AION-100: Design Study Status & Prospects

Atom interferometry

AION project status

Studies for siting

AION-100 @ CERN

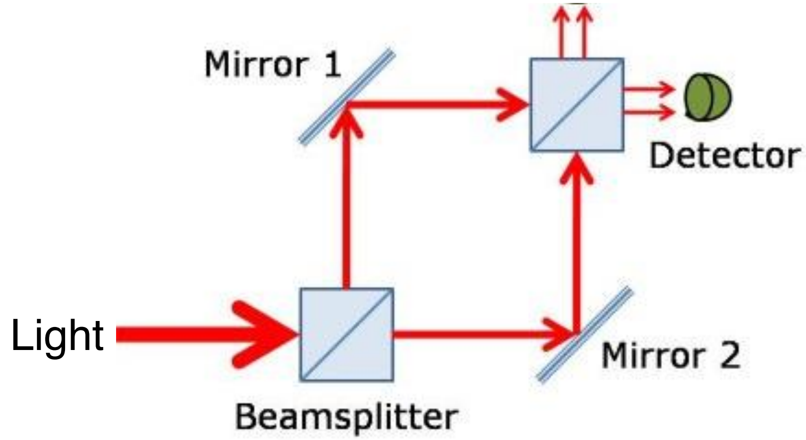
Update on AION science

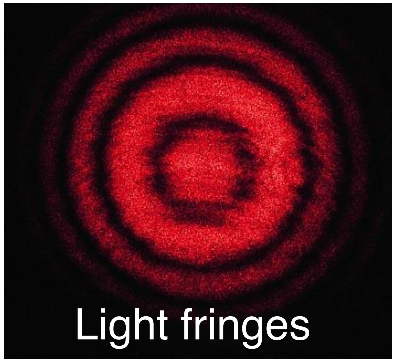
John Ellis

KING'S College LONDON

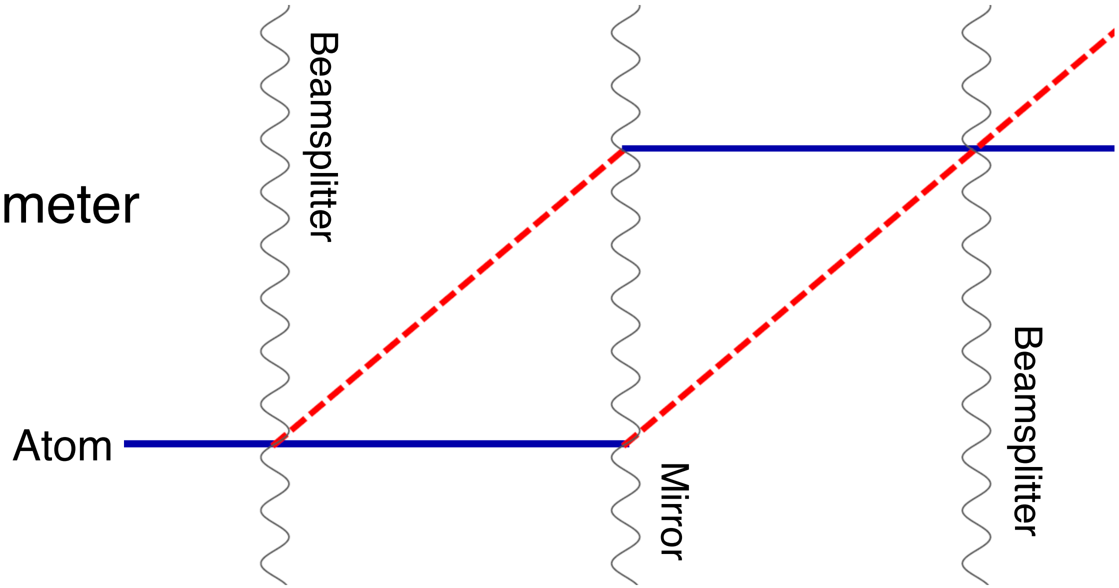
Principle of Atom Interferometry

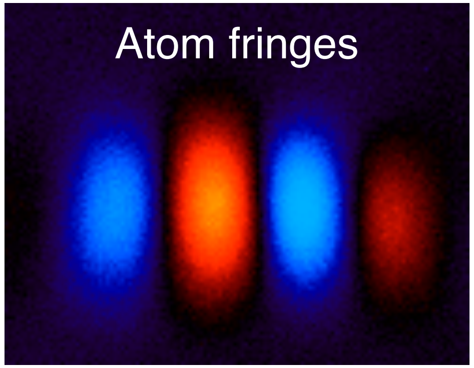
Light interferometer





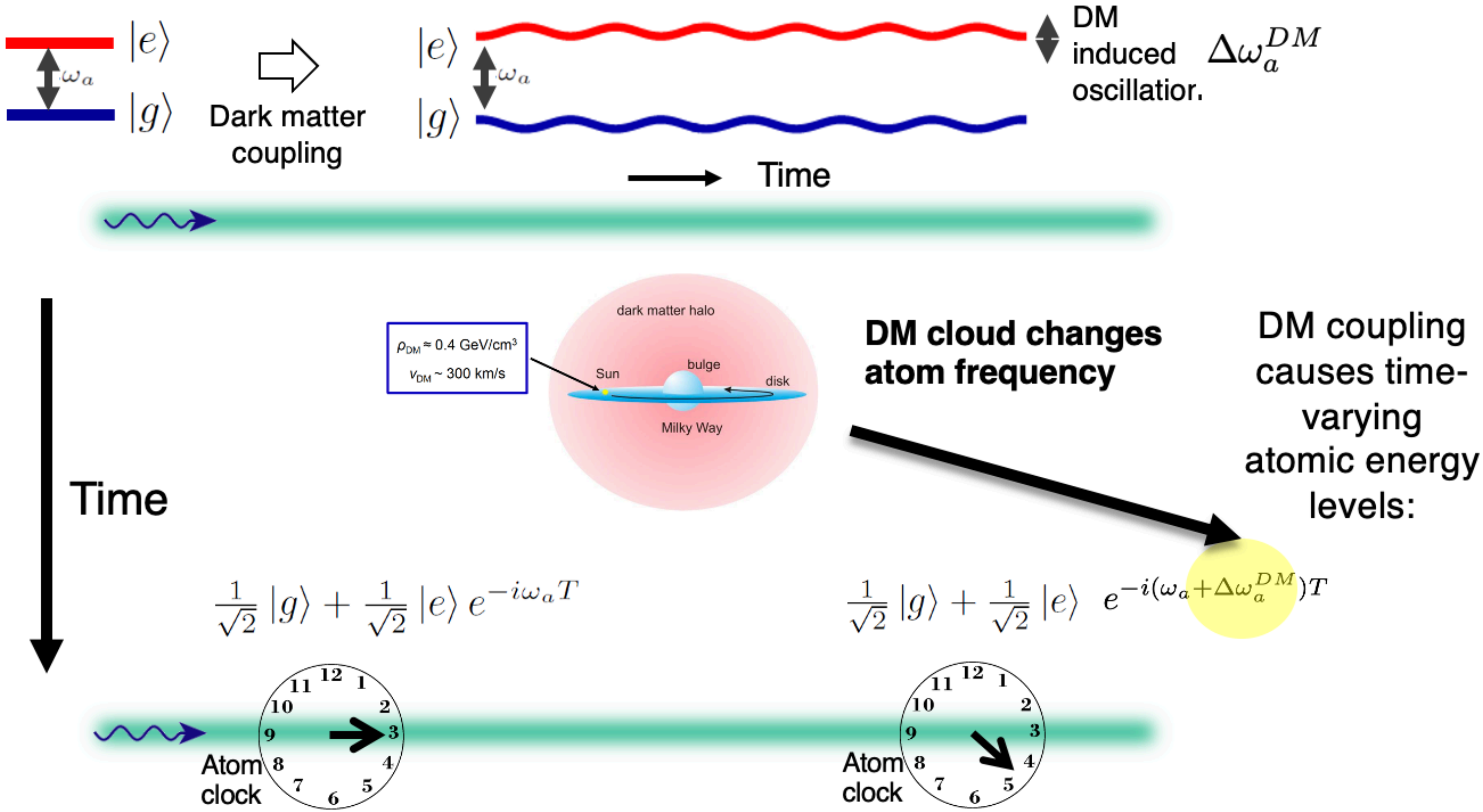
Atom interferometer



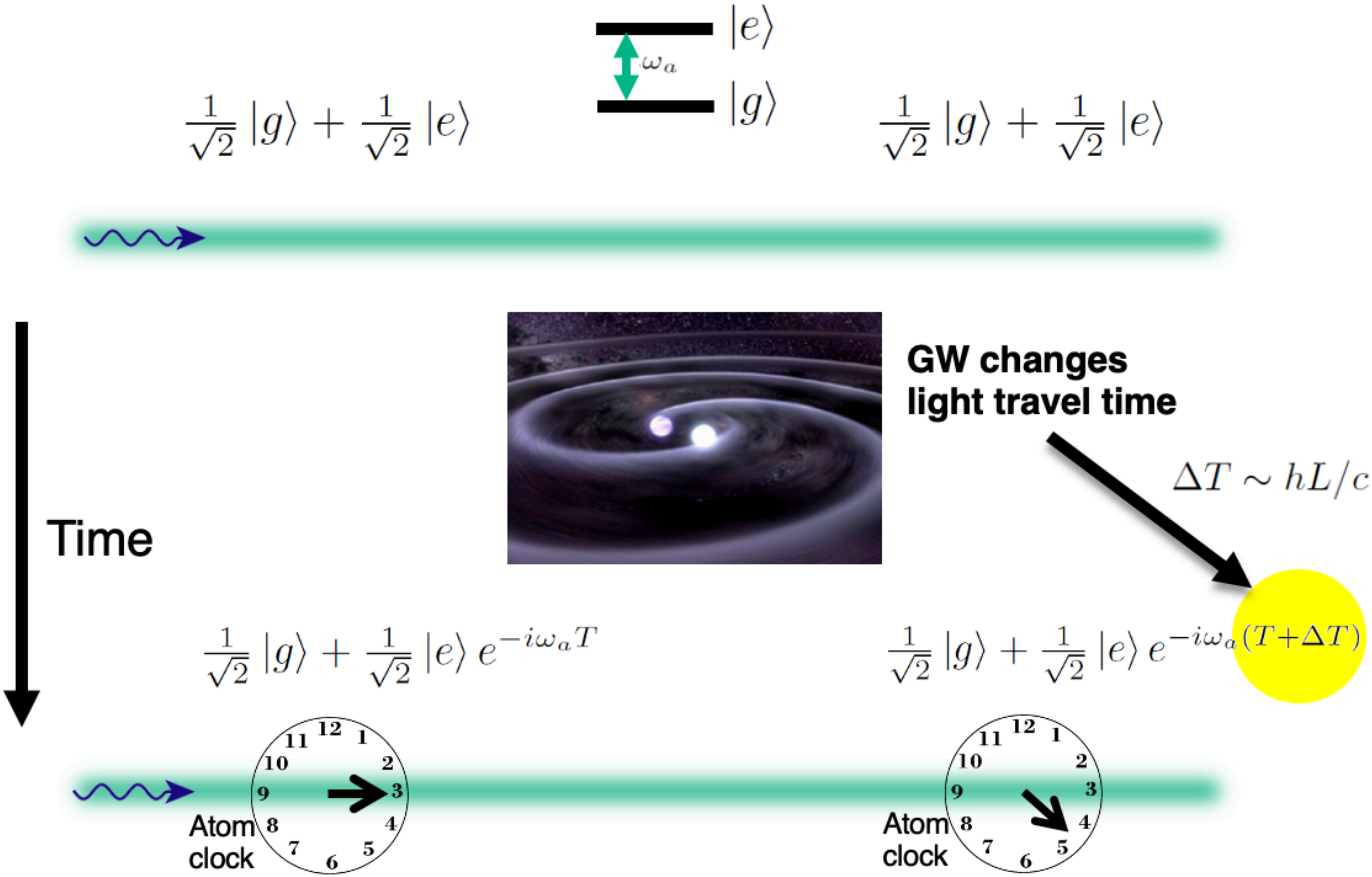


http://scienceblogs.com/principles/2013/10/22/quantum-erasure/
http://www.cobolt.se/interferometry.html

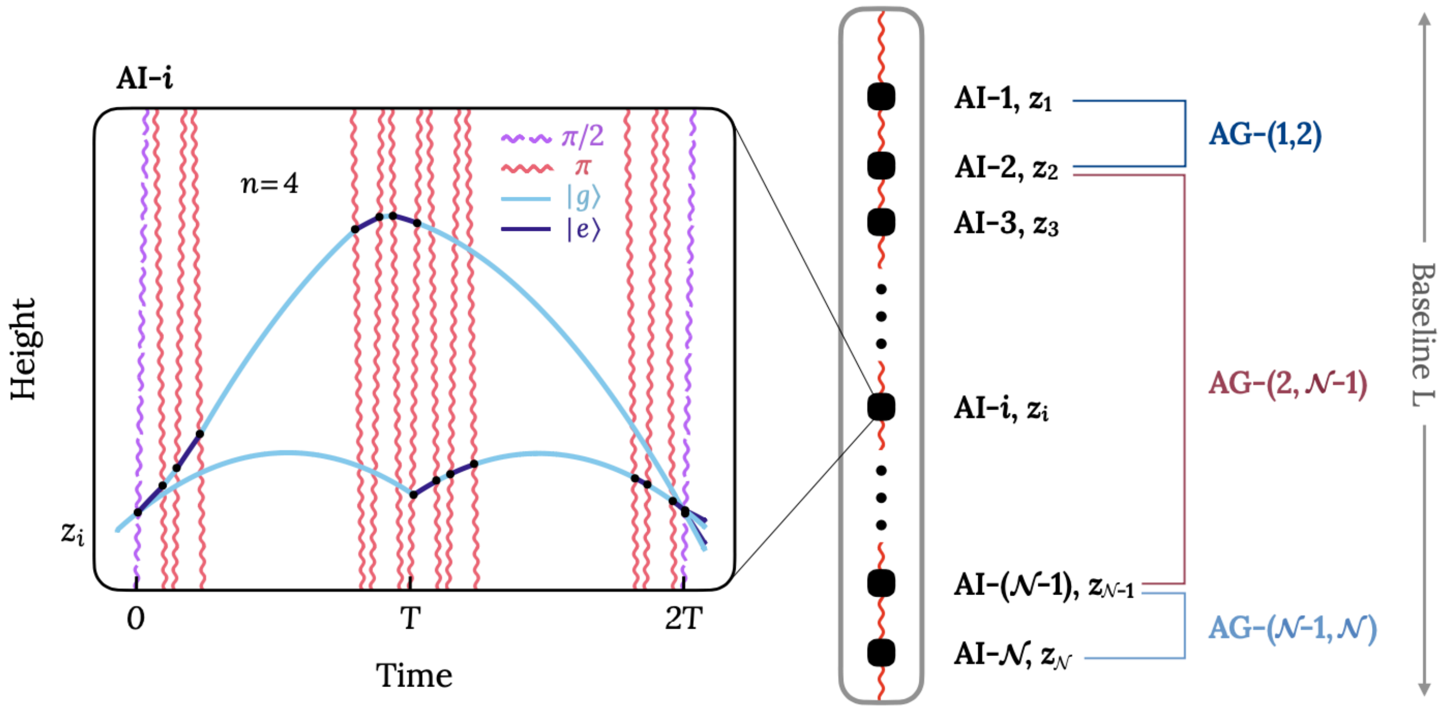
Effect of Dark Matter on Atom Interferometer



