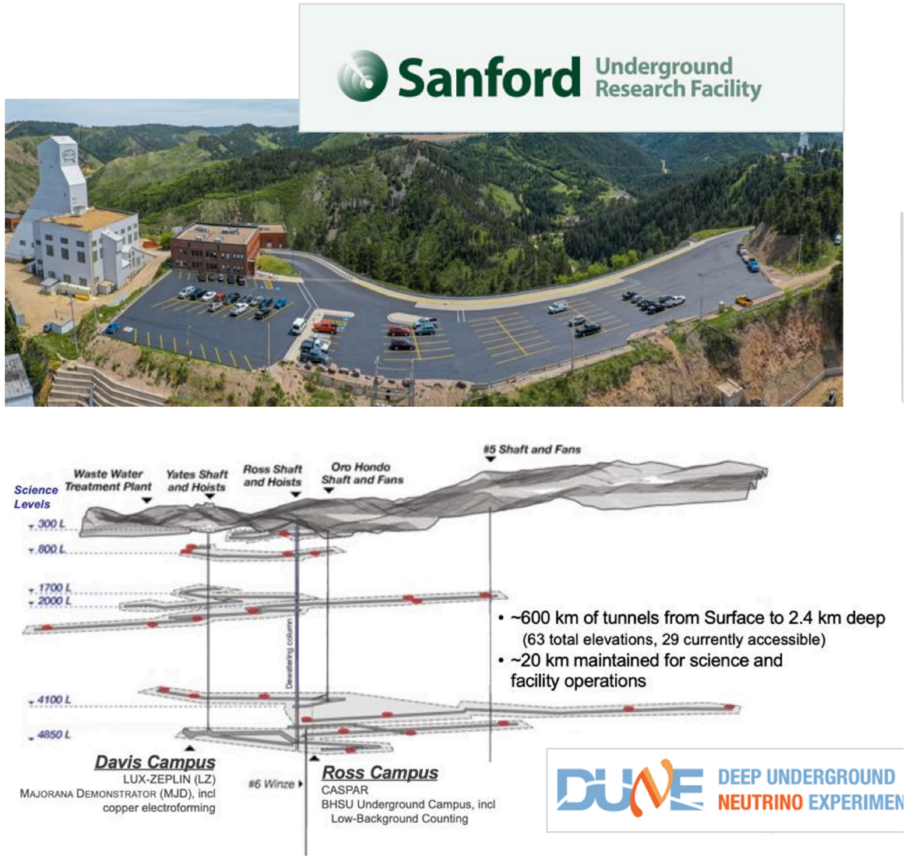
AION: Terrestrial shaft detector using atom interferometer at 10m – O(100m) planned
(UK)

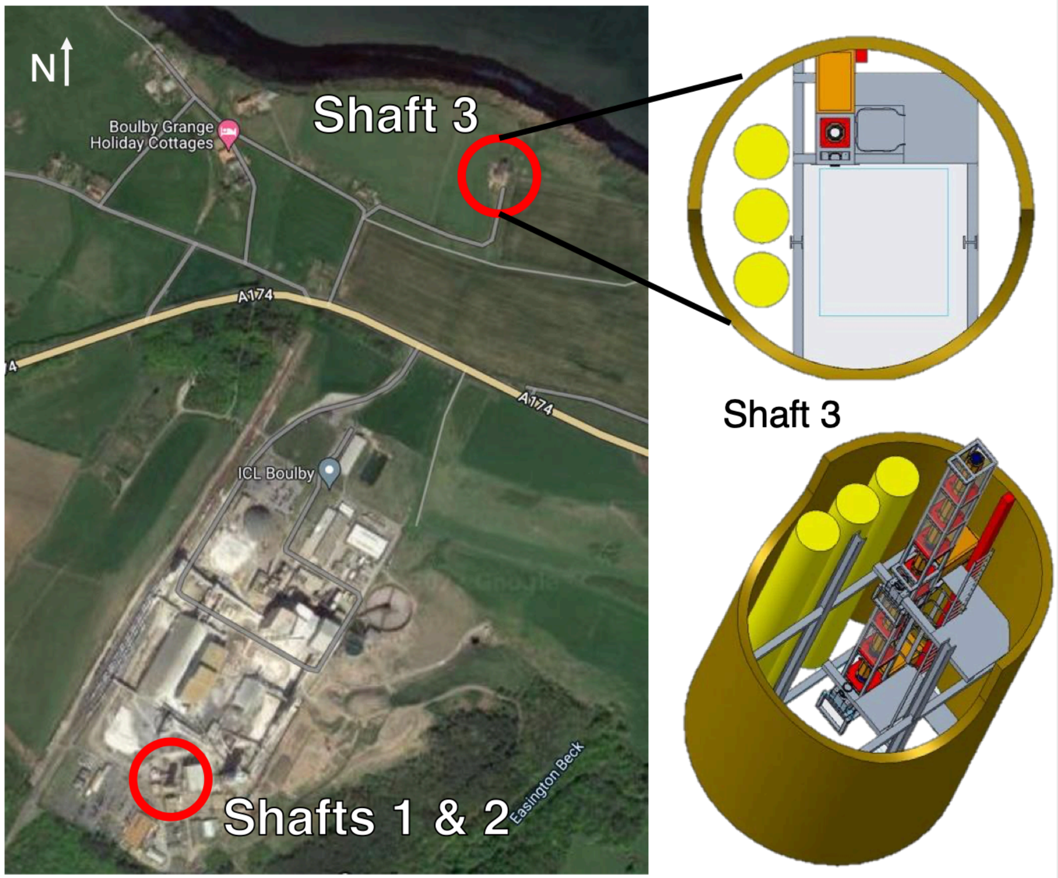


MAGIS: Terrestrial shaft detector using atom interferometer at O(100m)
(US)

