

# Towards a Road-Map for Cold Atoms in Space

<https://arxiv.org/pdf/2201.07789.pdf>

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Alonso et al, arXiv:2201.07789

*John Ellis*

**KING'S**  
*College*  
**LONDON**

# Cold Atoms in Space: Community Report & Road-Map

## Cold Atoms in Space:

### Community Workshop Summary and Proposed Road-Map

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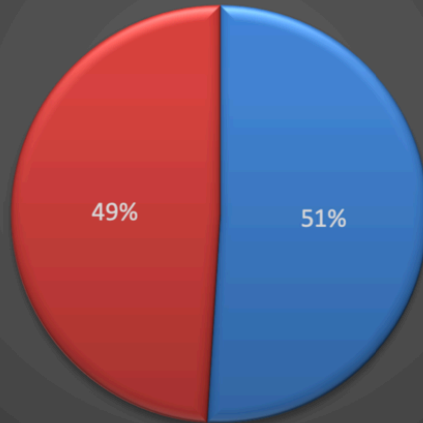
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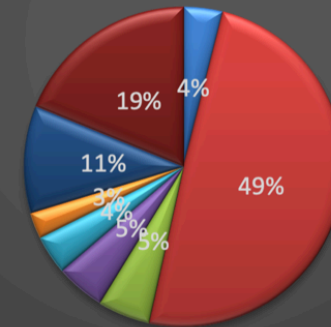
## Primary Research Area

User Community Cold Atom Technology



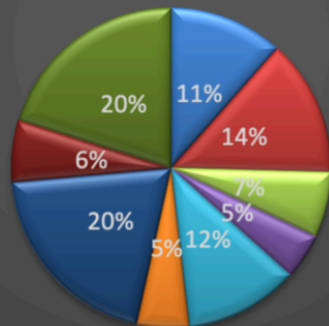
## Primary Research Area

Astrophysics Cold Atom Technology Cosmology  
Earth Observation Gravitational Waves Industry  
Others Particle Physics



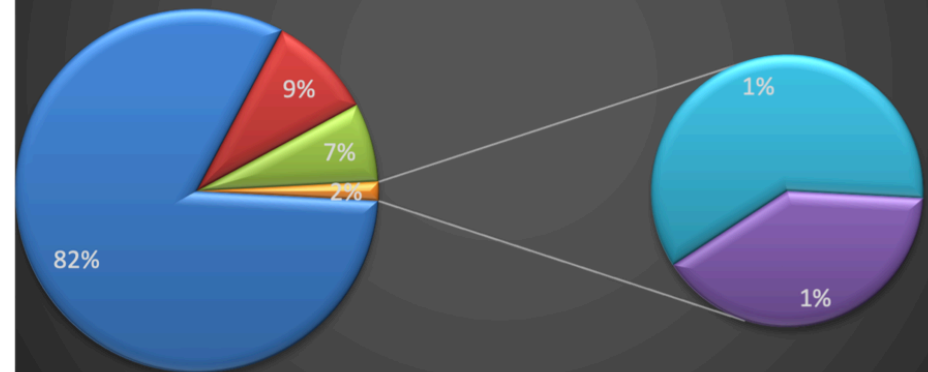
## Secondary Research Area

Astrophysics Cold Atom Technology Cosmology  
Earth Observation Gravitational Waves Industry  
Others Particle Physics Unspecified

