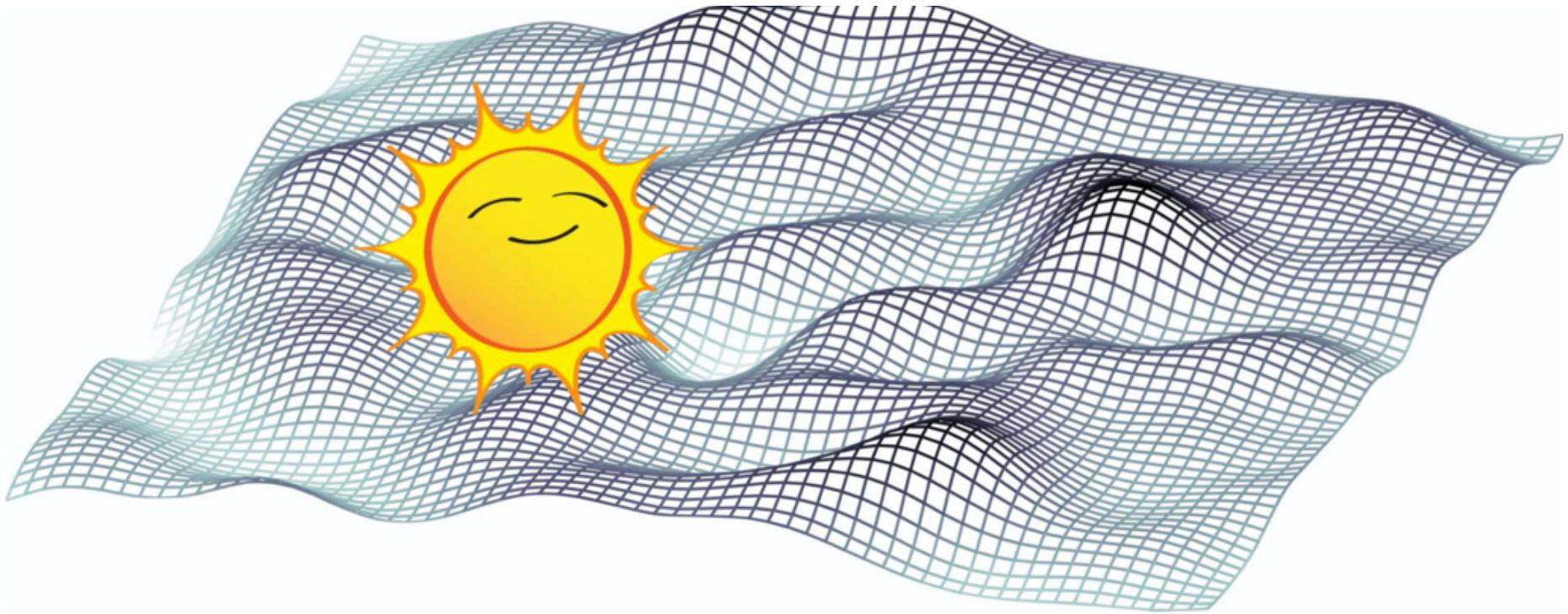


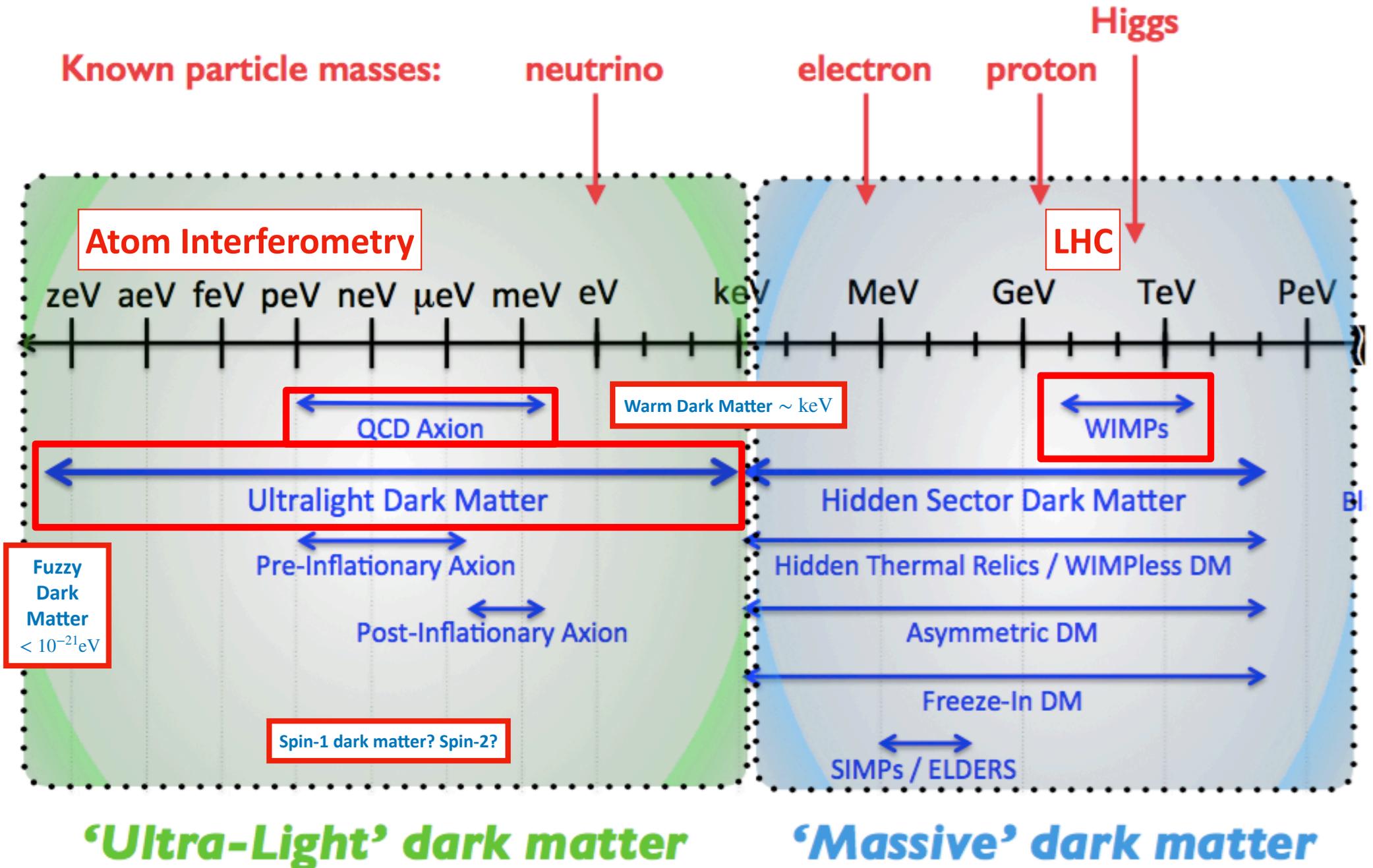
Introduction to Dark Matter

motivations and some candidates

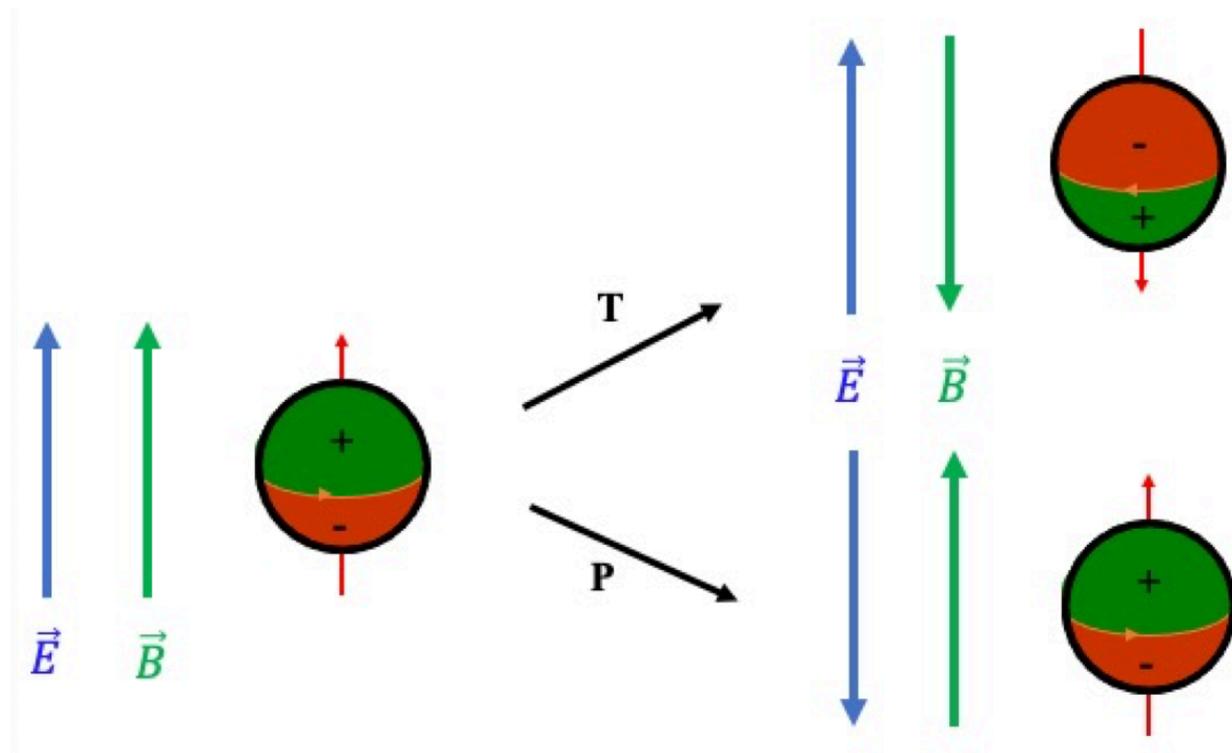


KMI, Nagoya University, March 2026

Particle Candidates for Dark Matter



Electric Dipole Moment



- Consider electric dipole interaction: $H = \mathbf{d} \cdot \mathbf{E}$
- \mathbf{d} changes sign under time reversal T, \mathbf{E} direction unchanged
- Therefore H violates T, and hence also CP

QCD and the Neutron EDM

- QCD Lagrangian has a CP-violating term $\mathcal{L} \ni \theta \frac{g_s^2}{16\pi^2} G \widetilde{G}$
- Theoretical calculations indicate $|\mathbf{d}| \sim 3.6 \times 10^{-16}$ e.cm
- Experimental upper limit $|\mathbf{d}| < 1.8 \times 10^{-26}$ e.cm, implying $|\theta| < 5 \times 10^{-11}$ e.cm.
- **Why so small?** Fine-tuning or symmetry?
- Peccei & Quinn proposed a new field $a(t, \mathbf{x})$: $\theta \propto a(t, \mathbf{x})$ for which $a = 0$ is energetically preferred
- Oscillations about this minimum correspond to new particle: **axion**

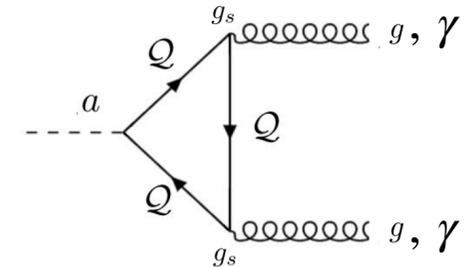
Peccei & Quinn, PRL 28, p1440

Weinberg; Wilczek, PRL 40

Simple Axion Model

- Complex singlet scalar field σ with spontaneously-broken $U(1)_{PQ}$ symmetry and an exotic quark: $\mathcal{L} \ni \left(|\sigma|^2 - v_{PQ}^2 \right)^2 + y\sigma\bar{Q}_L Q_R$
- Axion field $a(x)$: $\sigma(x) = \frac{1}{\sqrt{2}} \left(v_{PQ} + \rho(x) \right) e^{ia(x)/v_{PQ}}$, heavy modulus field $\sigma(x)$, heavy quark Q

- Axion interactions after integrating out heavy quarks:



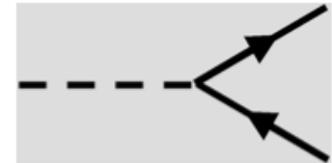
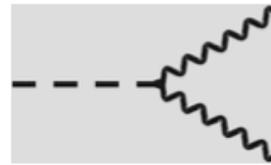
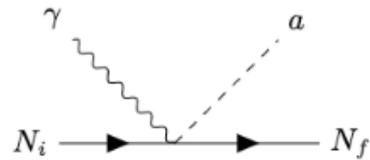
- $\mathcal{L}_{eff} \ni \frac{1}{2}\partial^\mu a \partial_\mu a + \frac{\alpha_s}{8\pi} \frac{a}{f_a} G_{\mu\nu} \widetilde{G}^{\mu\nu} + \frac{a}{4} g_{\alpha\gamma\gamma} F_{\mu\nu} \widetilde{F}^{\mu\nu} + \frac{\partial_\mu a}{2f_a} c_q \bar{q} \gamma_\mu \gamma_5 q : f_a = \frac{v_{PQ}}{N_Q}$

- θ can be eliminated: $a(x) \rightarrow a(x) + \theta f_a$

Effective Low-Energy Theory Below QCD Scale

- Interactions with Standard Model particles:

$$\mathcal{L} \ni -\frac{1}{2}m_a^2 - \frac{ieC_{NEDM}}{2f_a} a \bar{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu} + C_{a\gamma} \frac{\alpha}{8\pi} \frac{a}{f_a} F_{\mu\nu} \widetilde{F}^{\mu\nu} + \frac{1}{2} C_{af} \frac{\partial_\mu a}{f_a} \bar{\Psi} \gamma_\mu \gamma_5 \Psi$$



$$C_{NEDM} \simeq 2.4 \times 10^{-16} \text{cm}, C_{a\gamma} = \mathcal{O}(1), C_{aN} = \mathcal{O}(1)$$

- Mass of axion determined by interactions with quarks, calculated using

$$\text{chiral symmetry: } m_a \simeq \frac{\sqrt{z}}{1+z} \frac{m_\pi f_\pi}{f_a} \simeq 6 \text{ meV} \left(\frac{10^9 \text{ GeV}}{f_a} \right)$$

- Numerical coefficients model-dependent

KSVZ = Kim; Shifman, Vainshtein & Zakharov

DFSZ = Dine, Fischler & Srednicki; Zhitnitsky

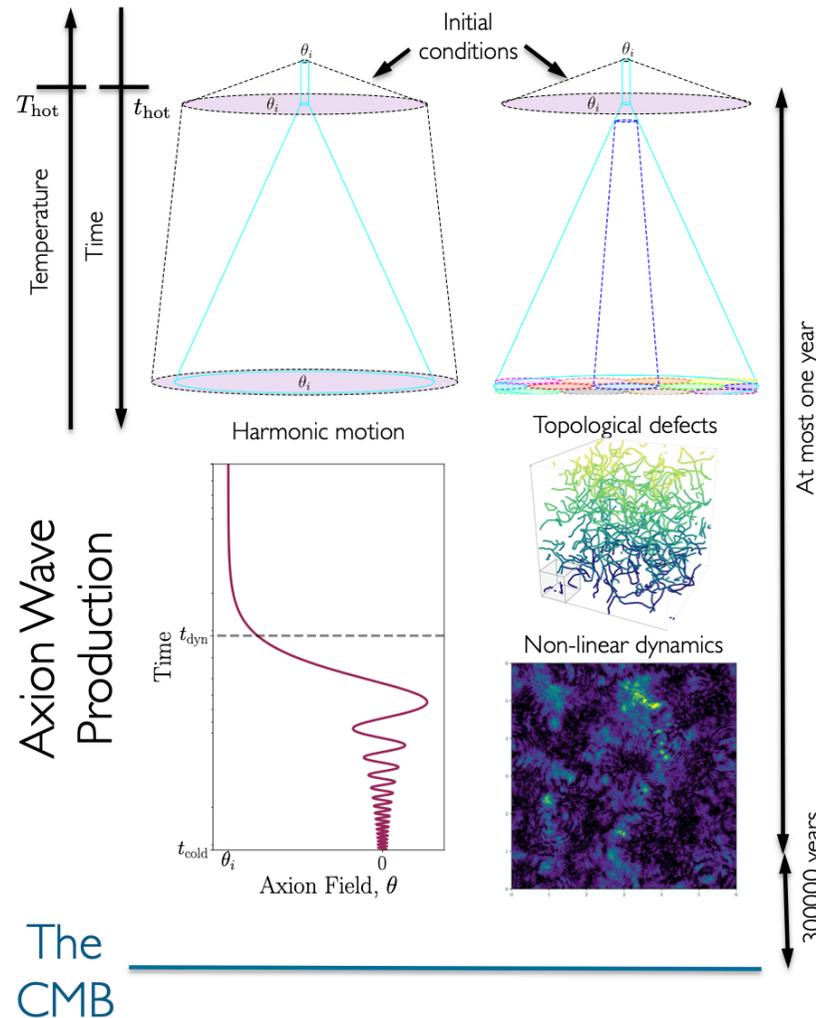
- For details, see [Grilli di Cortona et al, arXiv:1511.02867](https://arxiv.org/abs/1511.02867)

Axion Dark Matter Scenarios

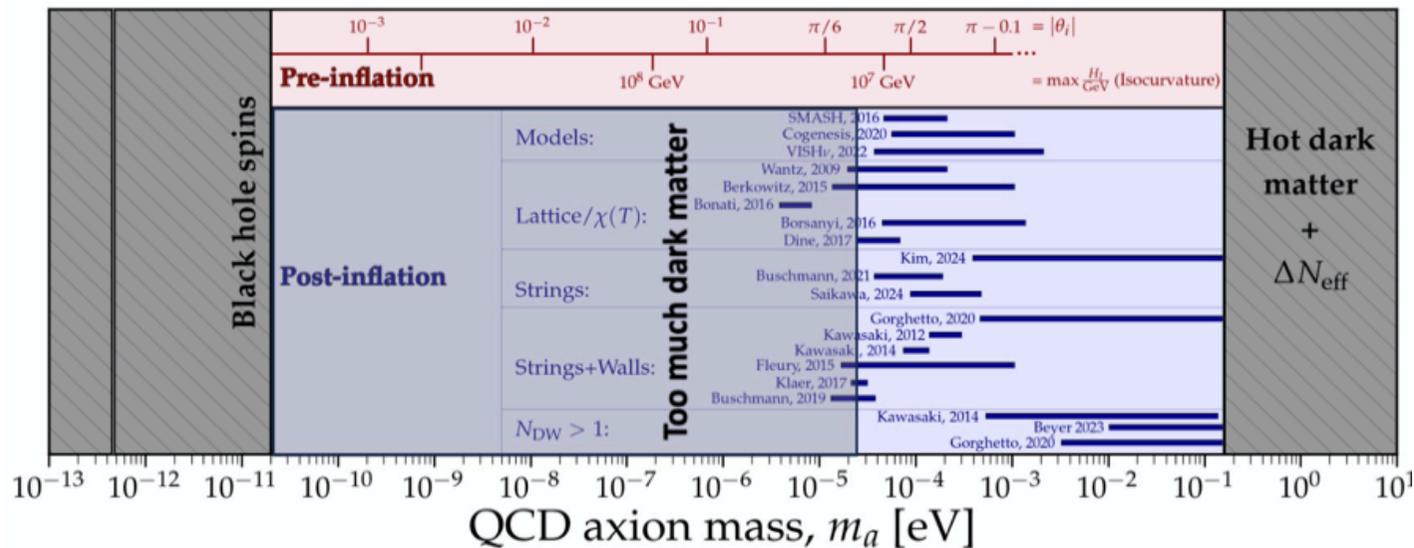
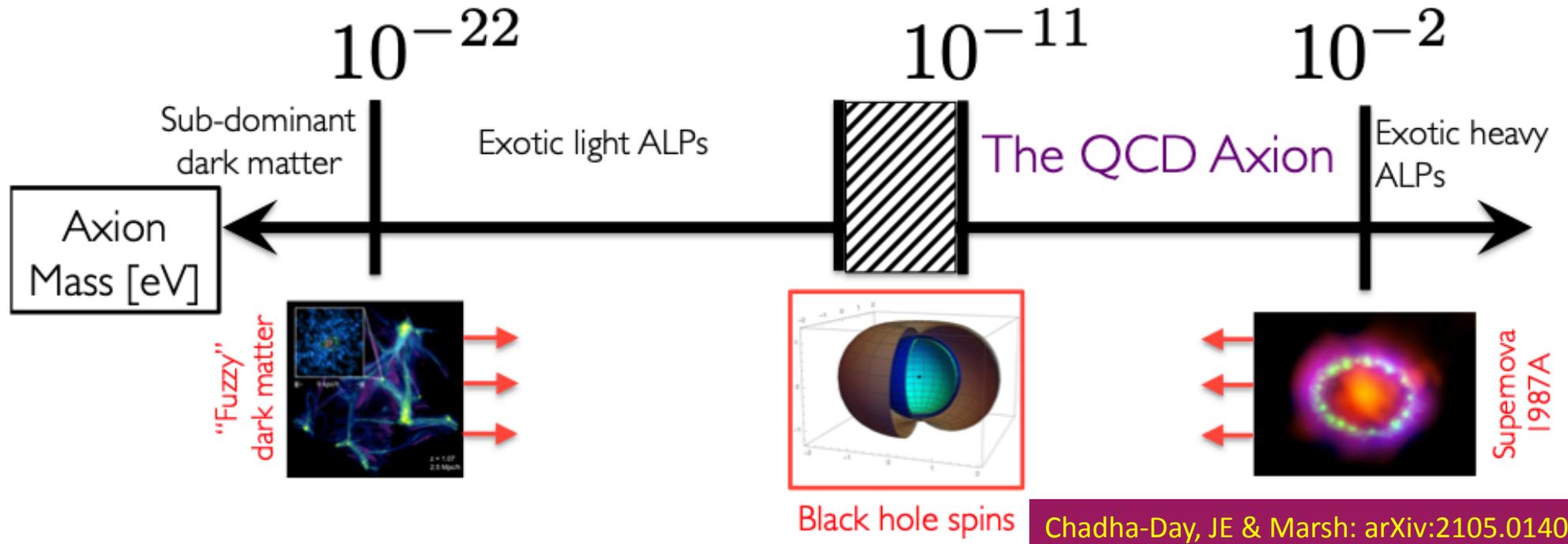
A: $T_{PQ} > T_{hot}$ B: $T_{PQ} < T_{hot}$