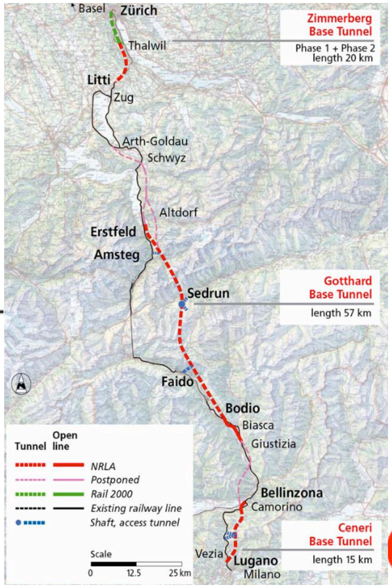
Planned network operation

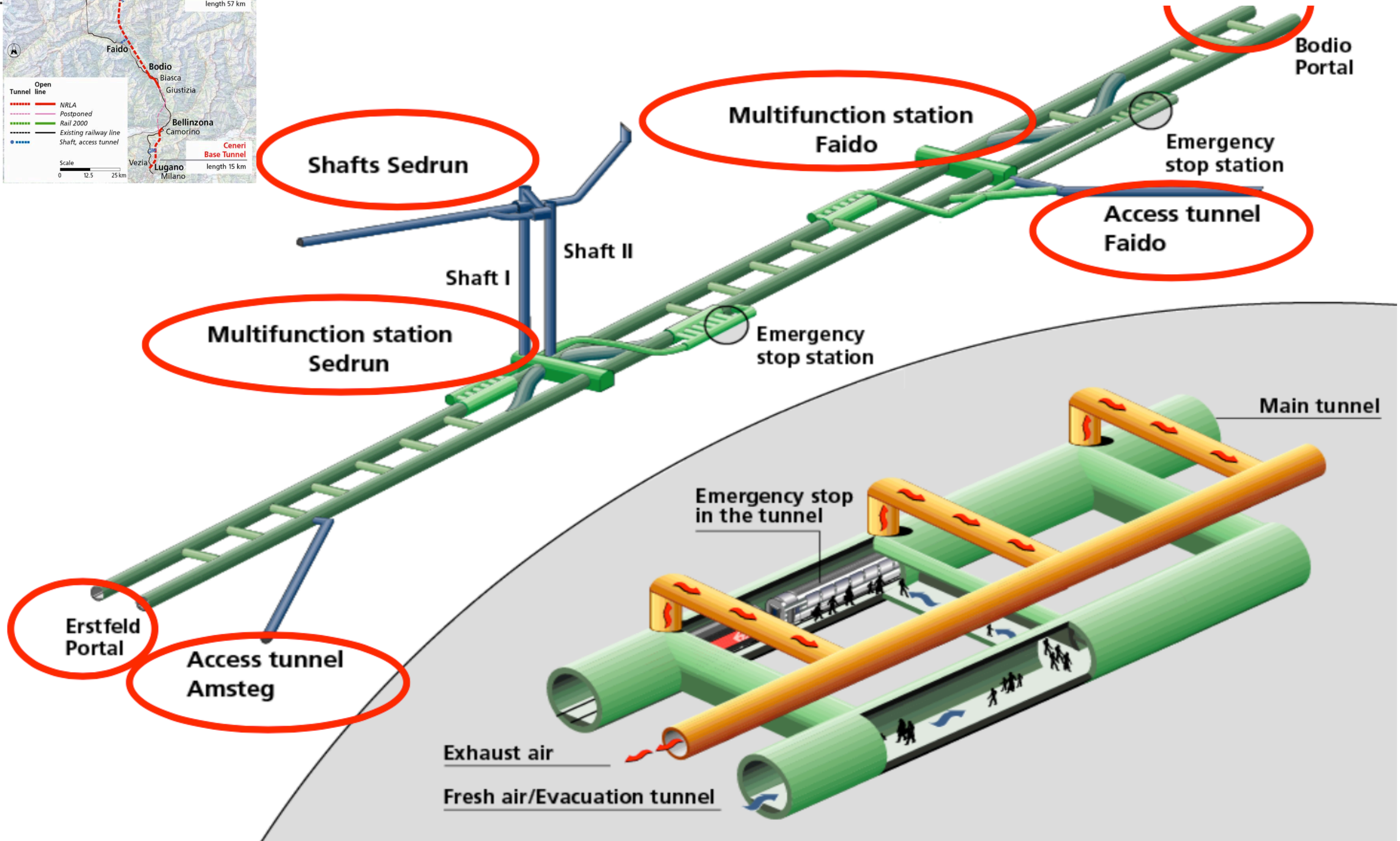
Examples of Possible 1km Sites





Gotthard Tunnel Layout

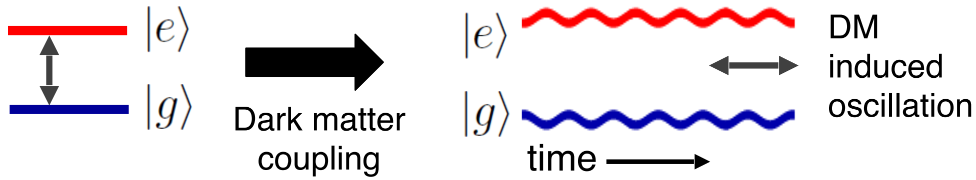


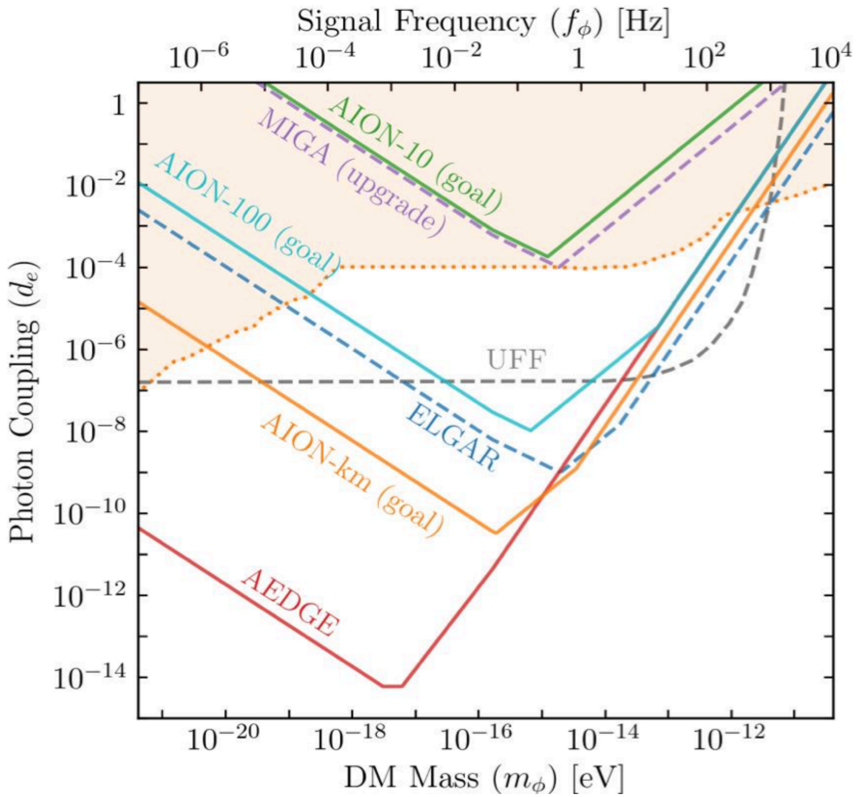


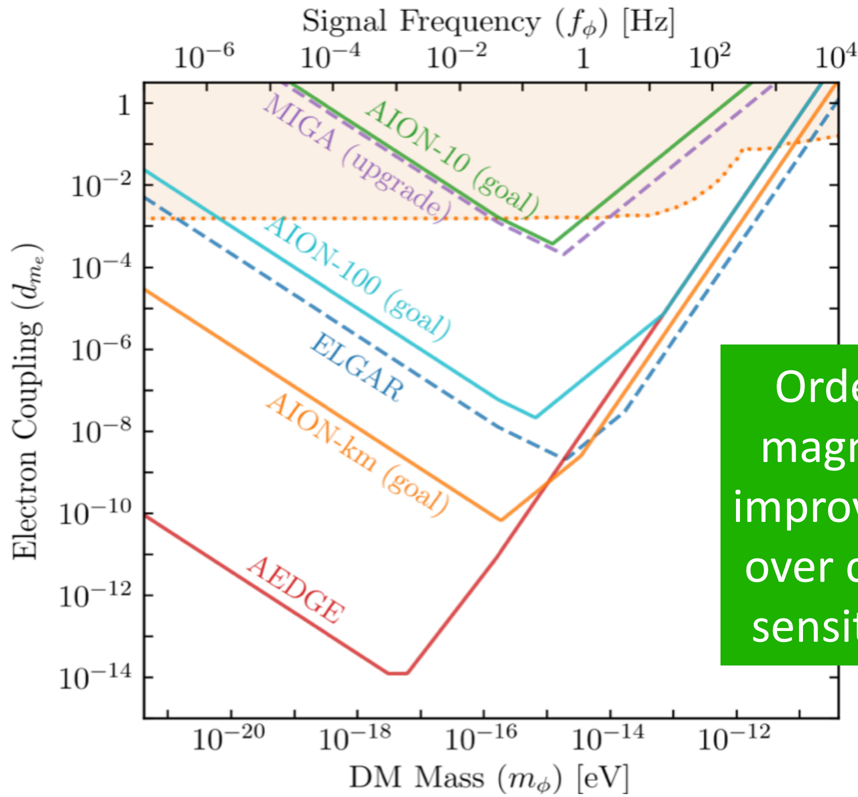
Searches for Light Dark Matter

Linear couplings to gauge fields and matter fermions

$$\mathcal{L}_{\mathrm{int}\phi} = \kappa\phi\left[+\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{d_g\beta_3}{2g_3}F^A_{\mu\nu}F^{A\mu\nu} - \sum_{i=e,u,d}(d_{m_i} + \gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right]$$





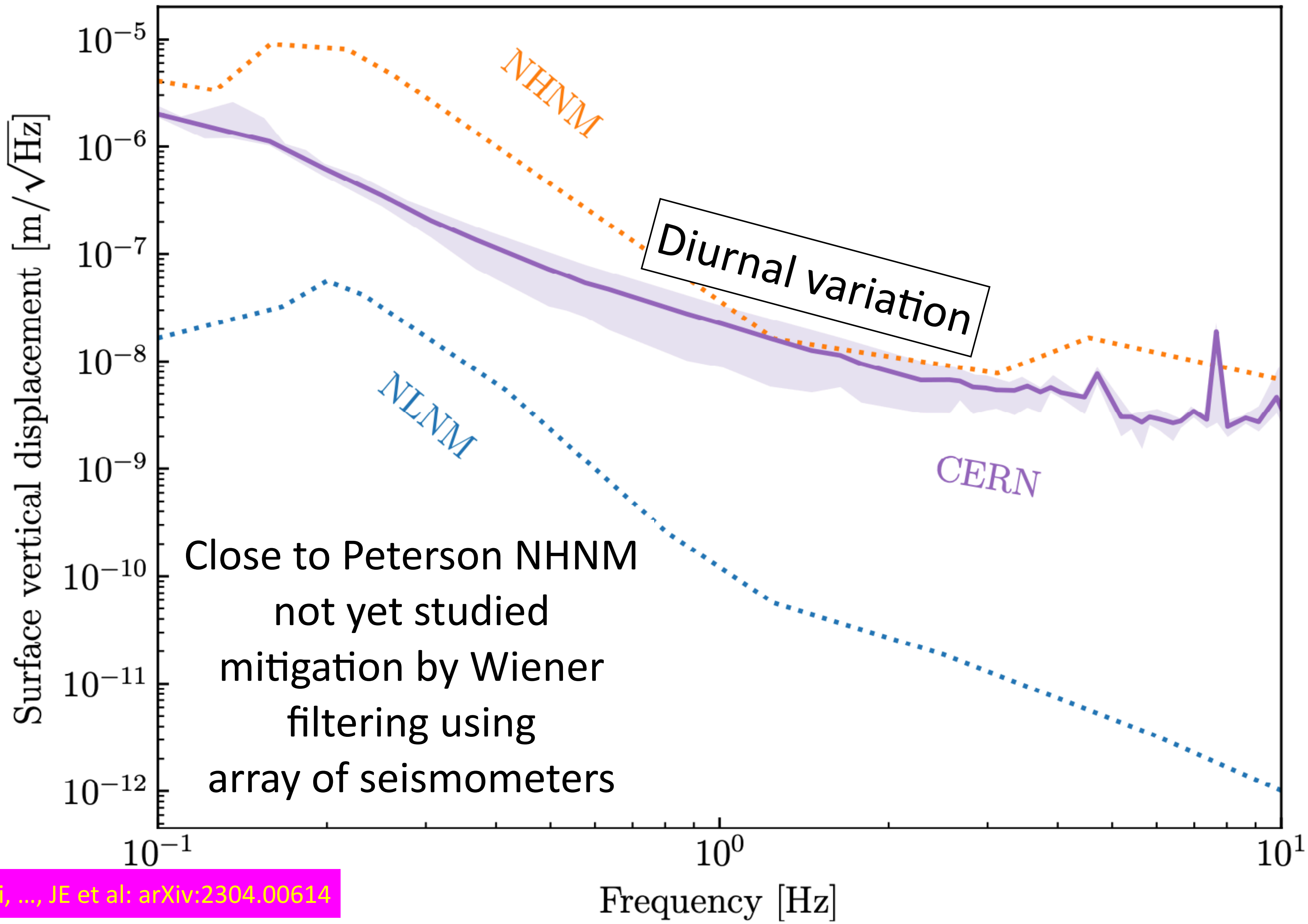


Orders of magnitude improvement over current sensitivities

AION Collaboration (Badurina, ..., JE et al): arXiv:1911.11755; Badurina, Buchmueller, JE, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

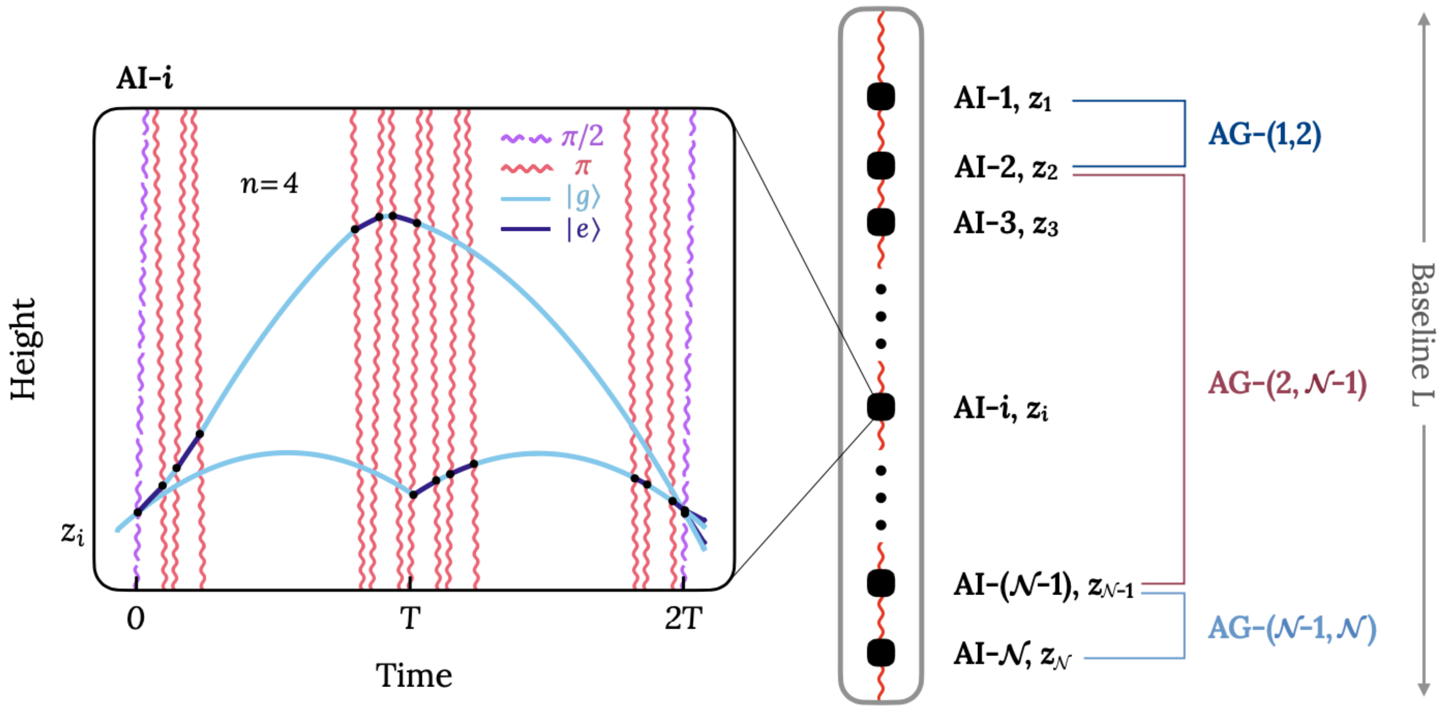
Gravity Gradient Noise @ CERN

AION



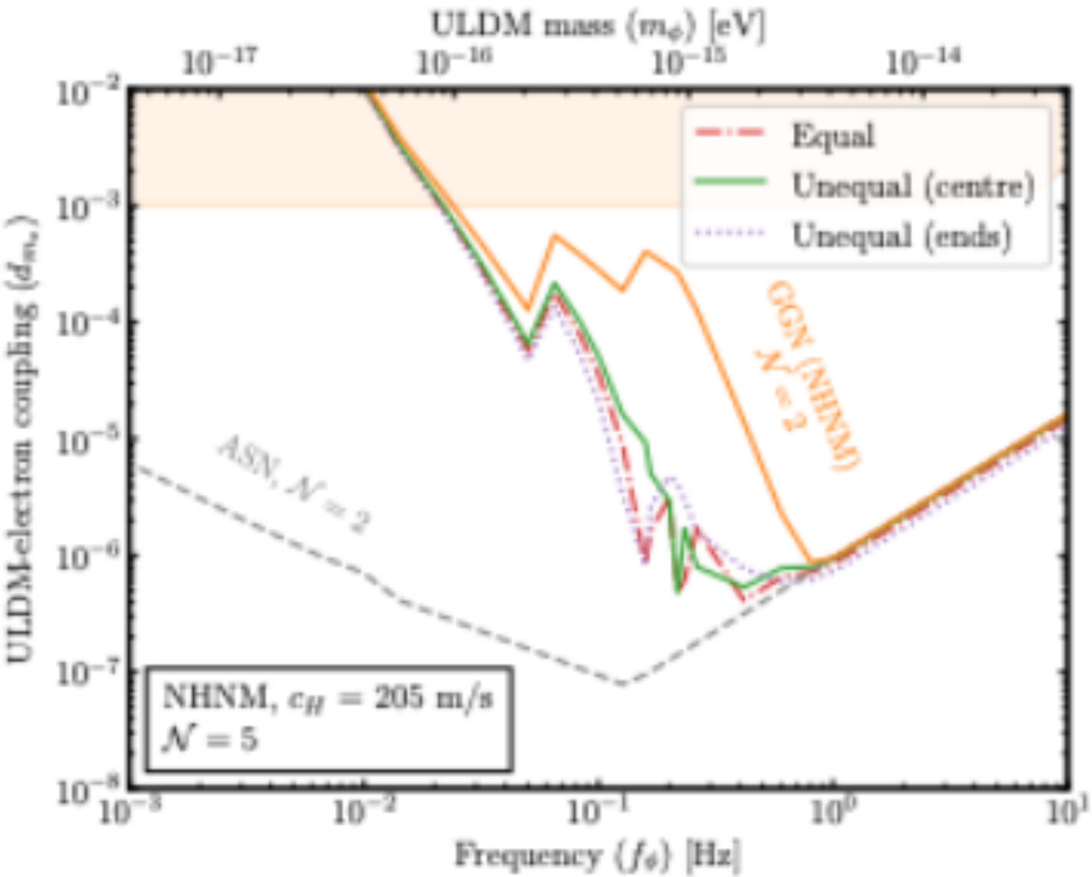
Arduini, ..., JE et al: arXiv:2304.00614