Effect of Gravitational Wave on Atom Interferometer



Atomic Multi-Gradiometer



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

AION Collaboration

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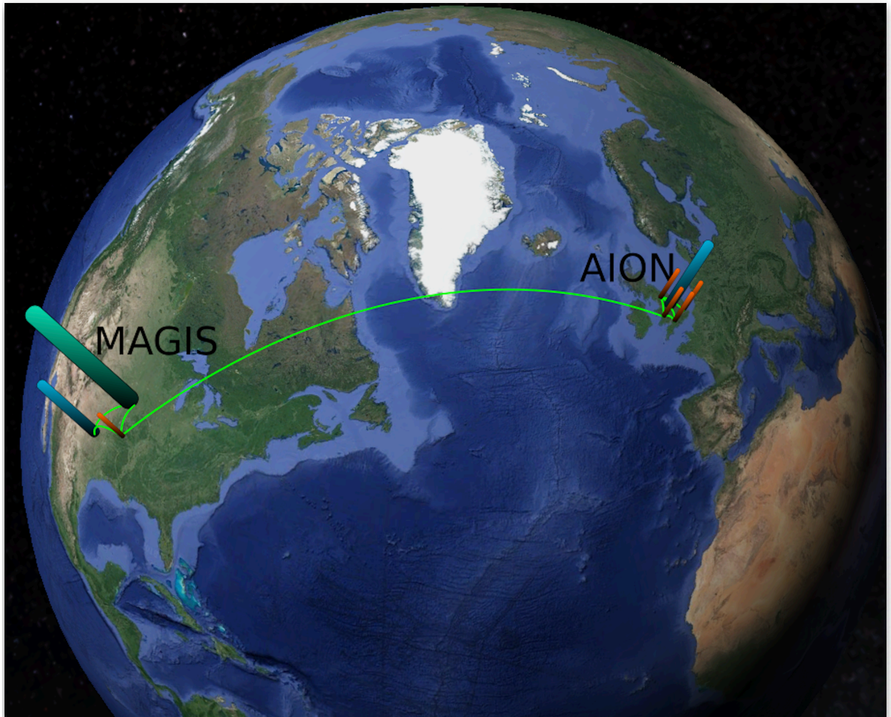


Network with MAGIS project in US

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 and planning for 1 km & beyond
- AION-SPACE (AEDGE): Stage 4 [after AION-km]
  - Space-based version

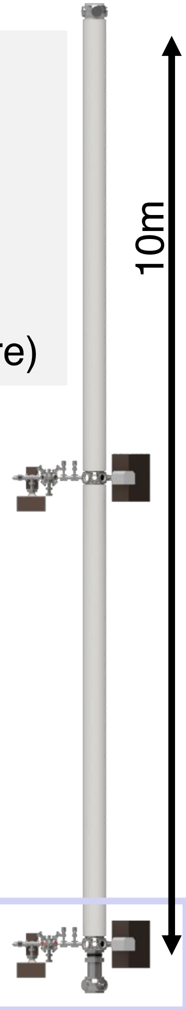
Workshop @ CERN, March 13/14, 2023

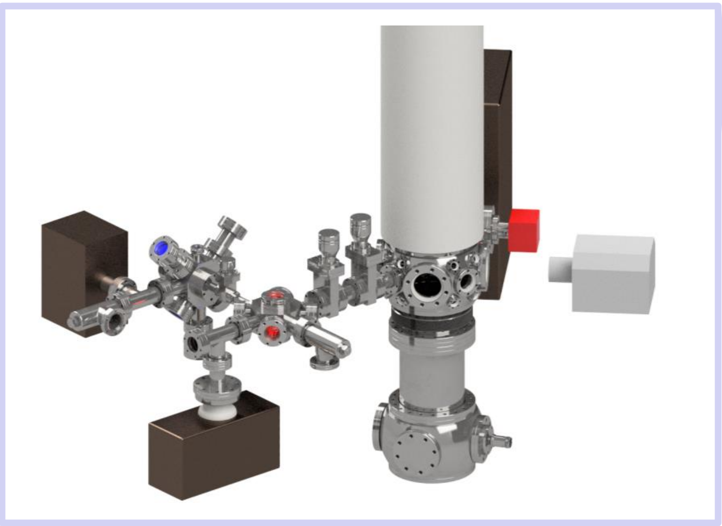
AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755

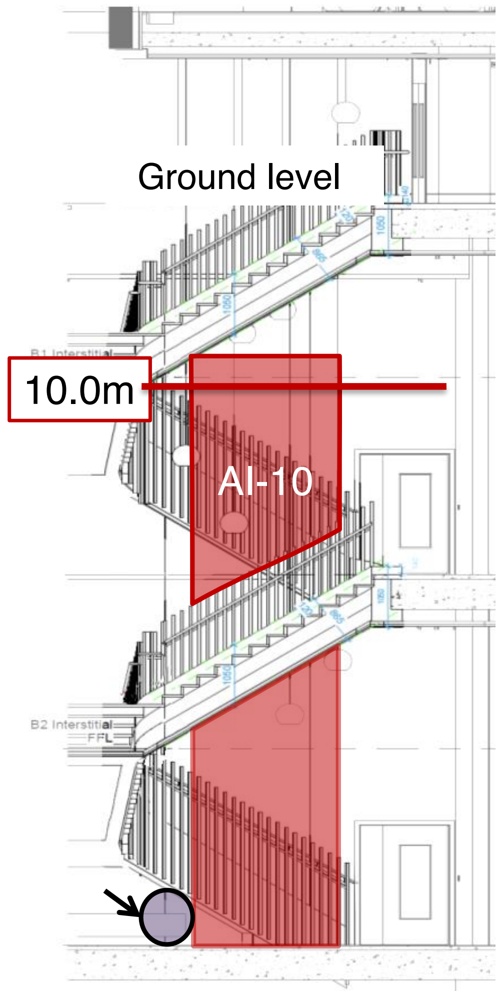
Planned Location of AION-10m

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)

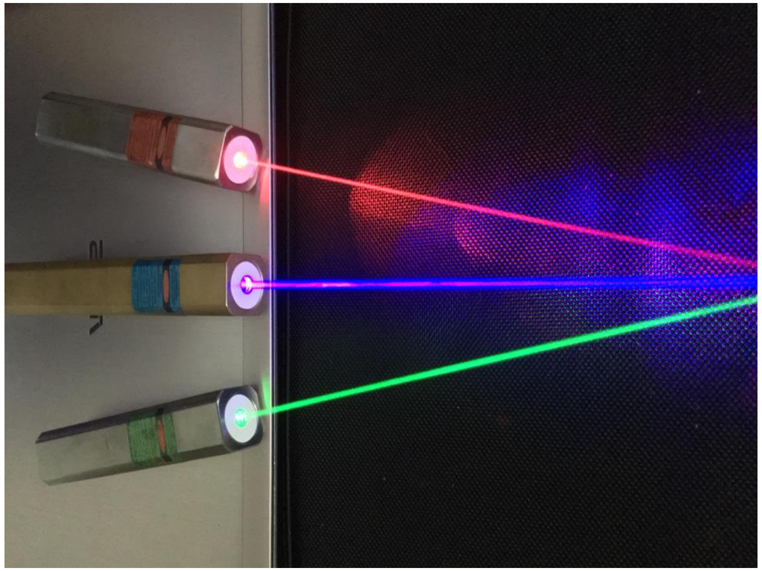


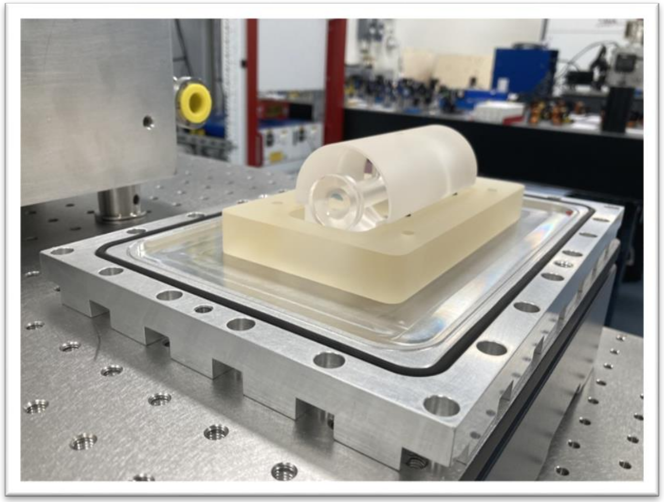


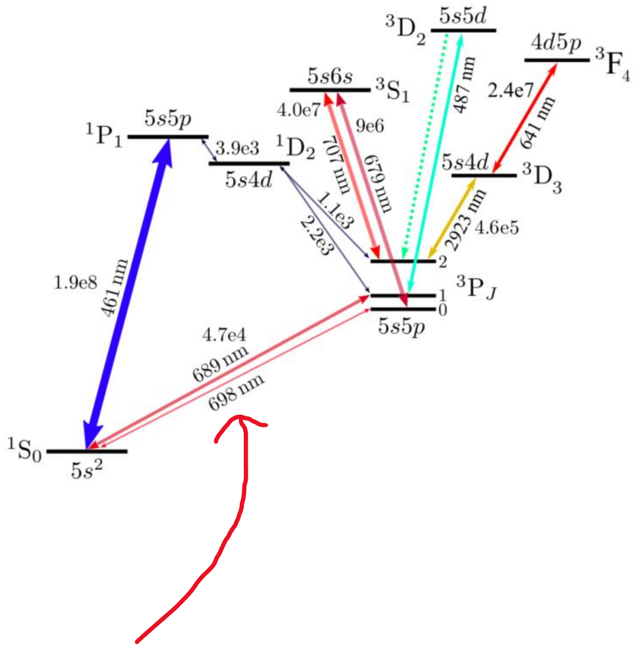



Cambridge July 2022
Oxford October 2022
AION
Laser Laboratories
Birmingham July 2022
Imperial July 2022

Laser Stability Tests



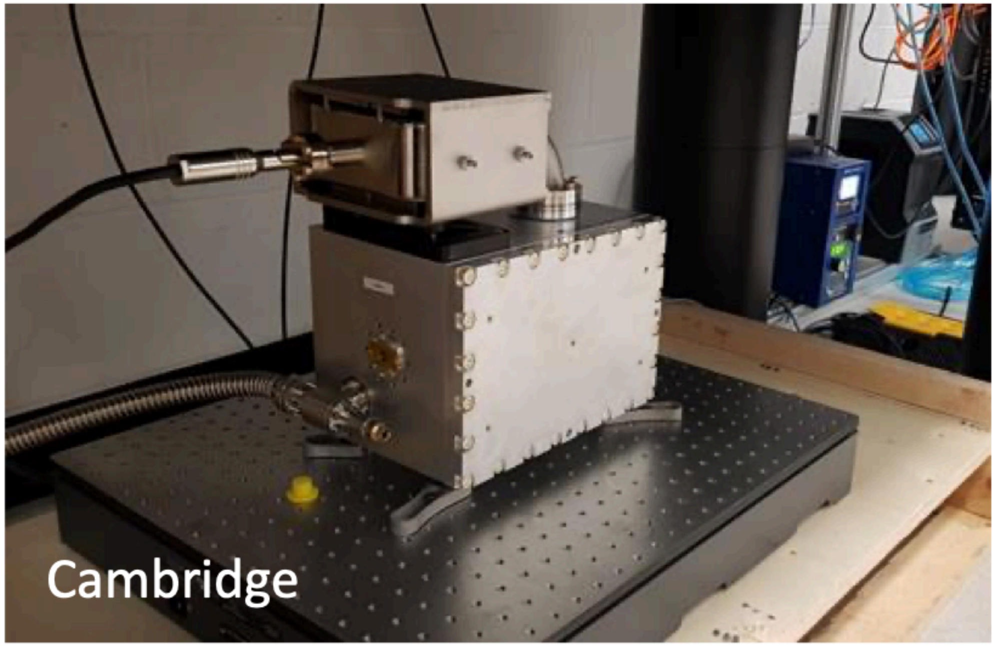


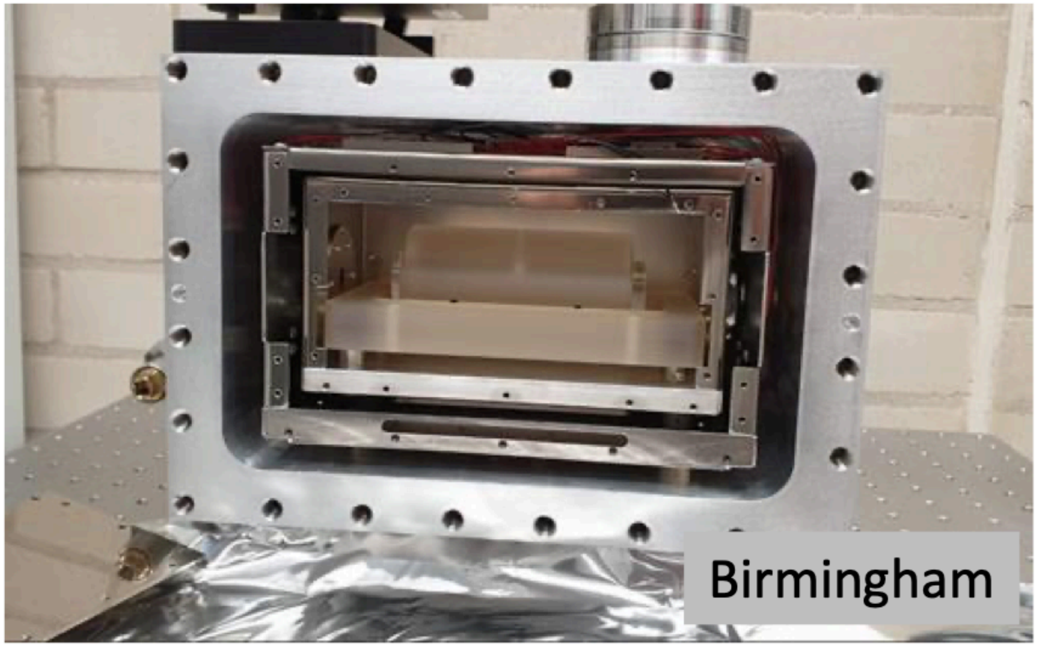


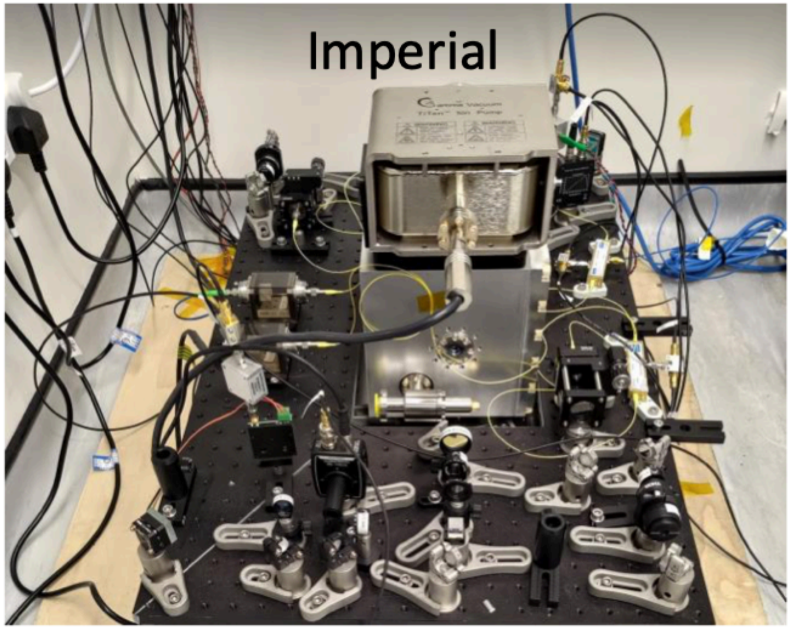
Need to stabilise 689 nm and 698 nm lasers in all 5 Sr labs