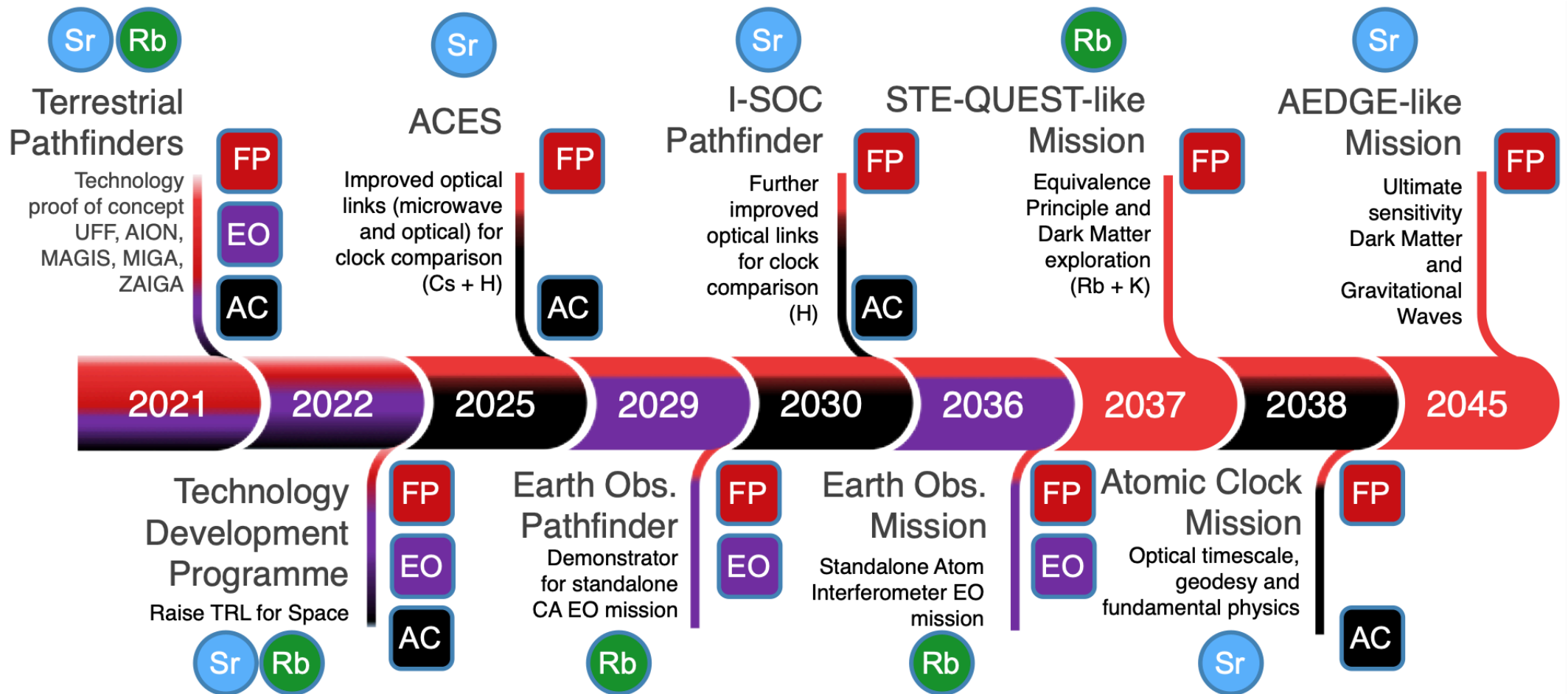


## Region

Europe North America Asia South America Africa



# Community Proposal for ESA Road-Map for Cold Atoms in Space



## Legends:

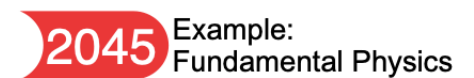
Main Cold Atom Species



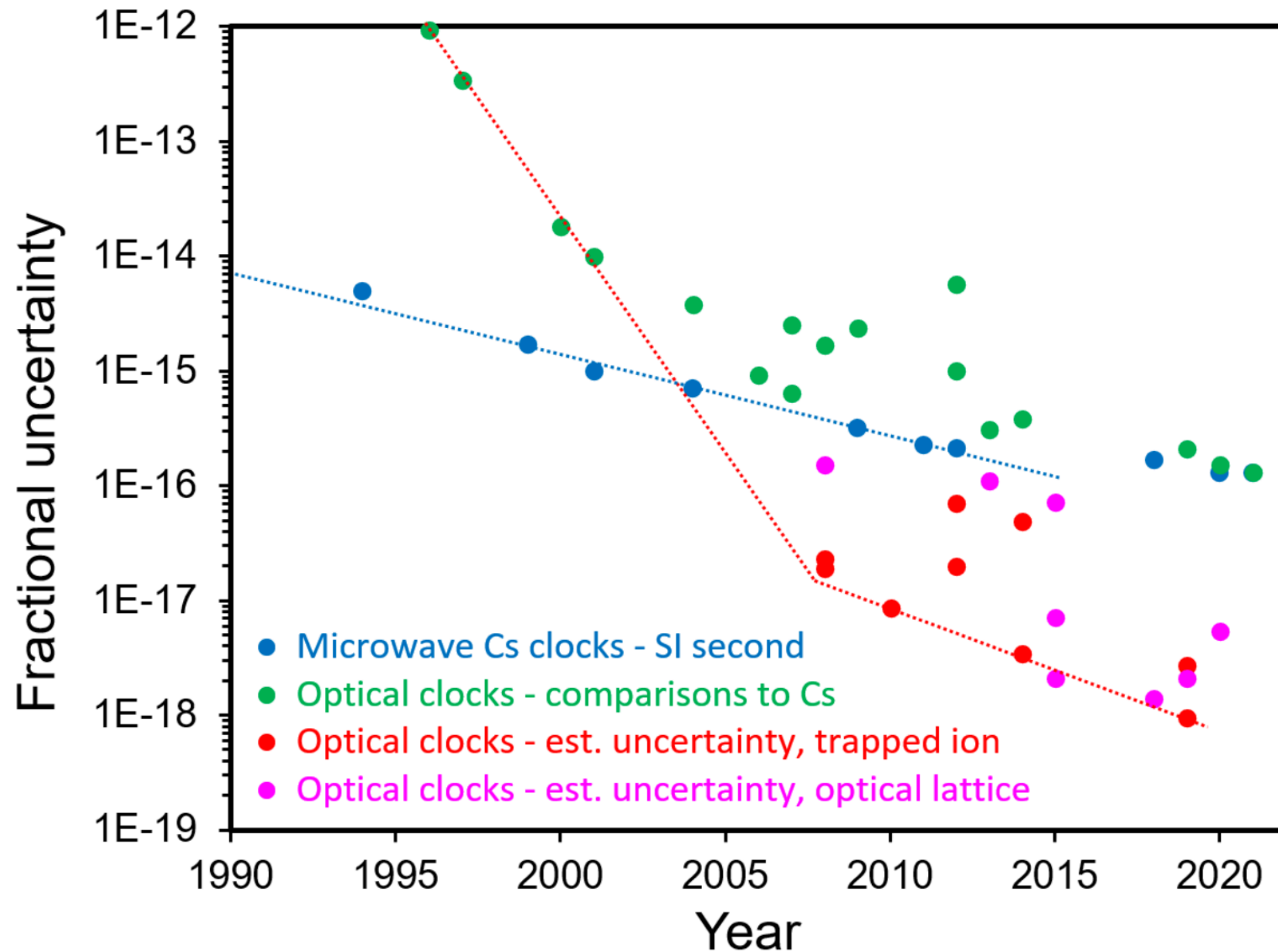
Areas of Relevance



Main Milestone Area (colour coded)