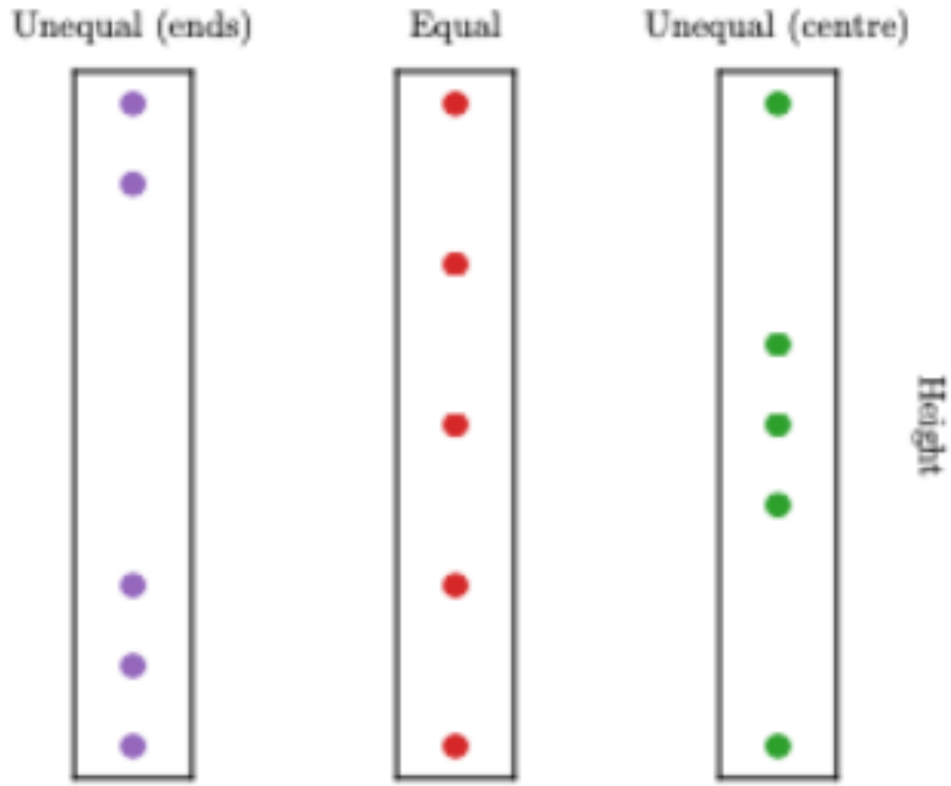
Atomic Multi-Gradiometer



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

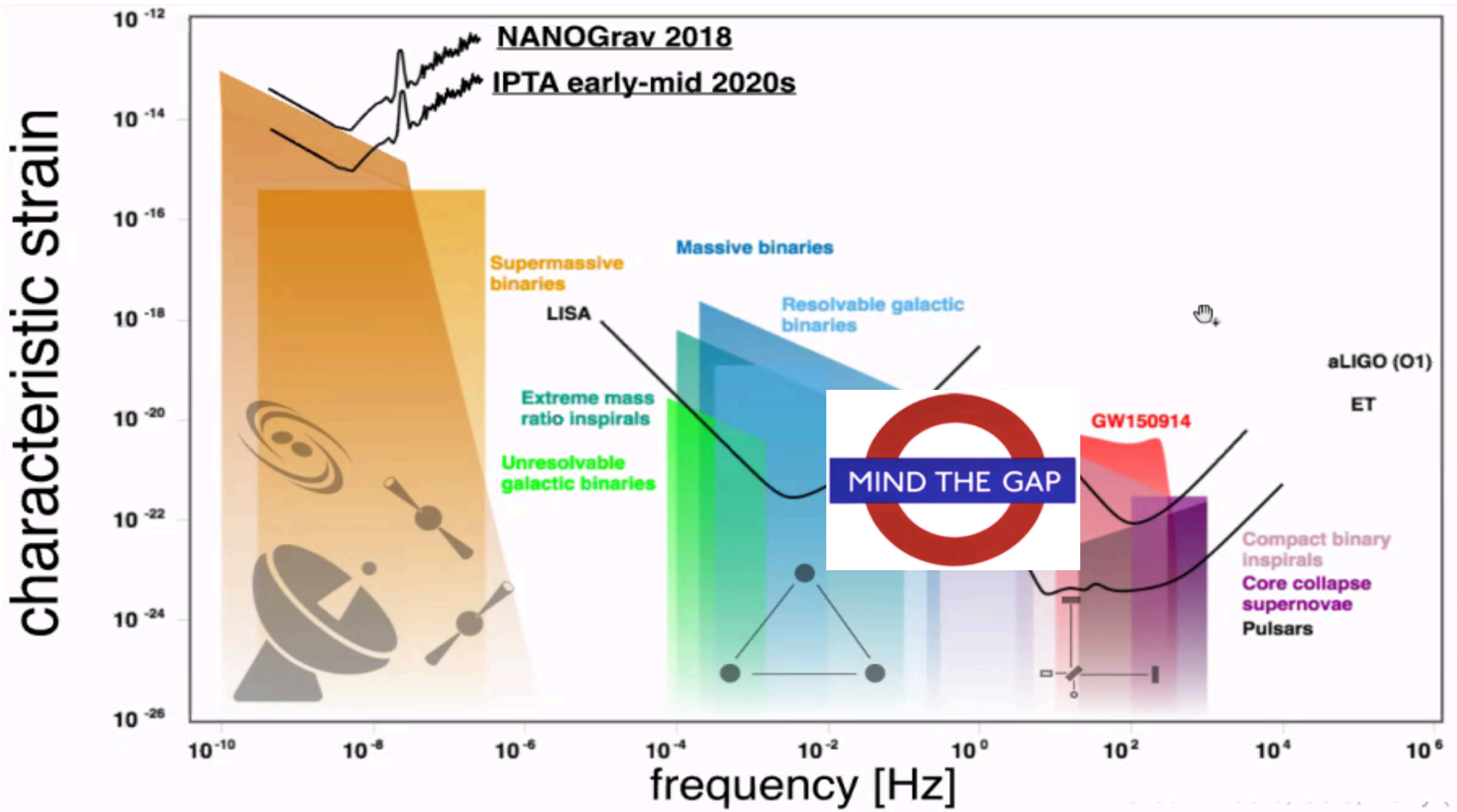
Gravity Gradient Noise (GGN): Mitigation for ULDM Search with AION-km





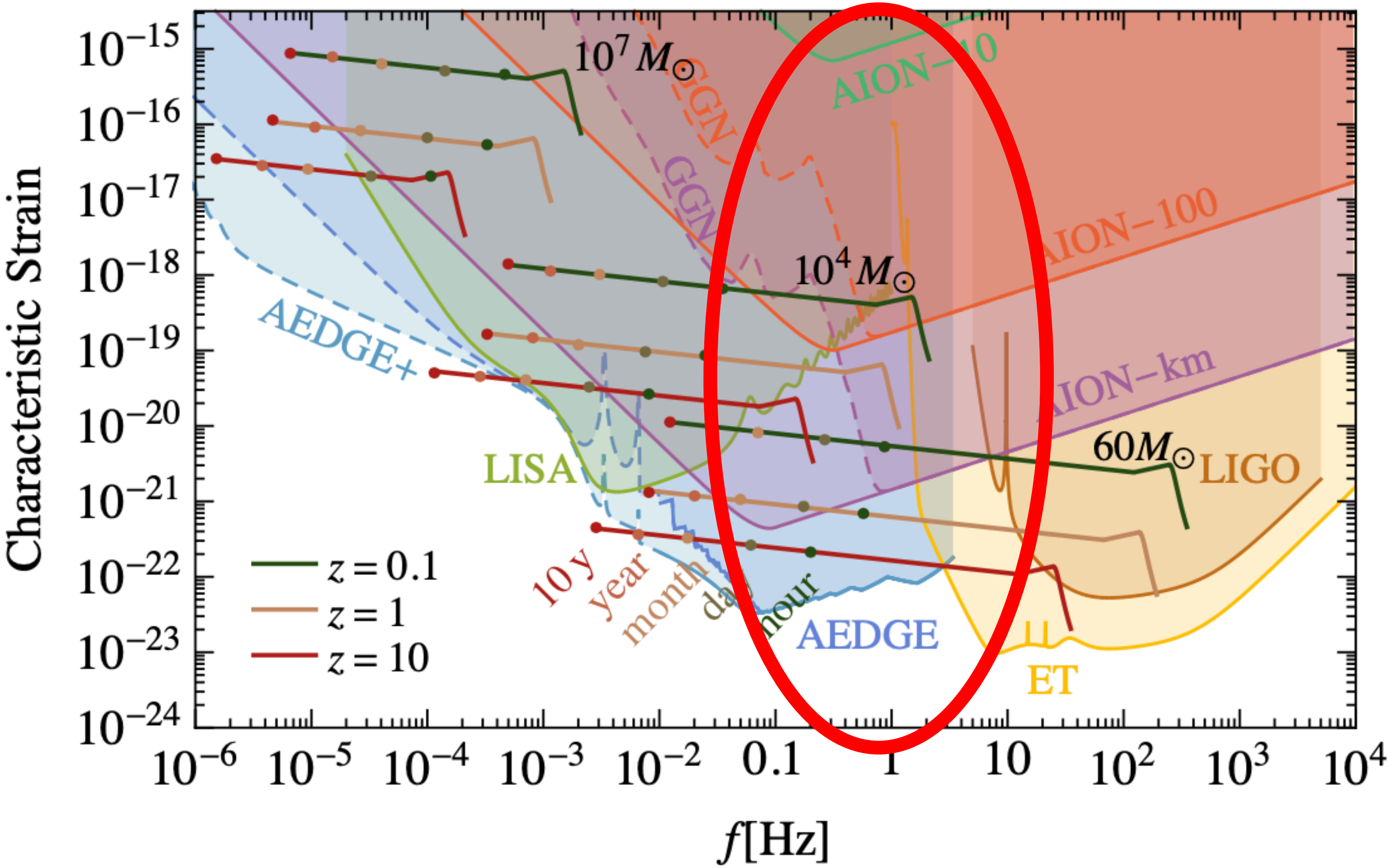
Multiple atom interferometers using same vertical laser beam