→ We can address the very narrow 689 nm and 698 nm atomic resonances

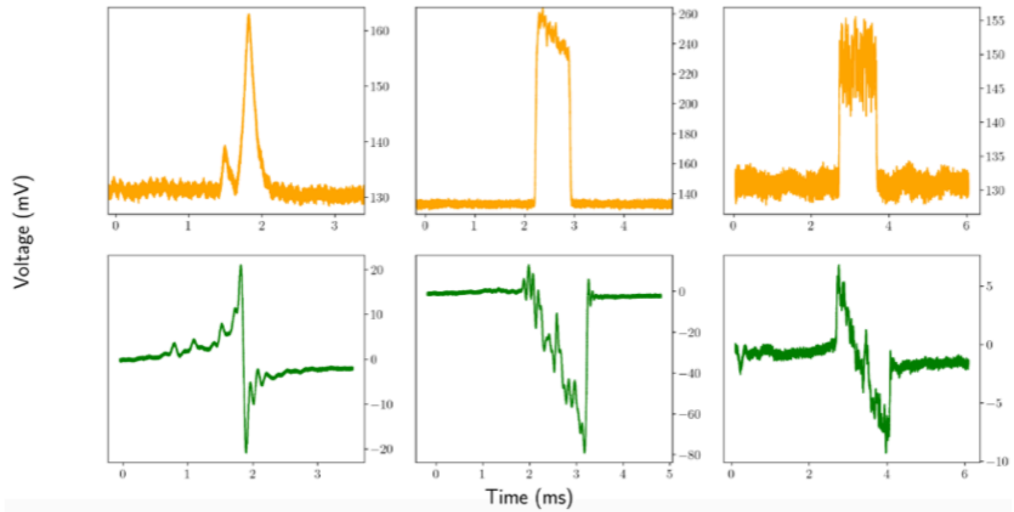
Laser Cavity Tests



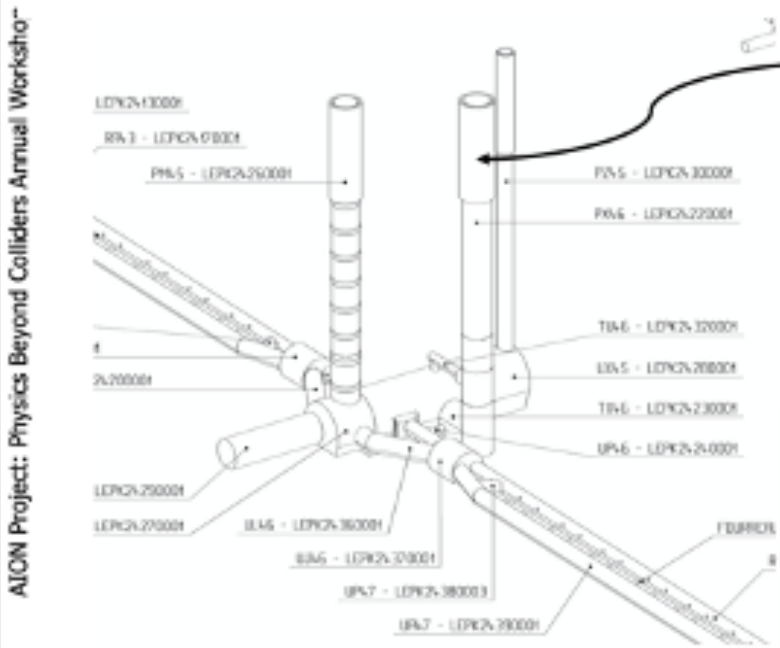




Below: Transmission and error signal data at Imperial
Laser stays locked for several days autonomously



Possible CERN Location of AION-100m



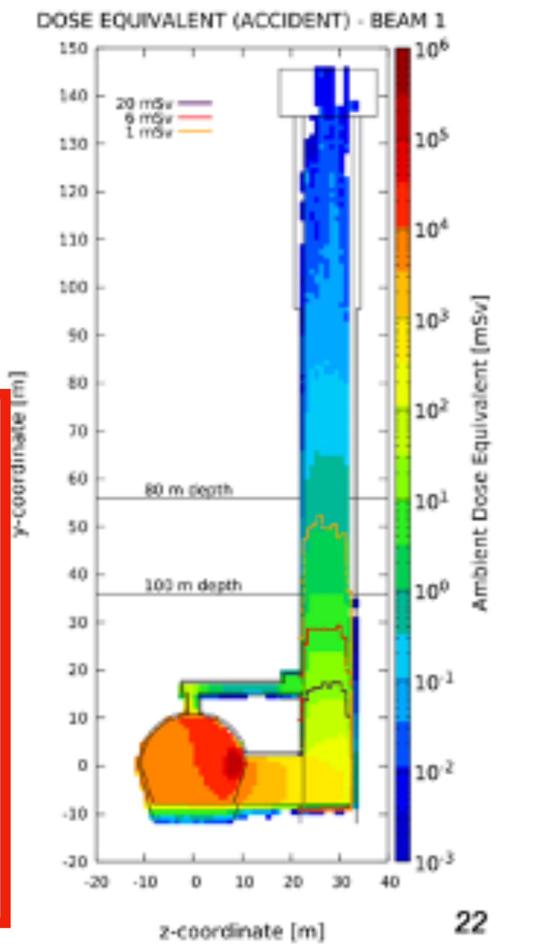
PX46 – P4 Support shaft

Lengths 143m

D = 10.10m

➢ **Ideal basic parameters for AION100**

Supported by CERN PBC Team
(Gianluigi Arduini, Sergio Calatroni …)
on feasibility study:
Seismology
Temperature
Ventilation
Radiation protection
Electromagnetic interference
Access & safety

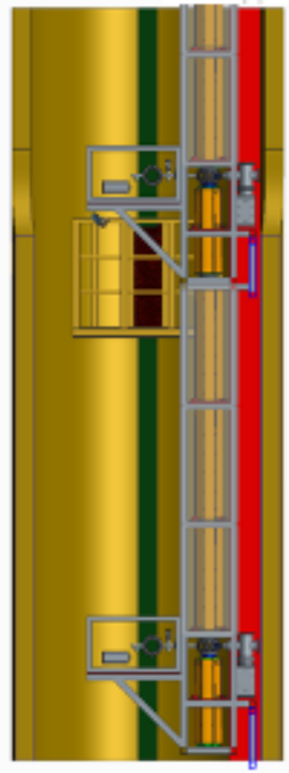


Also studying possible site at STFC Boulby Laboratory in UK

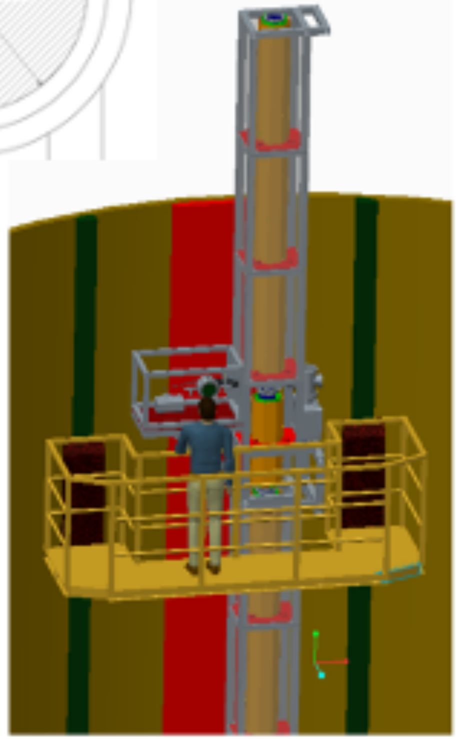
Possible CERN Location of AION-100m

Concept for layout

- **100 m long Interferometer**
  - Possibly built with 5m long modules
- **Moving platform around the detector**
  - Platforms to be able to carry atom sources, ion pumps up and down etc.
  - NOT free hanging, needs rails (avoids swinging cage colliding with detector
- **Need staircase for evacuation surrounding the platform (?)**