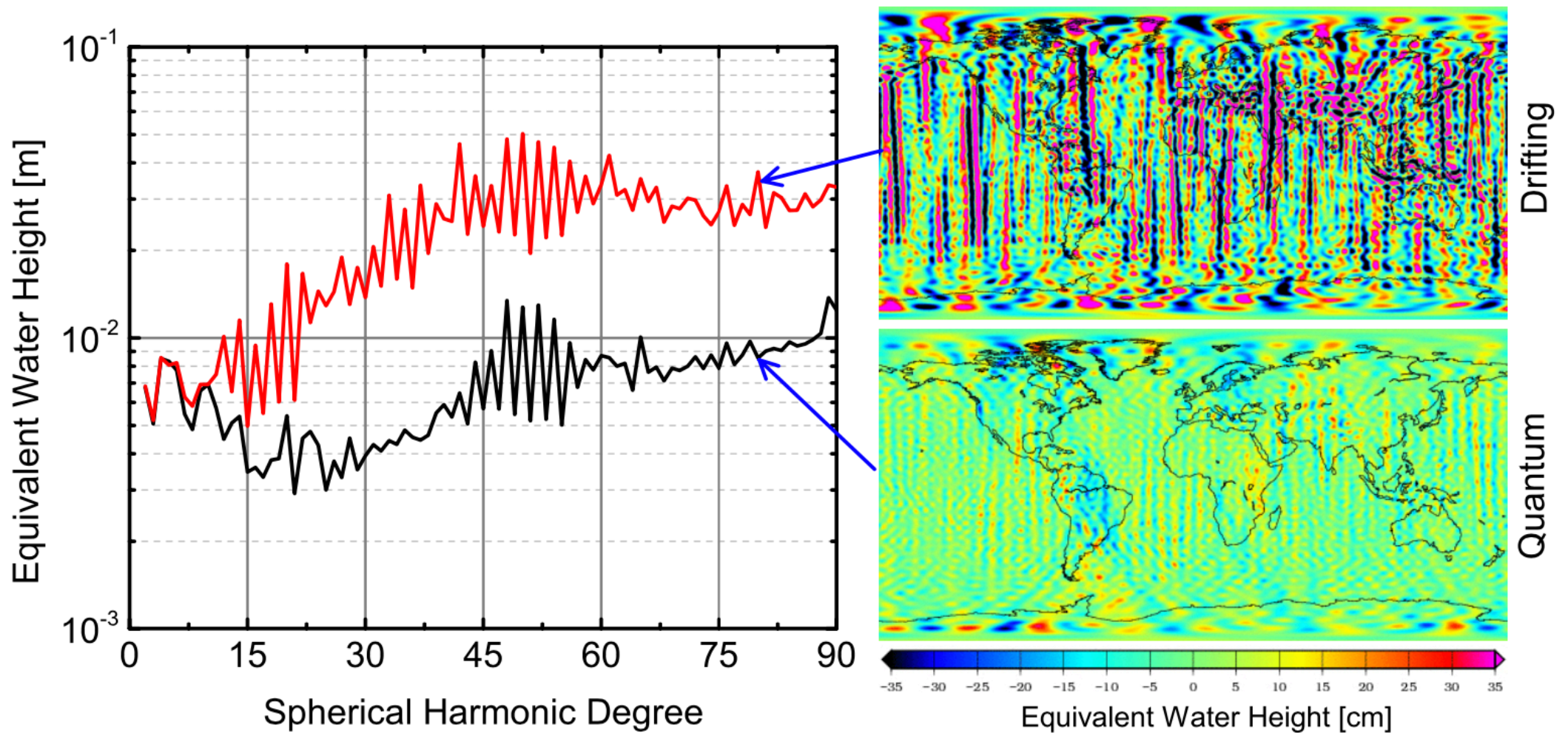


# Cold Atoms in Space: Advances of Atomic Clocks

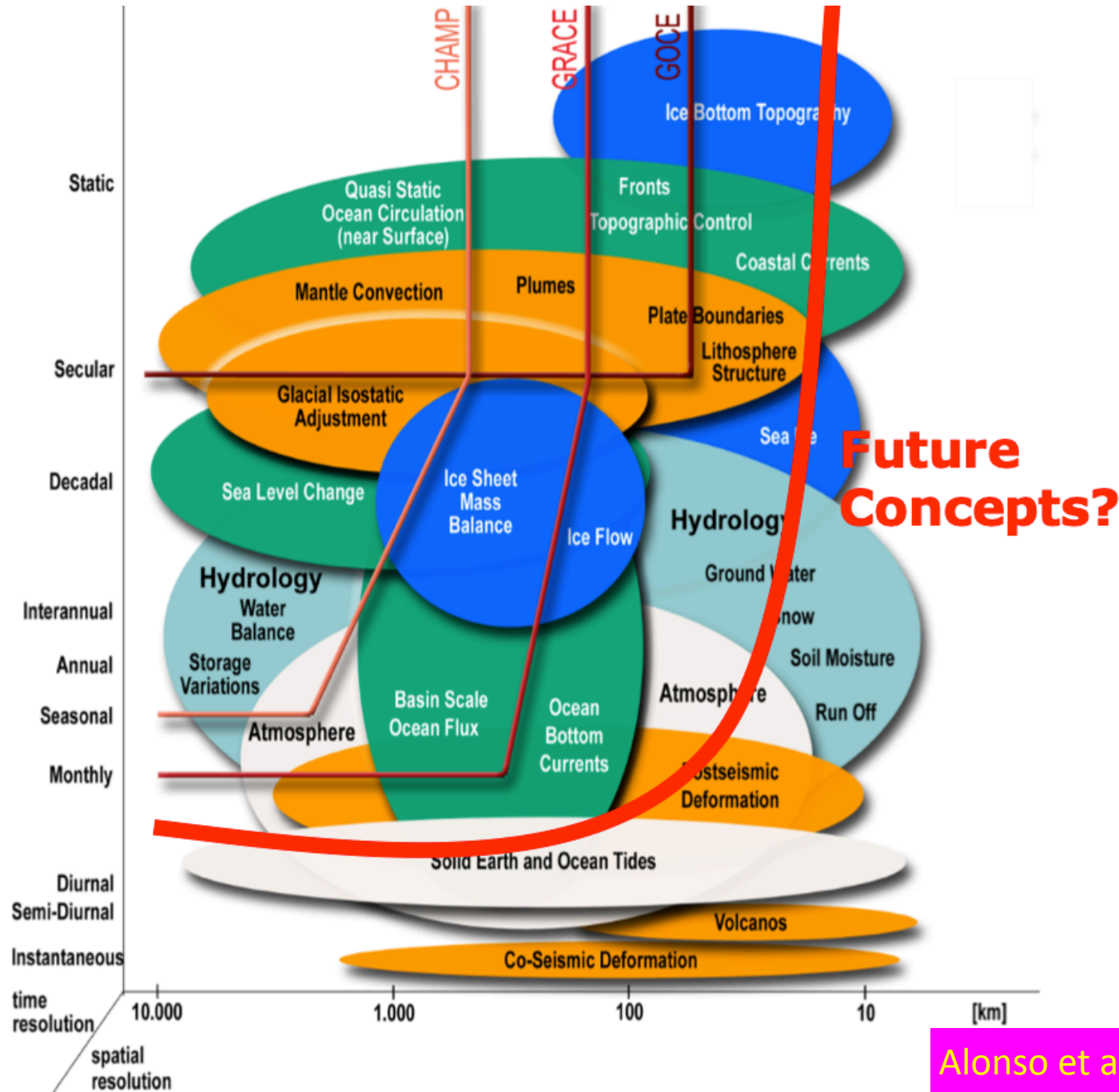




# Cold Atoms in Space: Earth Observation



# Cold Atoms in Space: Earth Observation



# STE-QUEST Proposal

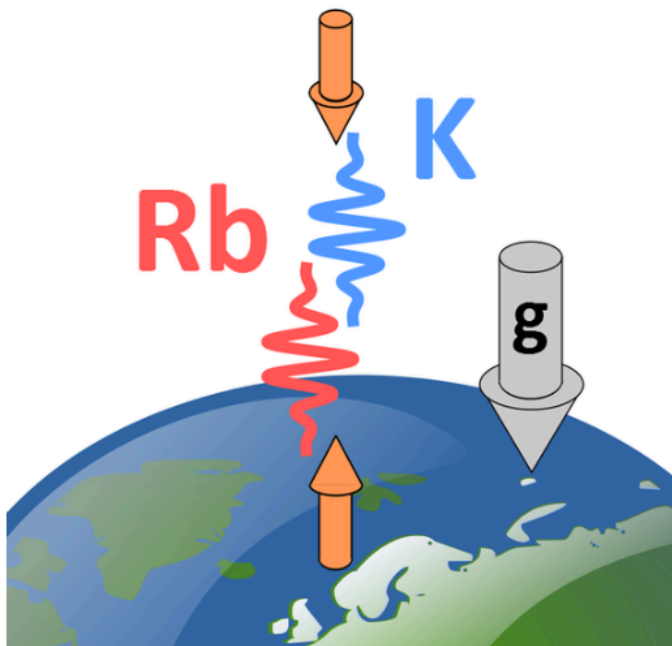
## STE-QUEST

Space Time Explorer and QUantum Equivalence principle Space Test

A M-class mission proposal in response to the 2022 call in ESA's science program

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February 15, 2022



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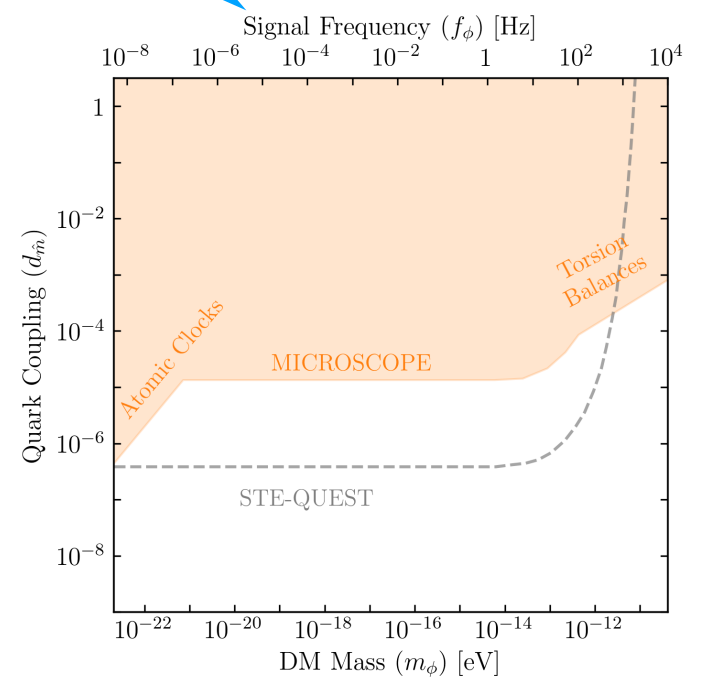
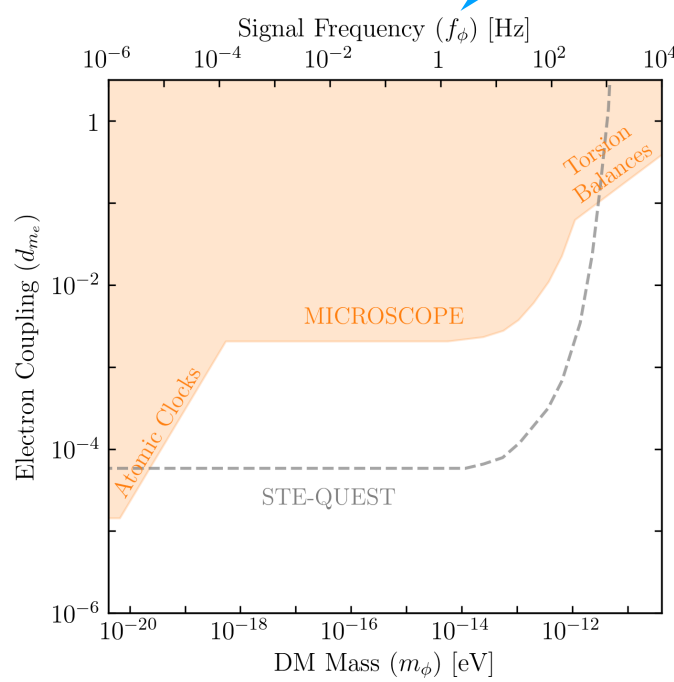
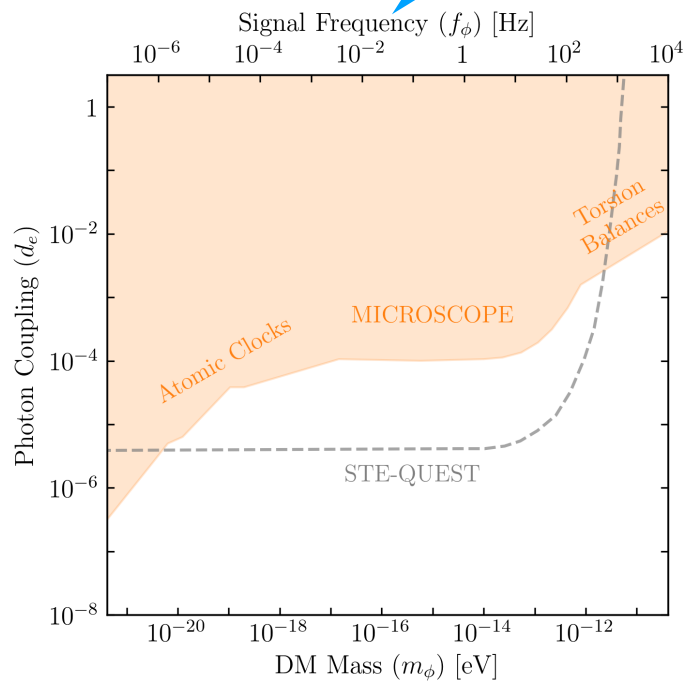


# STE-QUEST Science: Testing the Equivalence Principle

Class	Elements	$\eta$	Year [ref]	Comments
Classical	Be - Ti	$2 \times 10^{-13}$	2008	Torsion balance
	Pt - Ti	$1 \times 10^{-14}$	2017	MICROSCOPE first results
	Pt - Ti	$(10^{-15})$	2022+	MICROSCOPE full data