Scenario A:
axion dark matter density depends on θ at T_{hot} , followed by harmonic oscillations

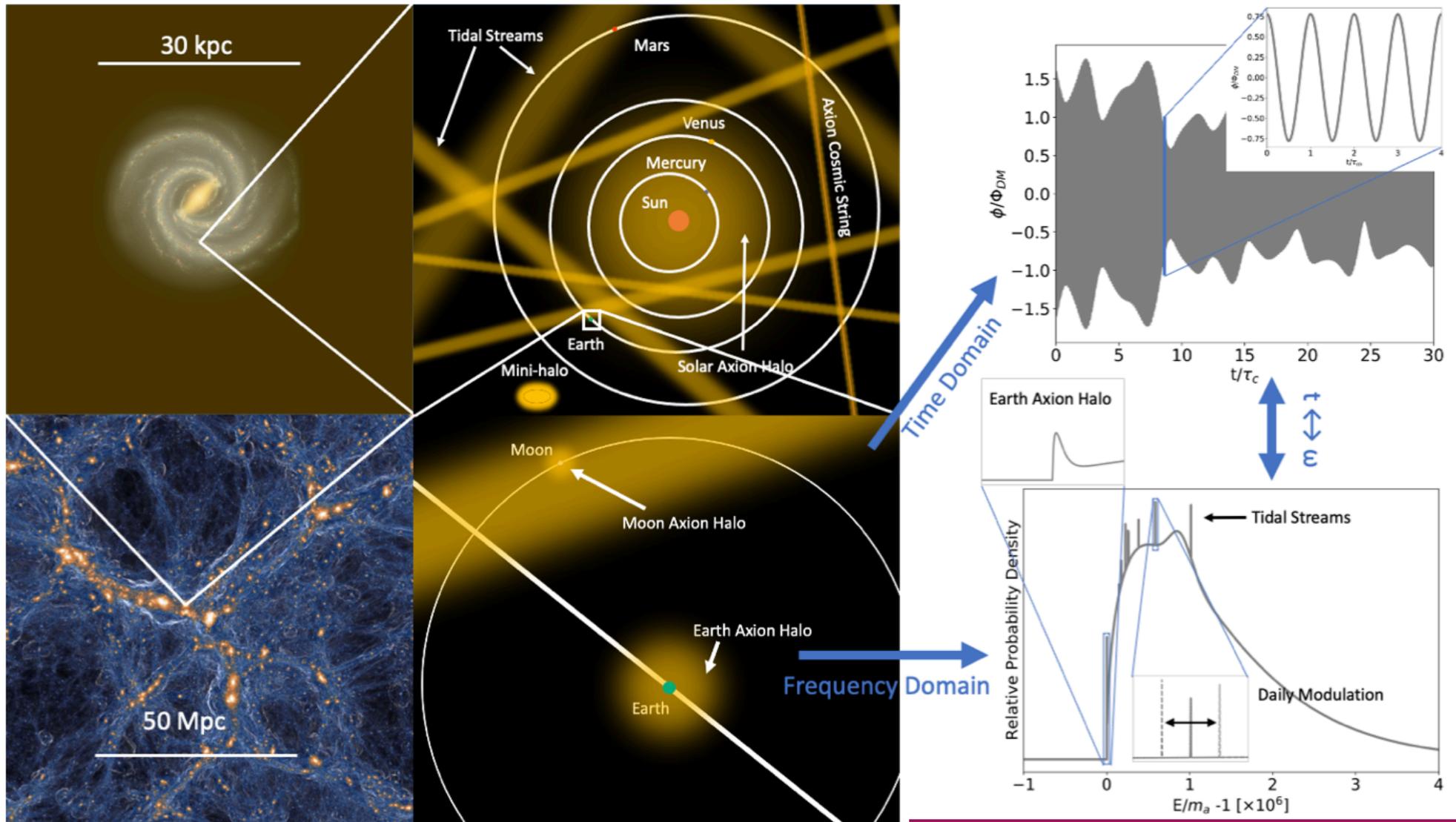
Scenario B:
axion dark matter density determined by decays of topological defects



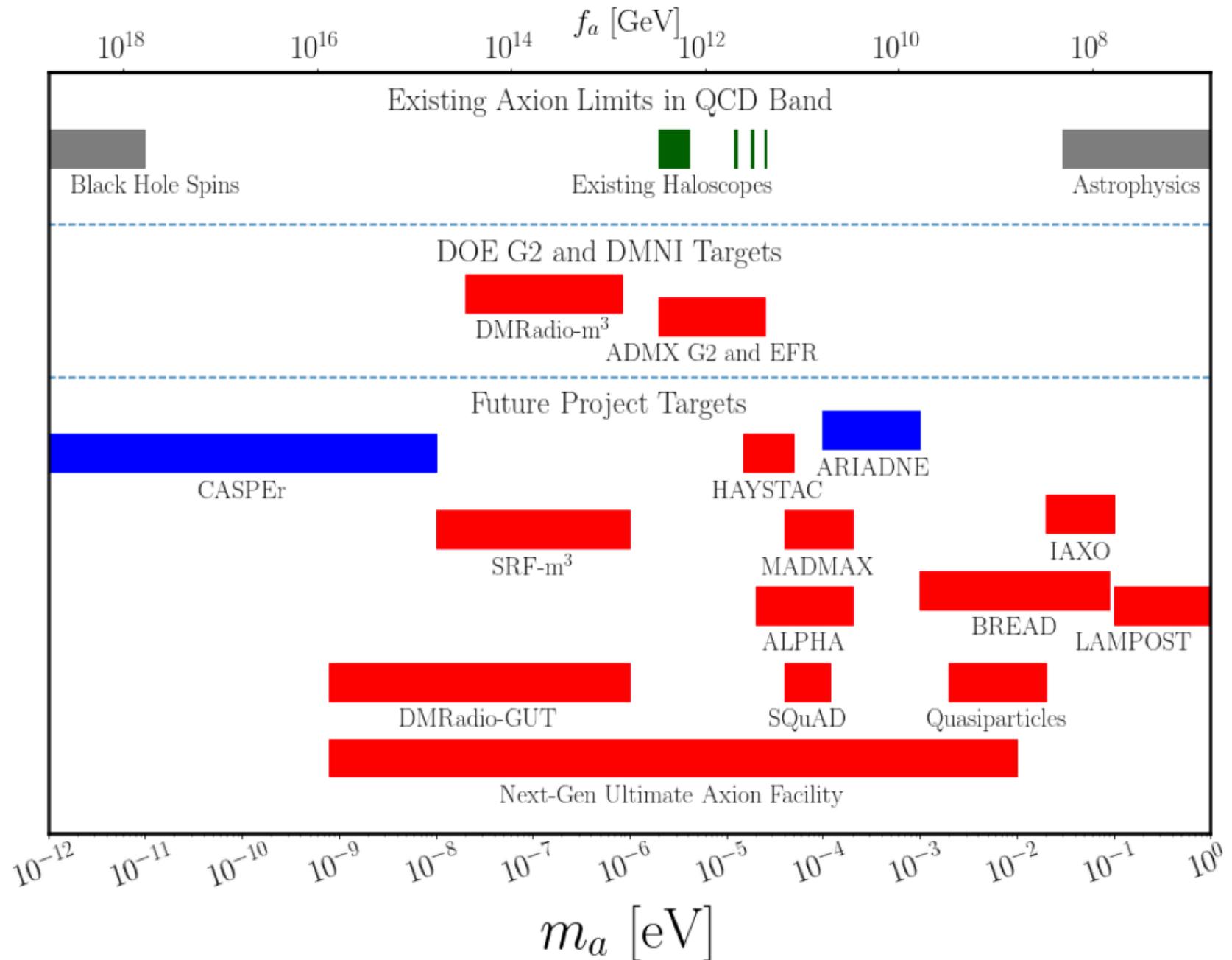
Overview of Constraints on Axion Mass



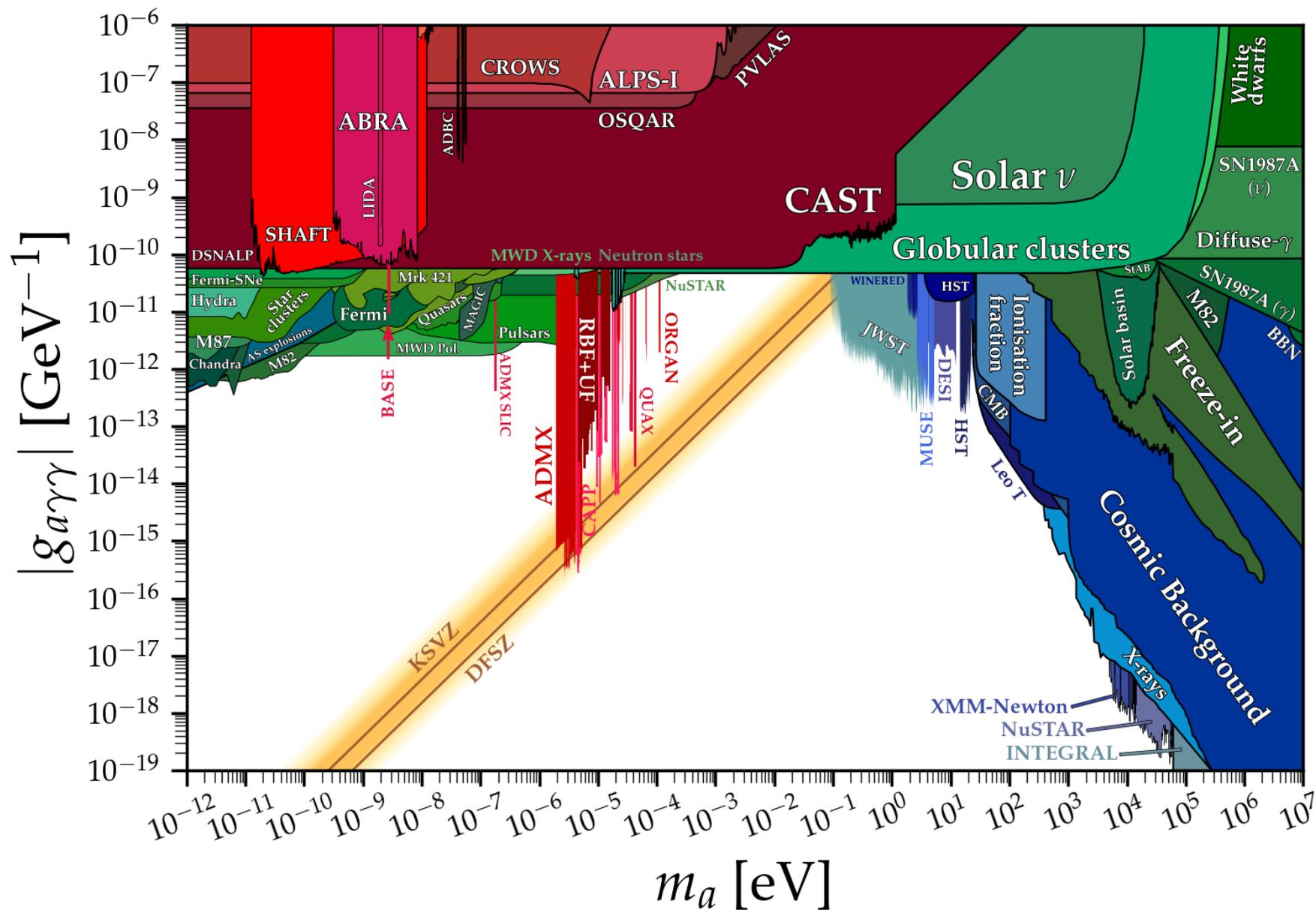
Axion Dark Matter Density



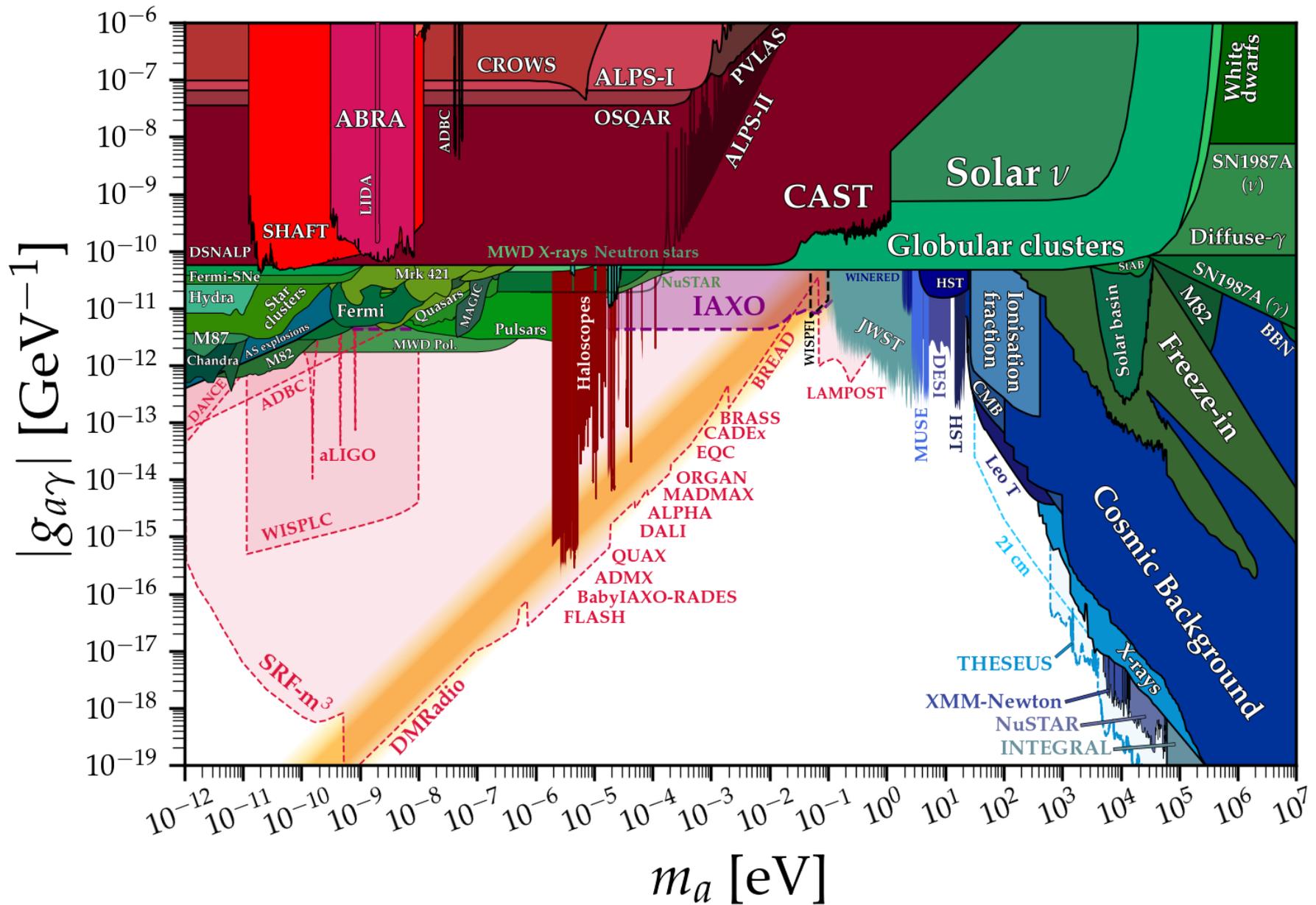
Existing & Prospective Axion Constraints