Gravitational Wave Spectrum



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

Gravitational Waves from IMBH Mergers



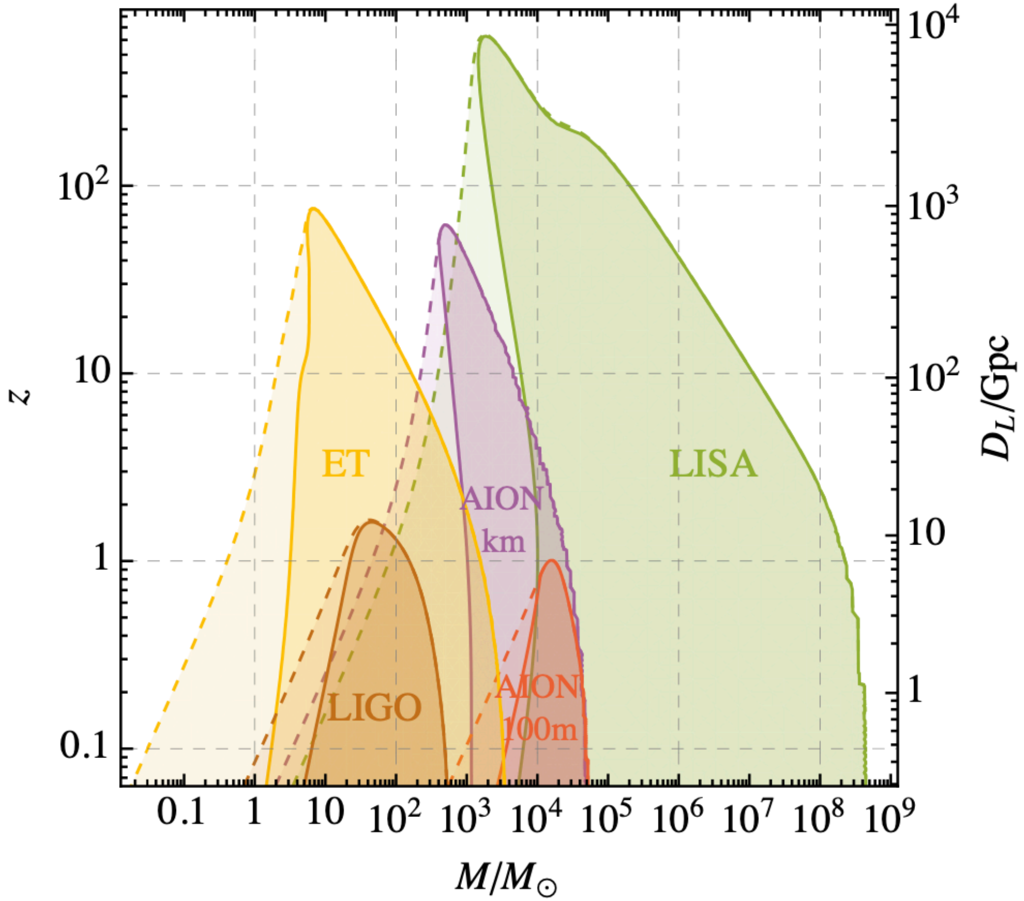
Probe formation of SMBHs

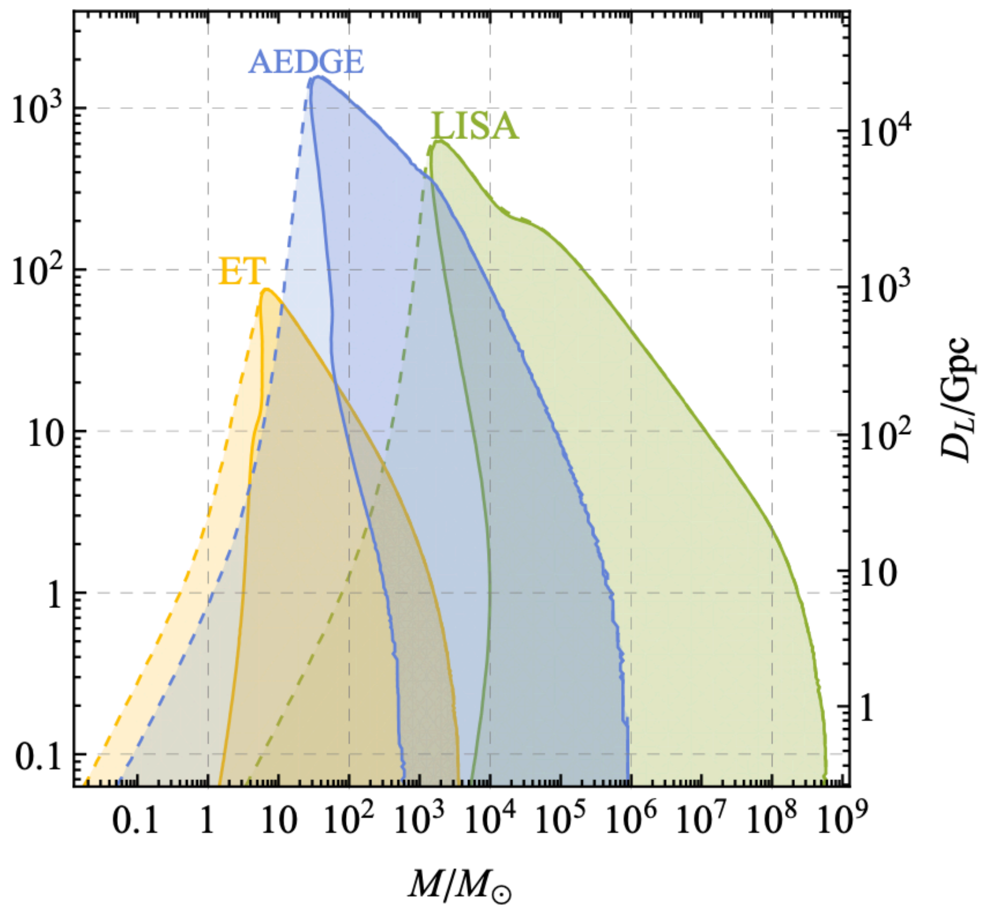
Synergies with other GW experiments (LIGO, LISA), test GR

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

AION

SNR = 8 Sensitivities to GWs from Mergers





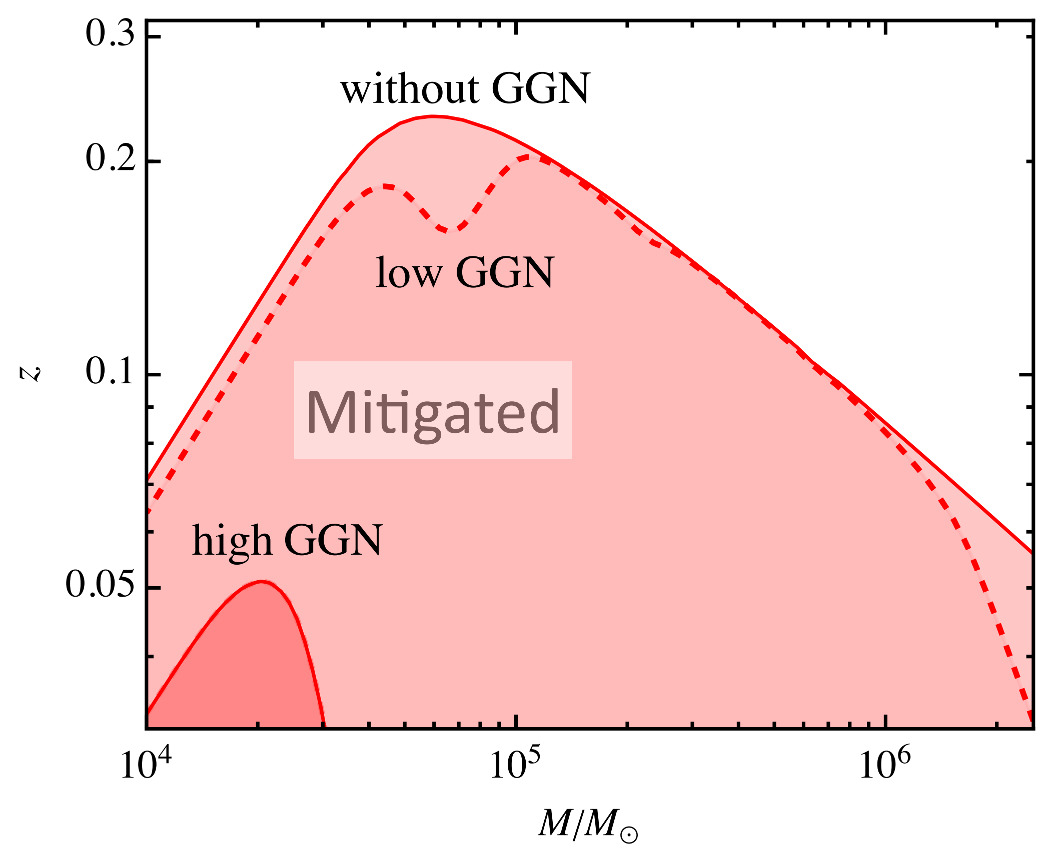
In the lighter regions between the dashed and solid lines the corresponding detector observes only the inspiral phase.

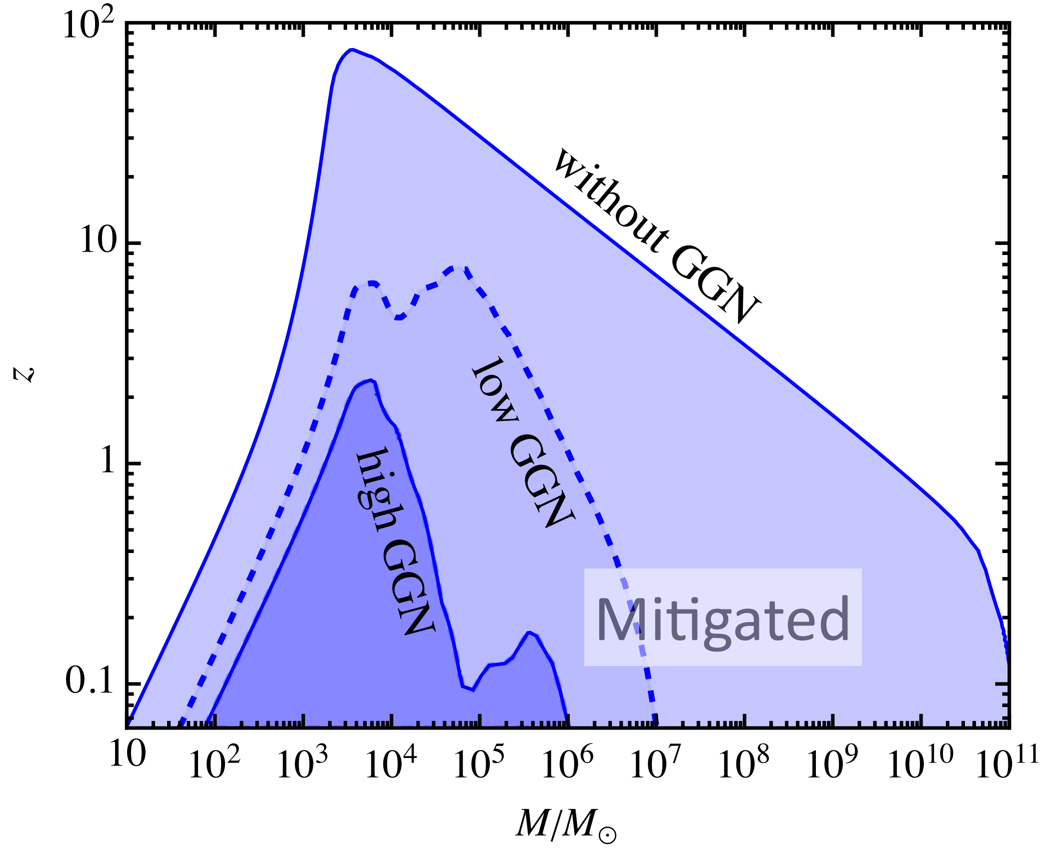
AION, arXiv:1911.11755

AEDGE, arXiv:1908.00802

Searching for IMBH Mergers with AION-100, AION-km

AION



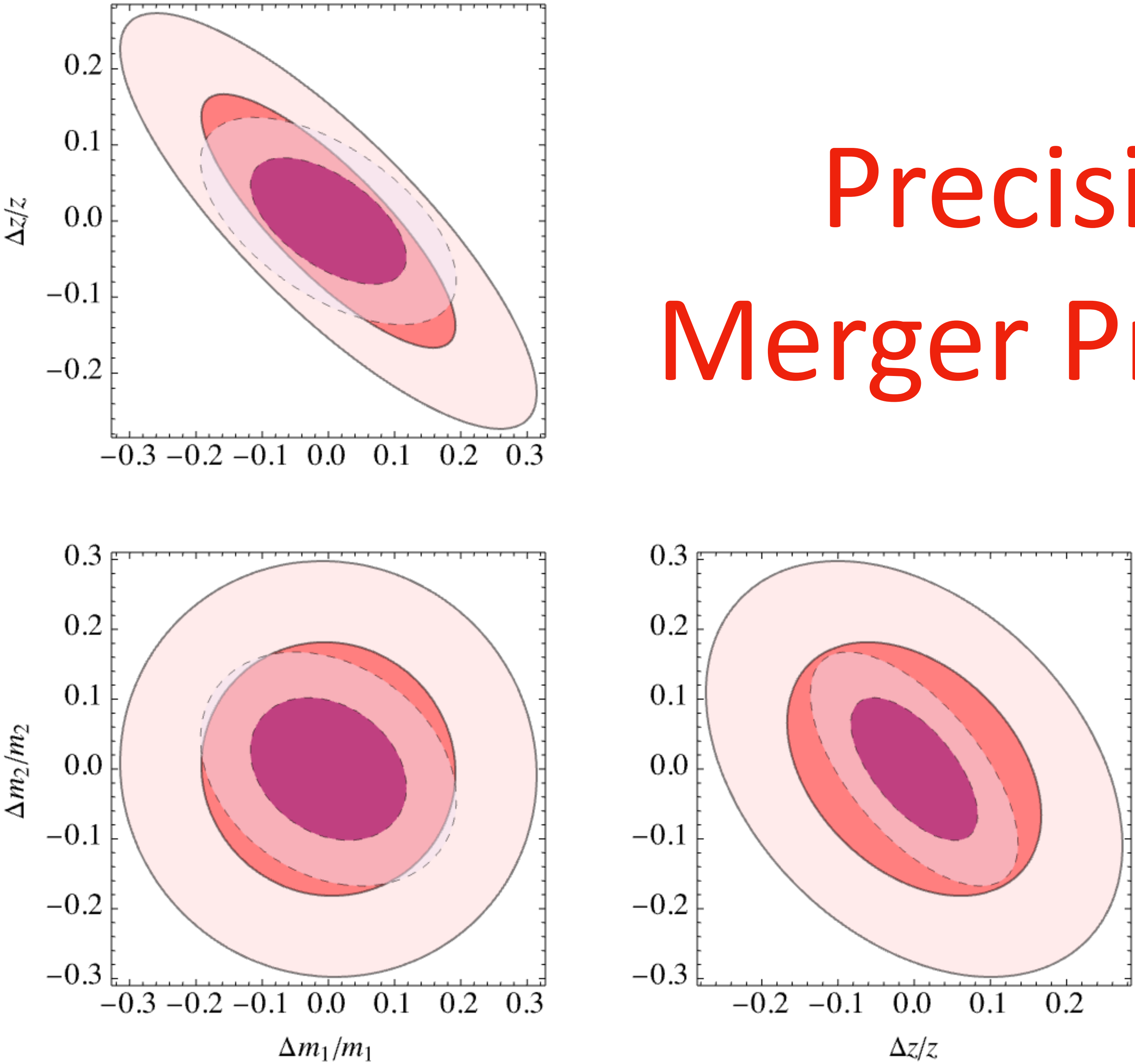


GGN partially mitigated using multiple interferometers;
further mitigation possible with external seismometer network,
to be studied