Hybrid	$^{133}\text{Cs}$ - CC	$7 \times 10^{-9}$	2001	Atom Interferometry
	$^{87}\text{Rb}$ - CC	$7 \times 10^{-9}$	2010	and macroscopic corner cube (CC)
Quantum	$^{39}\text{K}$ - $^{87}\text{Rb}$	$3 \times 10^{-7}$	2020	different elements
	$^{87}\text{Sr}$ - $^{88}\text{Sr}$	$2 \times 10^{-7}$	2014	same element, fermion vs. boson
	$^{85}\text{Rb}$ - $^{87}\text{Rb}$	$3 \times 10^{-8}$	2015	same element, different isotopes
	$^{85}\text{Rb}$ - $^{87}\text{Rb}$	$3.8 \times 10^{-12}$	2020	10 m tower
	$^{41}\text{K}$ - $^{87}\text{Rb}$	$(10^{-17})$	2037	STE-QUEST
Antimatter	$\bar{\text{H}}$ - H	$(10^{-2})$	2023+	under construction at CERN

# STE-QUEST Science: Searching for Ultralight Dark Matter

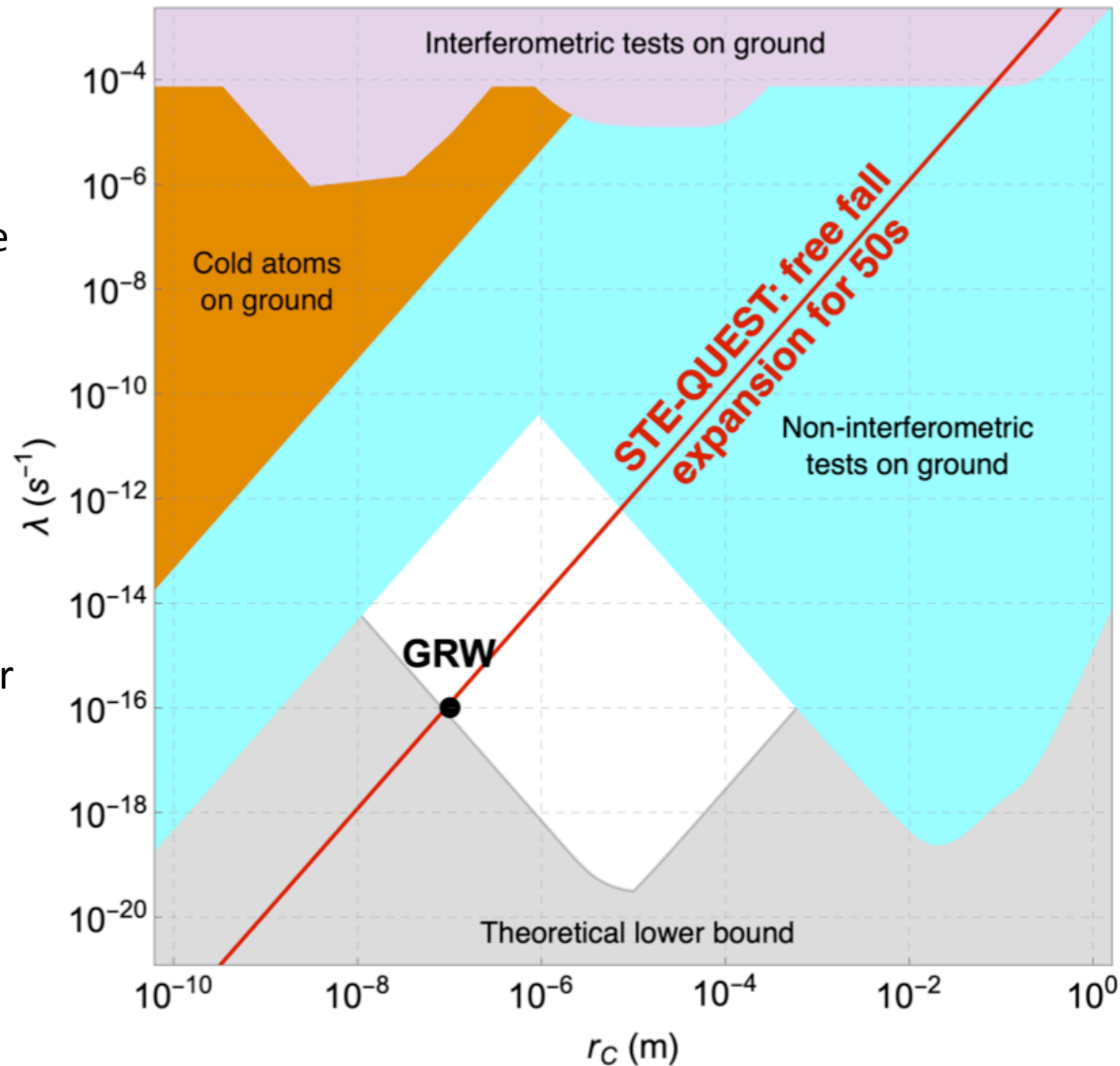
$$\mathcal{L}_{\text{int}\phi} = \kappa\phi \left[ +\frac{d_e}{4e^2} F_{\mu\nu} F^{\mu\nu} - \frac{d_g\beta_3}{2g_3} F_{\mu\nu}^A F^{A\mu\nu} - \sum_{i=e,u,d} (d_{m_i} + \gamma_{m_i} d_g) m_i \bar{\psi}_i \psi_i \right]$$