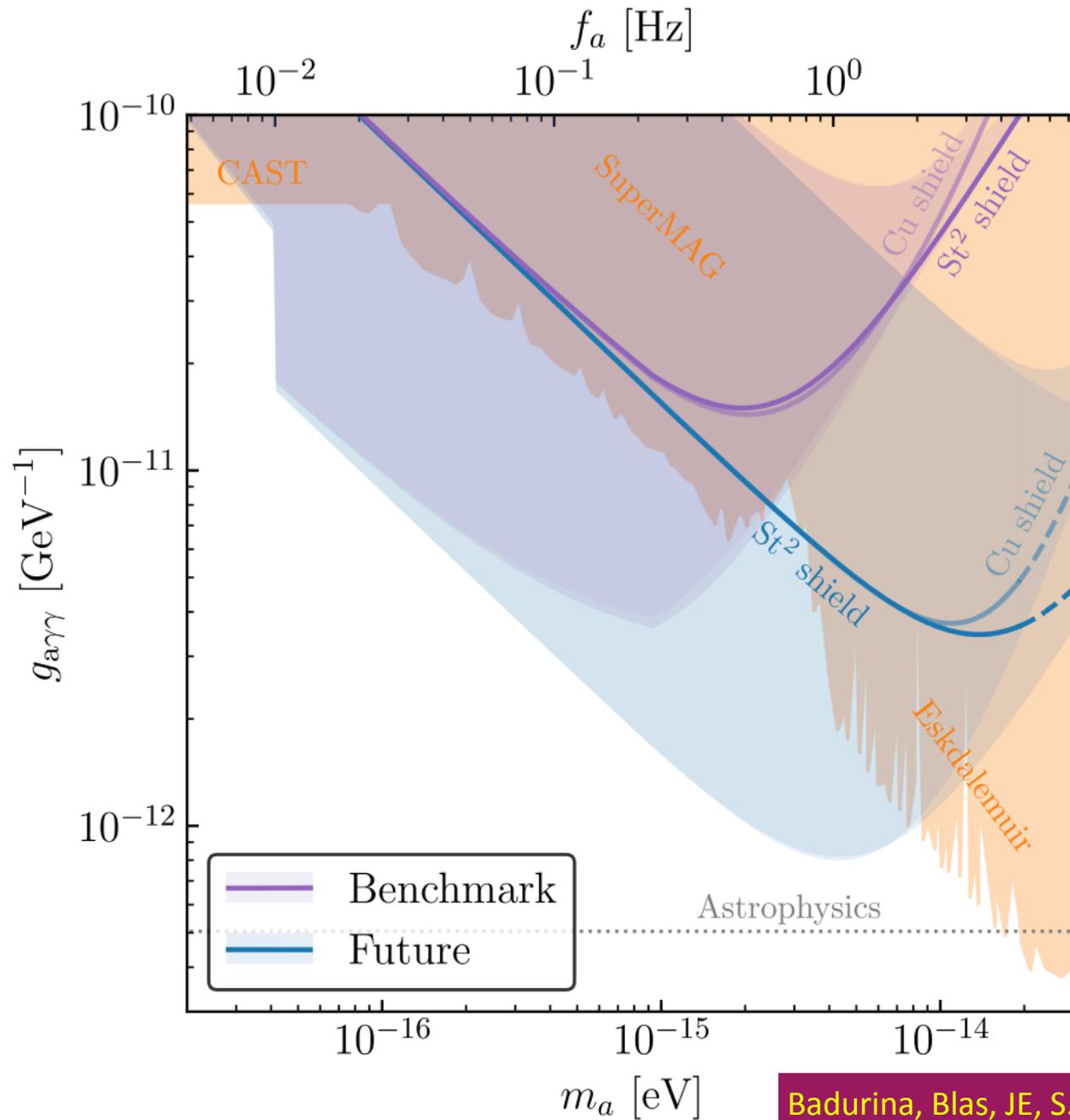
Existing ALP Constraints



Prospective ALP Constraints

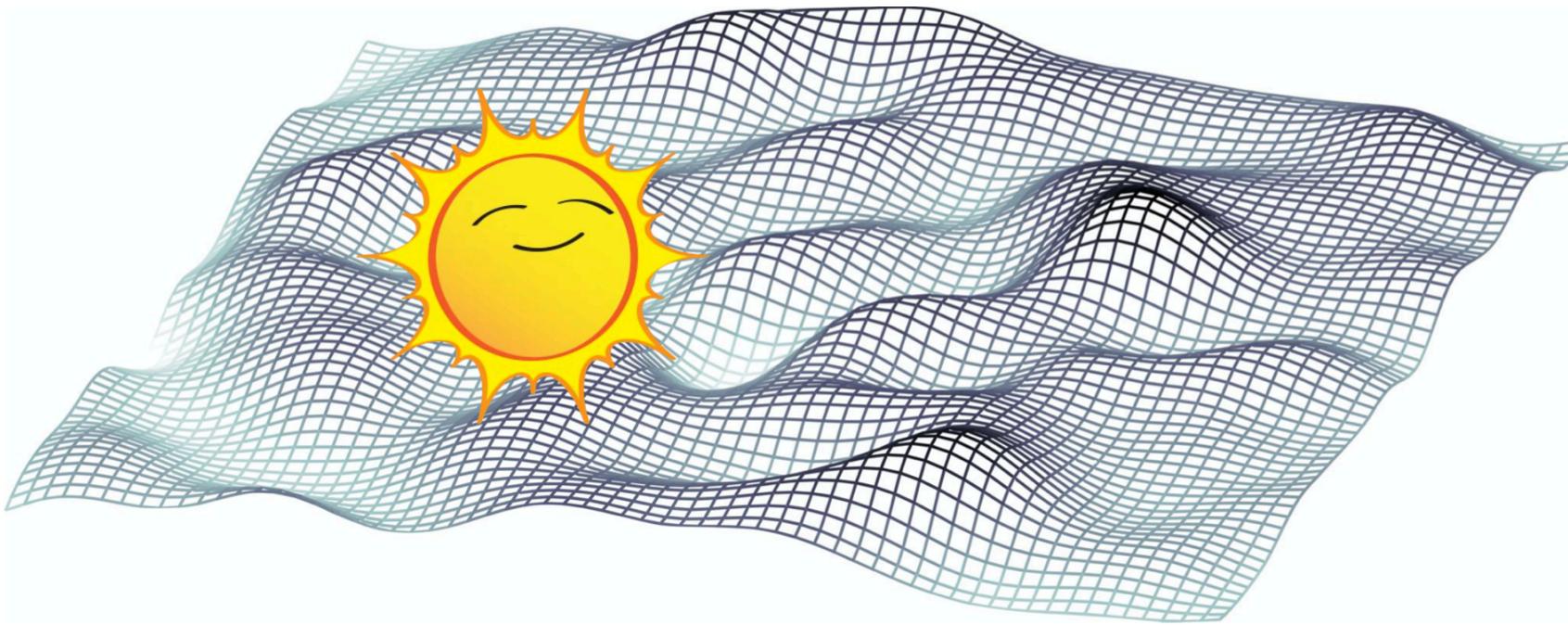


Low-Mass ALP Constraints



Ultralight Dark Matter

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

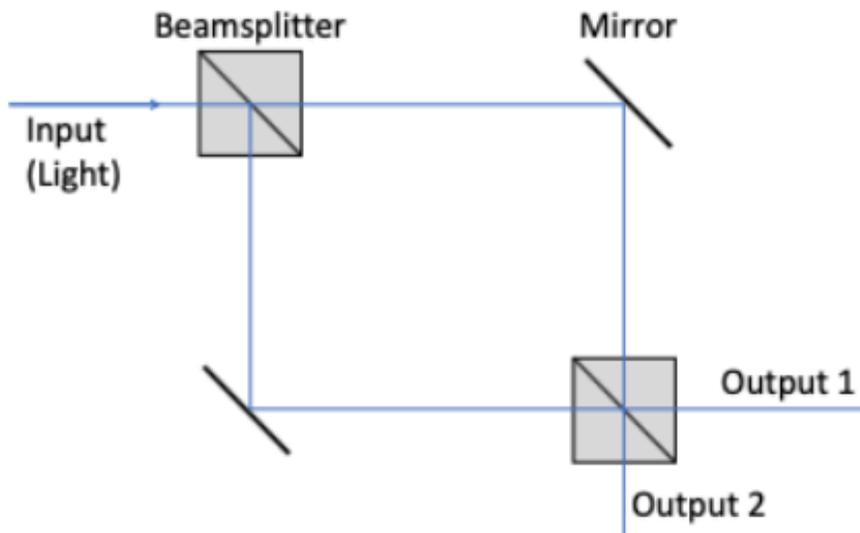


The wavelength depends on the ULDM mass: $\lambda \sim 10^8 \text{ km} \left(\frac{10^{-15} \text{ eV}}{m_\phi} \right)$

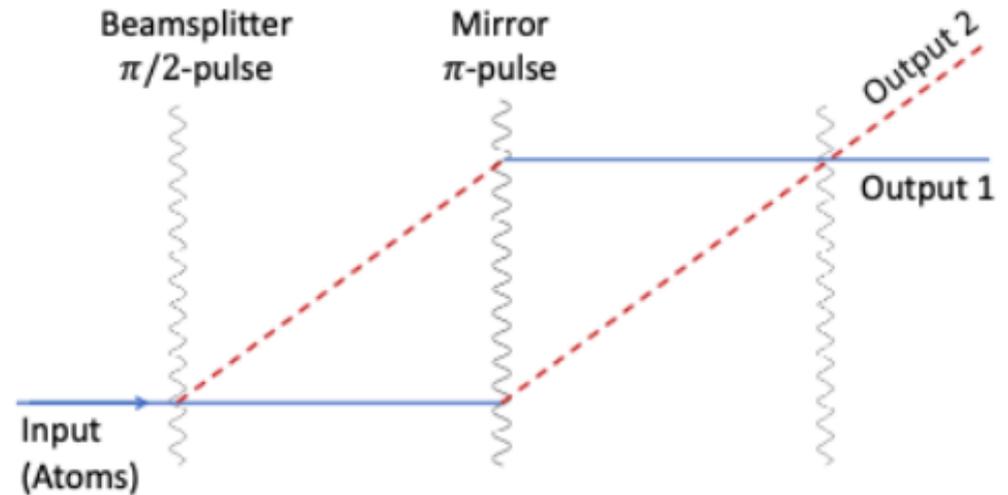
$$\phi(\mathbf{x}, t) = \frac{\sqrt{2\rho_{\text{DM}}}}{m_\phi} \cos[m_\phi(t - \mathbf{v}_\phi \cdot \mathbf{x}) + \dots]$$

Principle of Atom Interferometry

Mach-Zehnder Laser Interferometer

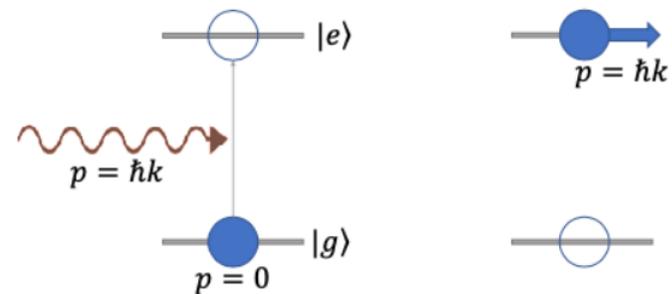


Atom Interferometer

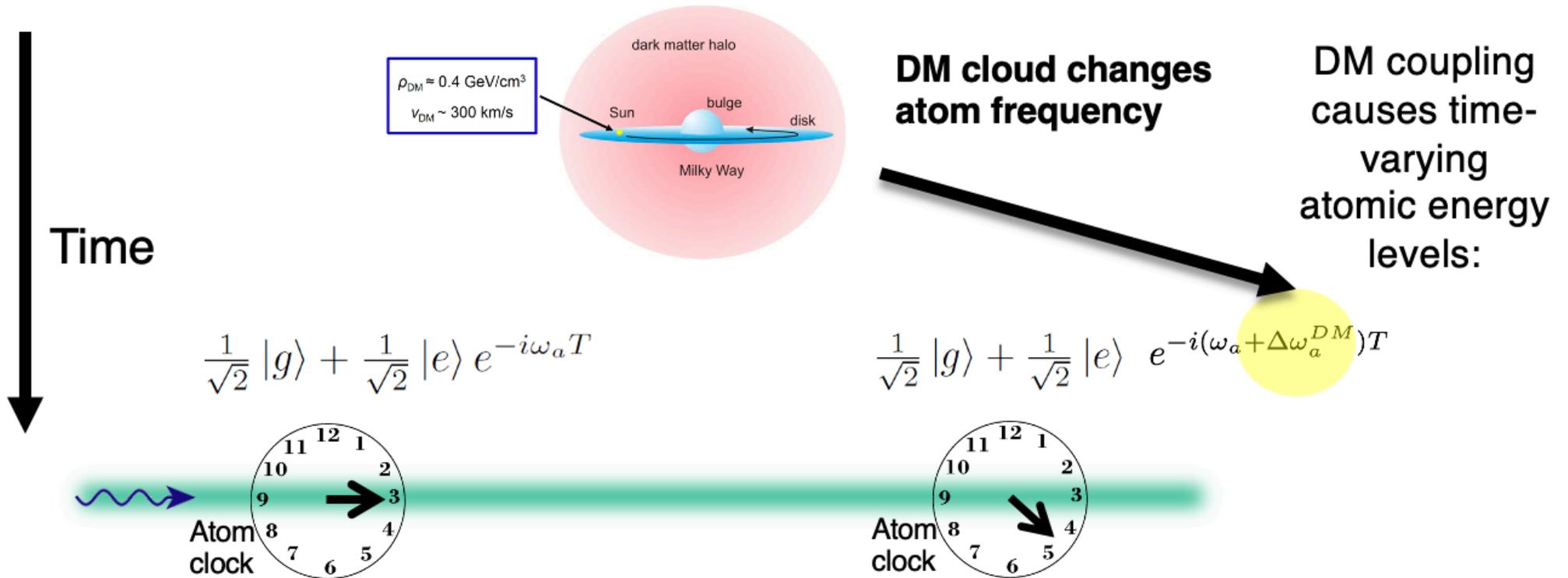
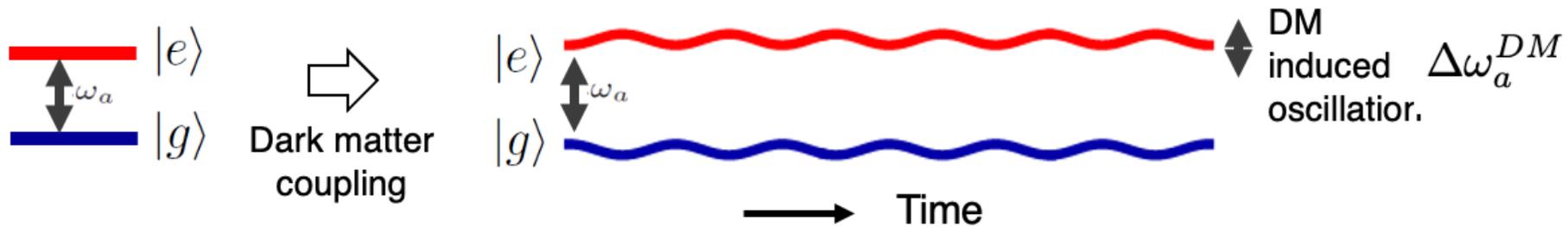


Laser excitation gives momentum kick to excited atom, which follows separated space-time path

Interference between atoms following different paths

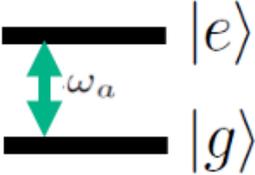


Effect of Dark Matter on Atom Interferometer



Effect of Gravitational Wave on Atom Interferometer

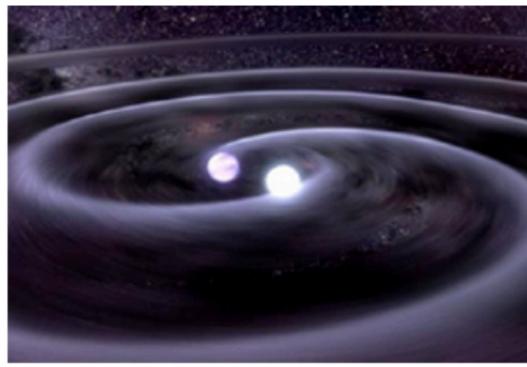
$$\frac{1}{\sqrt{2}} |g\rangle + \frac{1}{\sqrt{2}} |e\rangle$$



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



Time

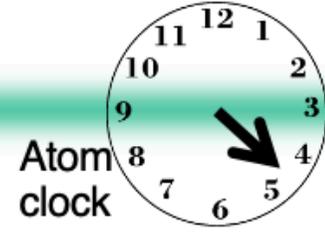
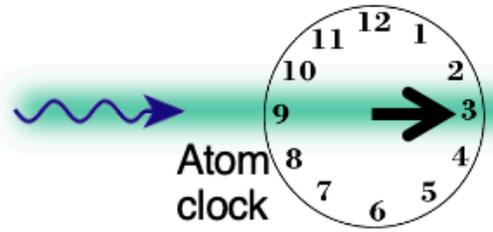


GW changes light travel time

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

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

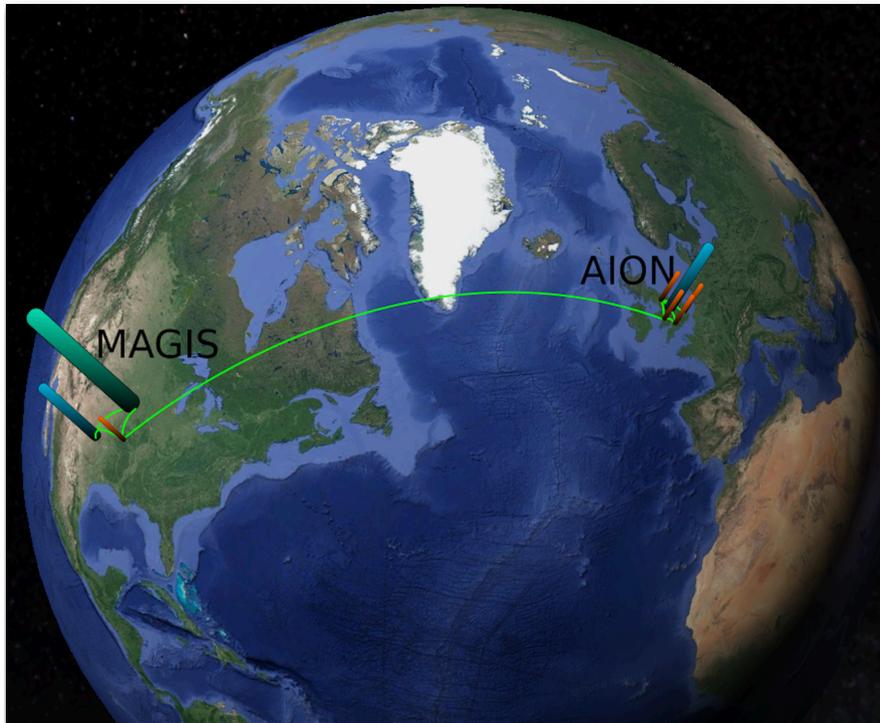
$$\frac{1}{\sqrt{2}} |g\rangle + \frac{1}{\sqrt{2}} |e\rangle e^{-i\omega_a (T+\Delta T)}$$



AION Collaboration

L. Badurina¹, S. Balashov², E. Bentin³, D. Blas¹, J. Boehm², K. Bongs⁶, A. Beniwal¹,
 D. Bortoletto⁶, J. Bowcock⁵, W. Bowden^{6,*}, C. Brew⁶, O. Buchmueller⁶, J. Coleman⁶, J. Carlton⁶,
 G. Elert⁶, J. Ellis^{1,*}, C. Foot³, V. Gibson⁷, M. Haehnel⁷, T. Harte⁷, R. Hobson^{6,*},
 M. Holynski⁶, A. Khazov², M. Langlois⁴, S. L'Allouch⁴, Y.H. Lien⁴, R. Maiolino⁷,
 P. Majewski², S. Malik⁶, J. March-Russell⁶, C. McCabe⁶, D. Newbold², R. Preece³,
 B. Sauer⁶, U. Schneider⁶, I. Shipsey⁶, V. Singh⁶, M. Tarbutt⁶, M. A. Uchida⁷,
 T. V-Salazar², M. van der Grinten⁶, J. Vosseveld⁴, D. Weatherill³, I. Wilmut⁷,
 J. Zielinska⁶

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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