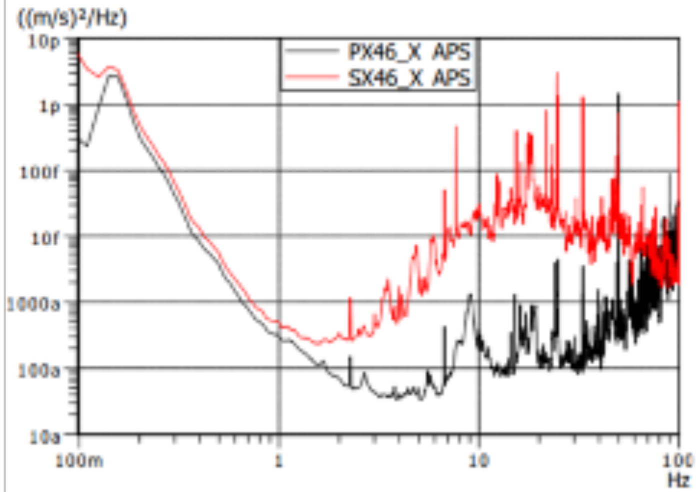


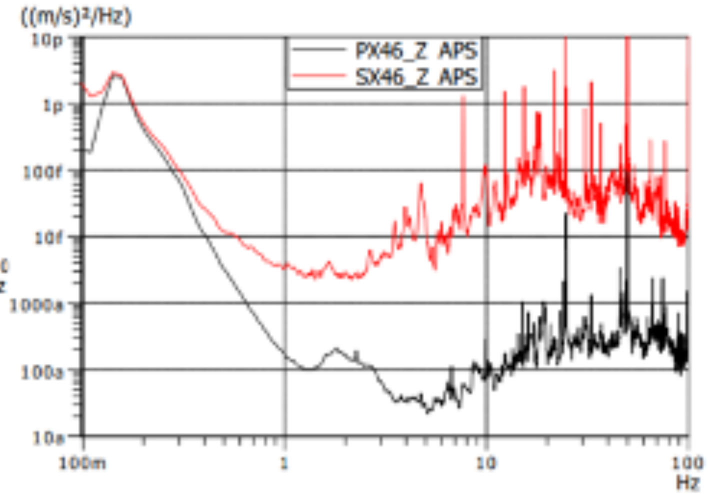
Single module of 5m

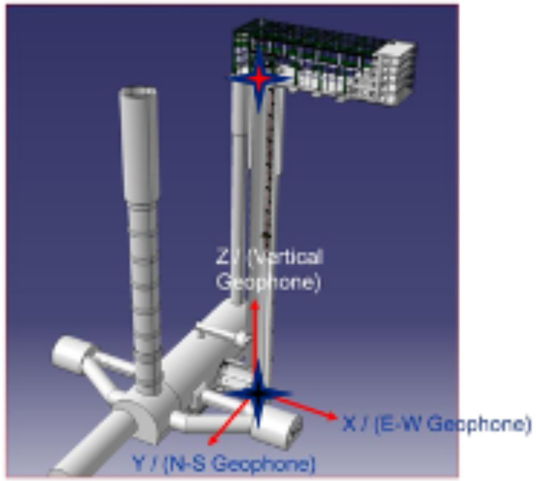


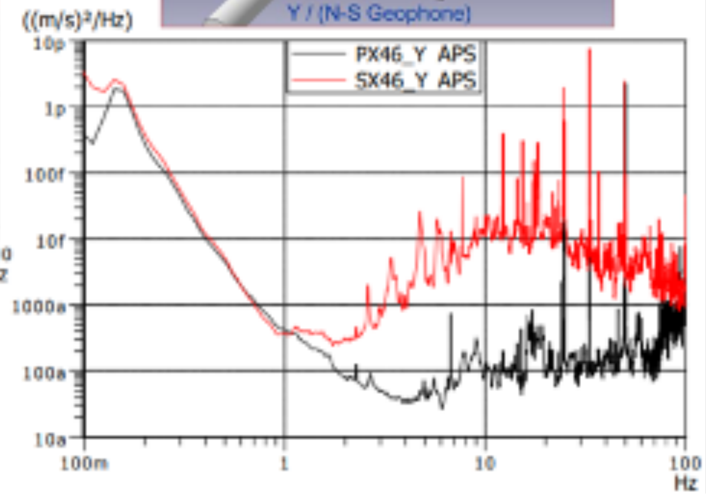
Seismological Measurements

Comparison of measurements at top & bottom of PX46

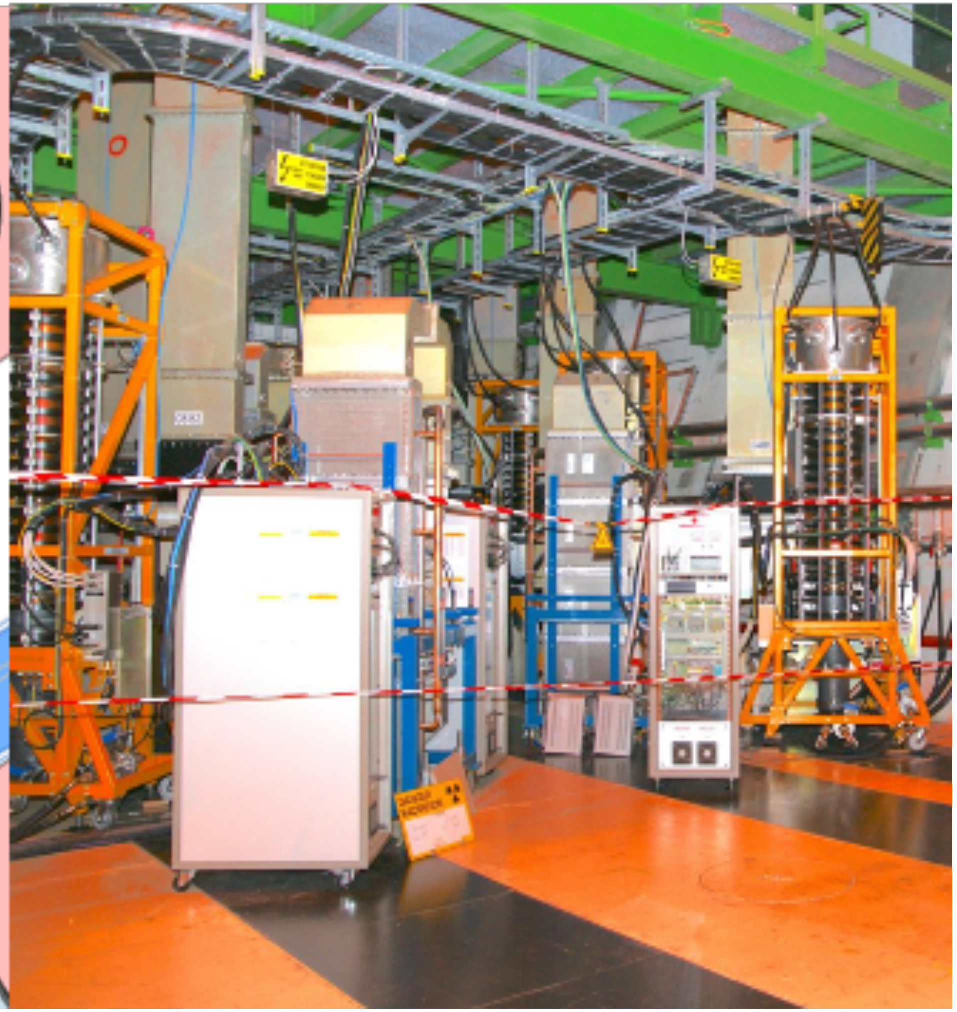




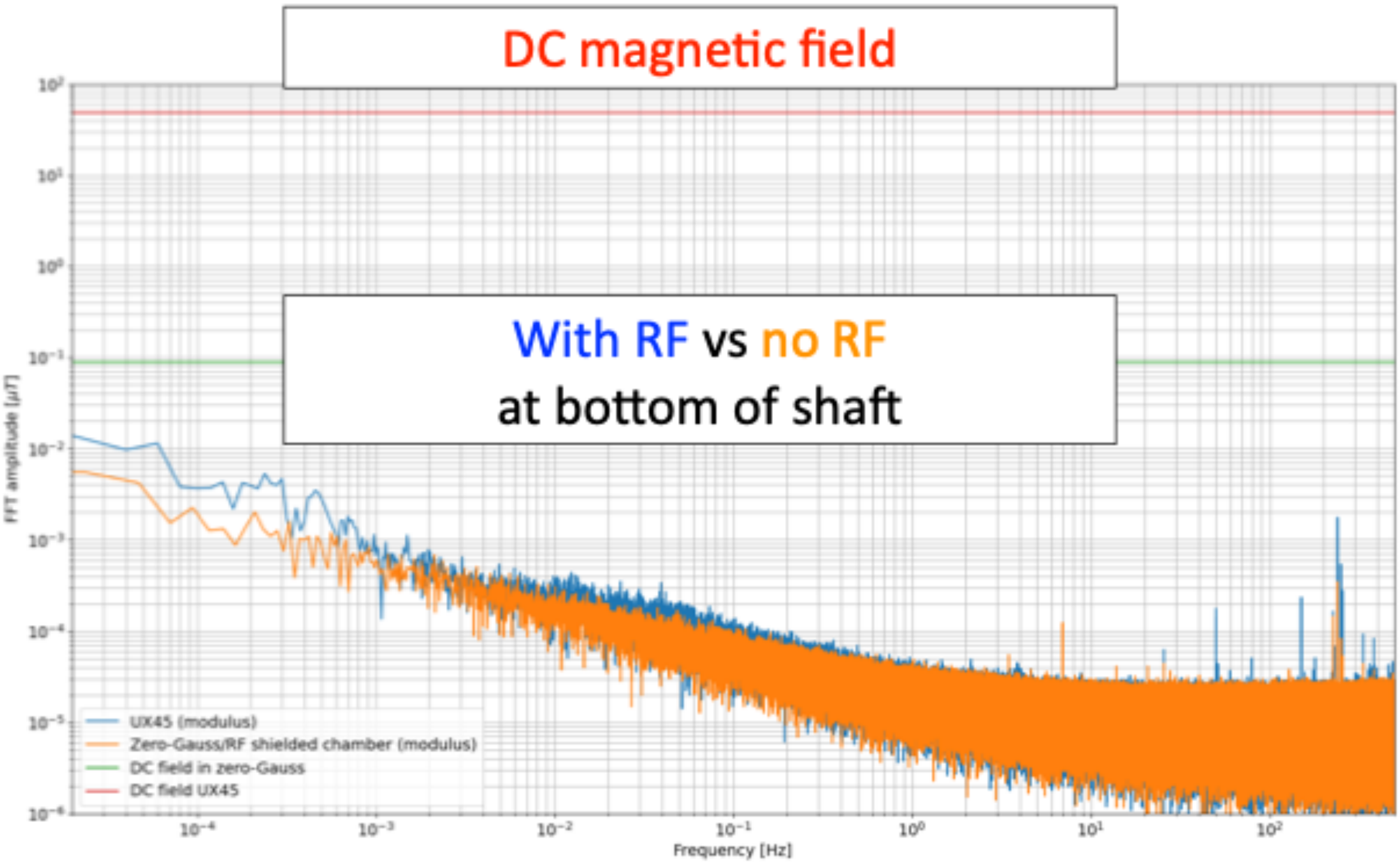




Electromagnetic Interference?



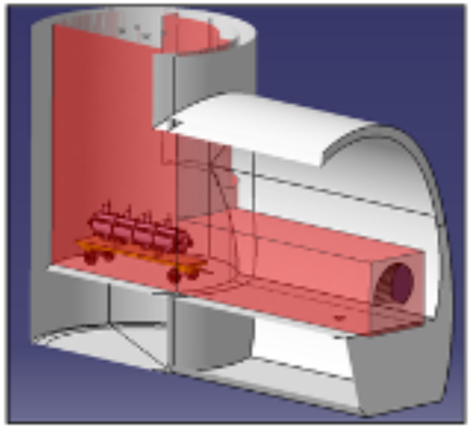
Electromagnetic Studies for AION-100



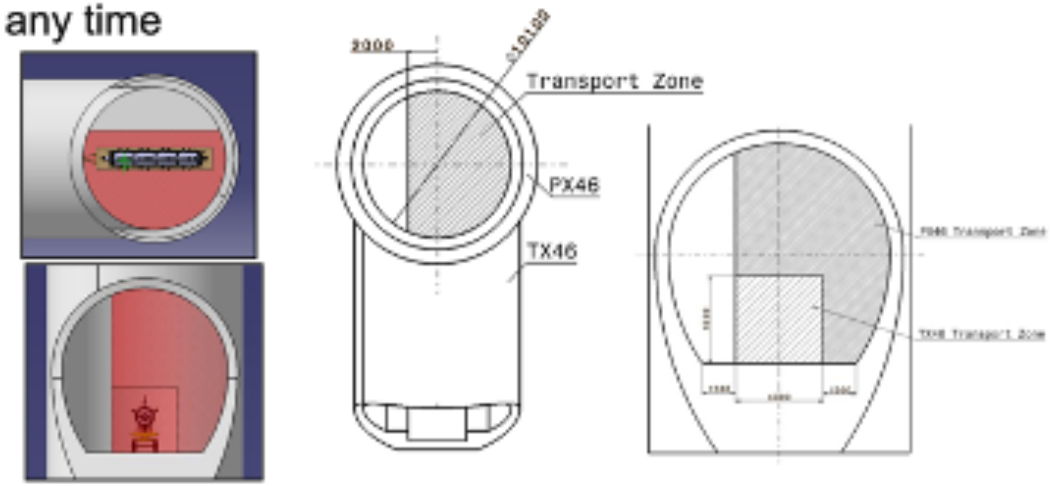
Radiation Shielding Options

Shielding options

- **Handling constraints:**
  - Shaft used to raise/lower LHC and HL elements, PX46, TX46 need to stay open at any time

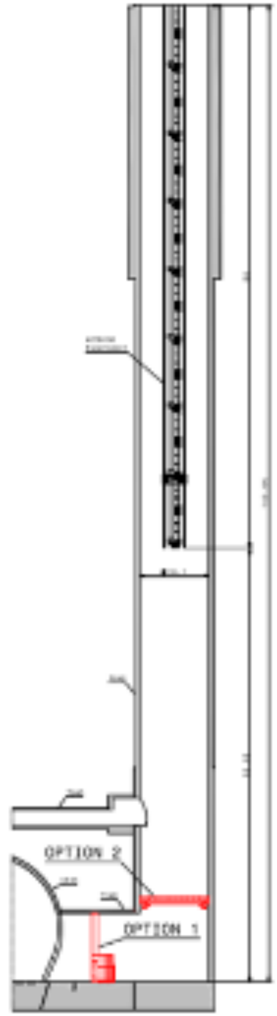


Courtesy of EN-HE-PO



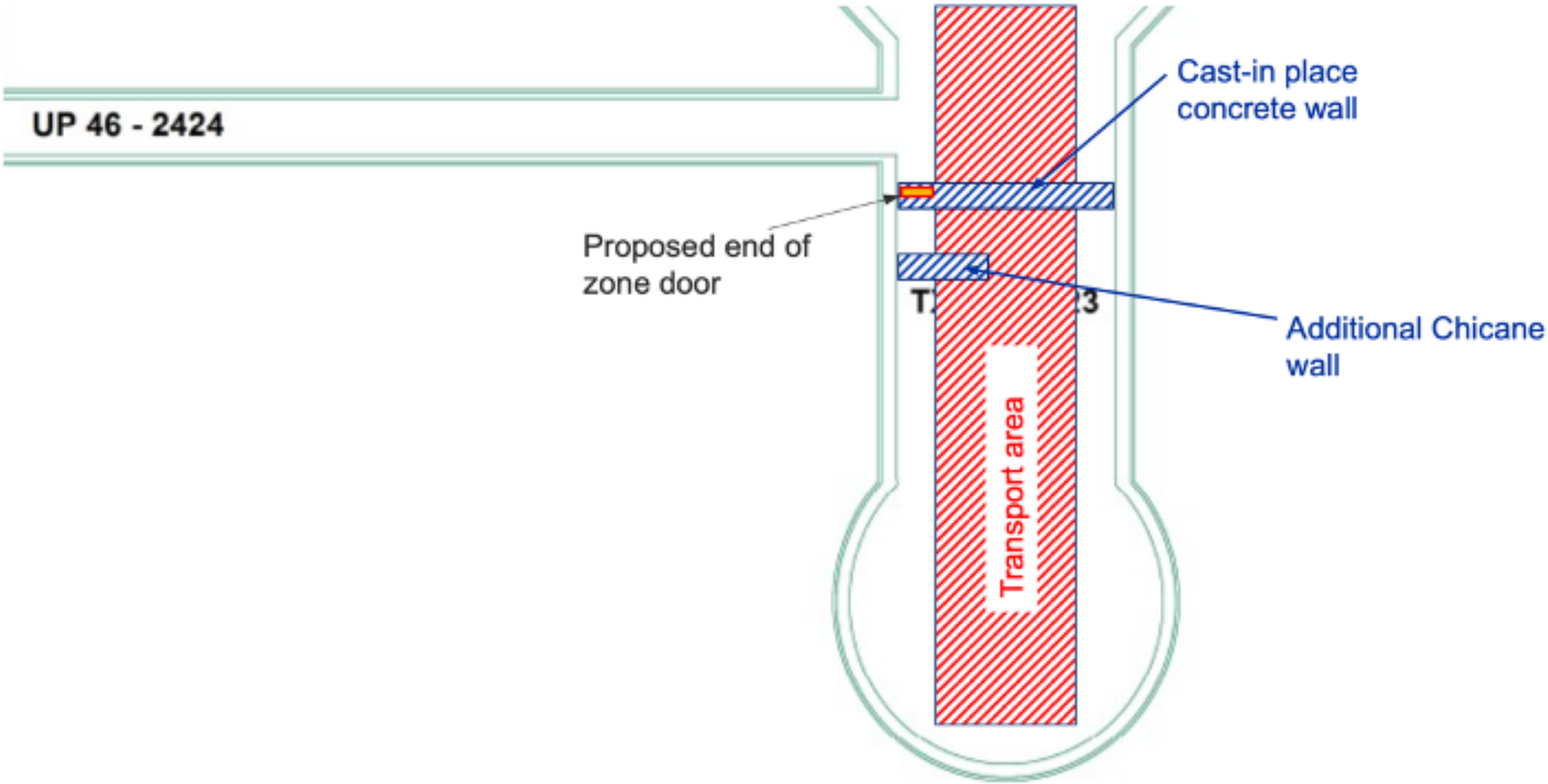
Transport zone required to be kept in the TX46, PX46

- **Two solutions proposed by CE**
- **Solutions with removable shielding blocks to avoid blocking the area reserved for transportation**



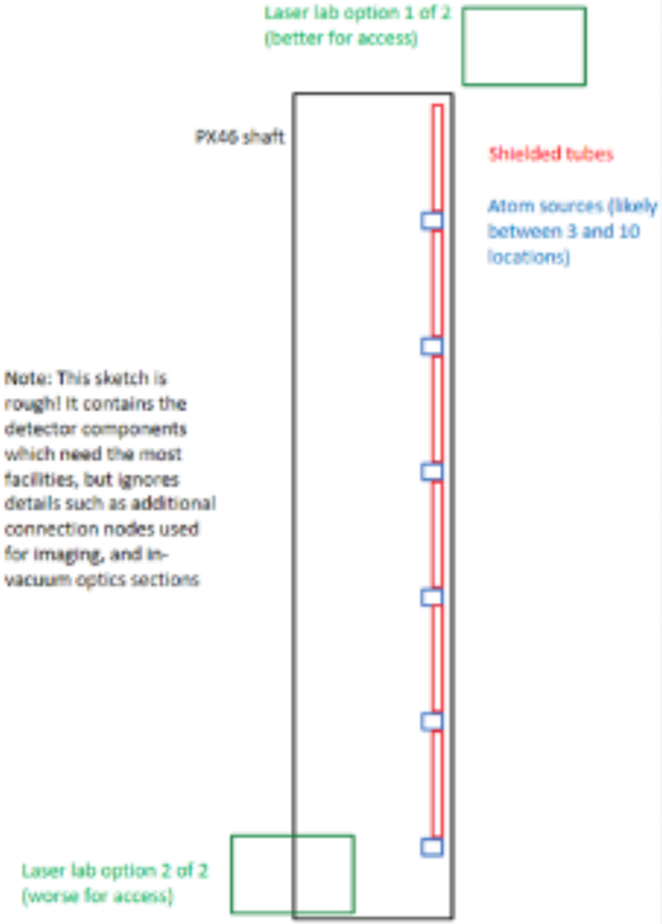
Proposed location for shielding

Proposed Shielding Option



AION Requirements/Requests

AION



Note: This sketch is rough! It contains the detector components which need the most facilities, but ignores details such as additional connection nodes used for imaging, and in-vacuum optics sections

Richard Hobson
&
Charles Baynham

Requirement	Shielded tube (per tube)	Atom source (per source)	Laser lab
Volume	~ 1 x 1 meter cross-section	- ~ 1 meter in radial direction, ~ 2 meter in tangential direction, ~ 1 meter in vertical direction	Floor area > 50 m^2
Mains power	None	- Up to 10 kW total power consumption, one ~400V three-phase outlet and one ~240V 32A single-phase commando output	- 35 kW total, in ~ two three-phase outlets and 100 single-phase outlets
Control cables	Magnet coils x4, up to 10 amps each	- ~ 30 optical fibres from laser lab to atom source Different types: high-power steel-clad fibres, lower-power single-mode optical fibers, and network communication fibres - ~ 3 triaxial shielded cables from laser lab to atom source, rated up to 3 GHz	- ~ 30 network ports
Gases	None	Helium for leak testing (rare use, probably only during initial setup --> possibly easier to use a handheld can?)	Helium Compressed dry air Argon
Water cooling	None	5 kW water cooling capacity, ~ 5 barg, ~ 15 degrees C (but above dew point), stable to < +/- 1 deg C	30 kW cooling capacity
Cryogenics	None	None	None
Ventilation	Enough air flow to maintain temperature stability	Enough air flow to remove 5 kW per atom source	30 kW plant-generated heat removal capacity + whatever is required to remove ambient heat and maintain 21 deg C
Access	None foreseen, but possible access for repair after unexpected failures	Almost certainly we require access during beam operation (i.e. year-round, ~ 12 hours/day). If not, then it will take considerable extra engineering effort - it would create a few years delay for technology development and testing of autonomous atom sources.	Year-round access >~ 12 hours/day
Temperature stability	< 1 K/hour drift	Temperature-controlled enclosure required, < 0.5K pk-pk temperature fluctuations, HEPA-filtered air flow	22 deg C with < 1 K pk-pk fluctuations
Smoke detector	Yes, why not	Yes, why not	Yes, why not
Oxygen depletion monitor	Not needed	Not needed	Yes
Special	Free-space laser beam delivery (one beam) from laser lab to shaft. Rigid 20 cm diameter straight steel tube (potentially with right-angle joints, and mirrors but not too many) running from laser lab to the top of the detector in the shaft*		
Hoisting equipment	Each individual section could plausibly be constrained to < 907 kg (this is the capacity of the MAGIS crane), but additional capacity could be helpful if available		

*Alternatively, we could have the laser stationed at the base of the shaft, so that we no longer need free-space access through the lid of the shaft. This would require similar temperature control requirements to the laser lab, and approx. 10 kW electrical cooling power (but this could need to be larger depending on laser technology used - R&D is required to determine this).