# STE-QUEST Science: Probe of Quantum Mechanics

Models for  
wave-function collapse  
parameterised by  
time-scale  $\lambda$   
and range  $r_C$

GRW = parameters  
proposed by  
Ghirardi, Rimini, Weber

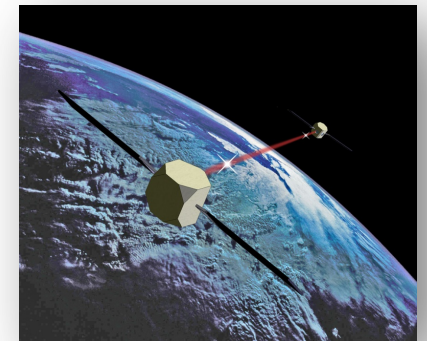


# AEDGE:

## Atomic Experiment for Dark Matter and Gravity Exploration in Space

Beyond LISA

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Saurabh Pandey,<sup>13</sup> Dimitris Papazoglou,<sup>51</sup> Mauro Paternostro,<sup>52</sup> Bjoern Penning,<sup>53</sup>  
Achim Peters,<sup>3,\*</sup> Marco Prevedelli,<sup>54</sup> Vishnupriya Puthiya-Veetil,<sup>55</sup> John Quenby,<sup>4</sup>  
Ernst Rasel,<sup>36,\*</sup> Sean Ravenhall,<sup>9</sup> Haifa Rejeb Sfar,<sup>29</sup> Jack Ringwood,<sup>16</sup> Albert Roura,<sup>56,\*</sup>  
Dylan Sabulsky,<sup>8,\*</sup> Muhammed Sameed,<sup>57</sup> Ben Sauer,<sup>4</sup> Stefan Alaric Schäffer,<sup>58</sup>  
Stephan Schiller,<sup>59,\*</sup> Vladimir Schkolnik,<sup>3</sup> Dennis Schlippert,<sup>36</sup> Christian Schubert,<sup>3,\*</sup>  
Armin Shayeghi,<sup>60</sup> Ian Shipsey,<sup>9</sup> Carla Signorini,<sup>21,22</sup> Marcelle Soares-Santos,<sup>53</sup>  
Fiodor Sorrentino,<sup>61,\*</sup> Yajpal Singh,<sup>14,\*</sup> Timothy Sumner,<sup>4</sup> Konstantinos Tassis,<sup>13</sup>  
Silvia Tentindo,<sup>62</sup> Guglielmo Maria Tino,<sup>63,64,\*</sup> Jonathan N. Tinsley,<sup>63</sup> James Unwin,<sup>65</sup>  
Tristan Valenzuela,<sup>11</sup> Georgios Vasilakis,<sup>13</sup> Ville Vaskonen,<sup>12,32,\*</sup> Christian Vogt,<sup>66</sup>  
Alex Webber-Date,<sup>16</sup> André Wenzlawski,<sup>67</sup> Patrick Windpassinger,<sup>67</sup> Marian Woltmann,<sup>66</sup>  
Michael Holynski,<sup>14</sup> Efe Yazgan,<sup>68</sup> Ming-Sheng Zhan,<sup>69,\*</sup> Xinhao Zou,<sup>8</sup> Jure Zupan<sup>70</sup>



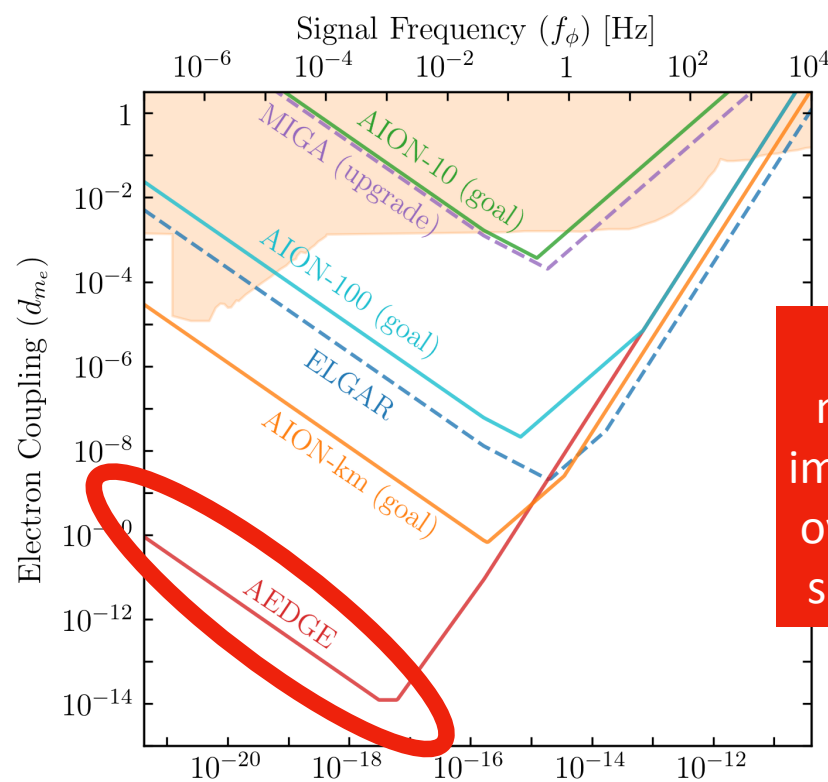
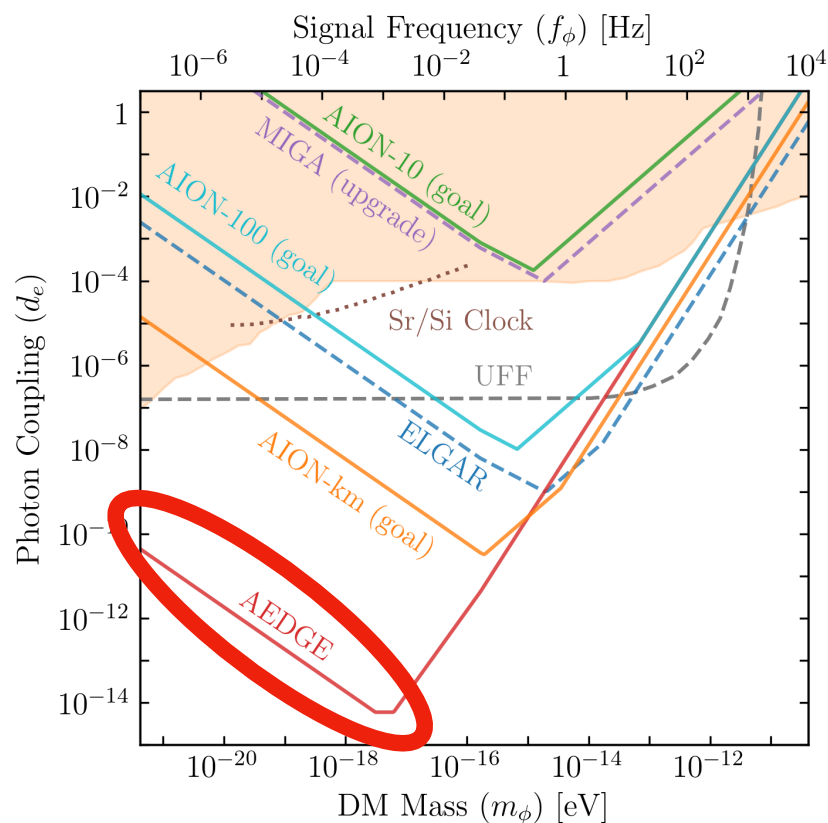
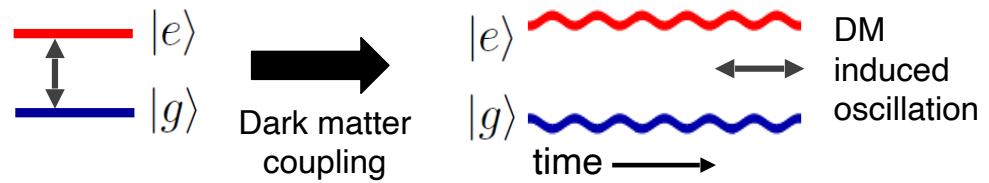
White paper  
submitted to  
ESA Voyage  
2050 Call