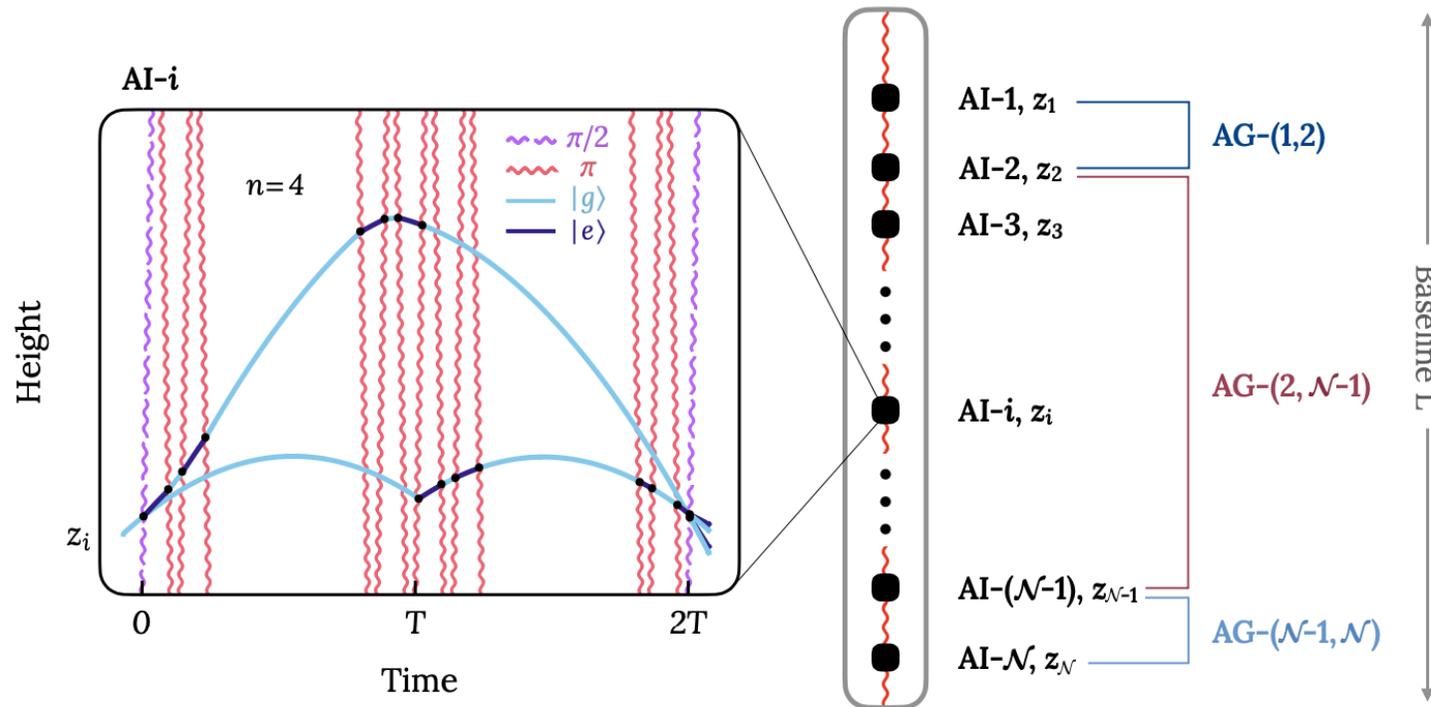


AION – Staged Programme

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

Initial funding from UK STFC

Atomic Multi-Gradiometer



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

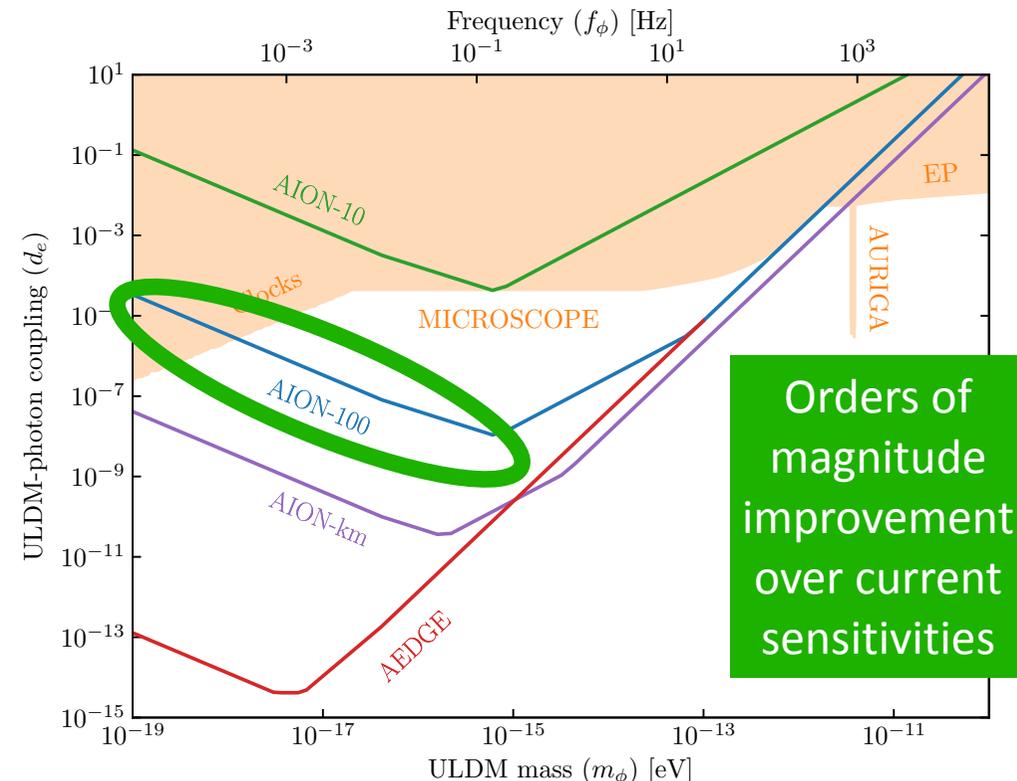
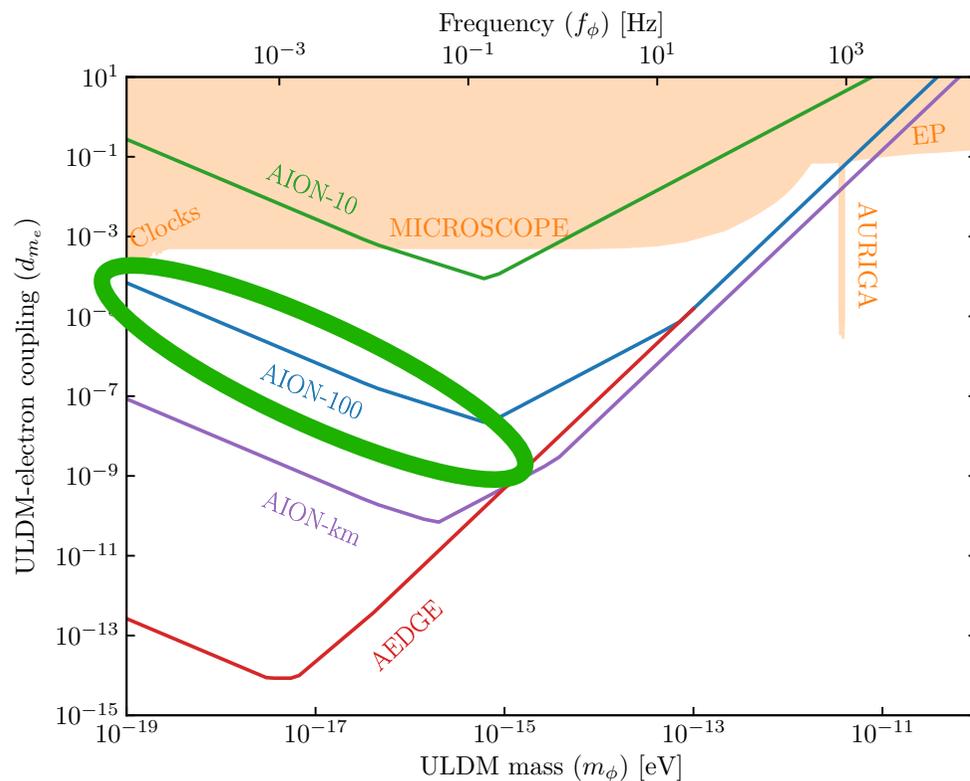
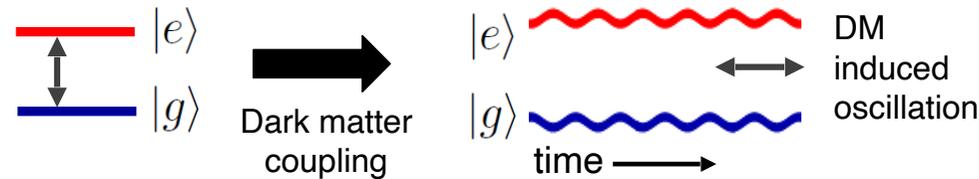
Eliminate laser noise, minimize gravity gradient noise
(direct effect on atoms of earth motion).

Many laser interactions to generate large momentum transfers

Searches for Light Dark Matter

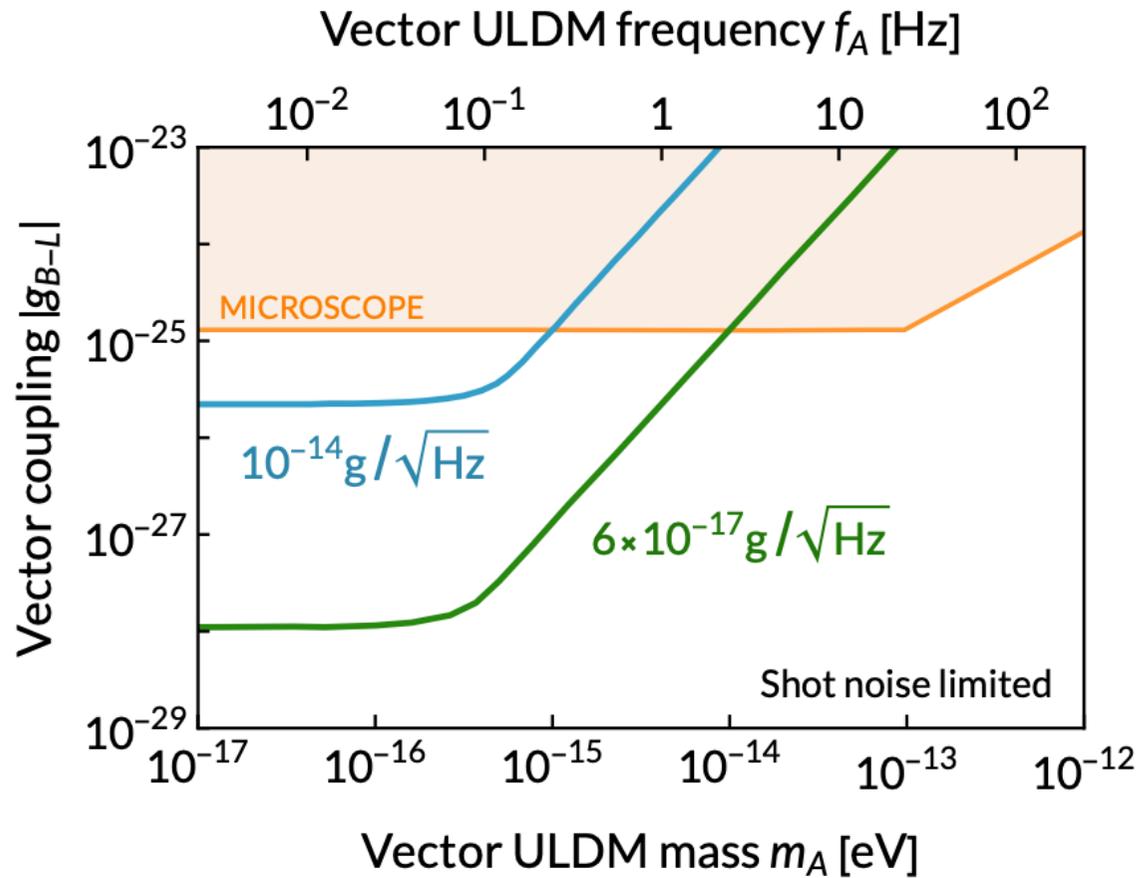
Linear couplings to gauge fields and matter fermions

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



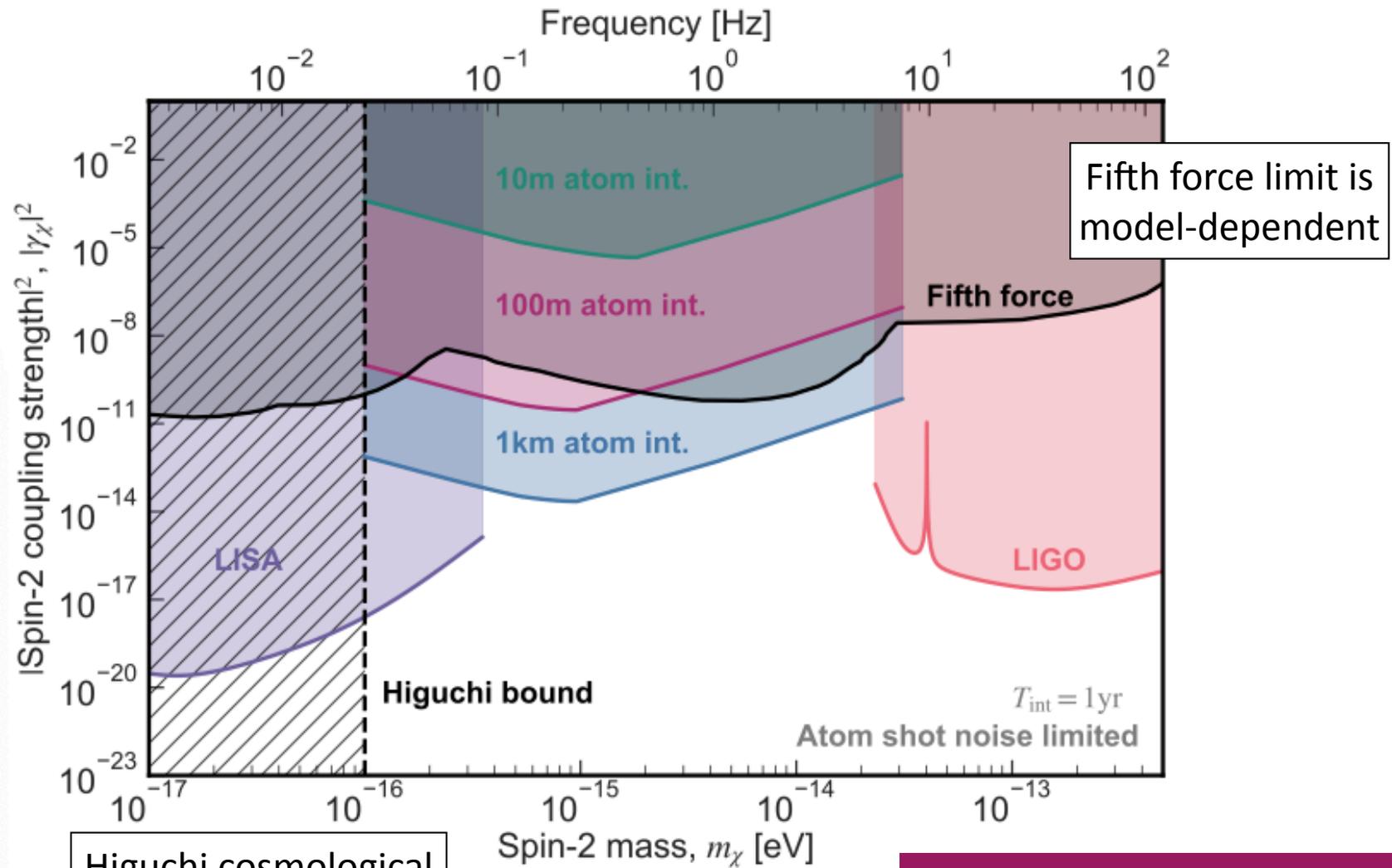
Orders of magnitude improvement over current sensitivities

Vector Dark Matter



Dual-species interferometer: ^{87}Sr & ^{88}Sr

Ultralight Spin-2 Dark Matter?



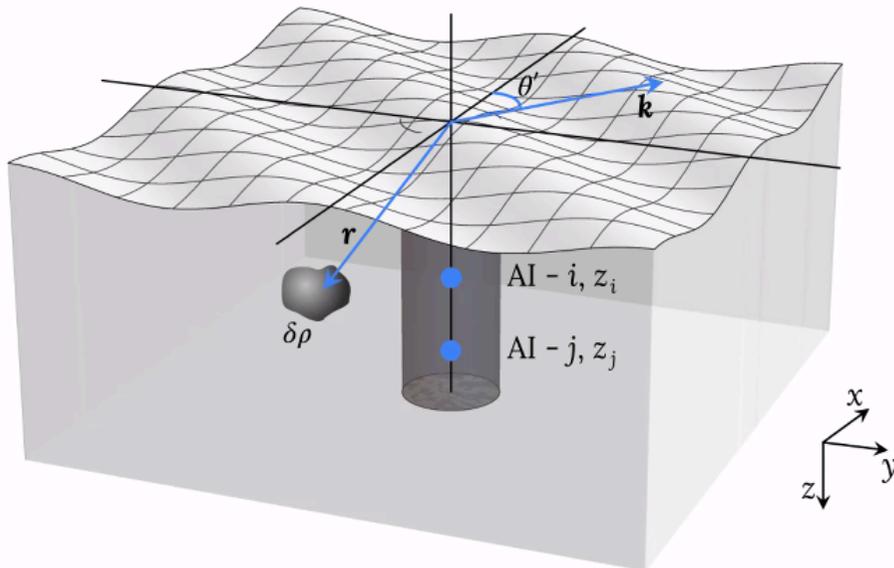
Higuchi cosmological instability limit is model-dependent

Blas, Carlton & McCabe, arXiv:2412.14282

Higuchi, NPB282, 197 (1987)

Gravity Gradient Noise

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



- The density variations give rise to a phase shift:

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

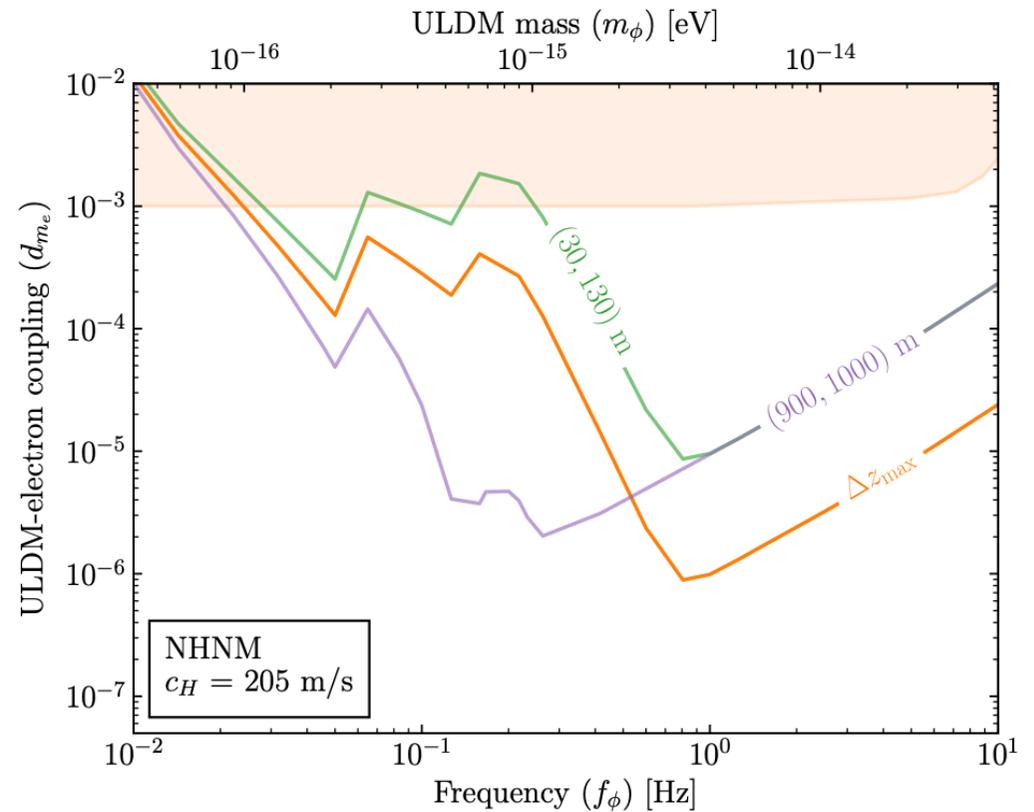
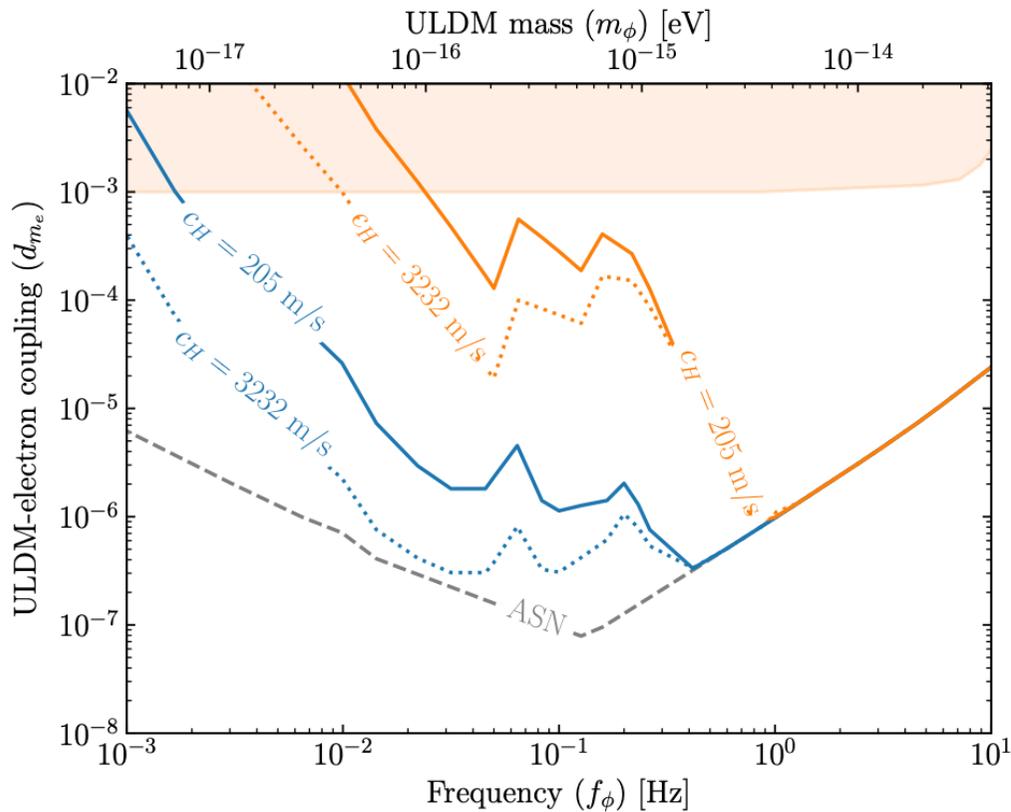
- Two key parameters:

1. ξ_a : surface displacement

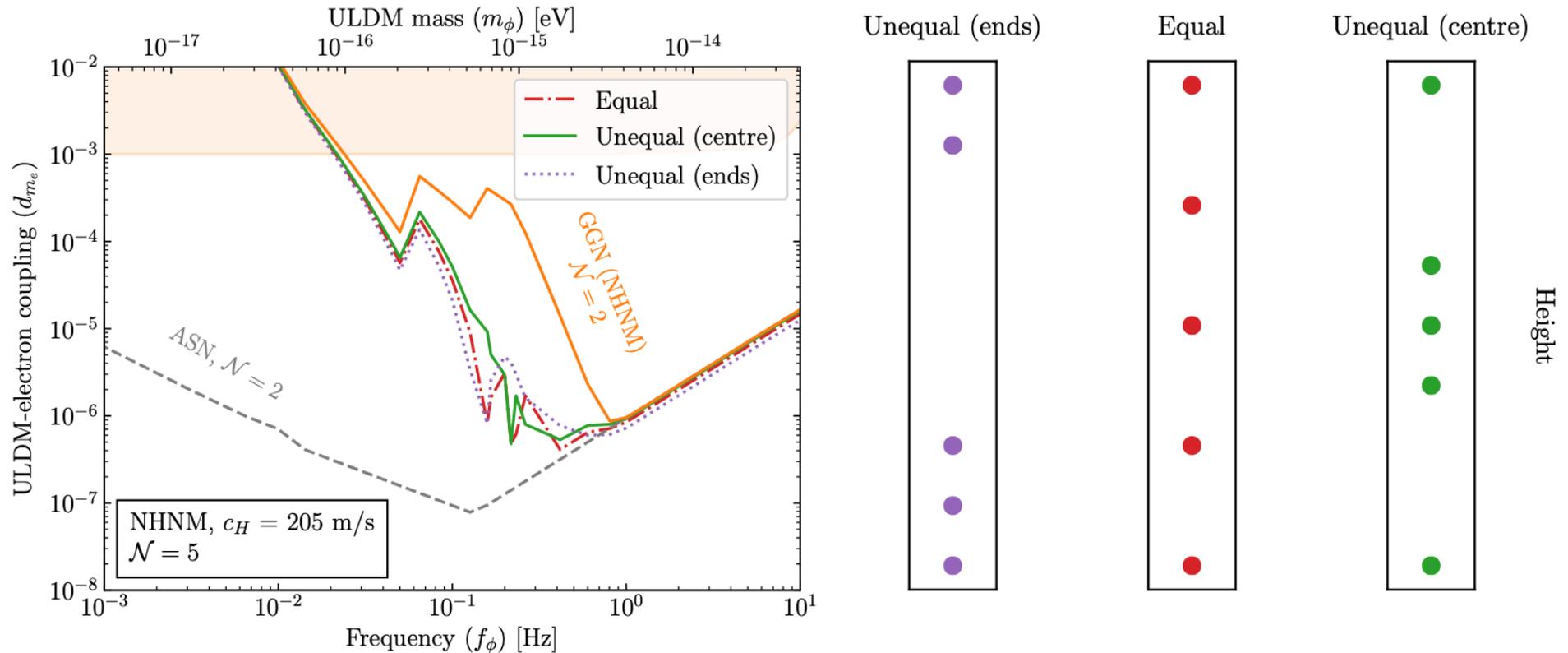
2. $\lambda_{\text{GGN}} = \frac{c_H}{\omega_a}$: decay length with depth

Key quantity: velocity c_H , depends on type of rock

Gravity Gradient Noise

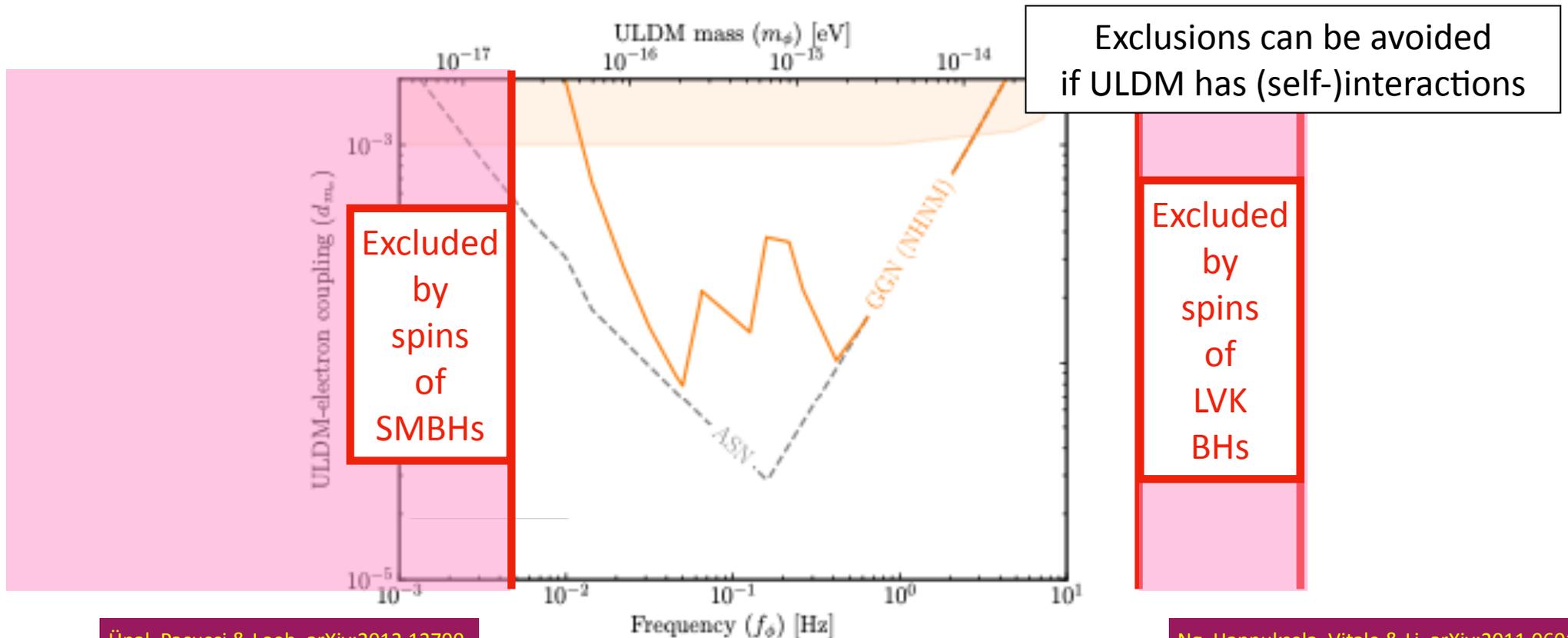


GGN Mitigation for AION-km



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

Radiation of Ultralight Dark Matter by Spinning Black Holes



Ünal, Pacucci & Loeb, arXiv:2012.12790

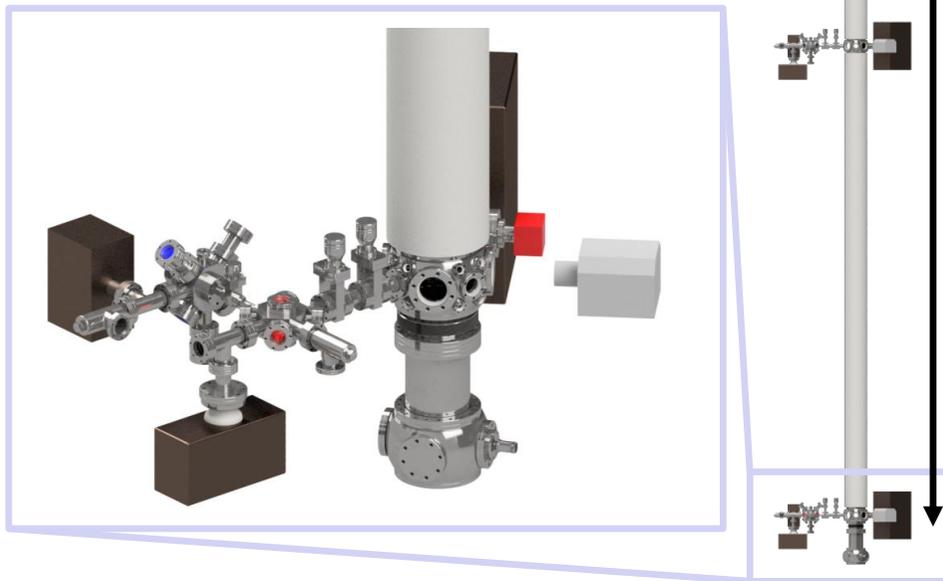
Ng, Hannuksela, Vitale & Li, arXiv:2011.06010

Can be explored by prospective AION-1km/AEDGE BH measurements of spinning intermediate-mass BHs

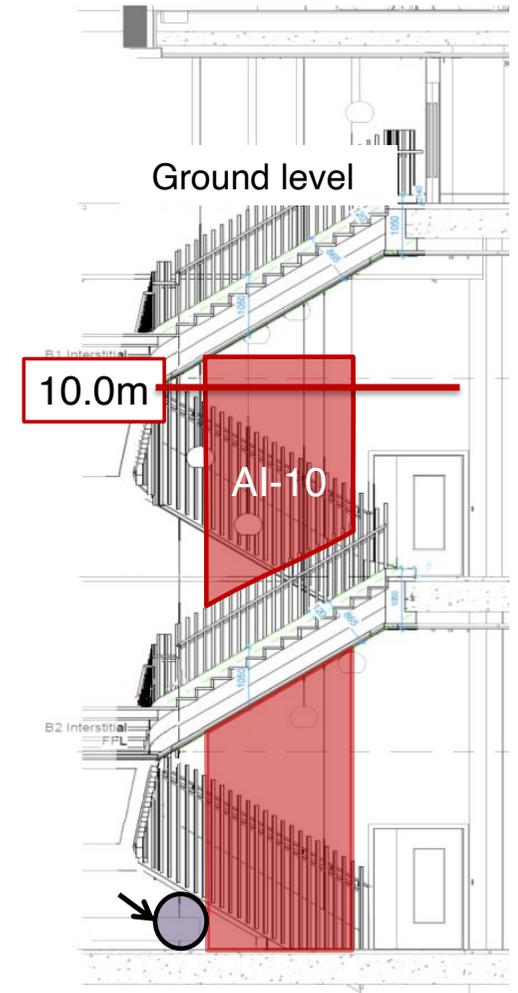
Planned Location of AION-10m

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)

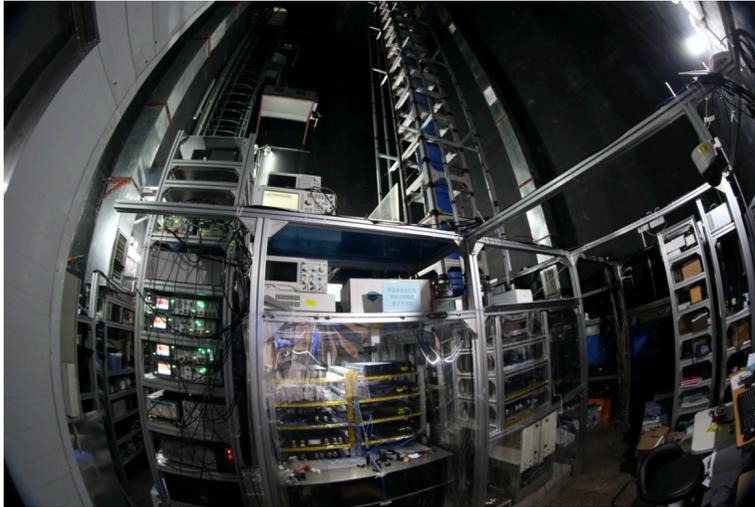


Laser lab for AION
vibration criterion, VC-G =
10nm@10Hz. Temperature
(22±0.1)° C

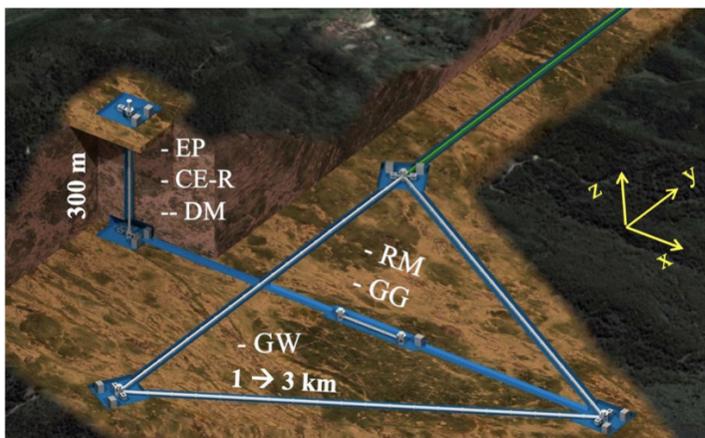


10 & 100m Projects

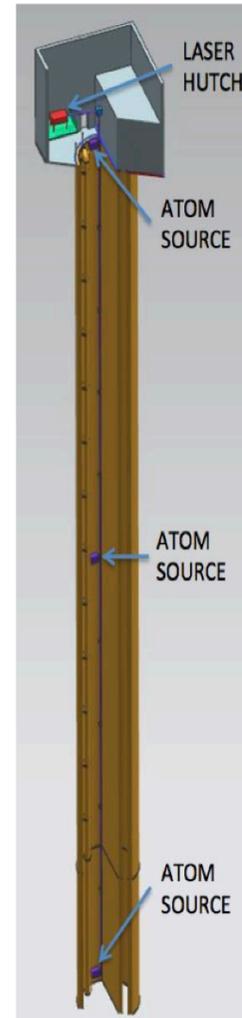
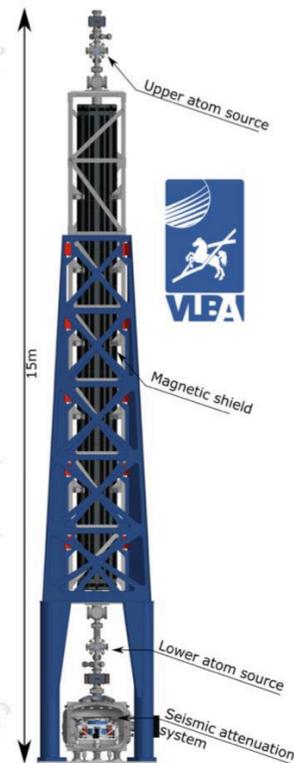
Wuhan: 10m prototype



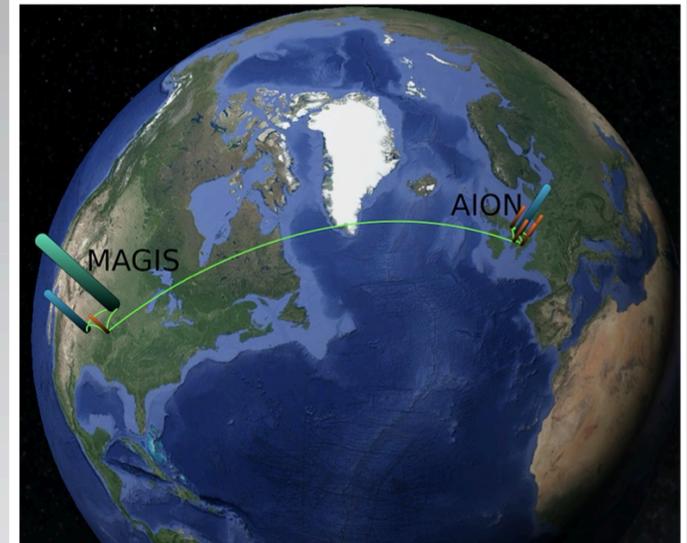
ZAIGA: Terrestrial detector for large scale atomic interferometers, gyros and clocks at O(100m)
(China)



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)