Vaskonen, AION Collaboration

AION

Precision of Merger Prediction



AION-km

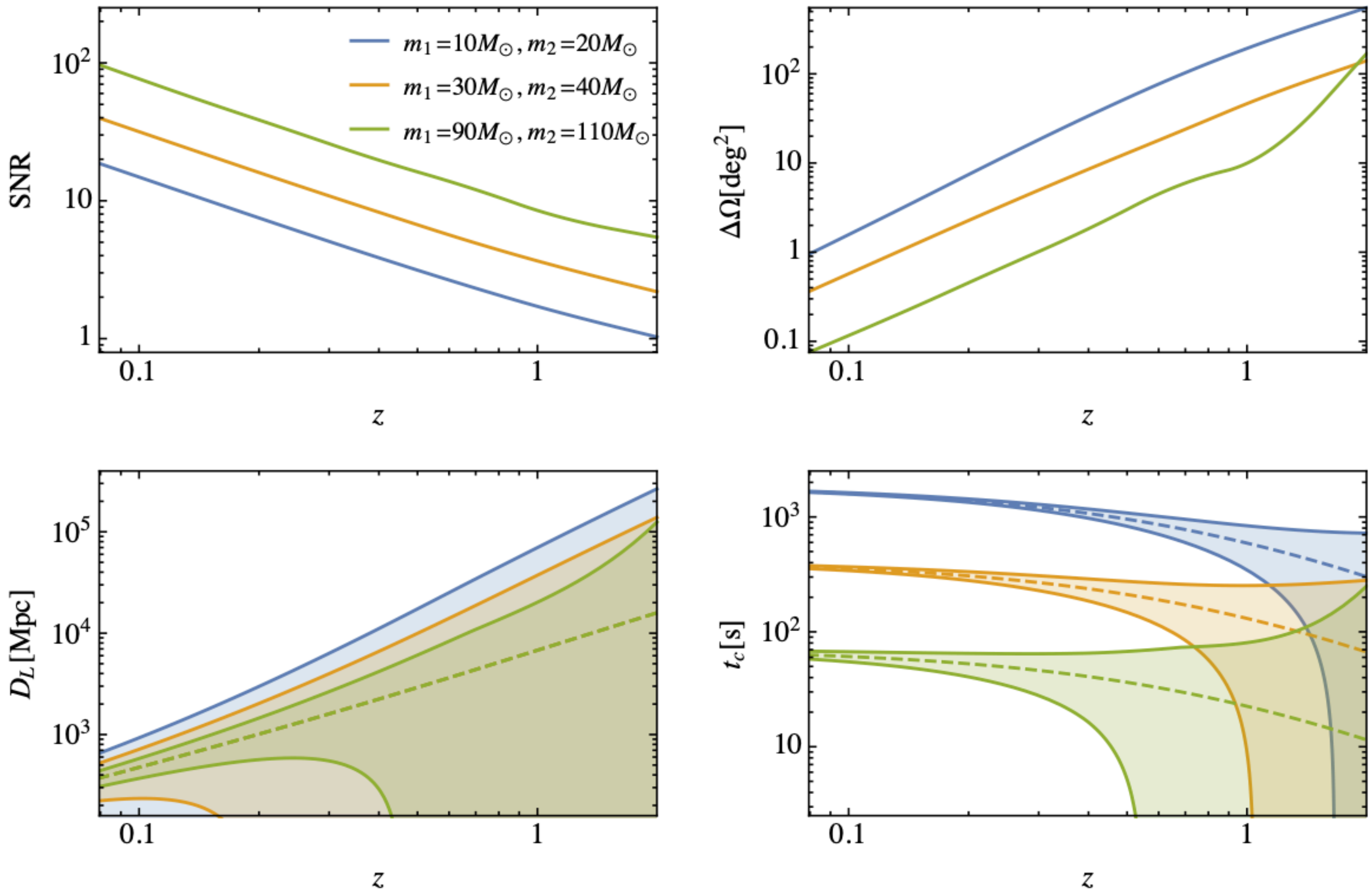
more precise than

LISA

(200, 800) solar masses at z = 4

JE, Fairbairn, Urrutia & Vaskonen, *unpublished*

Synergies with Higher-Frequency Experiments



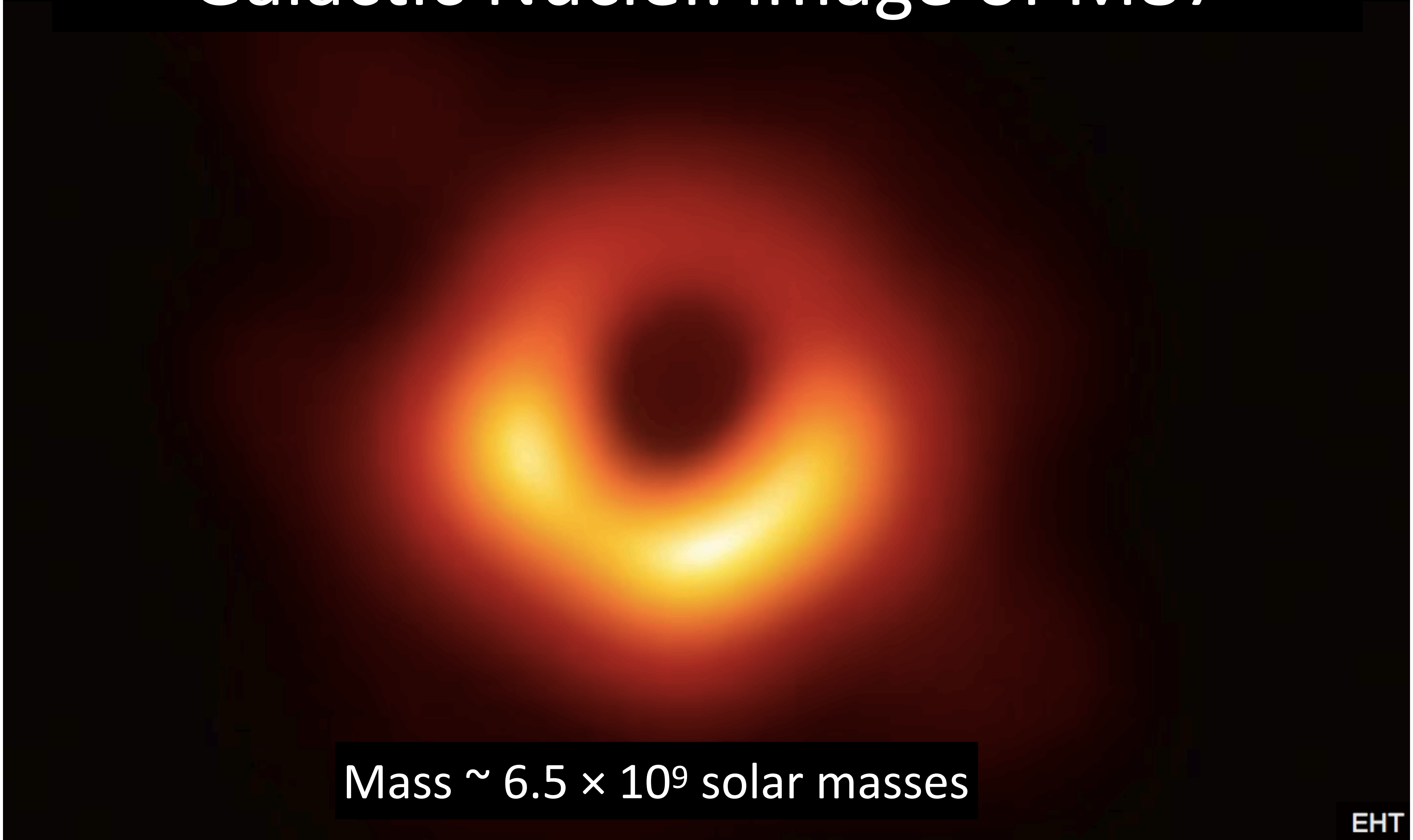
Predictions for future LVK/ET/CE measurements:

Direction, distance, time of merger

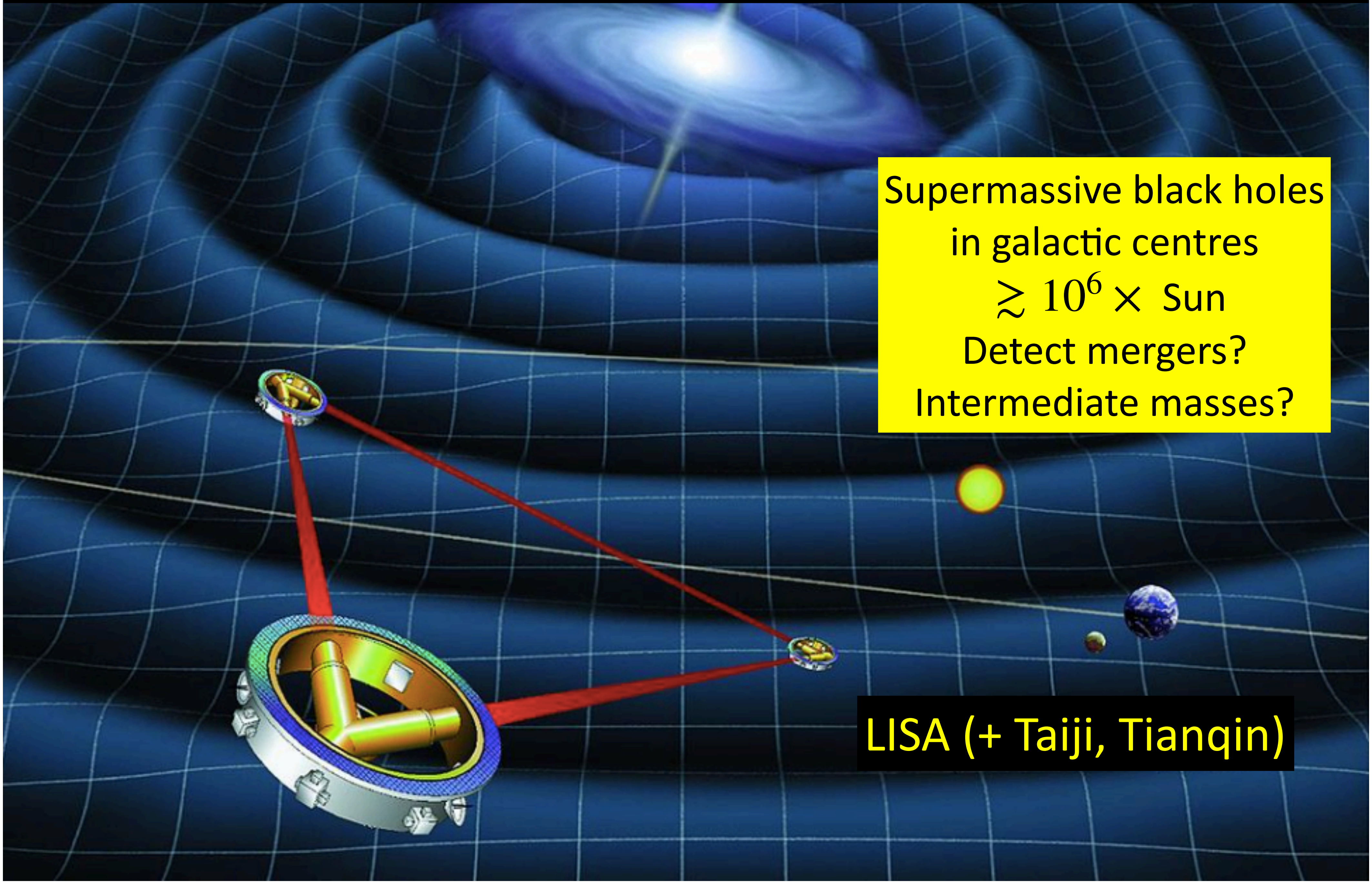
Prepare for multi-messenger observations