Abou El-Neaj, ..., JE et al:  
arXiv:1908.00802

# AEDGE: Searches for Ultralight Dark Matter

Linear couplings to gauge fields and matter fermions

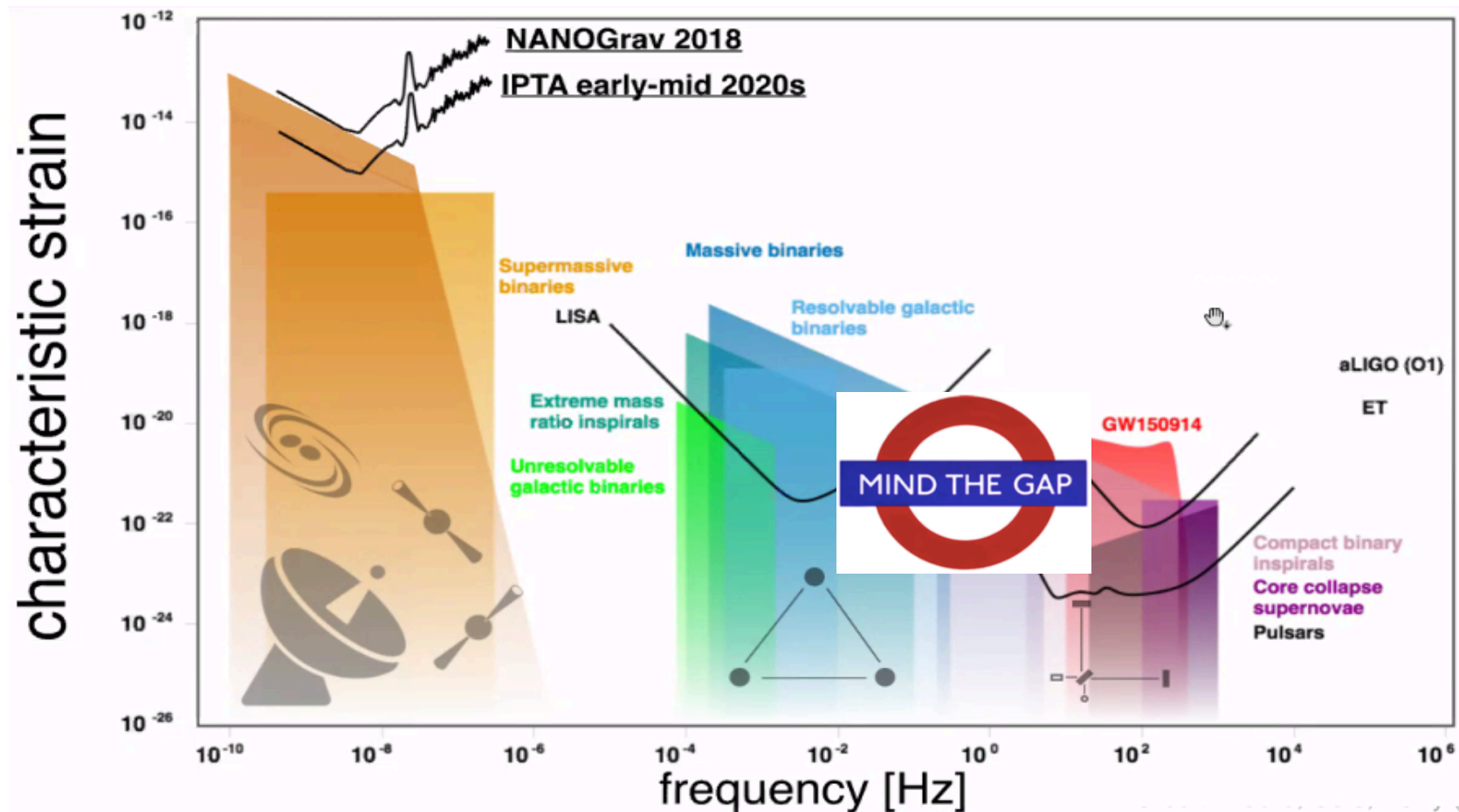
$$\mathcal{L}_{\text{int}\phi} = \kappa\phi \left[ +\frac{d_e}{4e^2} F_{\mu\nu} F^{\mu\nu} - \frac{d_g\beta_3}{2g_3} F_{\mu\nu}^A F^{A\mu\nu} - \sum_{i=e,u,d} (d_{m_i} + \gamma_{m_i} d_g) m_i \bar{\psi}_i \psi_i \right]$$