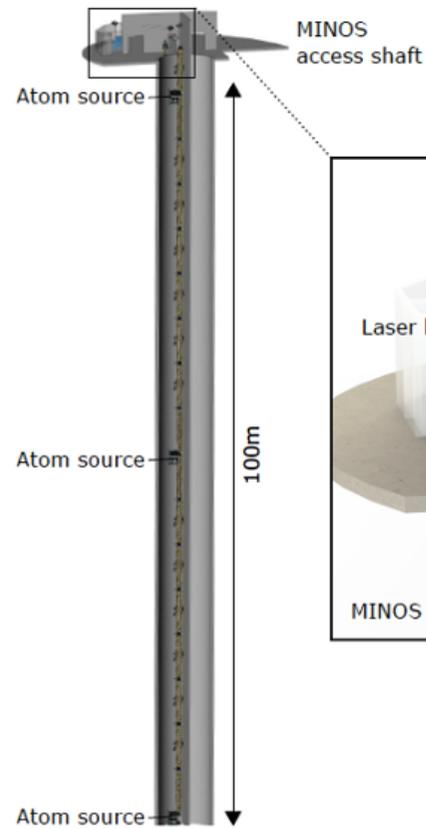
Planned network operation

MAGIS-100 Shaft & Design

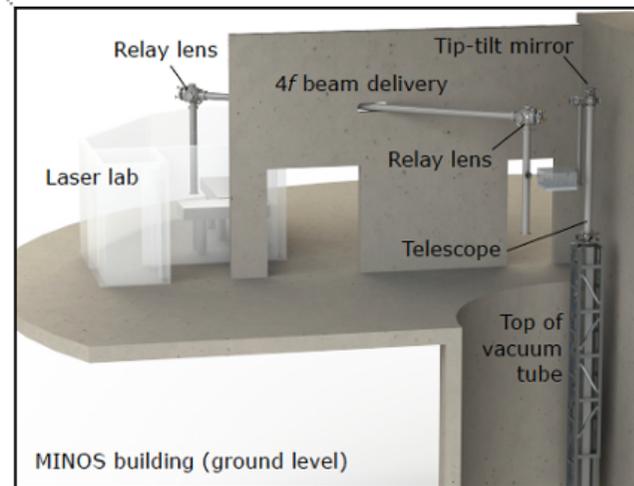
View along shaft



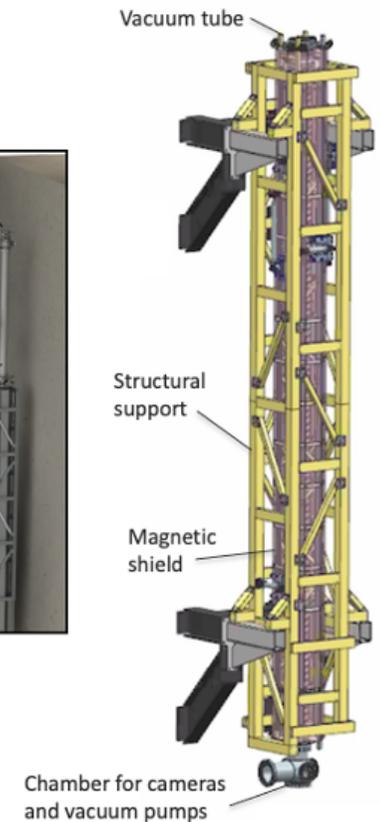
Source layout



Laser laboratory



Vacuum tube module





A Long-Baseline Atom Interferometer at CERN: Conceptual Feasibility Study

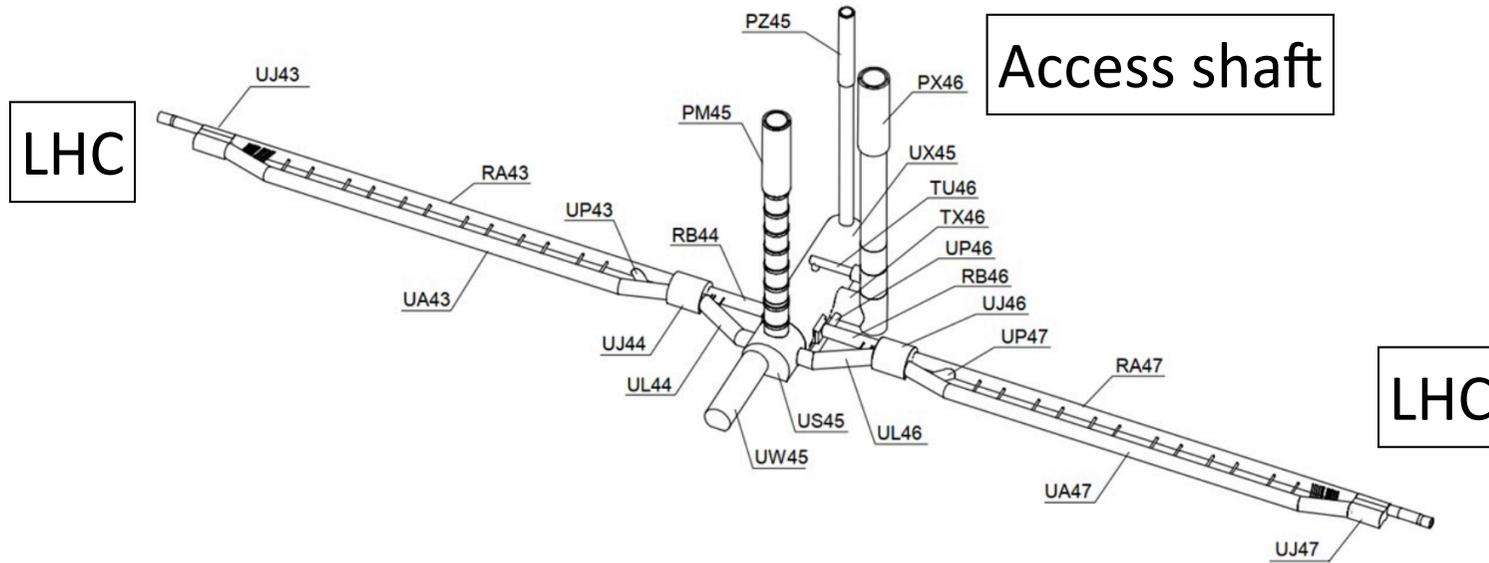
G. Arduini^{1,}, L. Badurina², K. Balazs¹, C. Baynham³, O. Buchmueller^{3,4,*},
M. Buzio¹, S. Calatroni^{1,*}, J.-P. Corso¹, J. Ellis^{1,2,*}, Ch. Gaignant¹,
M. Guinchard¹, T. Hakulinen¹, R. Hobson³, A. Infantino¹, D. Lafarge¹,
R. Langlois¹, C. Marcel¹, J. Mitchell⁵, M. Parodi¹, M. Pentella¹, D. Valuch¹,
H. Vincke¹*

¹ CERN, ² King's College London, ³ Imperial College London, ⁴ University of Oxford,

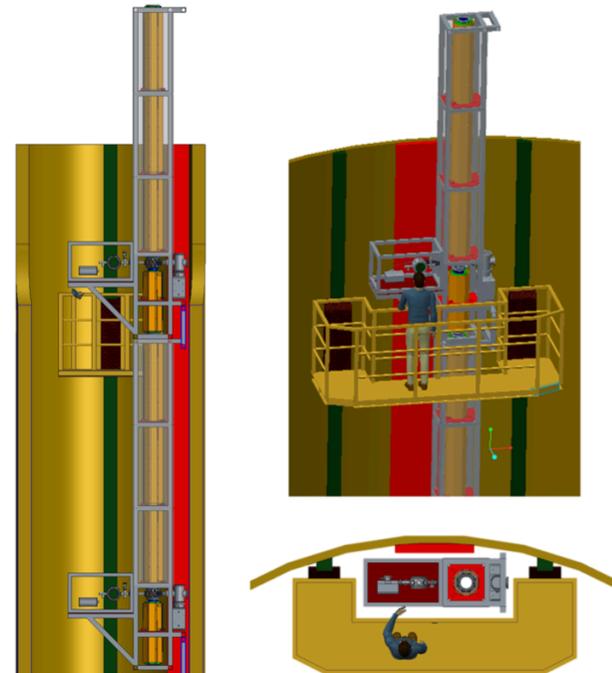
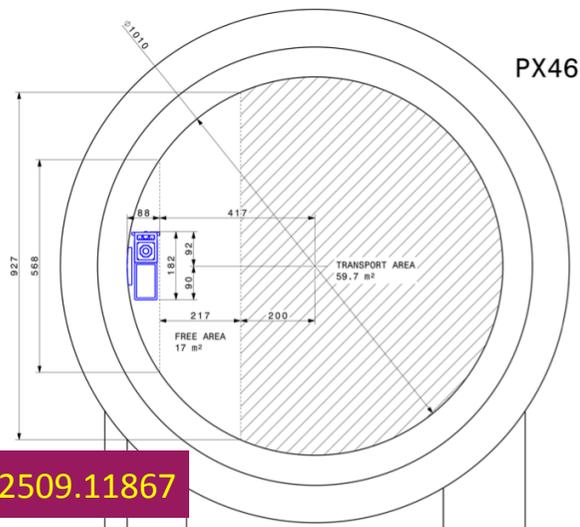
⁵ University of Cambridge

* Editors

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



Cross-section of access shaft



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

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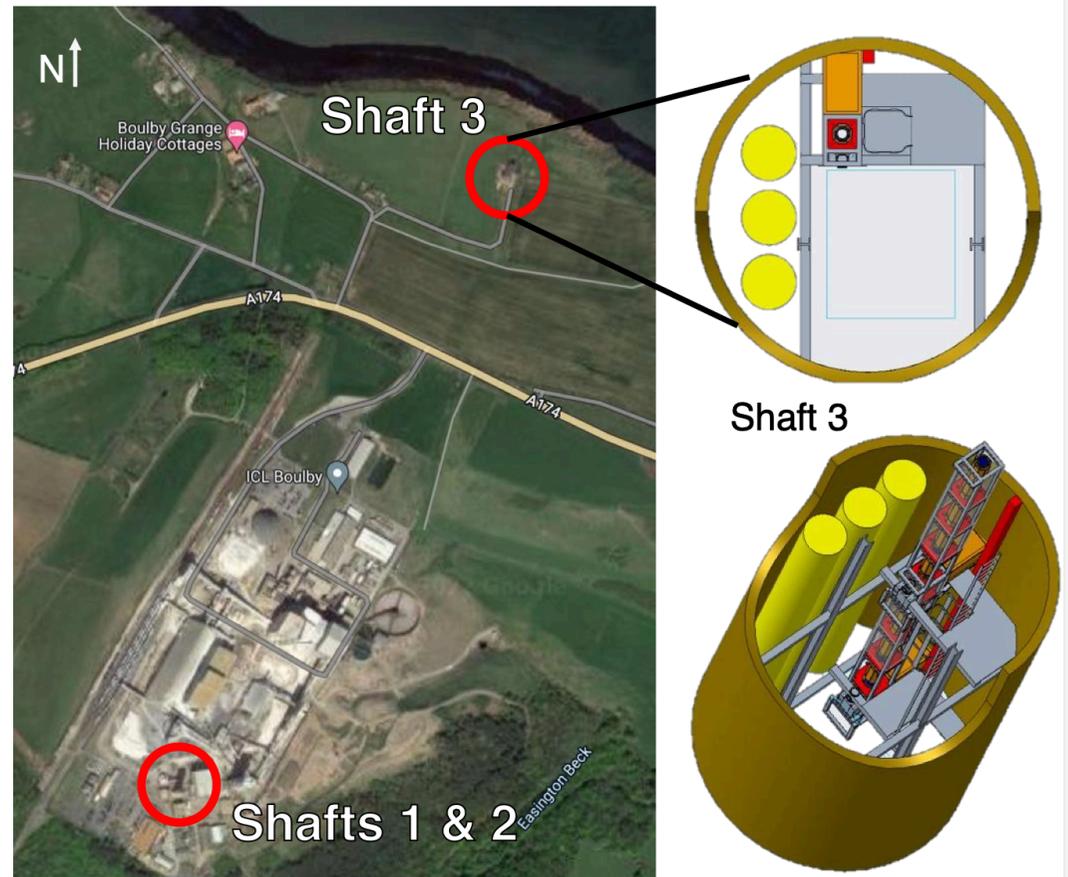
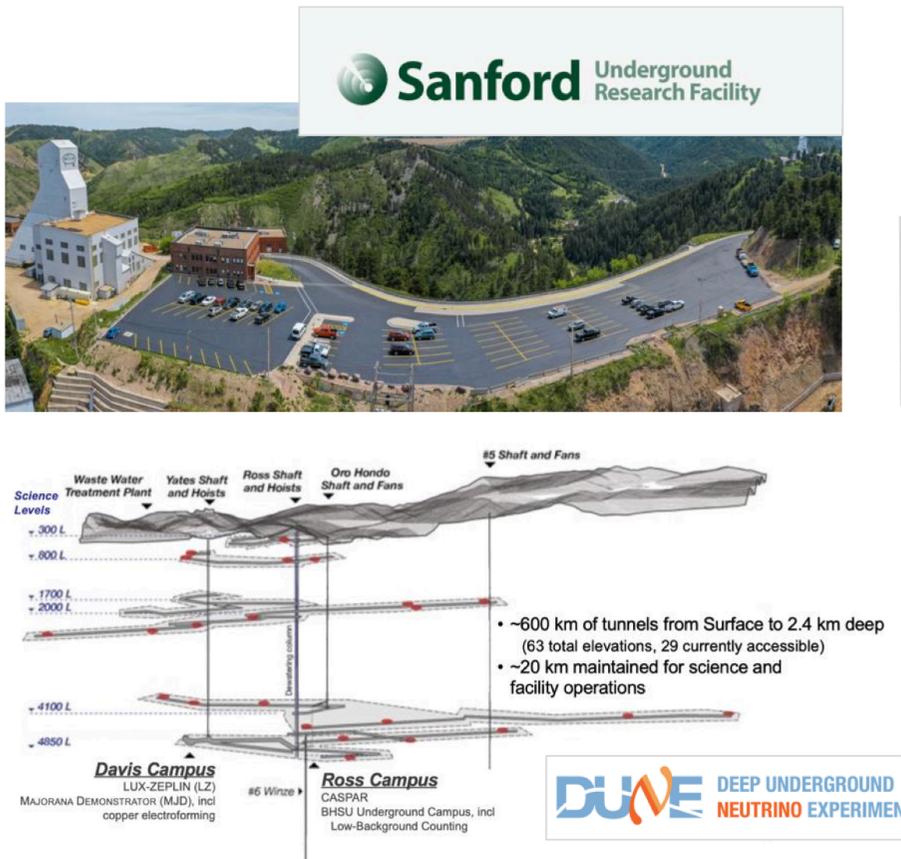
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¹⁴*School of Physics and Astronomy, University of Birmingham, B152TT Edgbaston, UK*

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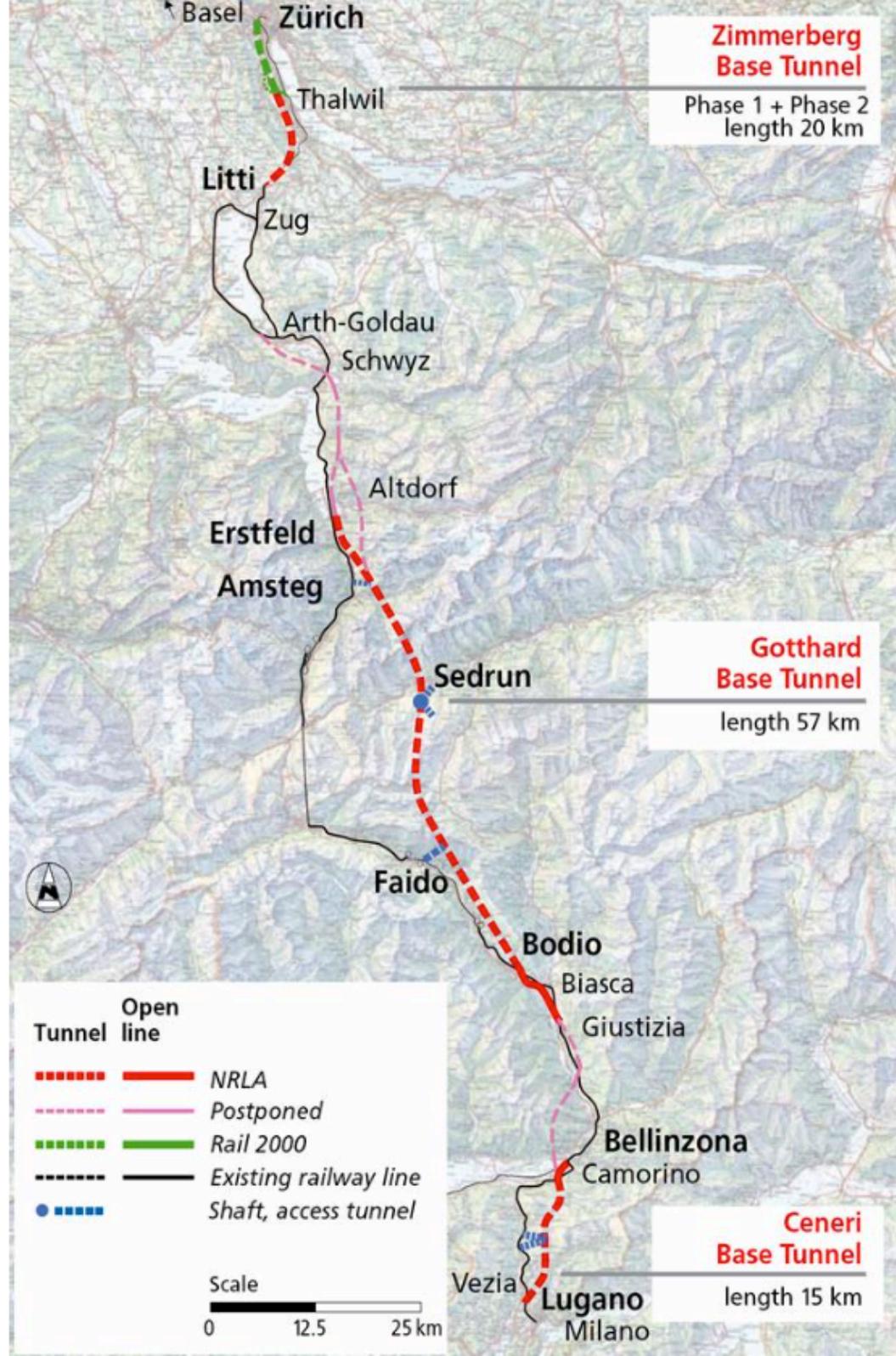
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Examples of Possible 1km Sites



Gotthard Base Tunnel

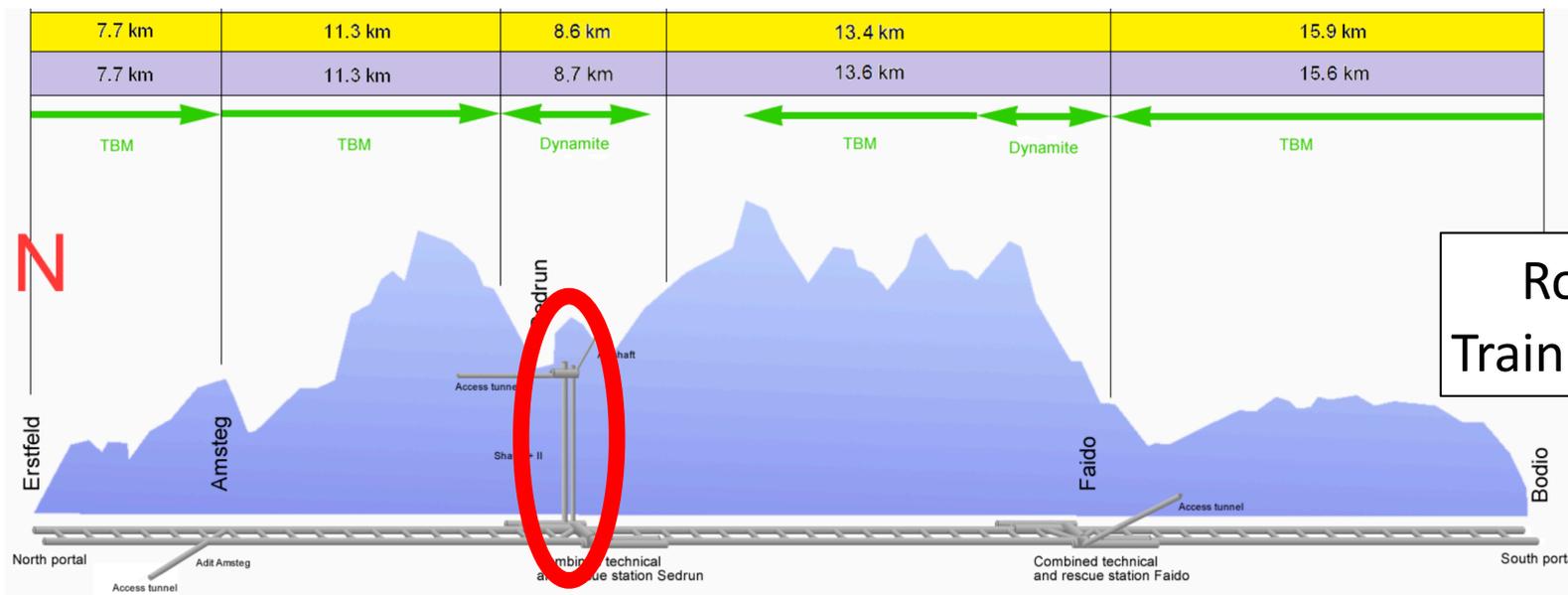
Longest operational railway tunnel in Europe
Length 57.1km
Opened for traffic in 2016
200 to 300 trains per day



Porta Alpina:

A possible site for a large terrestrial atom interferometer?