Questions:

- How do we get in and out? Ideally we'd avoid opening and closing the lid. In the scenario where we have full access (installing shielding at the bottom of the shaft to protect against beamline loss), can we just leave the lid open permanently?

Safety: Evacuation

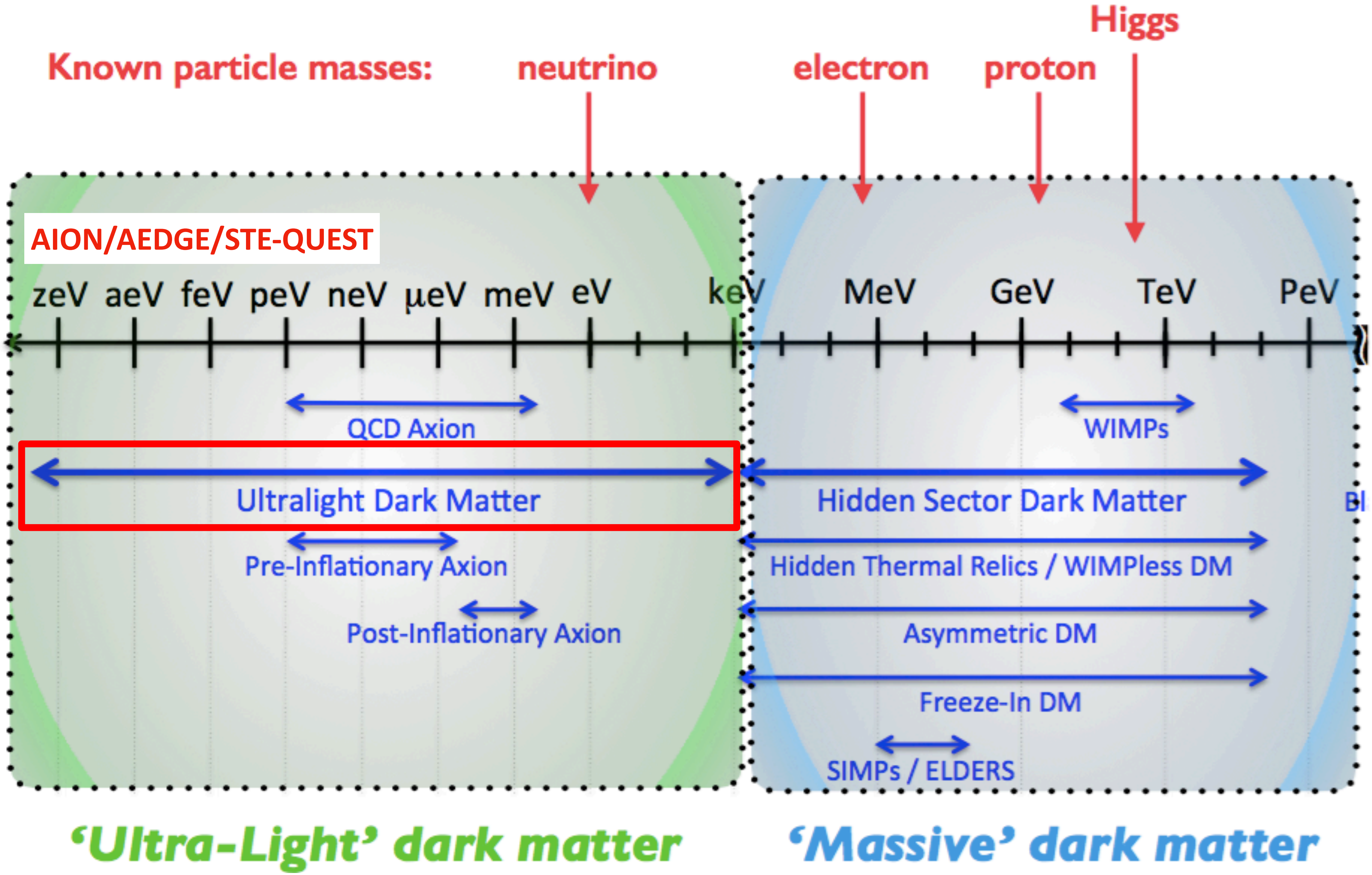
- The EN-HE group found a solution to access vertically to the experiment with a platform based on the European Standard EN1495. This platform allows a complete vertical access along the PX45 shaft in all positions, but has a maximum speed of 12 m/min, constraint coming from the European standards.
- Discussions with CERN safety unit: acceptable evacuation time is 2 minutes
- Evacuation from near surface requires speed of 70 m/min
- A standard machine based on EN1495 allows an evacuation in about 30 minutes, because the evacuation speed is approximately 6m/min and the evacuation system needs to cool down every 20m
- Two possible solutions:

  Building a machine based on EN1495 able to evacuate at the maximum speed of 12 m/min without pauses. This would mean an evacuation time of about 12 minutes (11,67 minutes)

  Building a special machine based on the European Machinery Directive, able to evacuate people faster than 12 m/min. The EN-HE group needs to launch a preliminary study to validate the feasibility and the maximum speed reachable considering the volume available for the platform

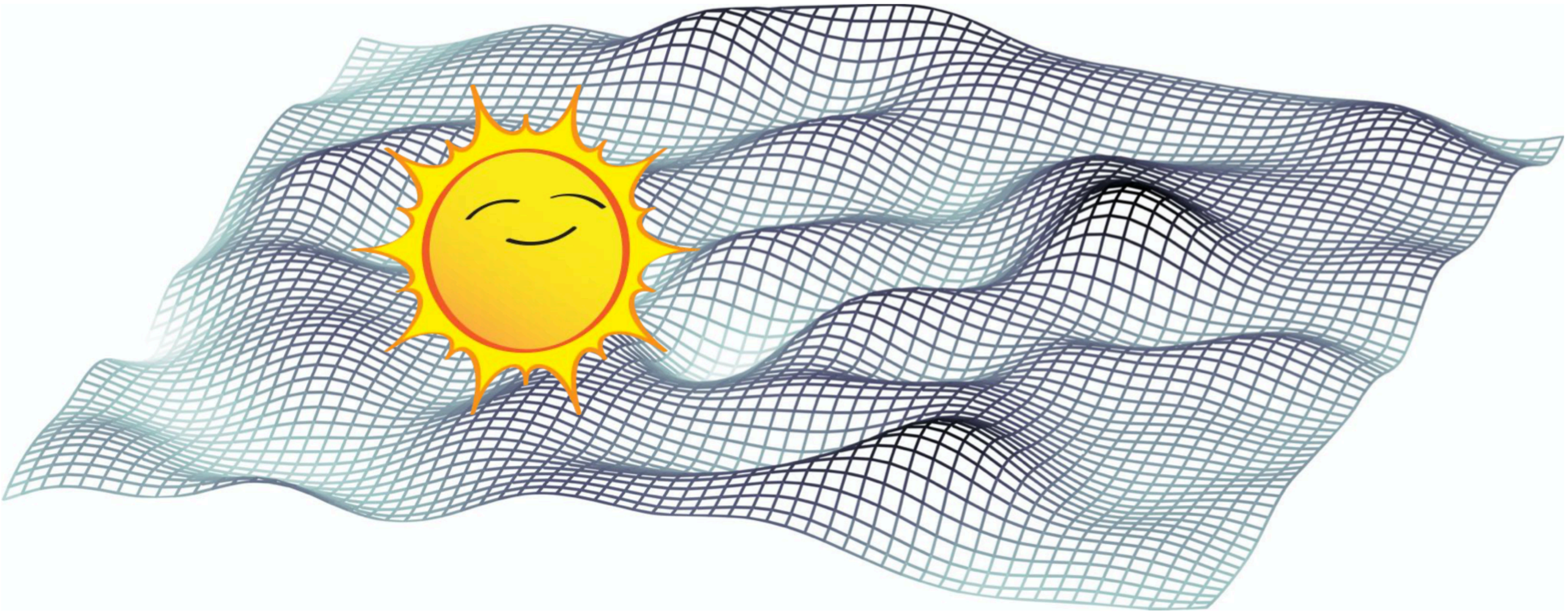
- **EN-HE is confident that a technical solution can be found**

Search for Ultralight Dark Matter



Ultralight Dark Matter

A scalar ULDM $\phi(\mathbf{x}, t)$ field would be present throughout the Solar System

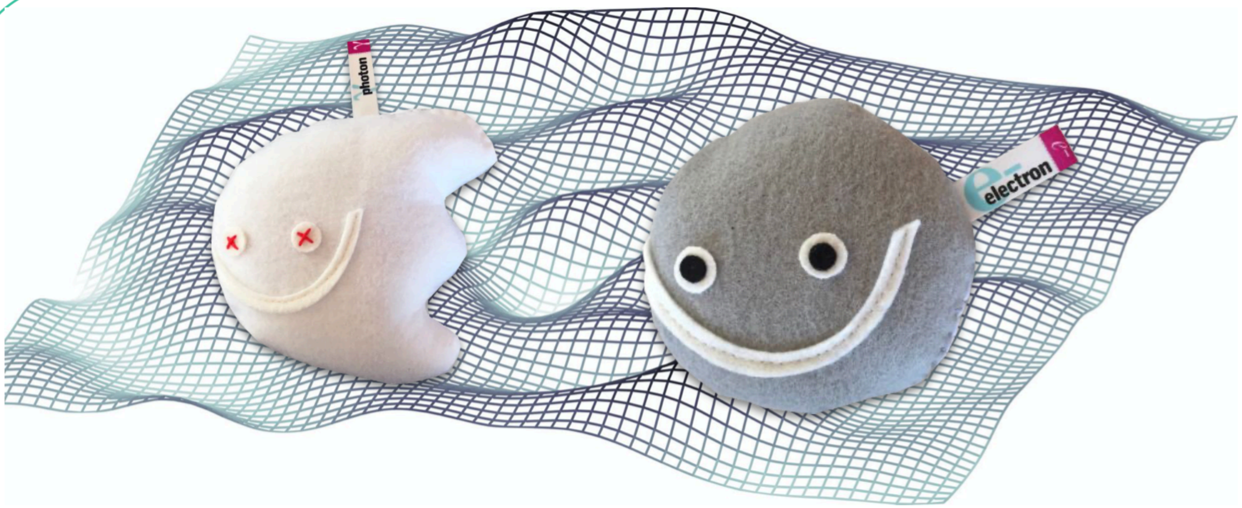


The wavelength depends on the ULDM mass: $\lambda \sim 10^8\,\mathrm{km}\left(\frac{10^{-15}\,\mathrm{eV}}{m_\phi}\right)$

AION

Ultralight Dark Matter

Interactions with the ULDM field lead to oscillations in fundamental ‘constants’



Time-dependent electron mass:

$$m_e(t, \mathbf{x}) = m_e \left[1 + \frac{d_{m_e}}{M_{\rm Pl}} \phi(t, \mathbf{x})\right]$$

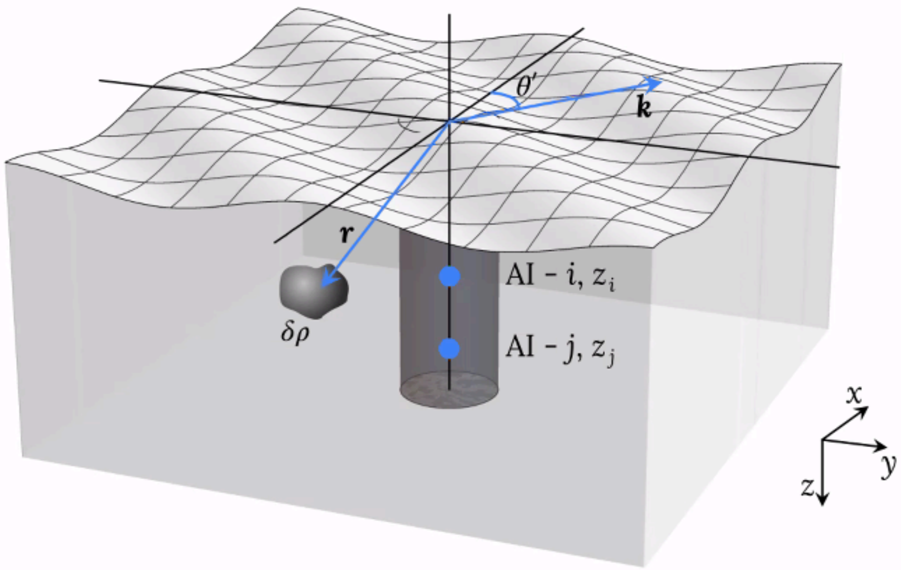
Time-dependent electromagnetic fine structure constant:

$$\alpha(t, \mathbf{x}) = \alpha \left[1 + \frac{d_e}{M_{\rm Pl}} \phi(t, \mathbf{x})\right]$$

Tiny oscillations induced in transition energies: $\dfrac{\delta\omega_{\rm Sr}}{\omega_{\rm Sr}} = \dfrac{\sqrt{2\rho_{\rm DM}}}{m_{\rm DM}} \dfrac{(d_{m_e} + \xi d_e)}{M_{\rm Pl}} \cos(m_{\rm DM} t)$

Gravity Gradient Noise

- **Rayleigh waves** propagating across the surface induce density variations underground



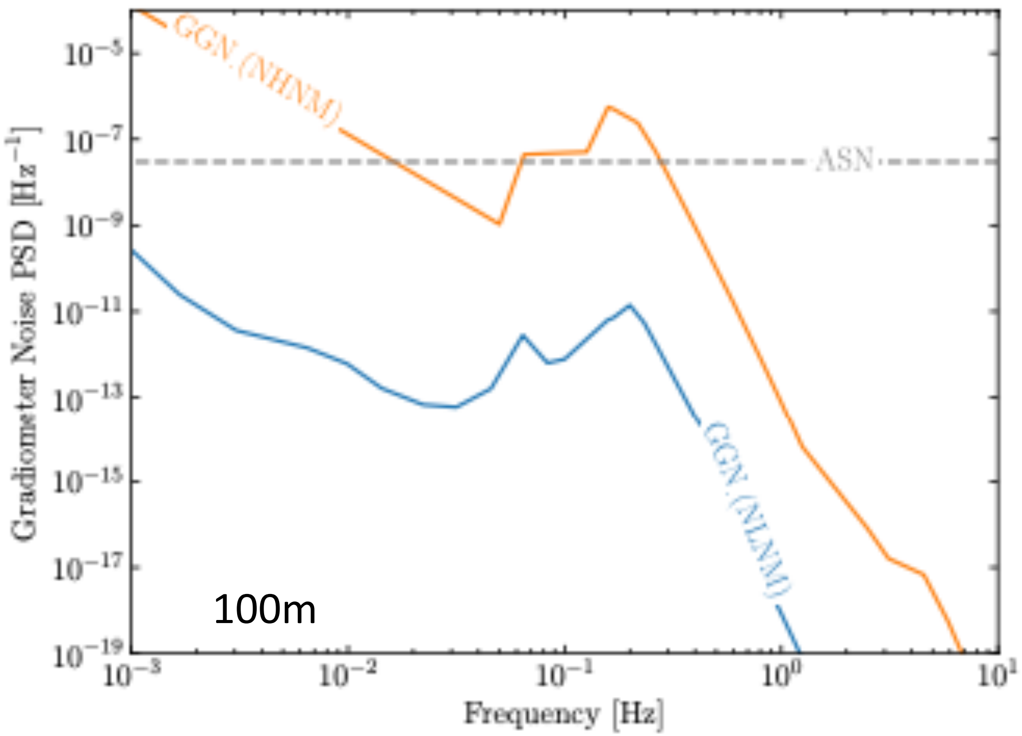
- The density variations give rise to a phase shift:

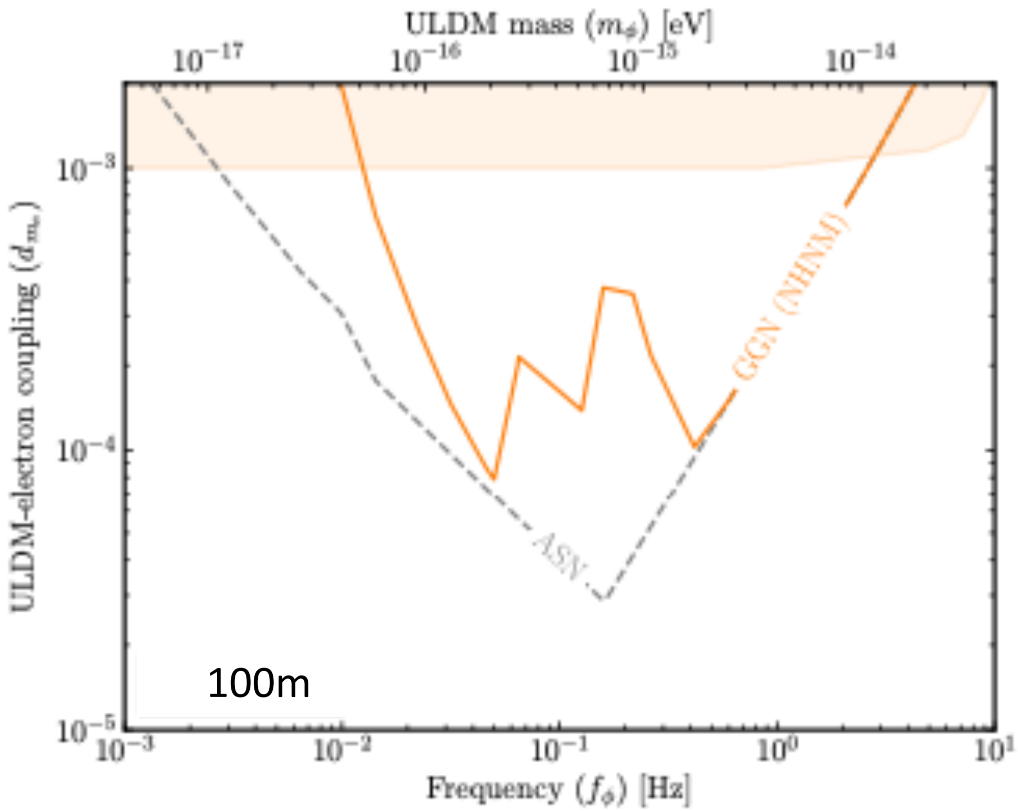
$$\Phi^{(i)}_{\mathrm{GGN},m} = \sum_a \xi_a \left[\widetilde{A}_a \exp\left(-q\frac{\omega_a z_i}{c_H}\right) + \widetilde{B}_a \exp\left(-\frac{\omega_a z_i}{c_H}\right)\right] \cos\widetilde{\phi}_{a,m}$$

- Two key parameters:
  1. ξ_a : surface displacement
  2. $\lambda_{\mathrm{GGN}} = \frac{c_H}{\omega_a}$: decay length with depth

Badurina, Gibson, McCabe & Mitchell, arXiv:2211.01854

Gravity Gradient Noise

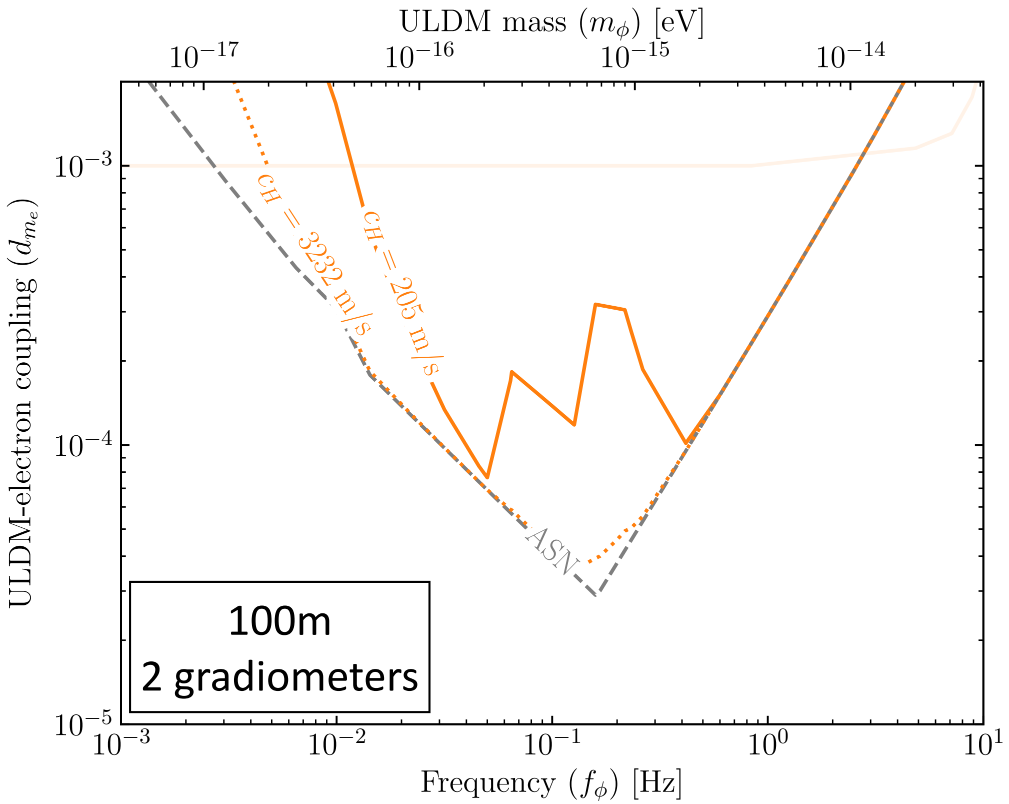


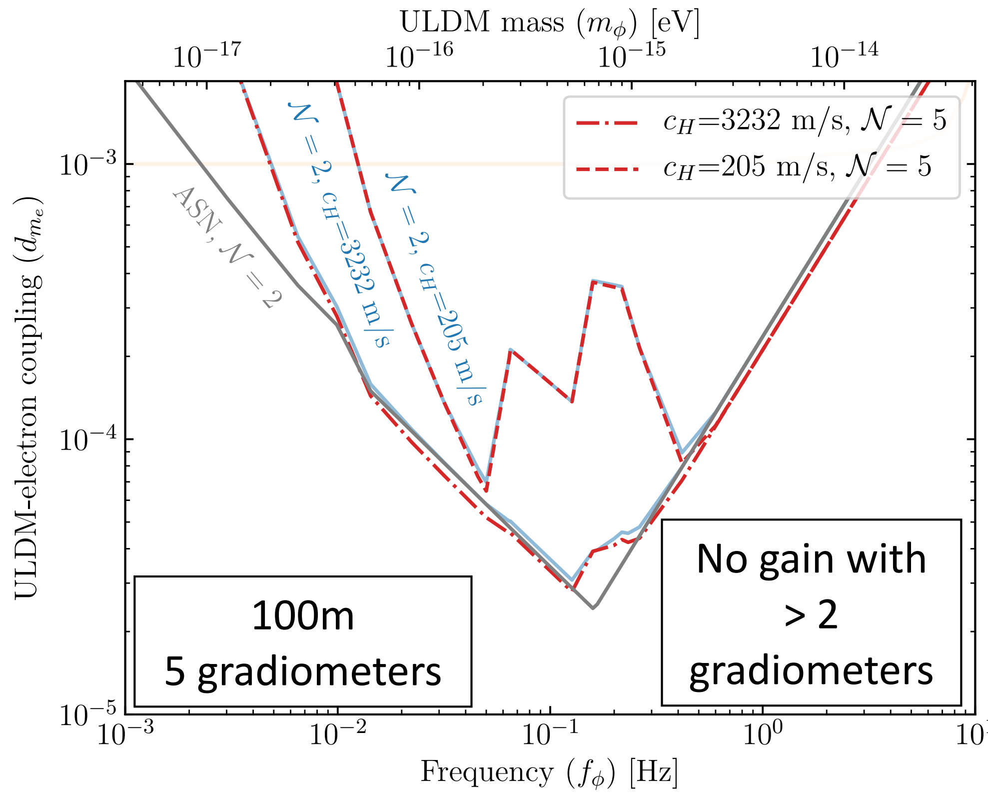


Assuming "infinite" isotropic medium
Unimportant for low background model

Badurina, Gibson, McCabe & Mitchell, arXiv:2211.01854

Gravity Gradient Noise





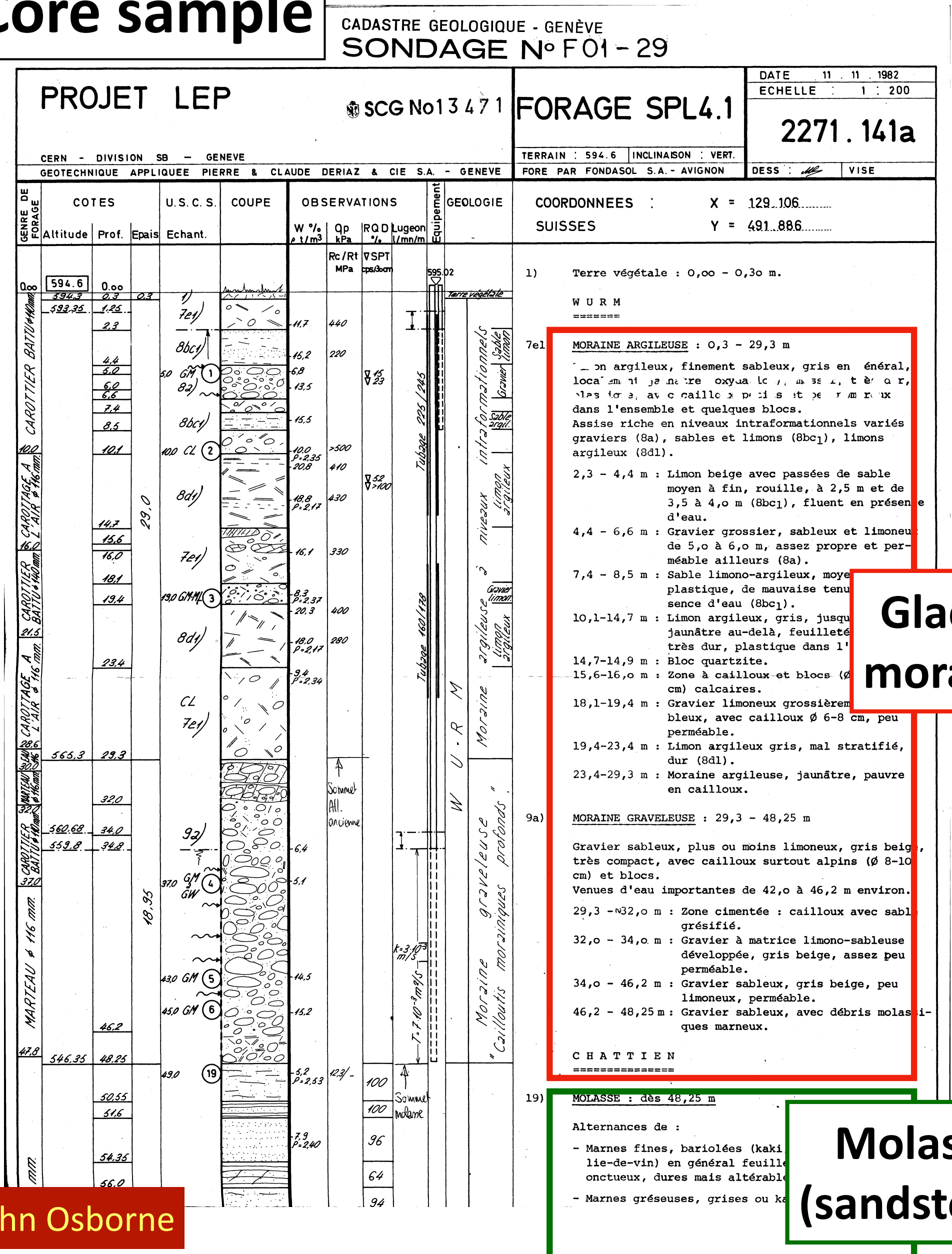
Importance of GGN depends on penetration depth of Rayleigh waves, which depends on speed c_H and is sensitive to rock composition

Material	c_H *[m\s]*
Sandstone	400
Shale	900
Chalk	1250
Granite	2800
Limestone	3200

Badurina, Gibson, McCabe & Mitchell, arXiv:2211.01854

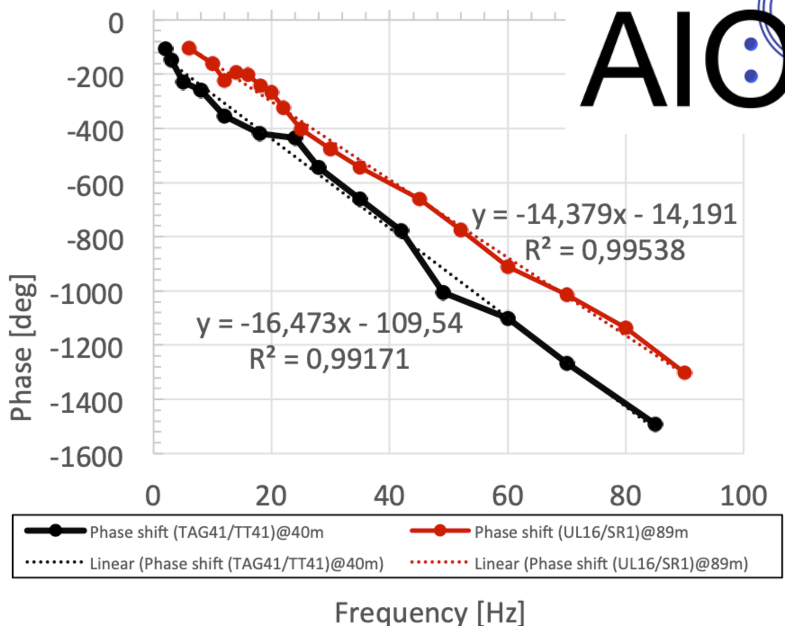
LHC Rock Studies

Core sample



Glacial moraine

Molasse (sandstone)



AION

$$V = \lambda \cdot f = 2\pi z \cdot f/\theta$$

λ – wavelength [m]

z – distance between geophones [m]

θ - phase shift between geophones [rad]