Orders of magnitude improvement over current sensitivities



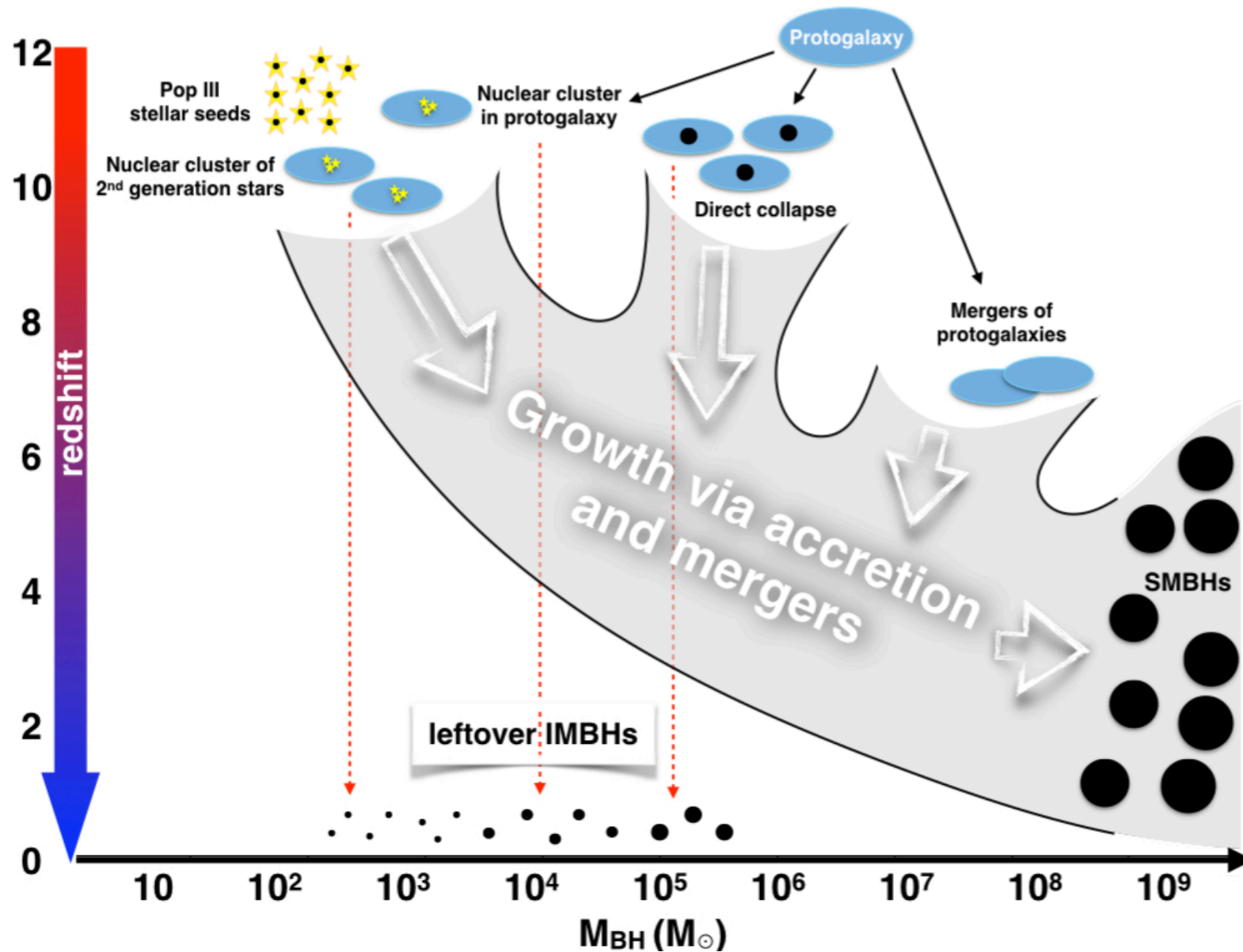
# Gravitational Wave Spectrum



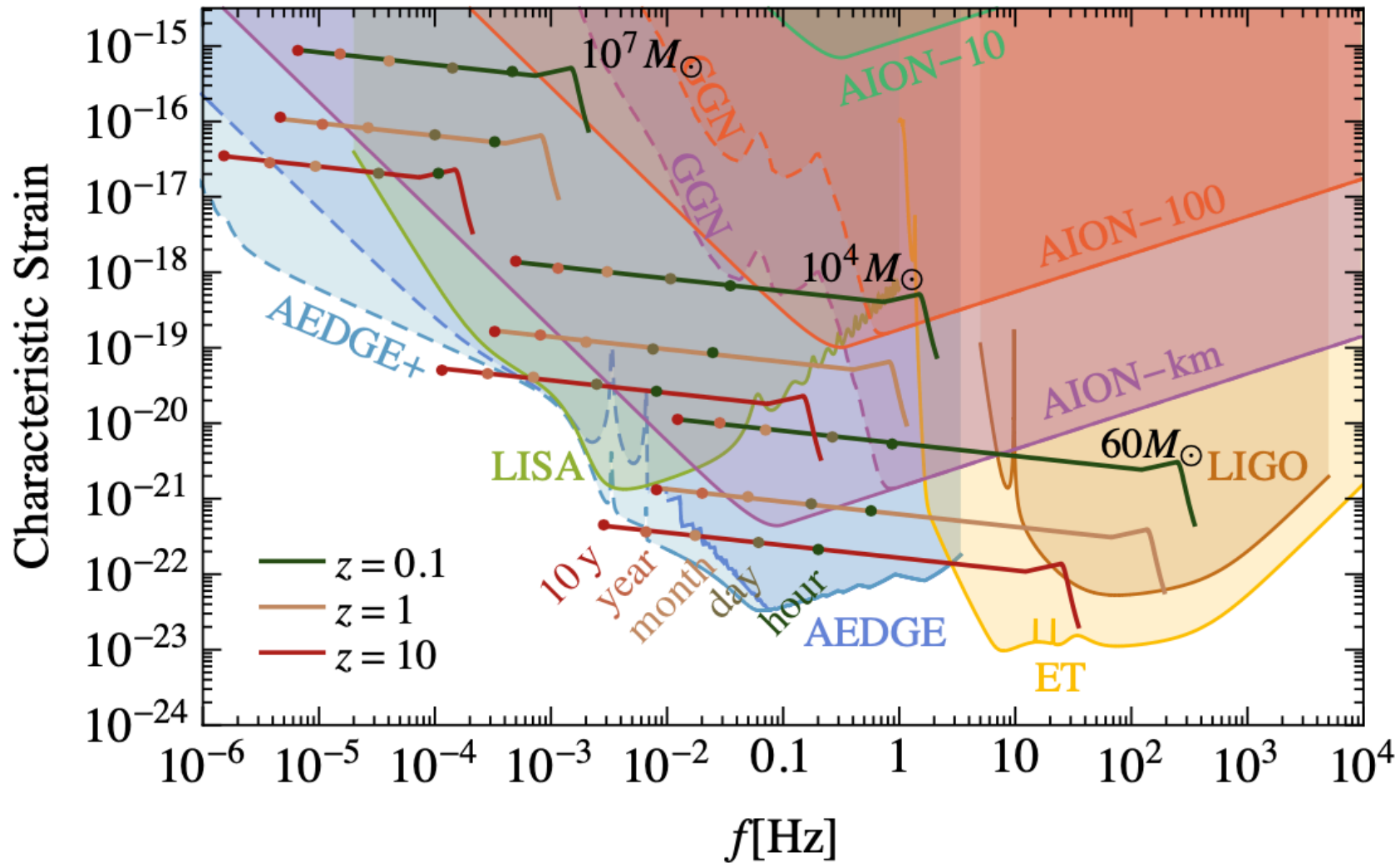
- Gap between ground-based optical interferometers & LISA
  - Formation of supermassive black holes (SMBHs)?
  - Electroweak phase transition? Cosmic strings?