JE & Vaskonen: arXiv:2003.13480

Supermassive Black Holes in Active Galactic Nuclei: Image of M87

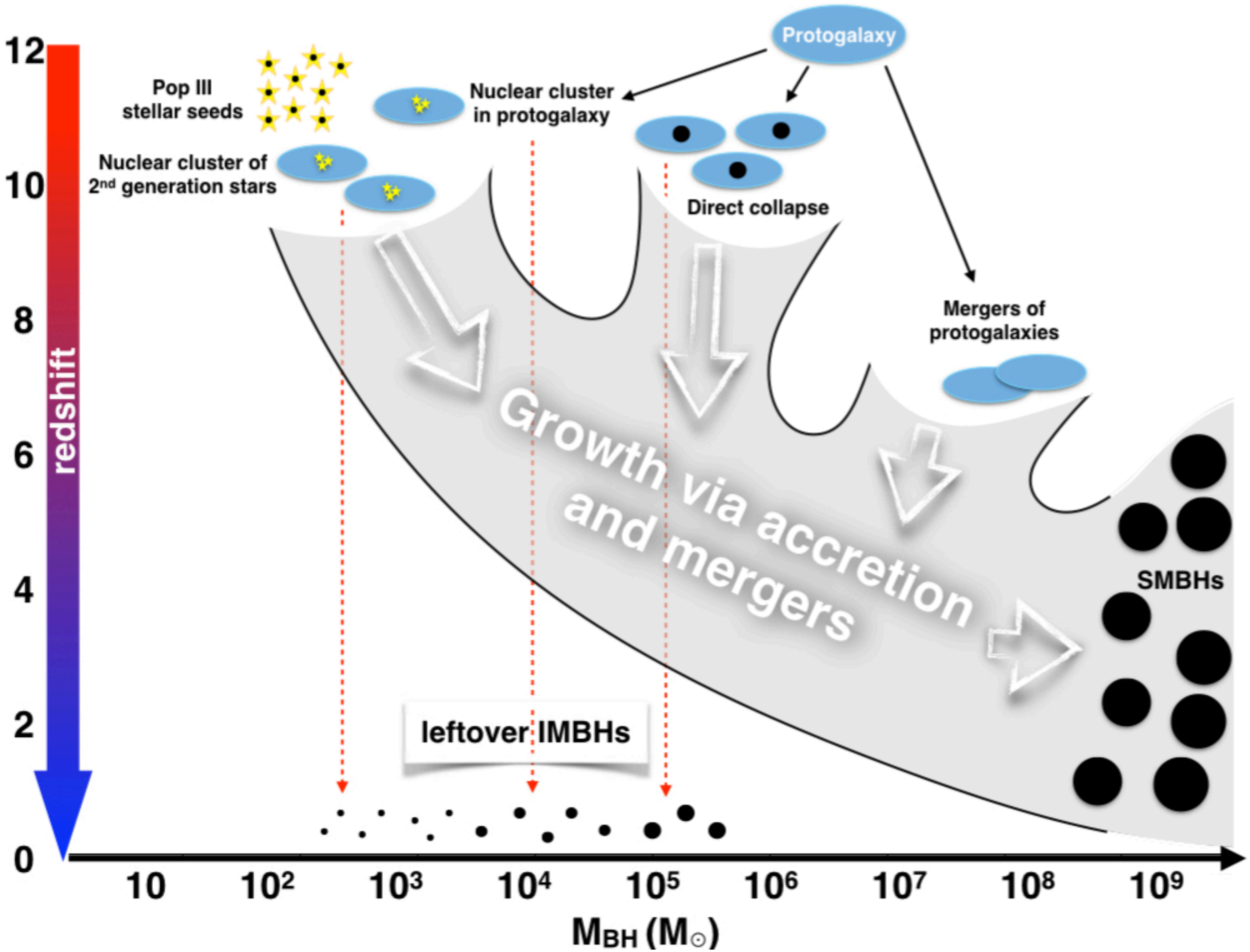


Future Step: Interferometer in Space



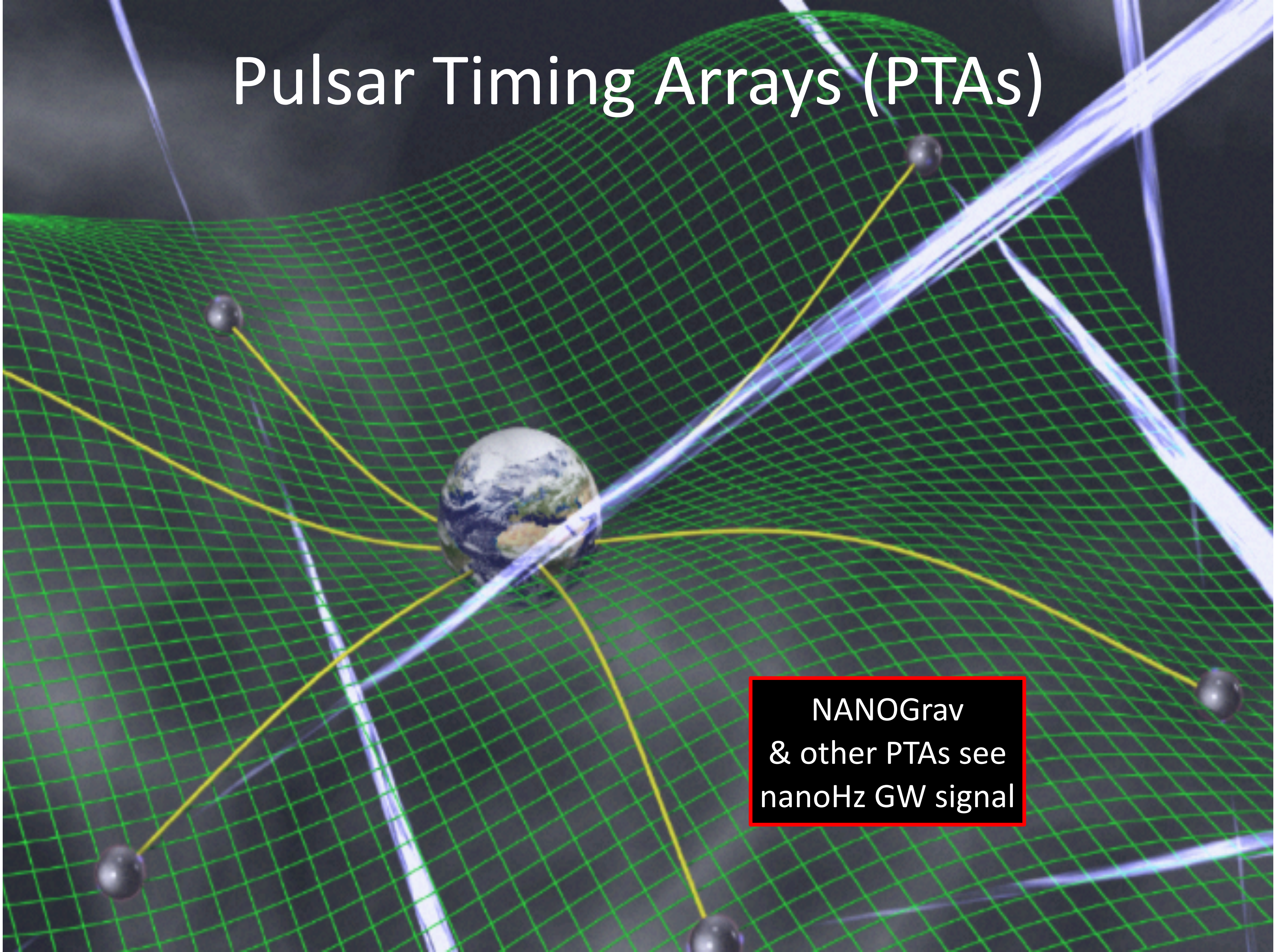
How to Make a Supermassive BH?

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



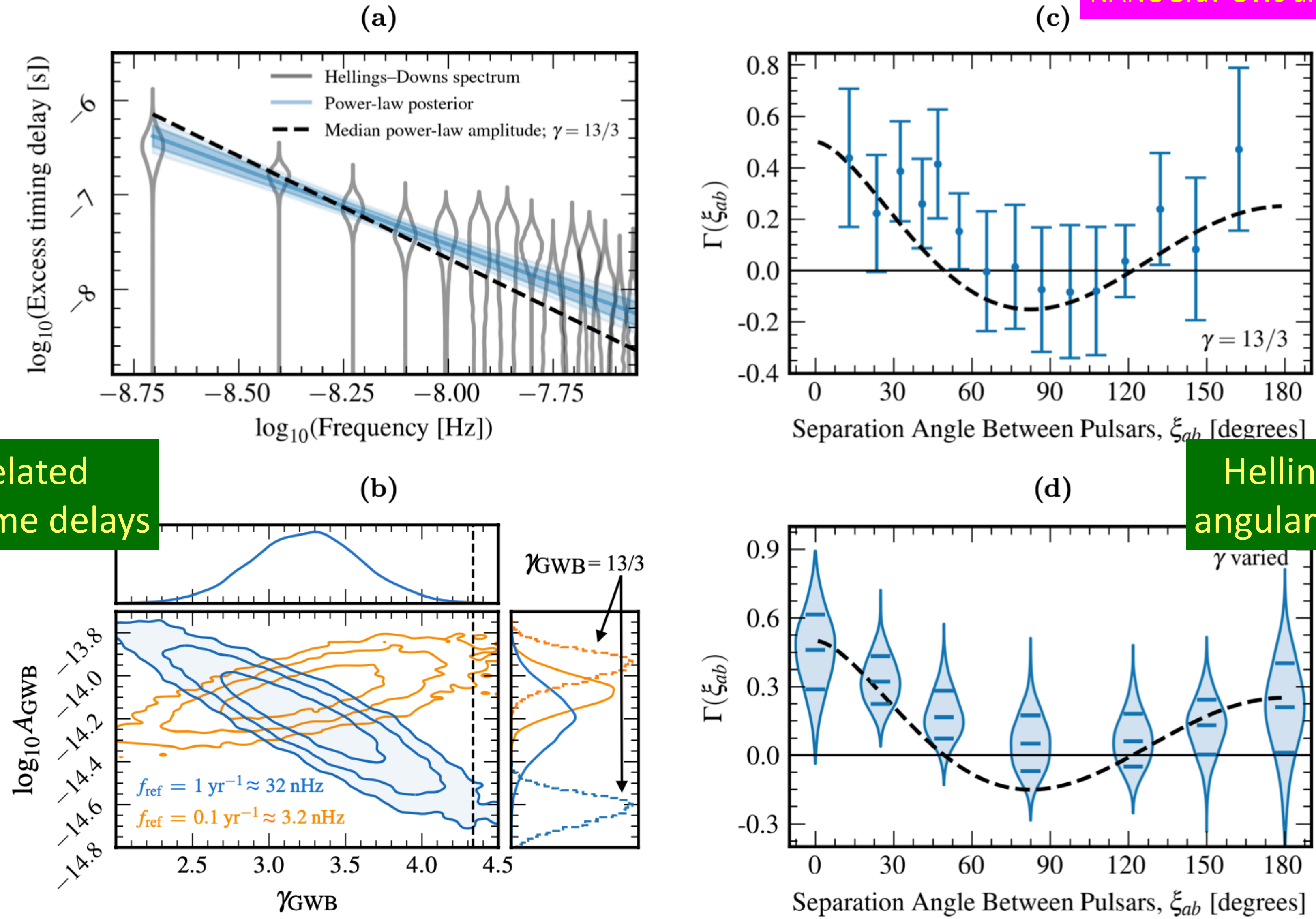
The Biggest Bangs since the Big Bang?

Pulsar Timing Arrays (PTAs)