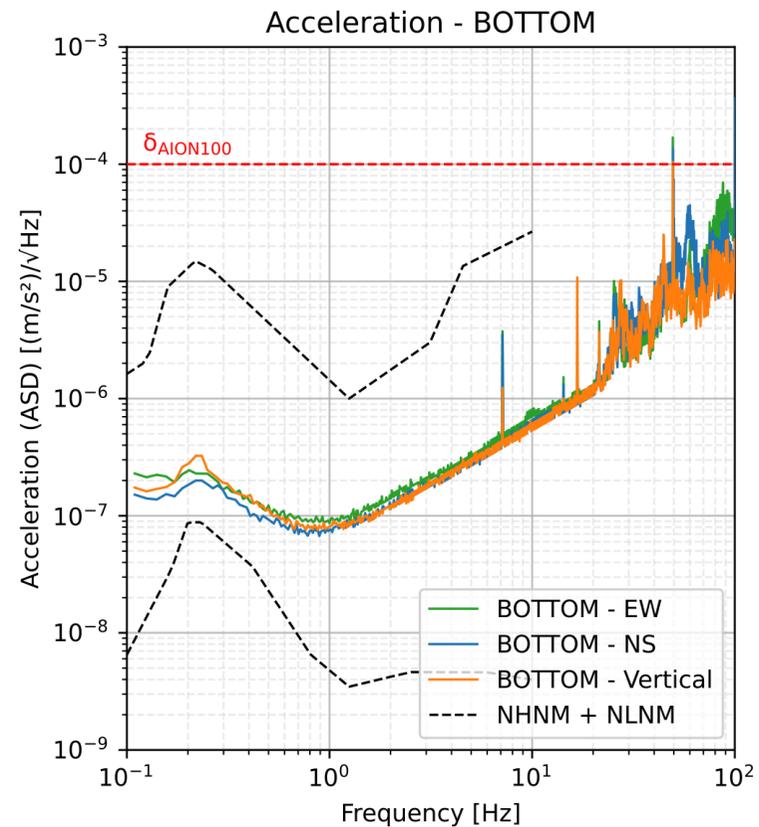
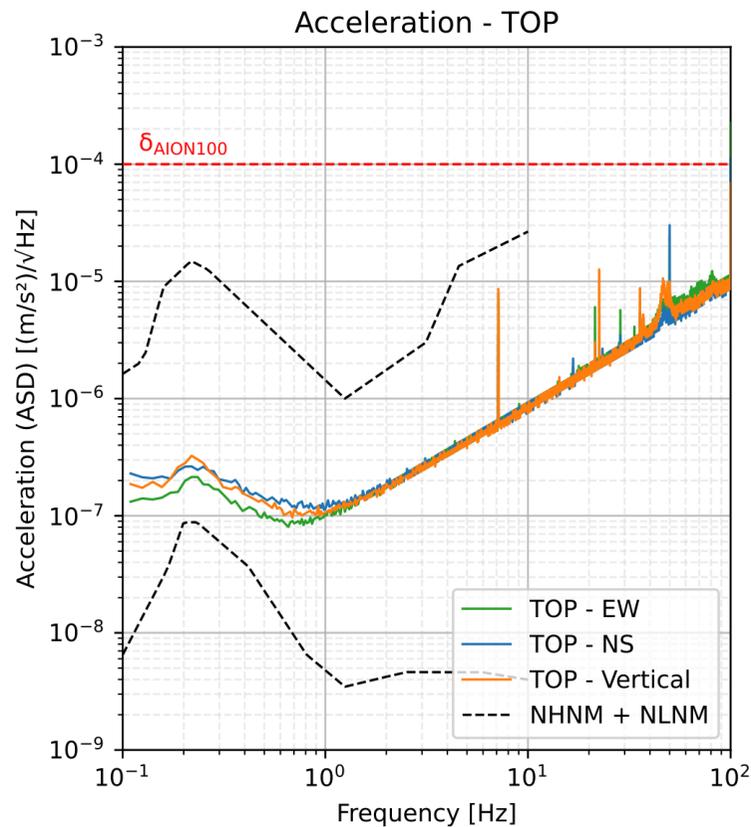
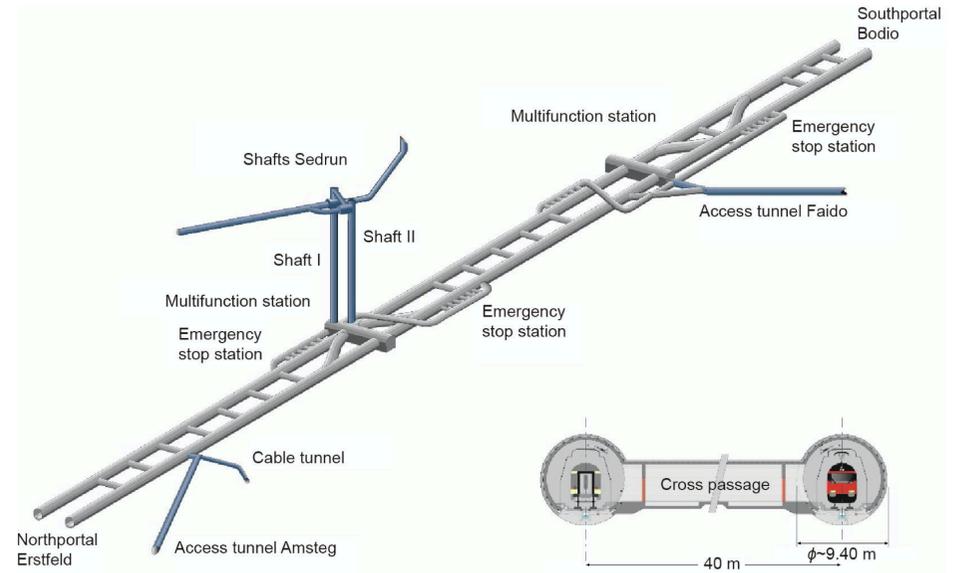
A pair of 800m vertical shafts down to the Gotthard base railway tunnel, with a 1km horizontal access tunnel



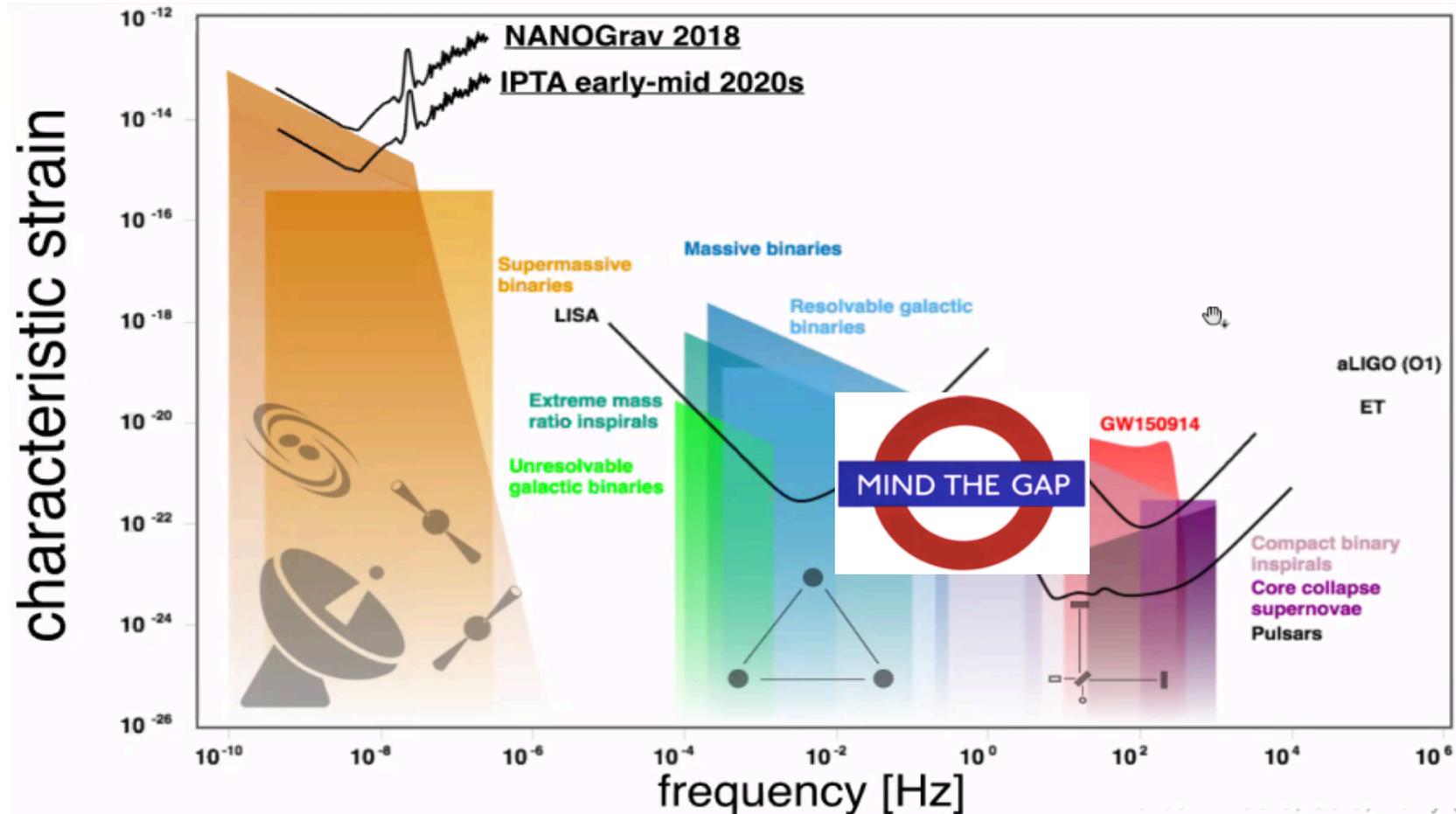
Road access at top
Train platform at bottom



Environmental Measurements at Porta Alpina

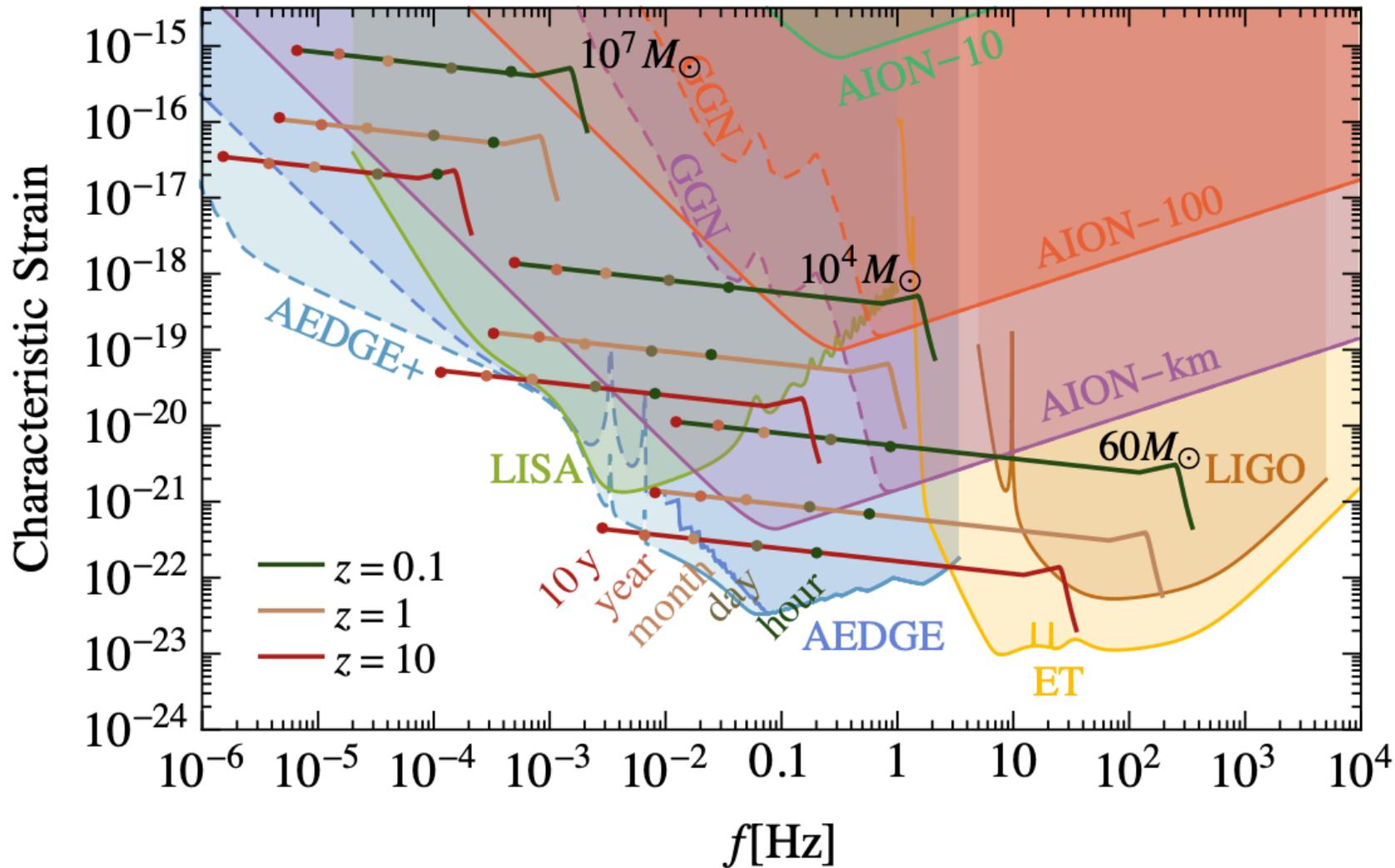


Gravitational Wave Spectrum



- 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?

Searching for Gravitational Waves

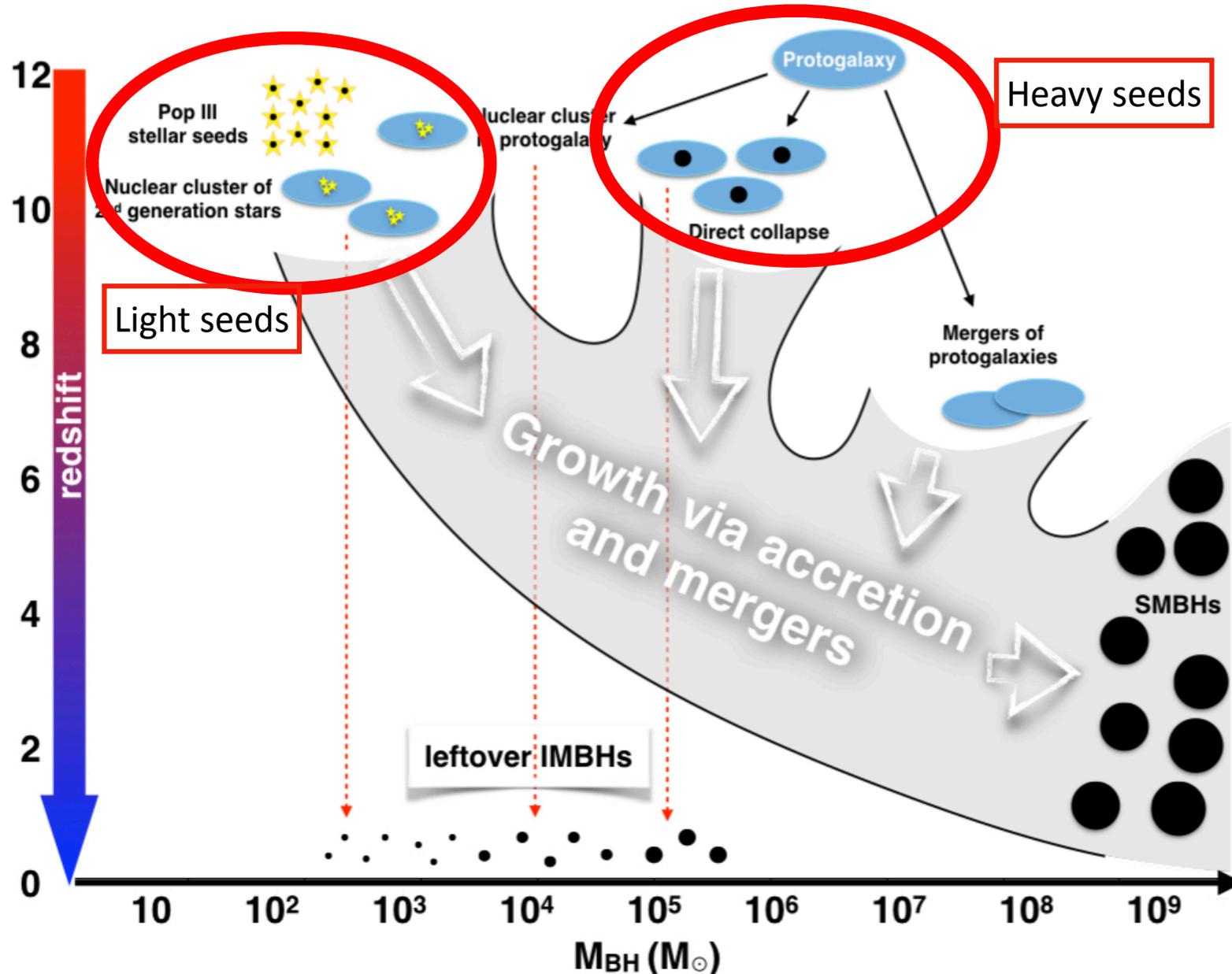


Probe formation of SMBHs

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

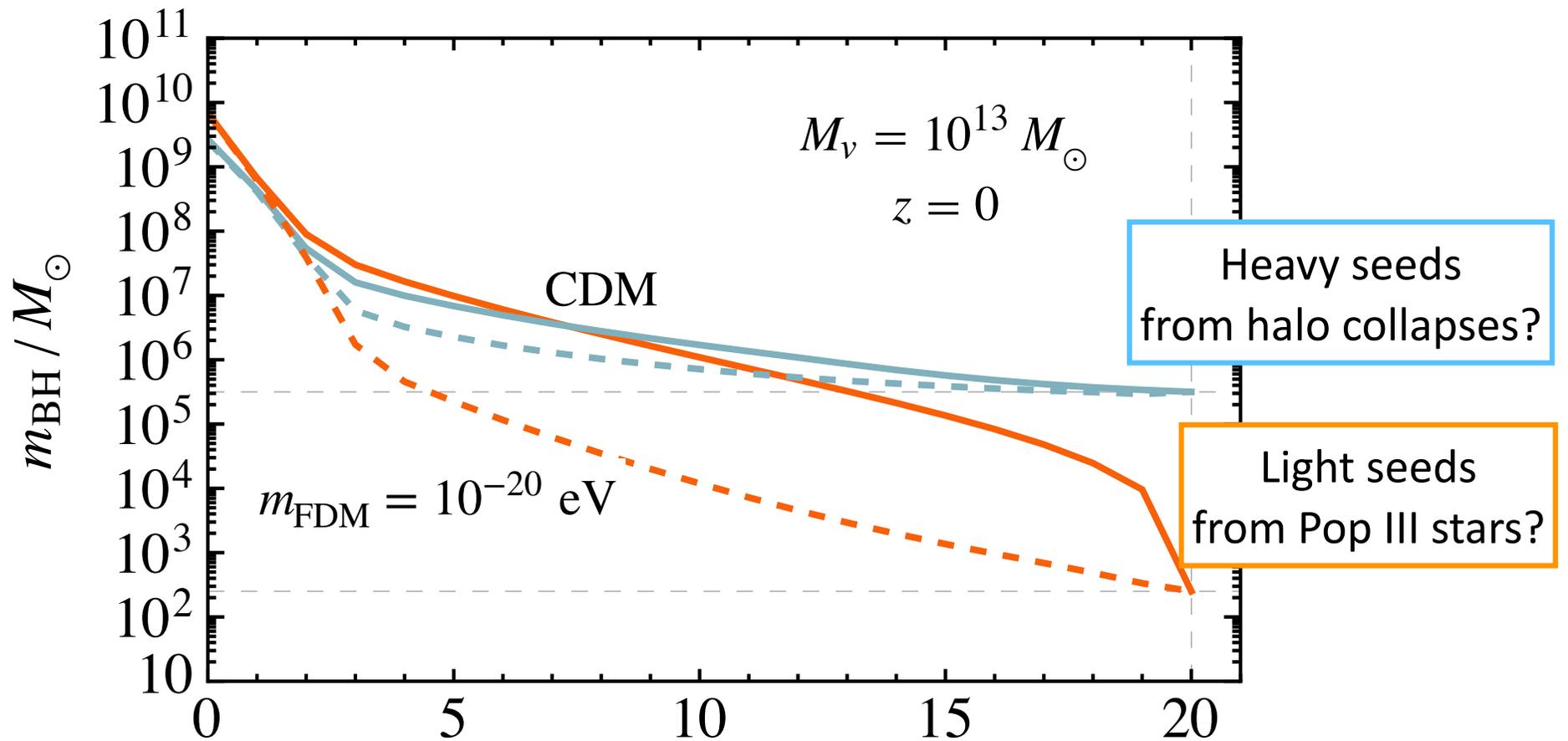
How to Make a Supermassive BH?