Positions	V [m/s]	Waves (*)
TT41-TAG41	≅900	Shear
UL16/SR1	≅2200	Pressure

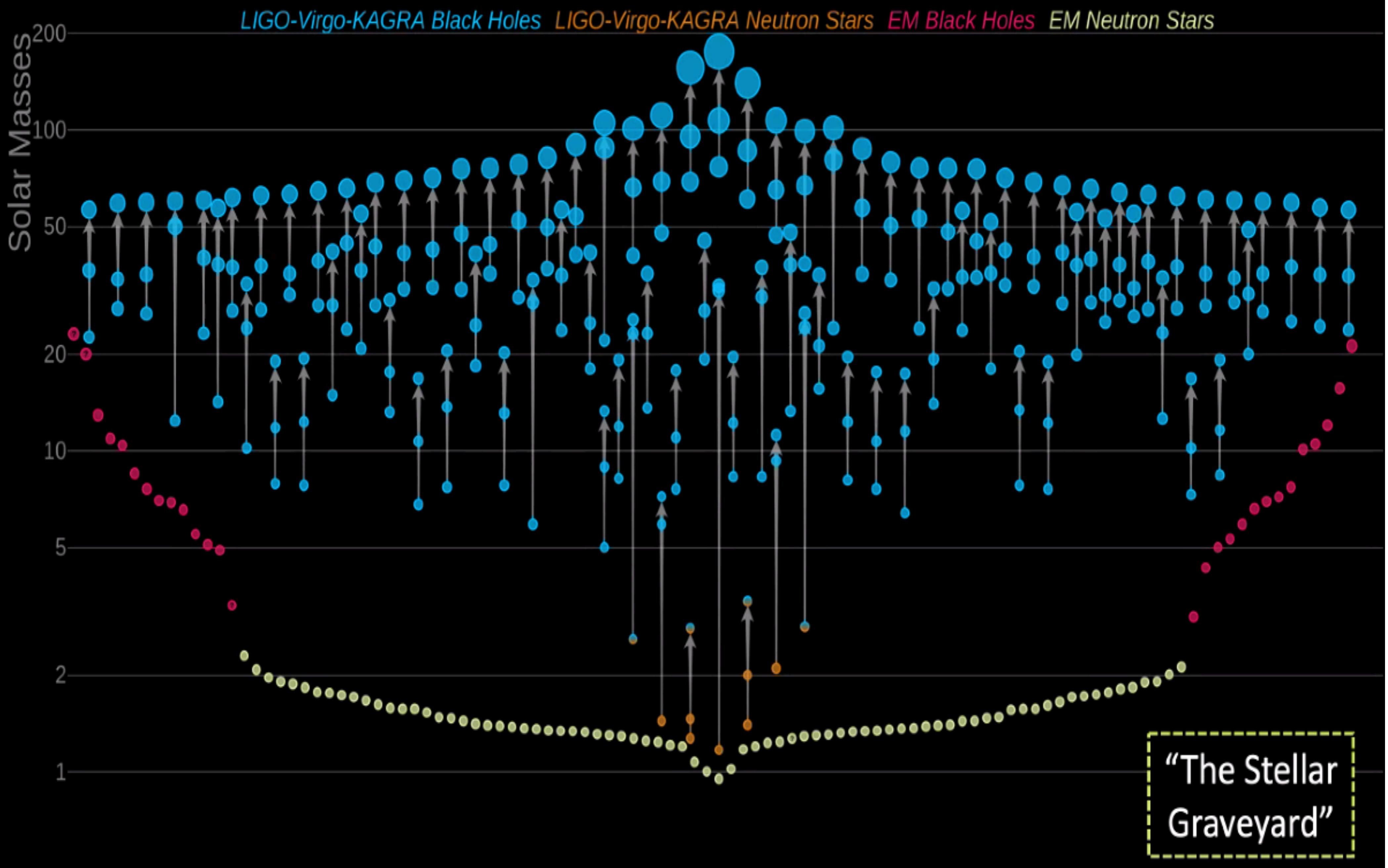
Waves velocity consistent with literature for the molasses

Typical rock velocities, from Bourbie, Coussy, and Zinszner, Acoustics of Porous Media, Gulf Publishing.

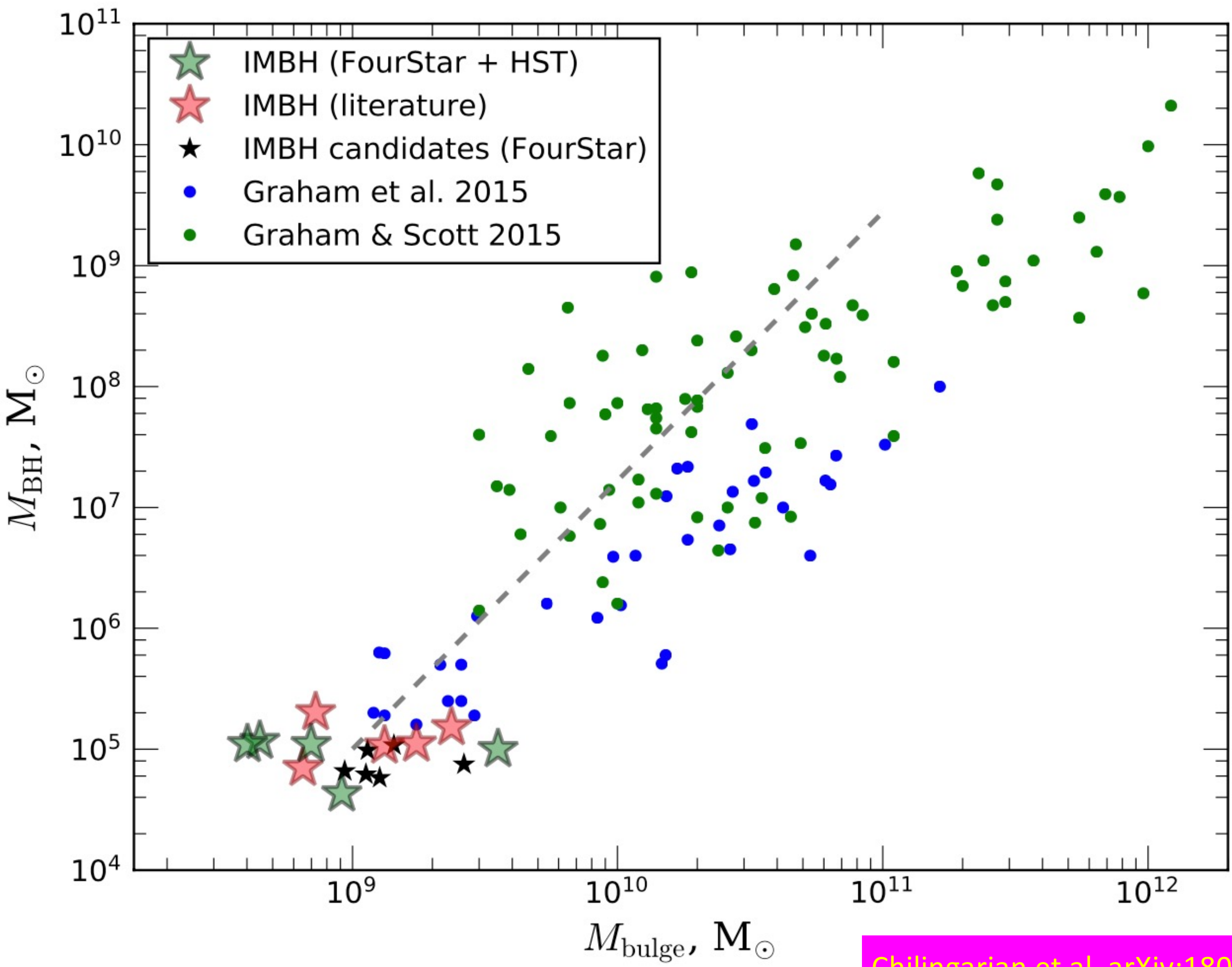
John Osborne

Michael Guinchard

LIGO-Virgo-KAGRA Black Hole & Neutron Stars

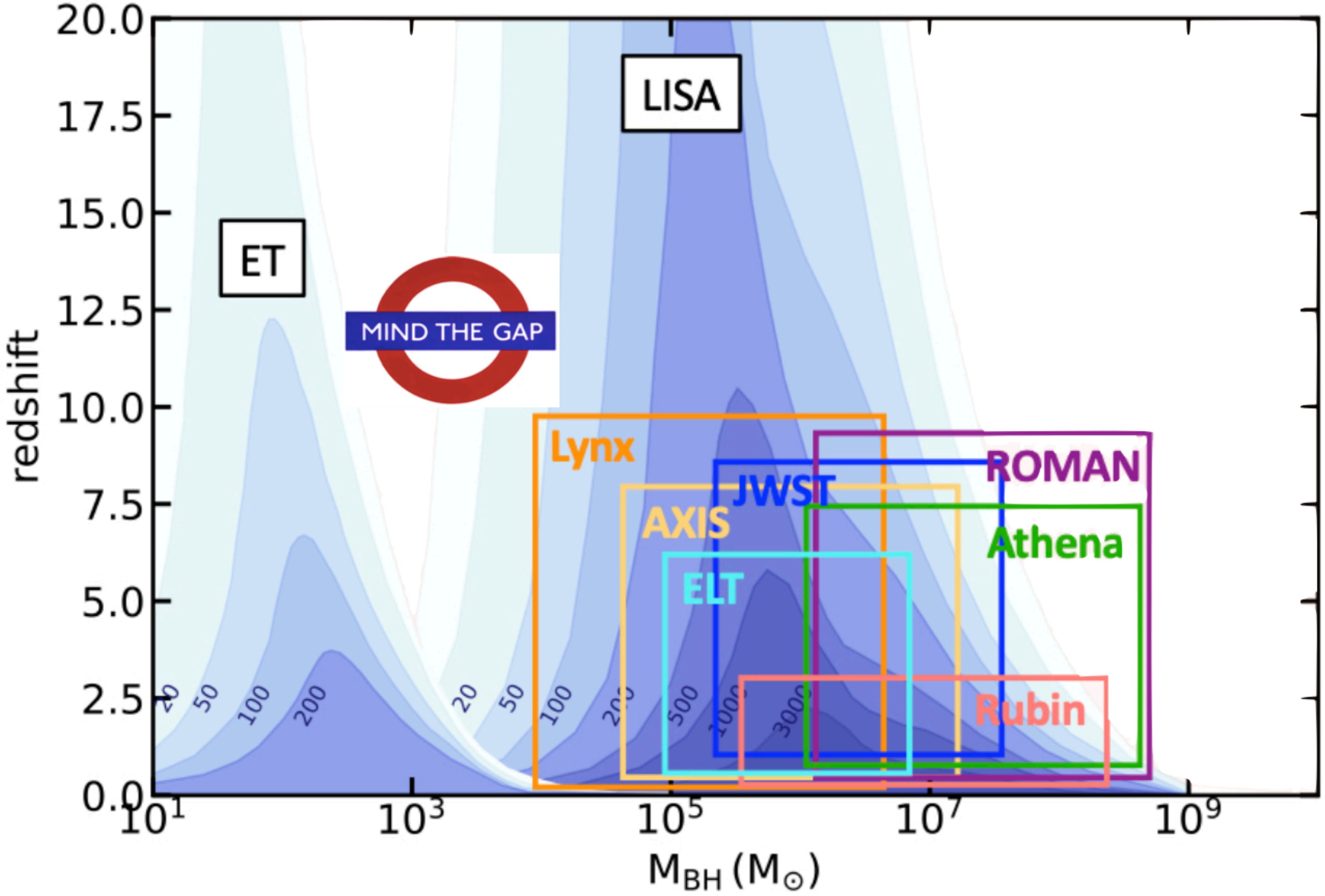


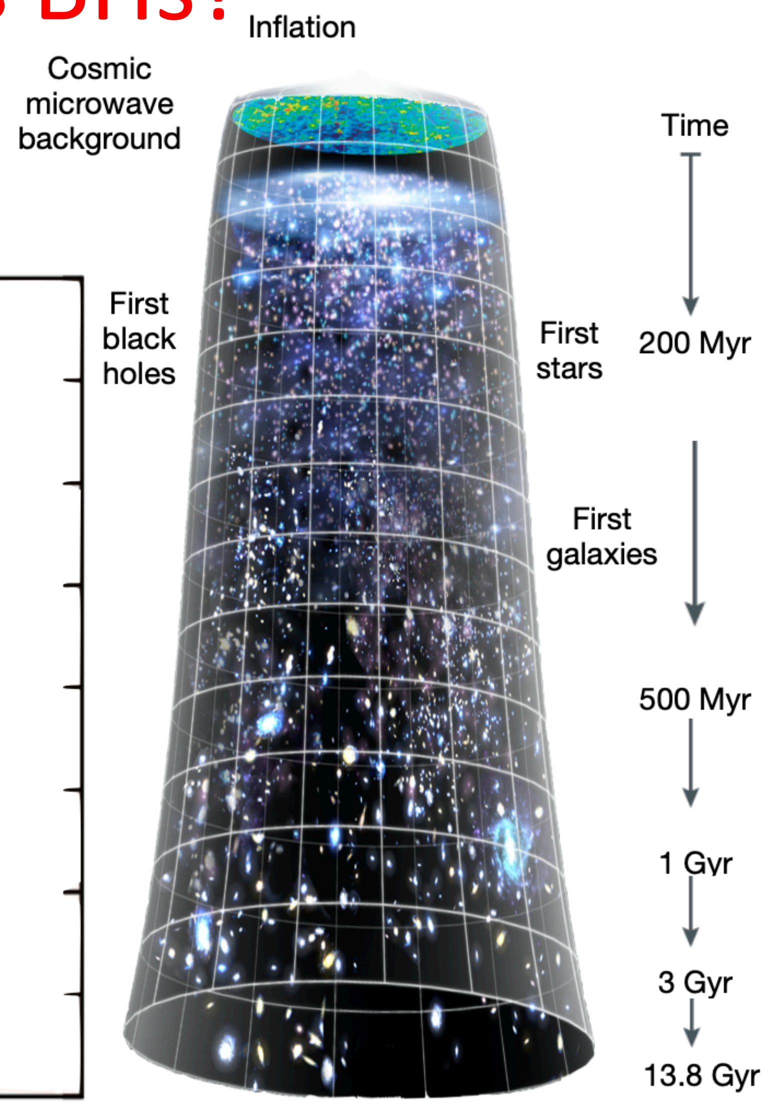
Intermediate Mass Black Holes Identified as Low-Luminosity Active Galactic Nuclei



Chilingarian et al, arXiv:1805.01467

How to Observe Mergers of Intermediate Mass BHs?