NANOGrav 15-Year Data

NANOGrav GWs arXiv:2306.16213

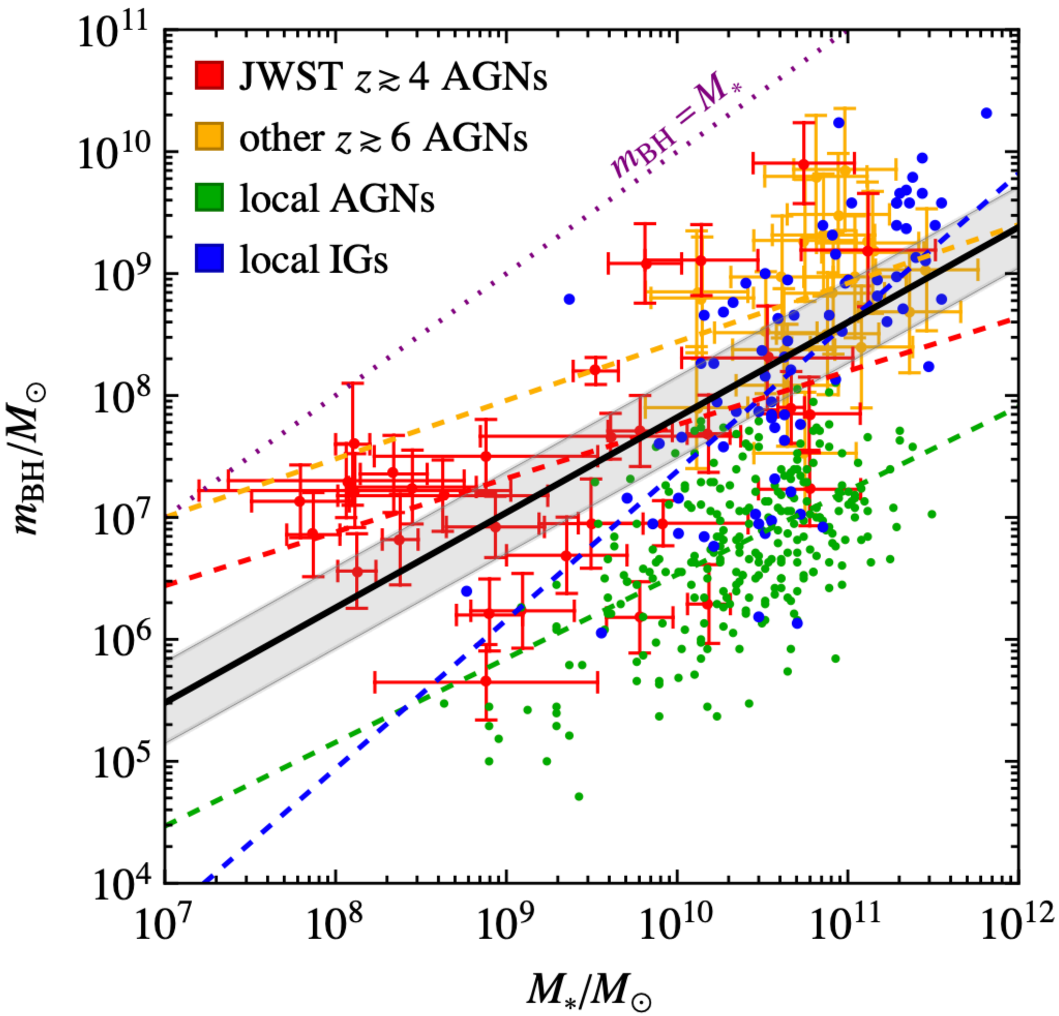


Correlated pulsar time delays

Hellings-Downs angular correlation

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

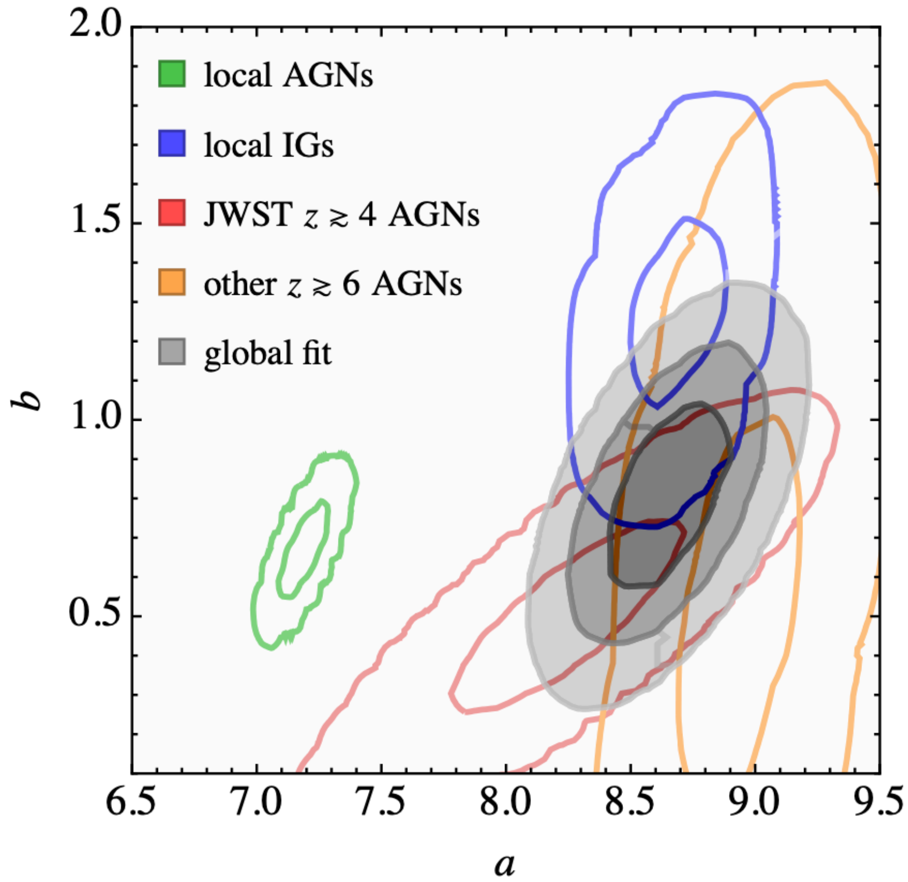
High-z SMBHs seen with JWST

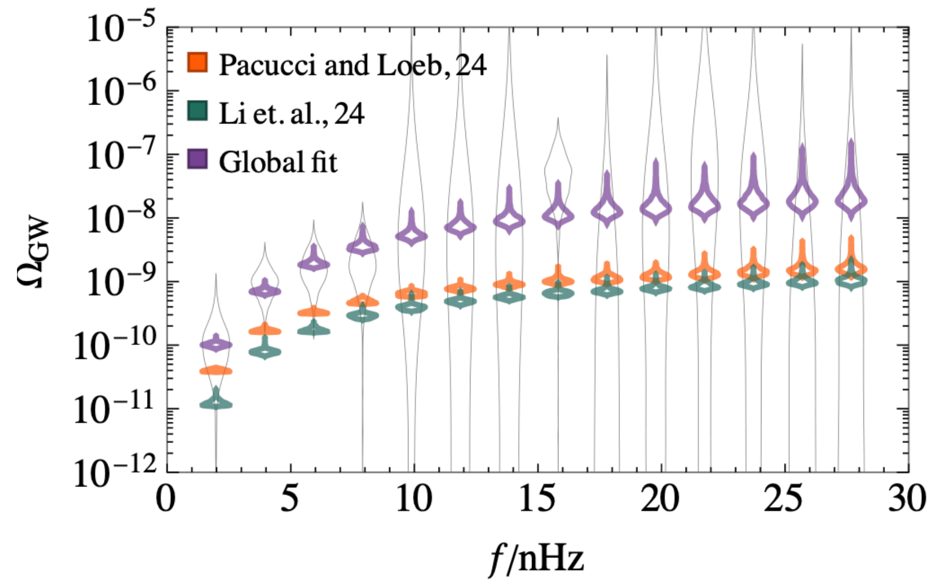


- "Surprisingly many"
- Also other telescopes
- Also dual systems
- Good news for GWs
- Consistent with PTAs

JE, Fairbairn, Hütsi, Urrutia, Vaskonen & Veermäe, arXiv:2403.19650

Consistent with NANOGrav



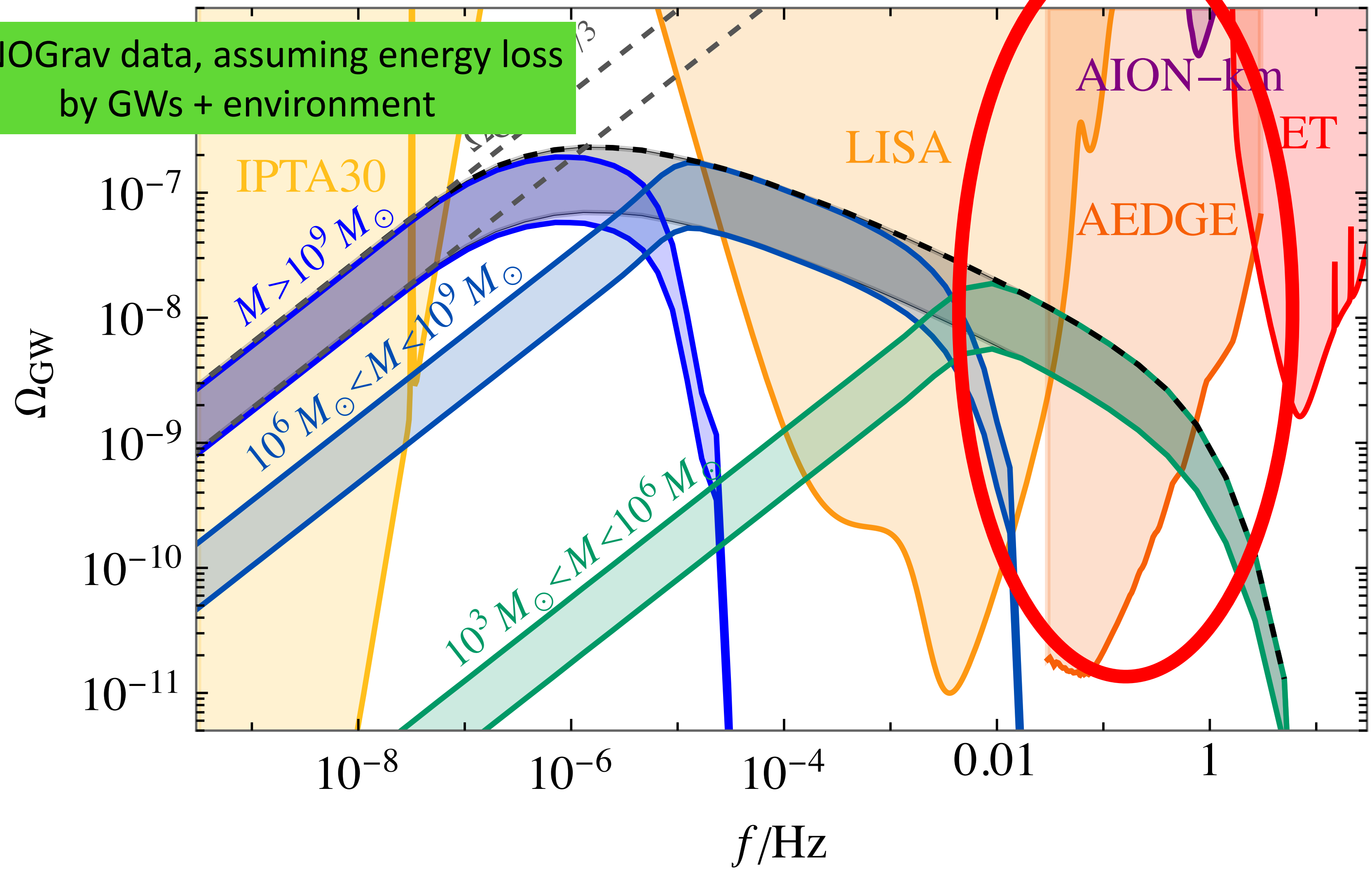


- Probably many SMBHs unseen in inactive galaxies
- Not just active galactic nuclei

JE, Fairbairn, Hütsi, Urrutia, Vaskonen & Veermäe, arXiv:2403.19650

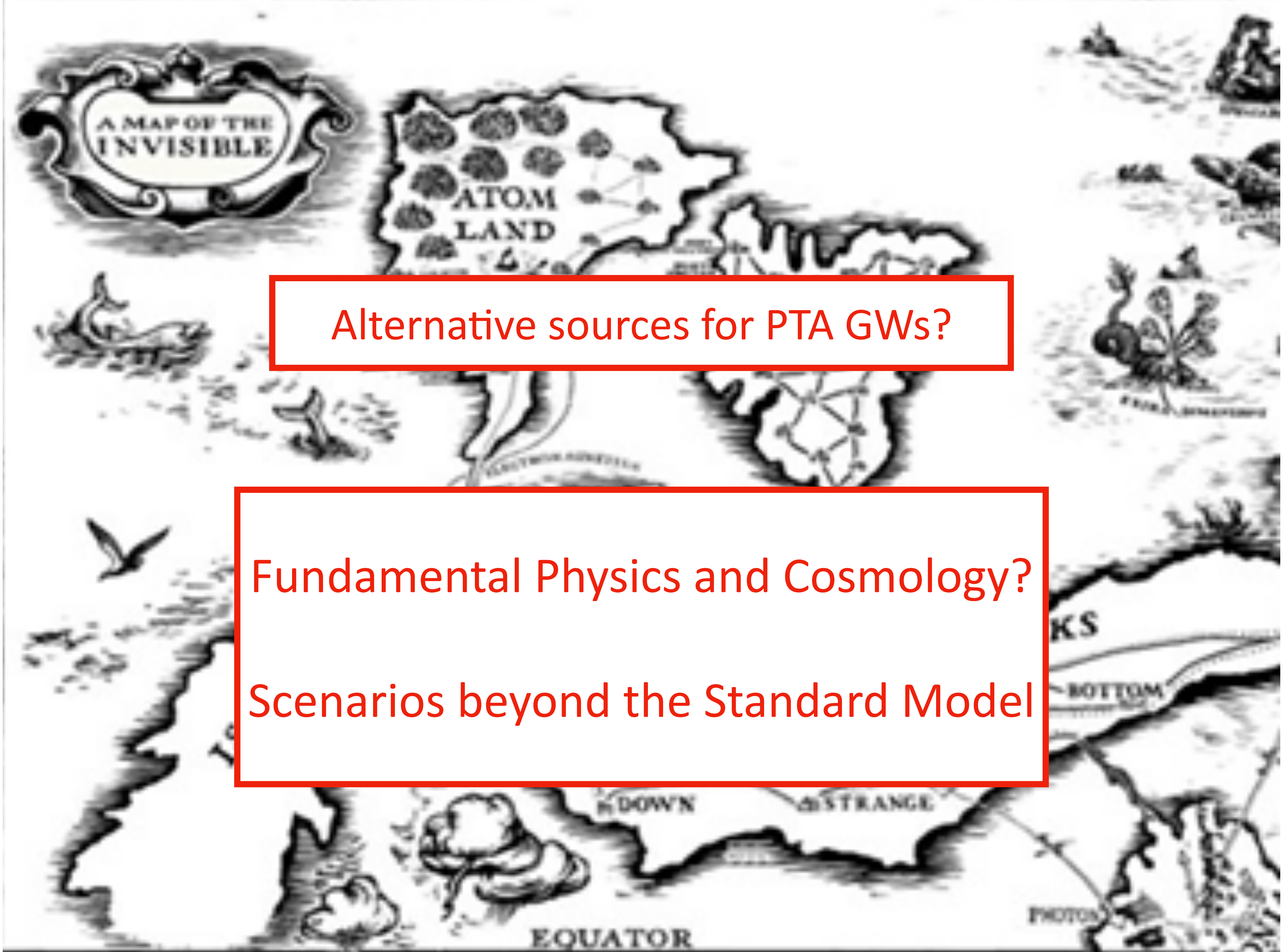
Stochastic GW Background from BH Mergers

NANOGrav data, assuming energy loss by GWs + environment



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

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

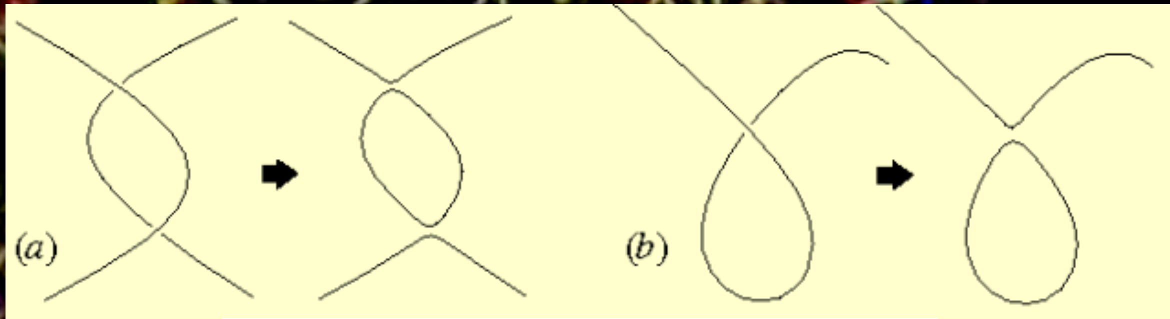


Alternative sources for PTA GWs?