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



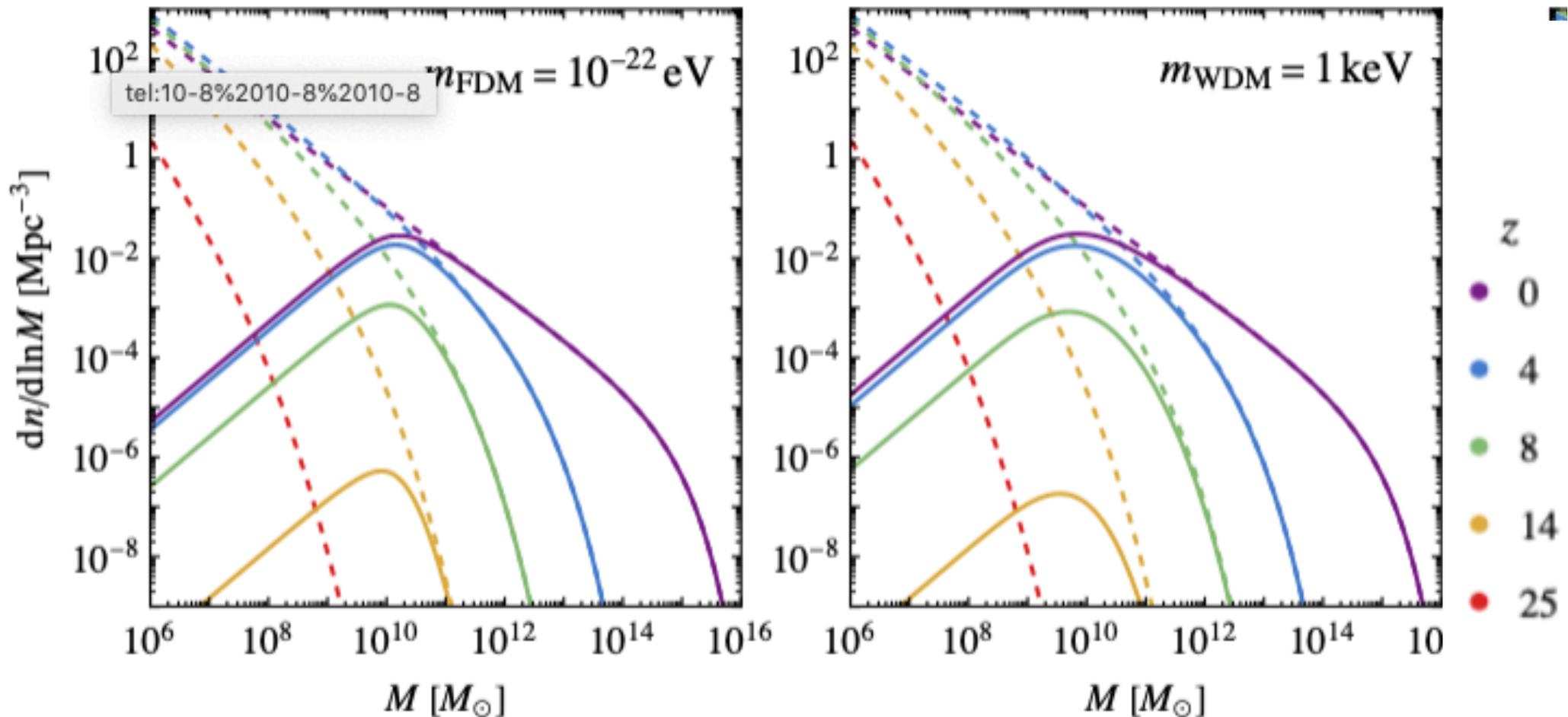
Growth of SMBH in CDM/FDM* with Light/Heavy Seeds

BH mass can grow by mergers or accretion



*Cold Dark Matter/Fuzzy Dark Matter

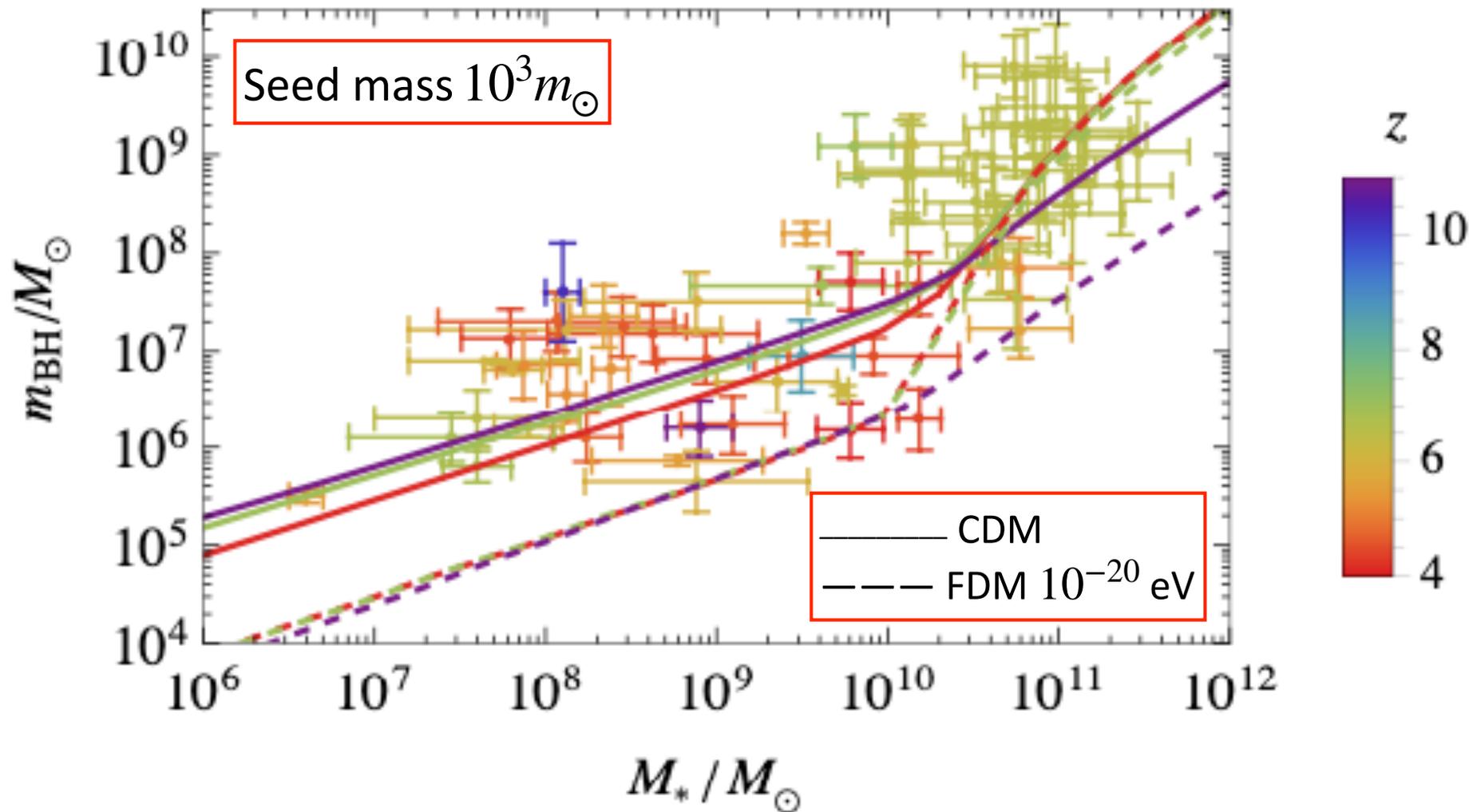
Halo Mass Function in CDM, FDM, WDM*



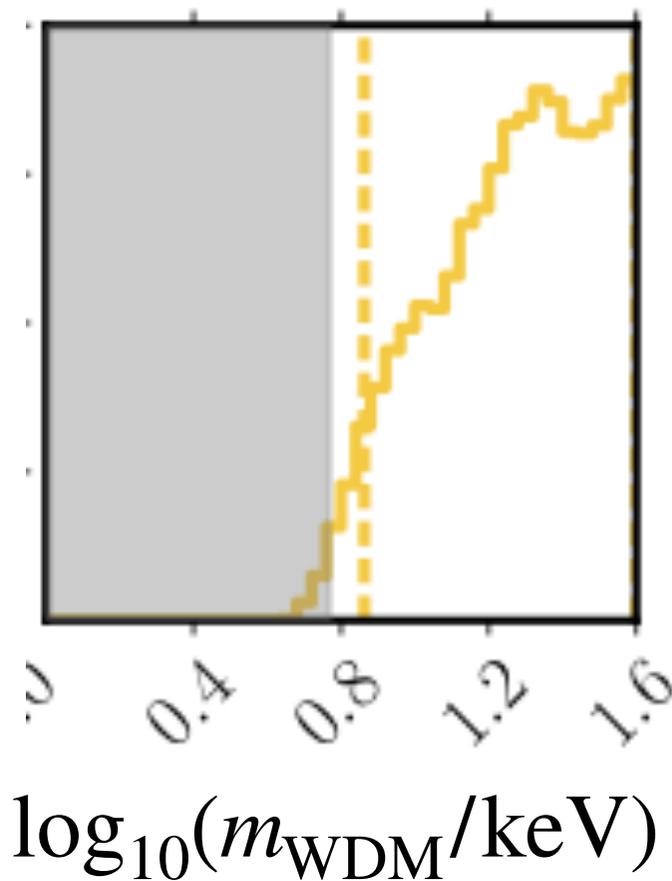
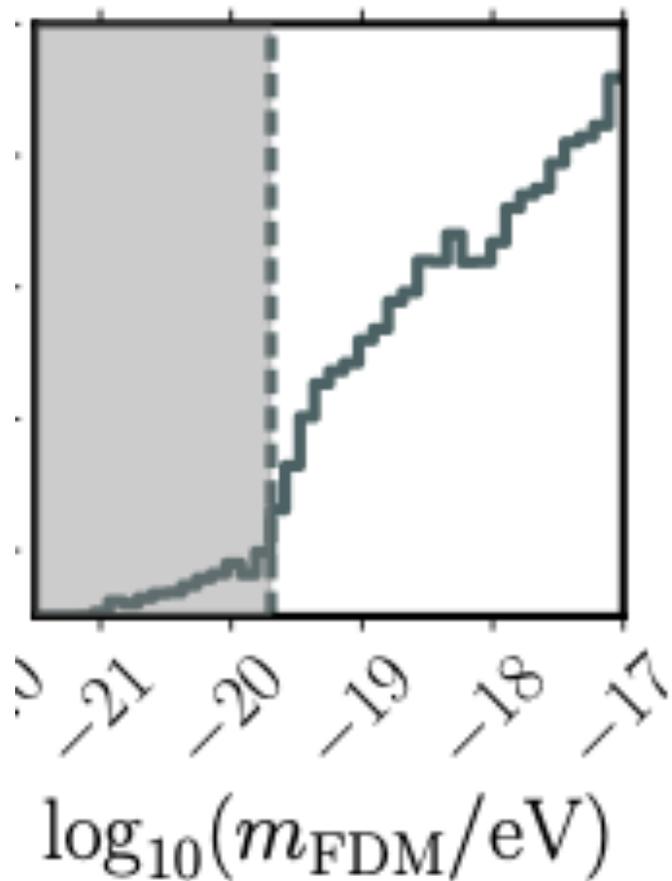
FDM and WDM show larger differences from CDM at high z

Novel way to probe FDM & CDM

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



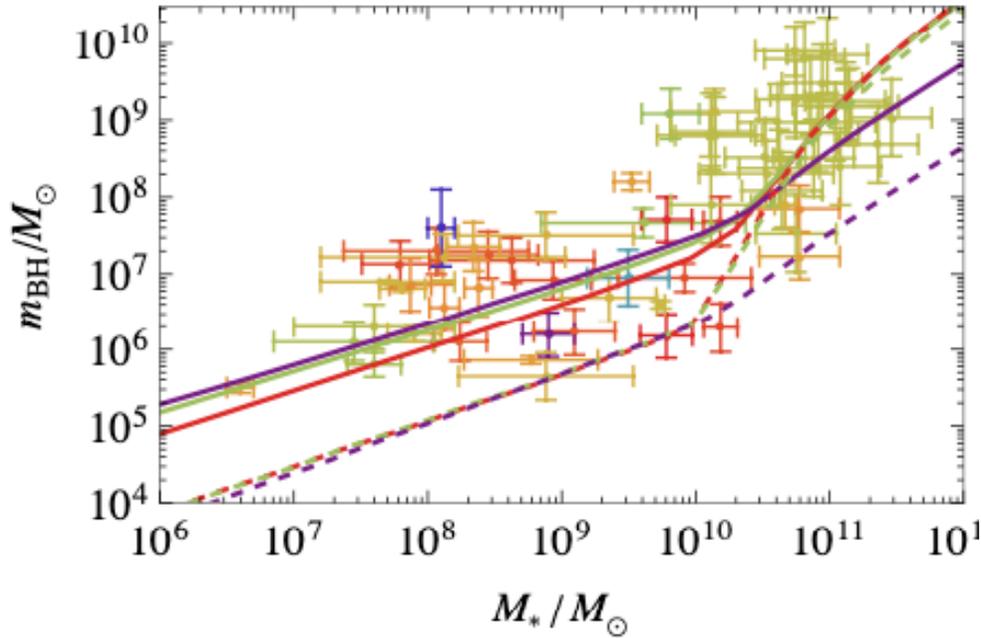
Posterior Density Functions from SMBH Mass Analysis



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.

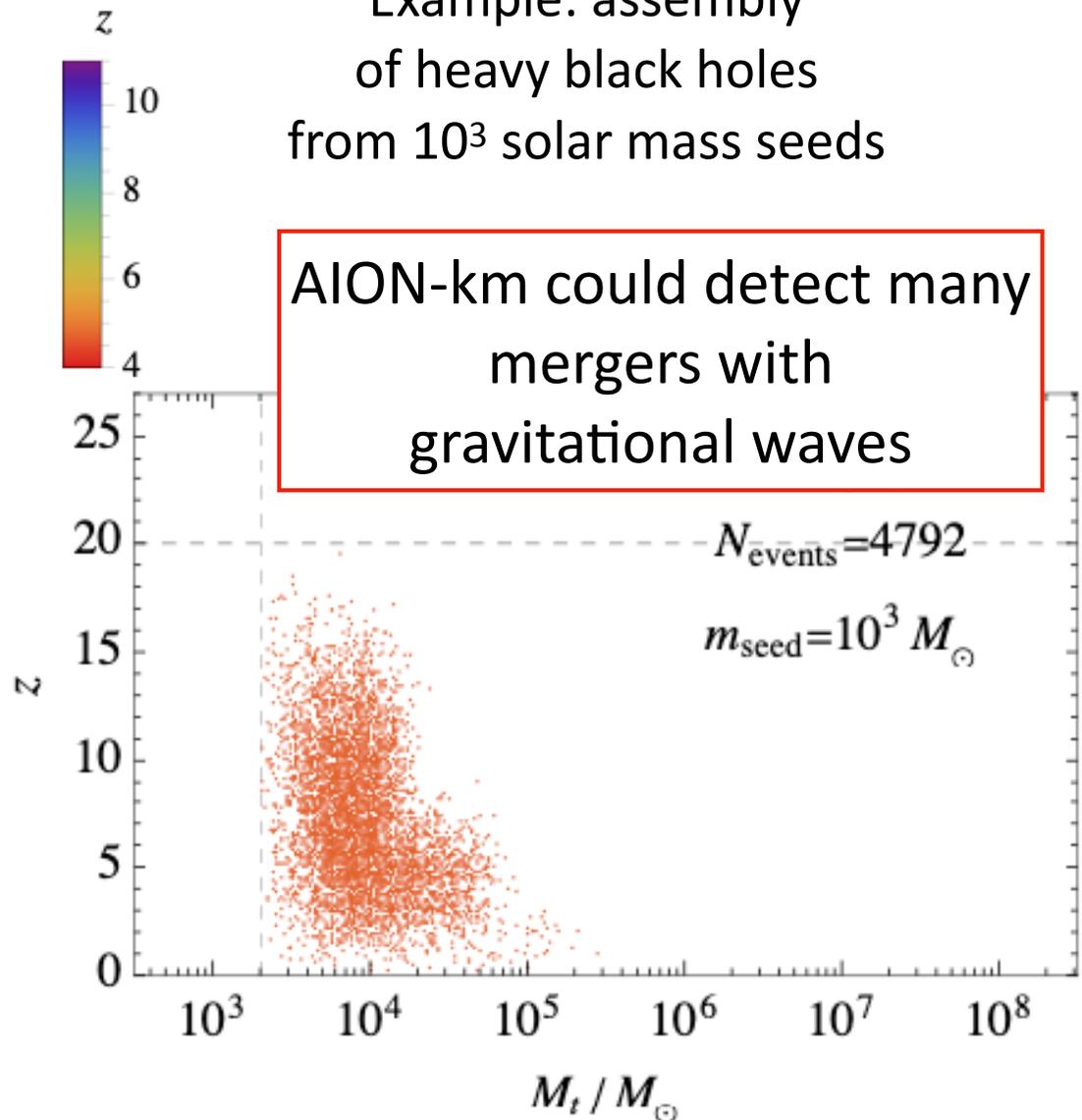
Probing Origin of Supermassive Black Holes with Gravitational Waves



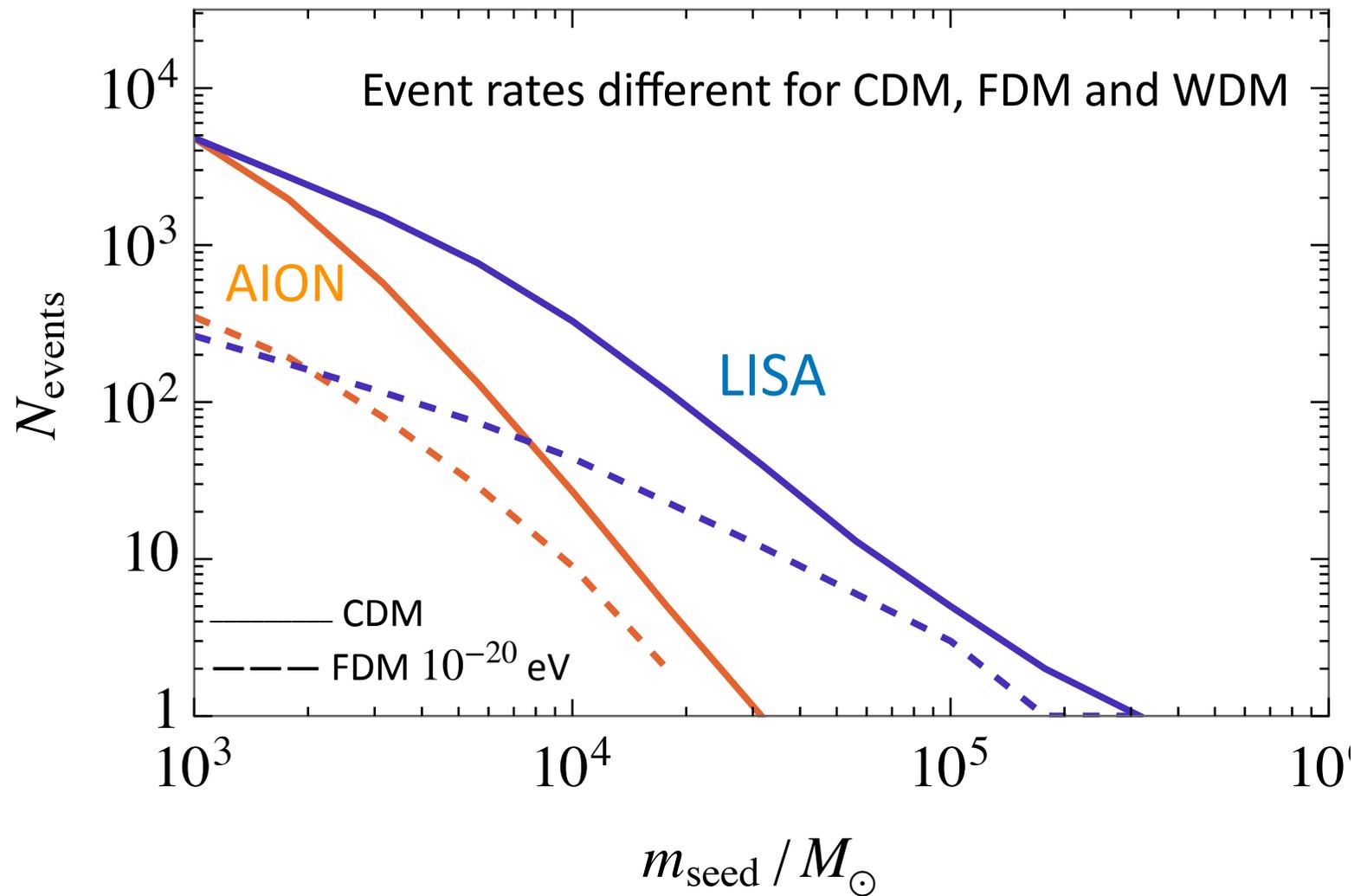
CDM model fits data on supermassive black holes at high & low redshifts

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



Particle Candidates for Dark Matter