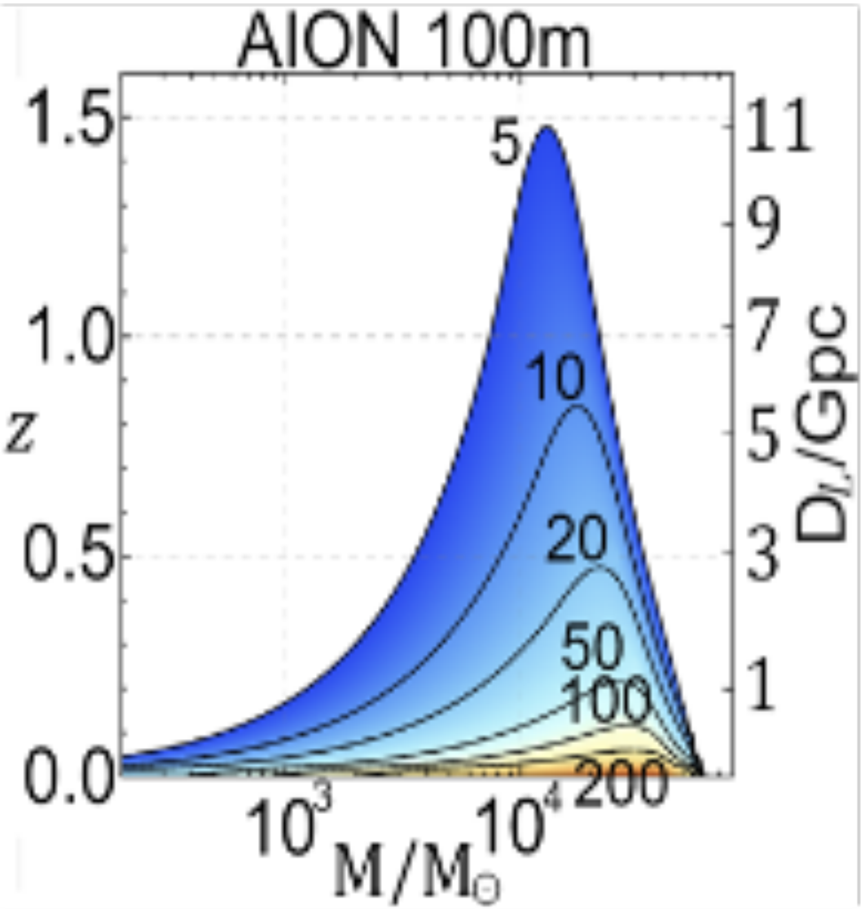




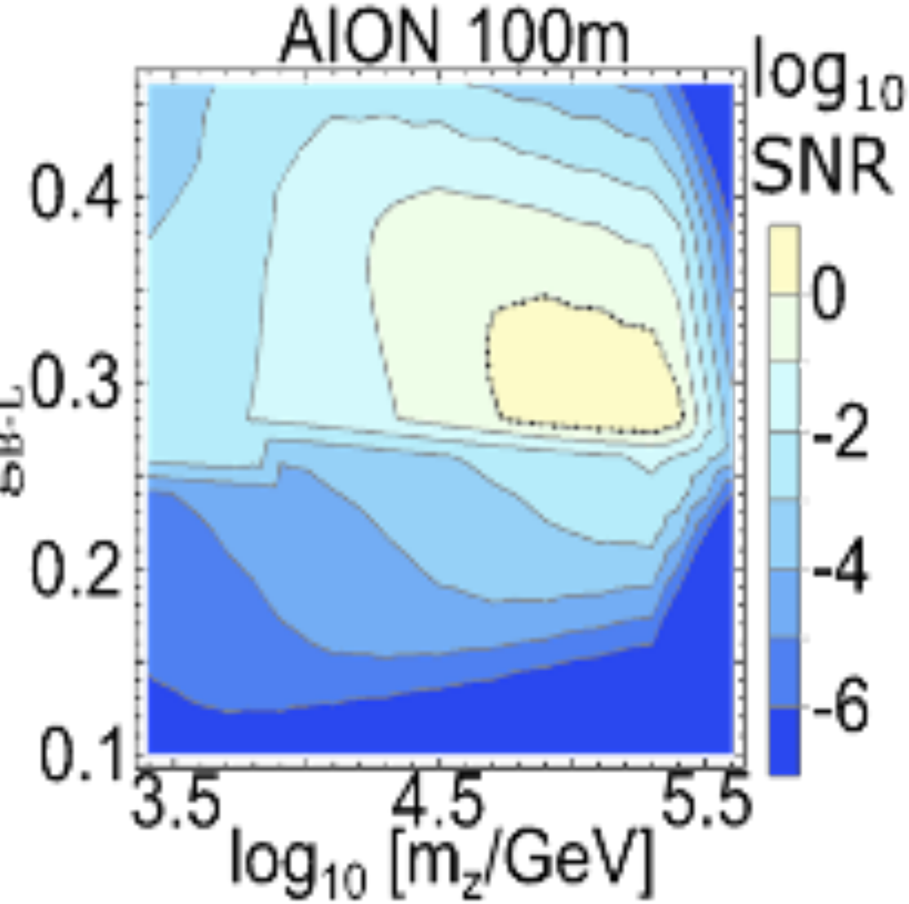
Volonteri, Habouzit & Colpi, arXiv:2110.10175

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

Signal-to Noise Ratios (SNRs) for Gravitational Waves in AION-100



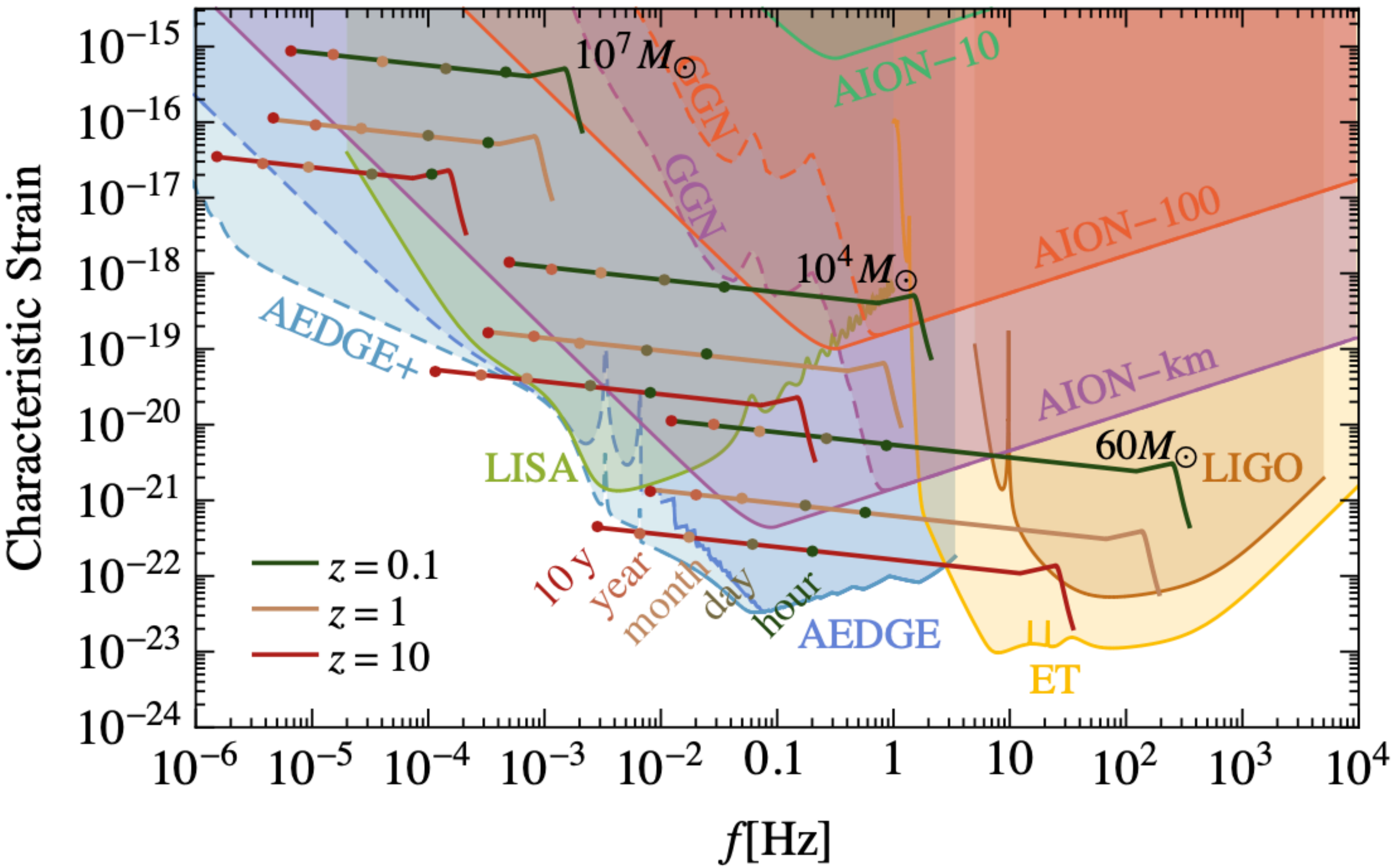
IMBH mergers



Cosmological U(1) phase transition

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

Gravitational Waves from IMBH Mergers



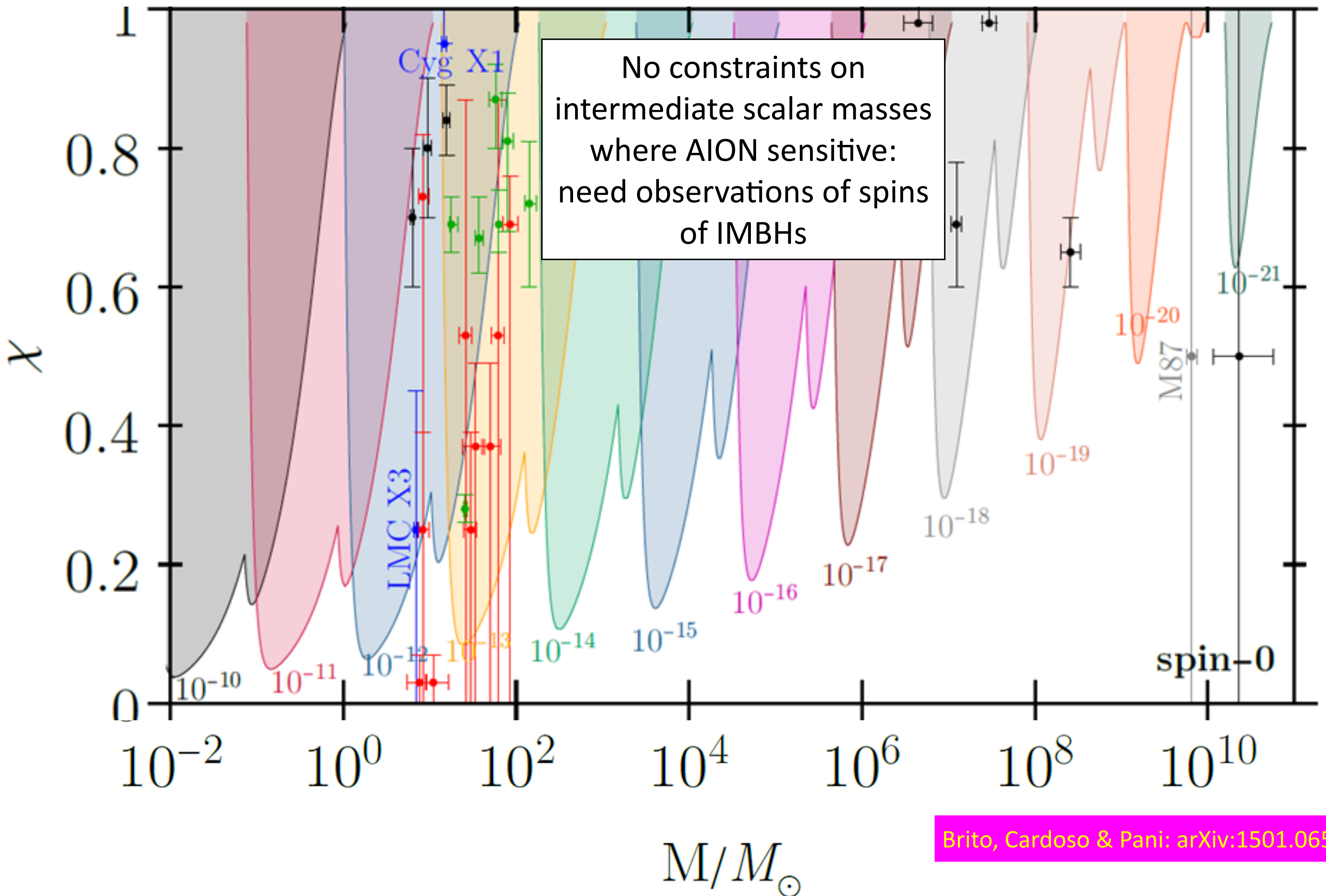
Probe formation of SMBHs

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

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

Black Hole Superradiance

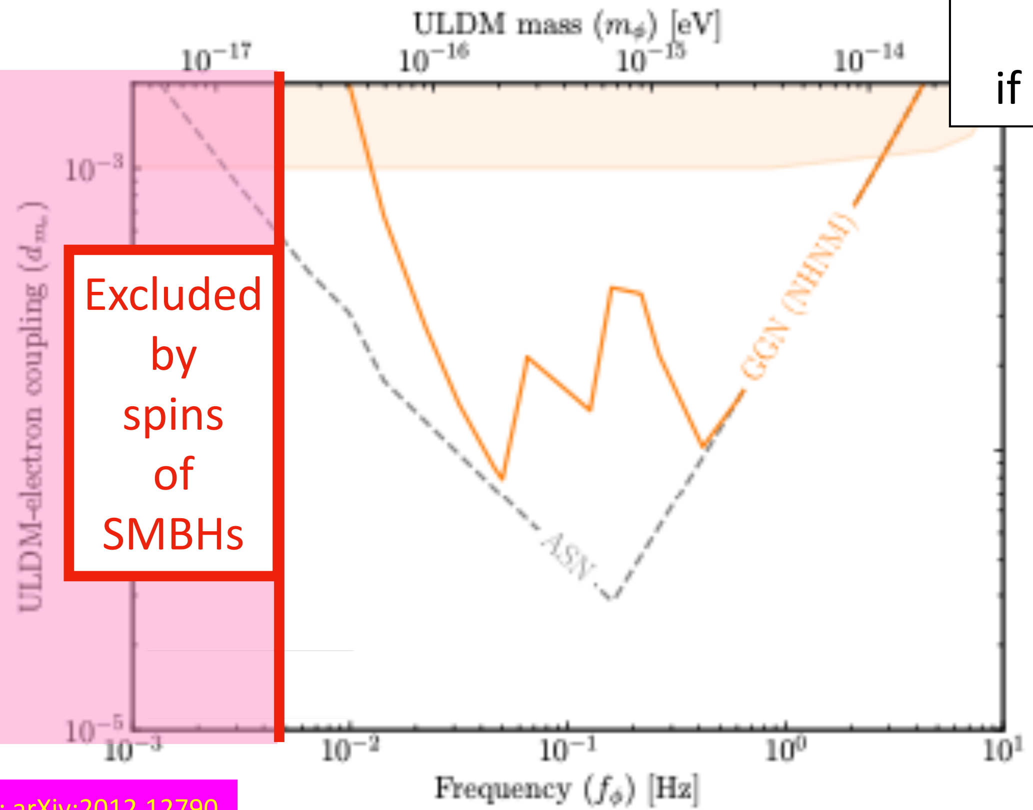
Boson emission may cause spin-down of black holes (if self-interactions weak)



Brito, Cardoso & Pani: arXiv:1501.06570

Black Holes vs Ultralight Dark Matter

Exclusions can be avoided if ULDM has (self-)interactions



Excluded by spins of SMBHs

Excluded by spins of LIGO BHs

Ünal, Pacucci & Loeb: arXiv:2012.12790

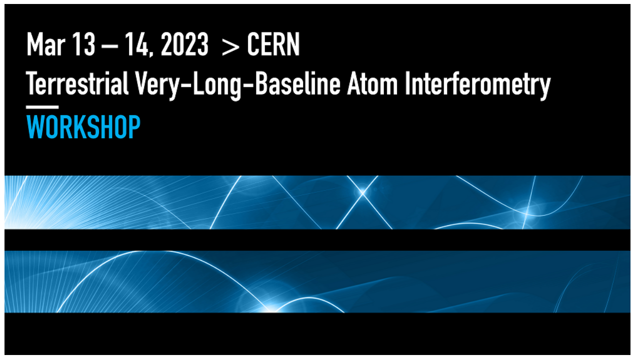
Ng, Hannuksela, Vitale & Li: arXiv:2011.06010

Can be explored by prospective AION-1km/AEDGE BH spin measurements

JE & Vaskonen: *in preparation*

Summary

- Good technical progress on AION-10
- Studies underway for siting AION-100 at CERN or in UK
  - No show-stoppers for AION-100 at CERN
  - Technical report on AION-100 @ CERN planned for Q1 2023
  - International interest in AION-100 @ CERN
- Science studies progressing
  - Study of (mitigation of) gravity gradient noise in ULDM search
  - Synergies of ULDM search with GW constraints on BH spins



Workshop on terrestrial long-baseline atom interferometry planned for March 13/14, 2023 @CERN