Fundamental Physics and Cosmology?

Scenarios beyond the Standard Model

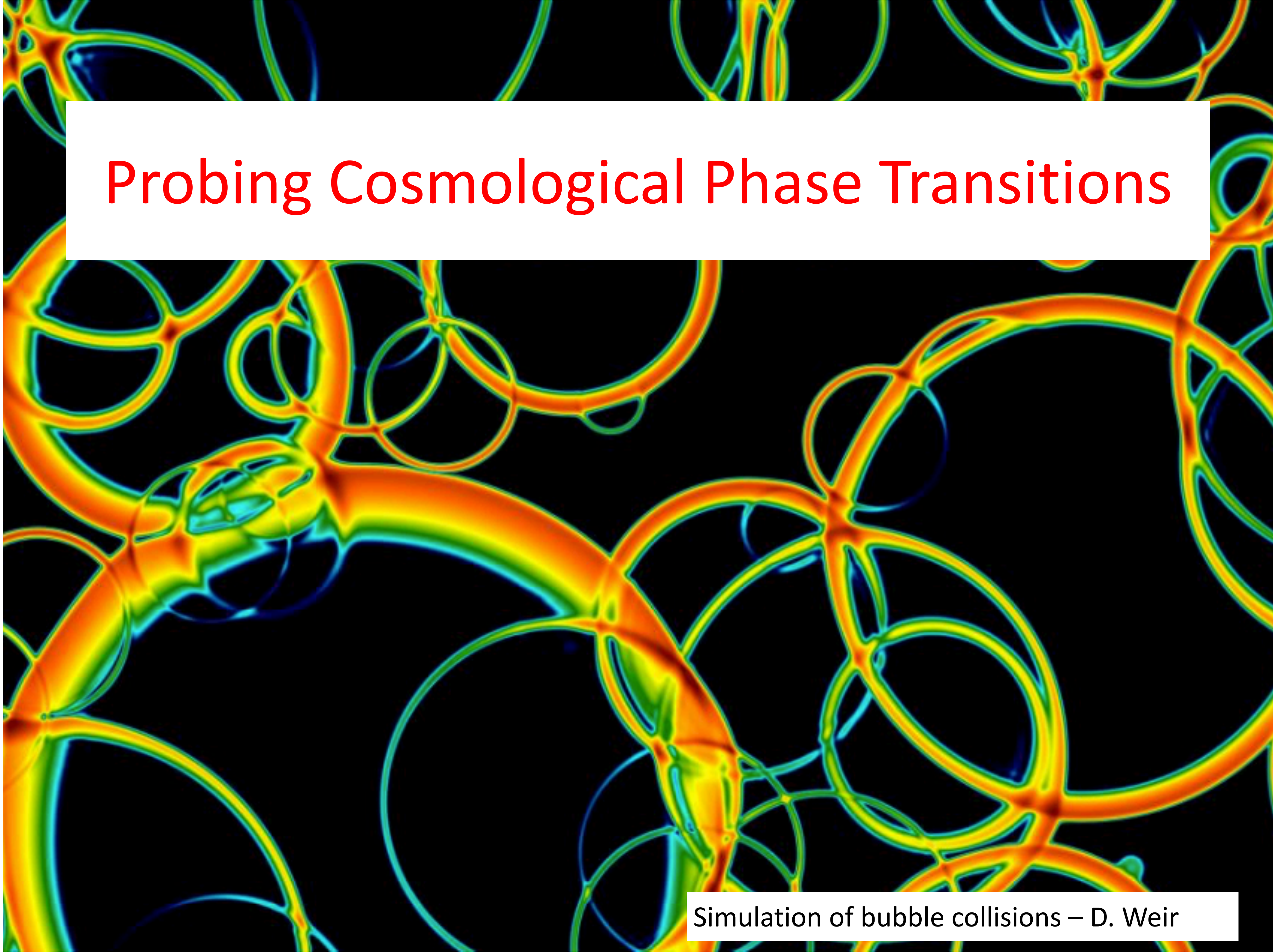
Probing Cosmic Strings



GW emission from string loops

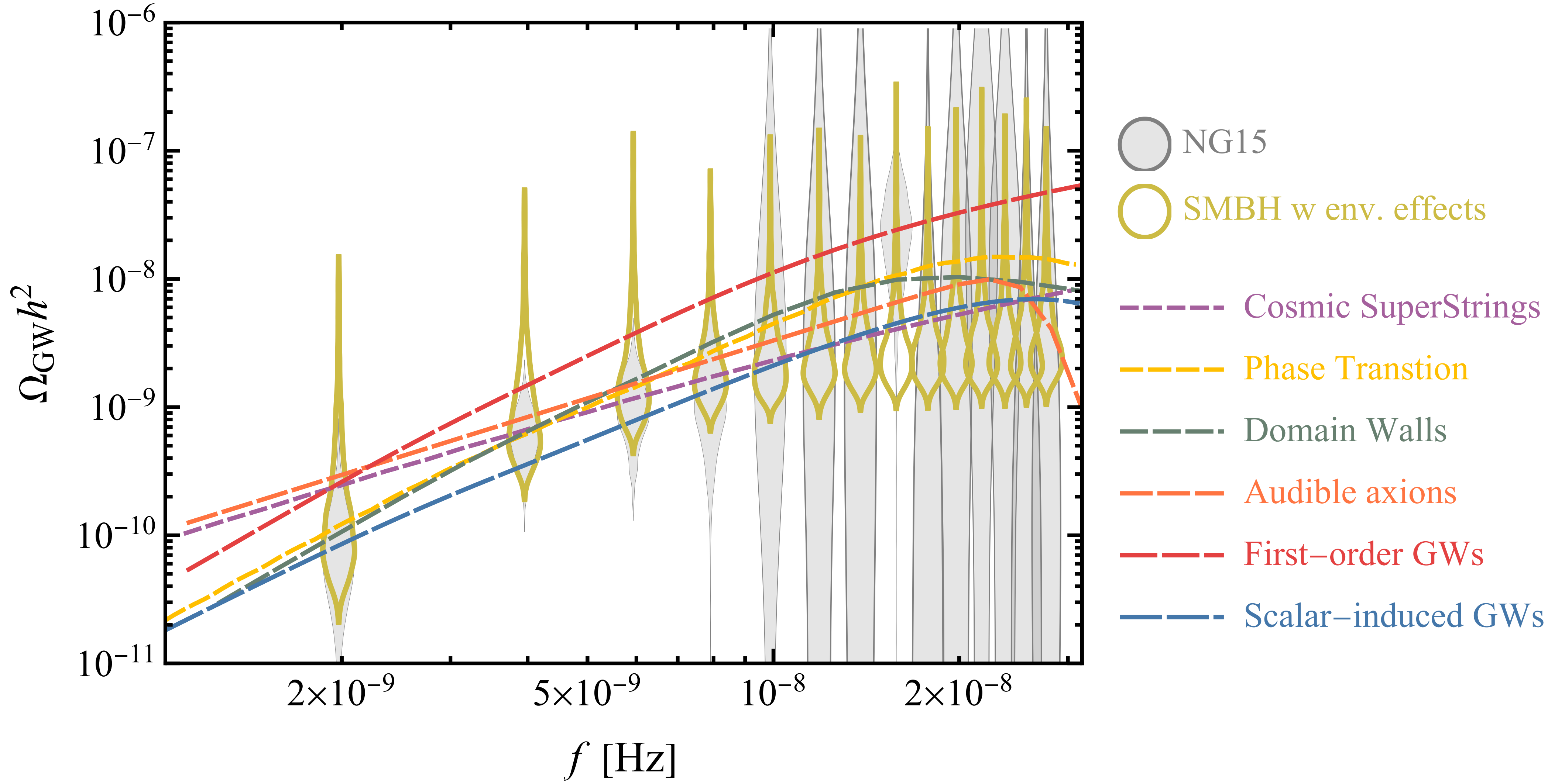
Simulation of cosmic string network – Cambridge cosmology group

Probing Cosmological Phase Transitions



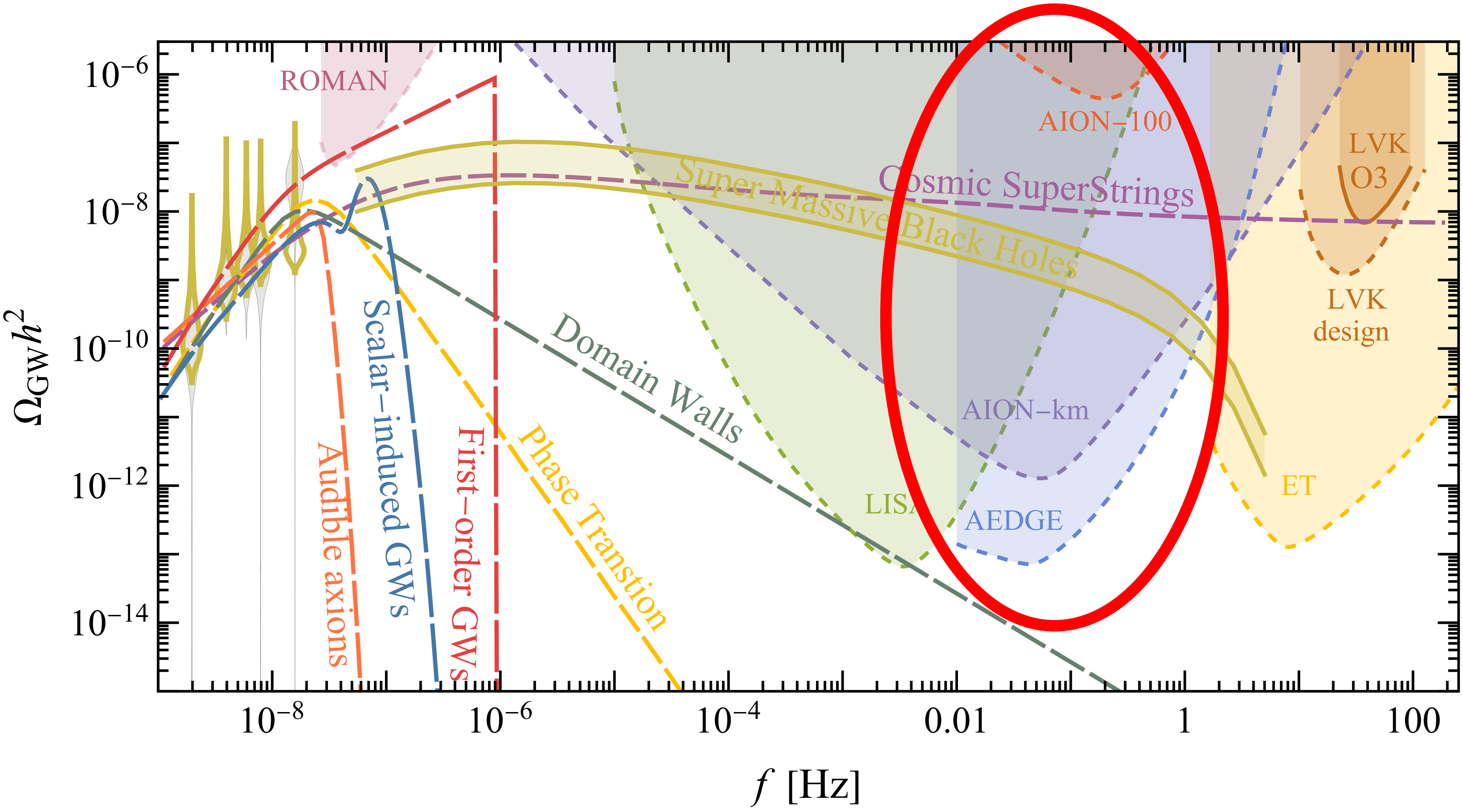
Simulation of bubble collisions – D. Weir

Fits to NANOGrav



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

Extension of Fits to Higher Frequencies



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

Very Long Baseline Atom Interferometers

- Unique reach for ultralight bosonic dark matter
- Measure gravitational waves in the deciHz range
- Intermediate mass black hole mergers?
- Assembly mechanisms for supermassive black holes?
- Prospects enhanced by PTA observations of GW background
- Biggest bangs since the Big Bang, or physics beyond the SM?