# How to Make a Supermassive BH?

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



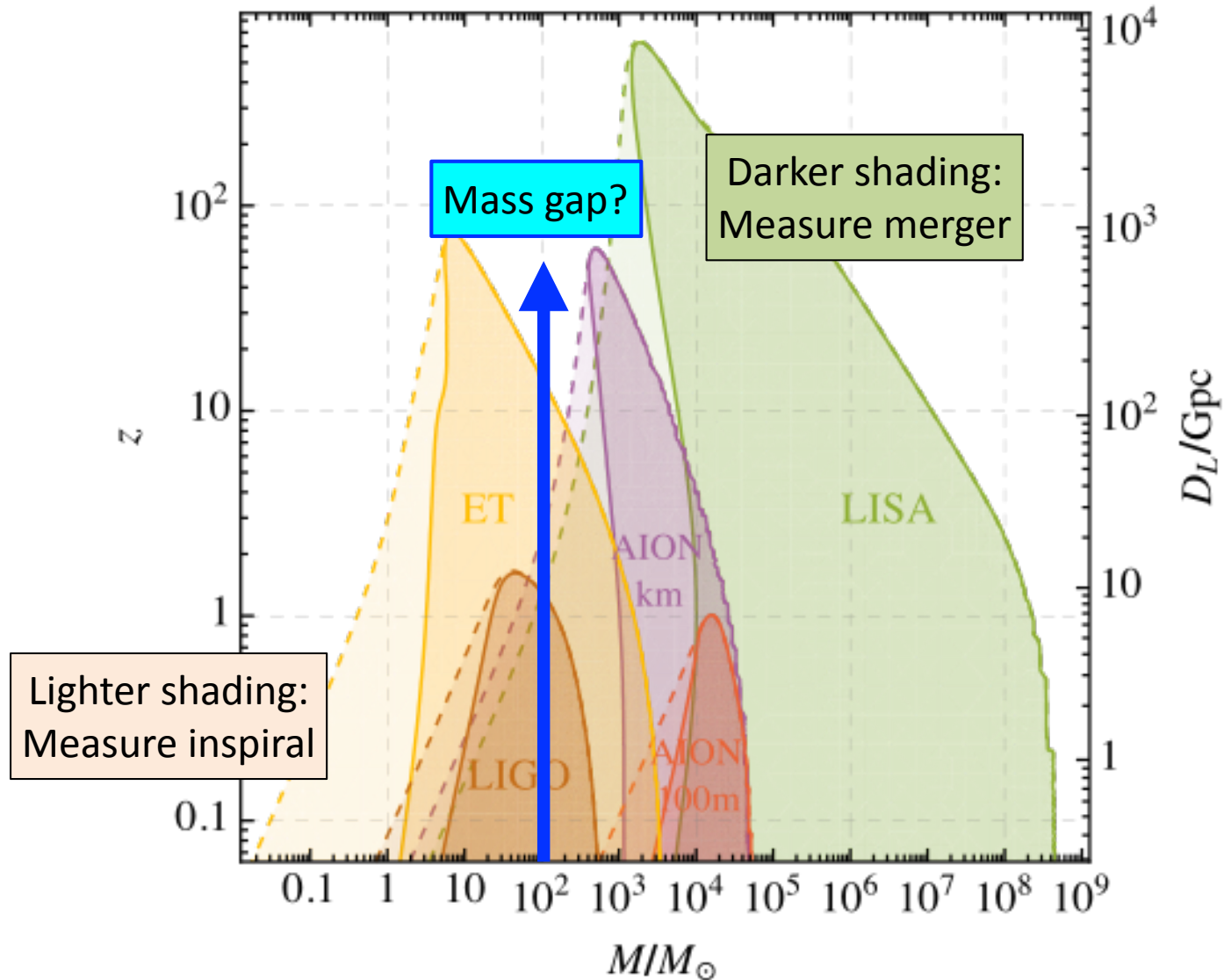
# AEDGE: Gravitational Waves from IMBH Mergers



Probe formation of SMBHs

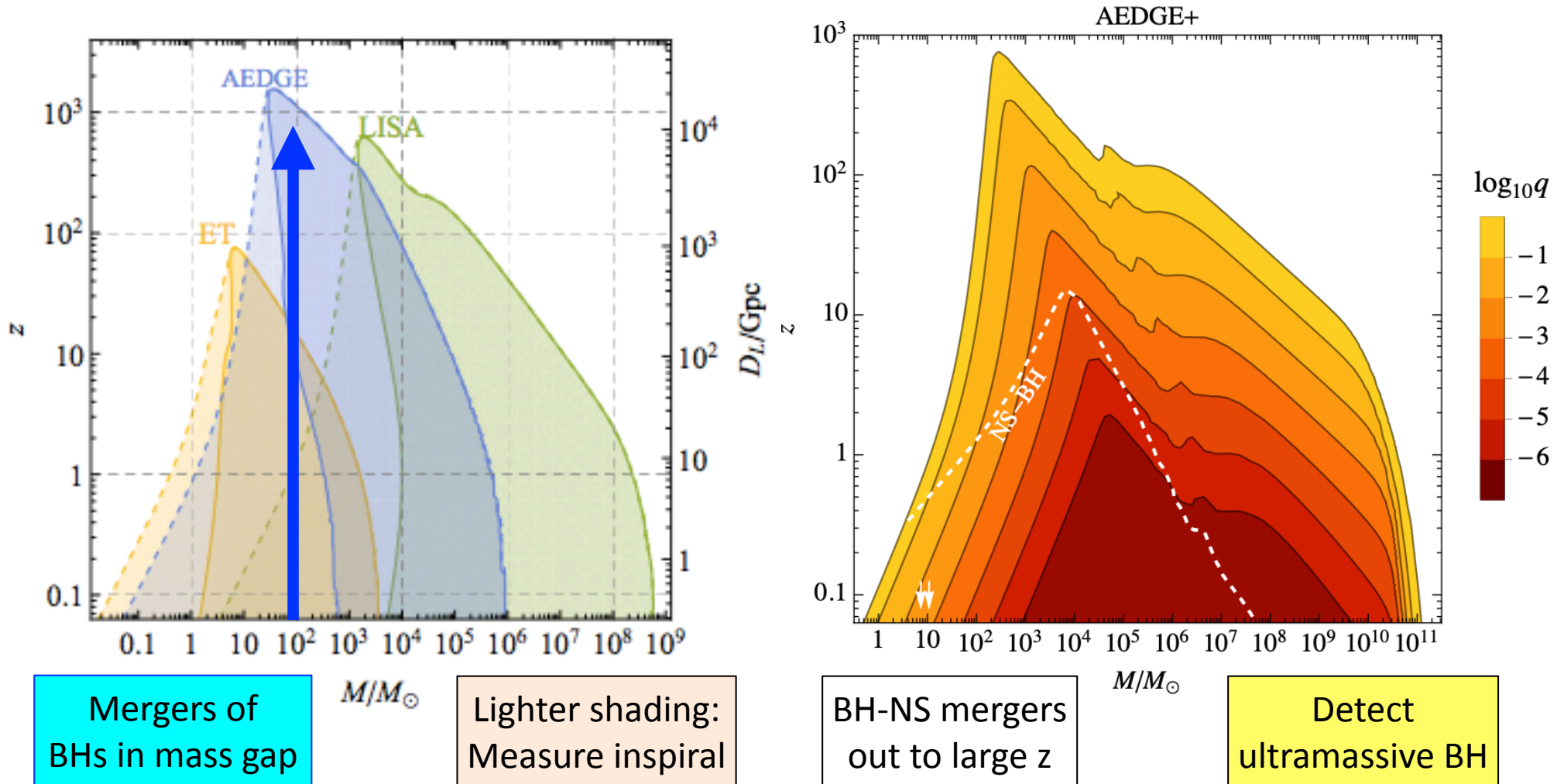
Synergies with other GW experiments (LIGO, LISA), test GR

# AEDGE: GWs from IMBH Mergers



AION complementary to LIGO, Einstein Telescope (ET)  
Operation before LISA

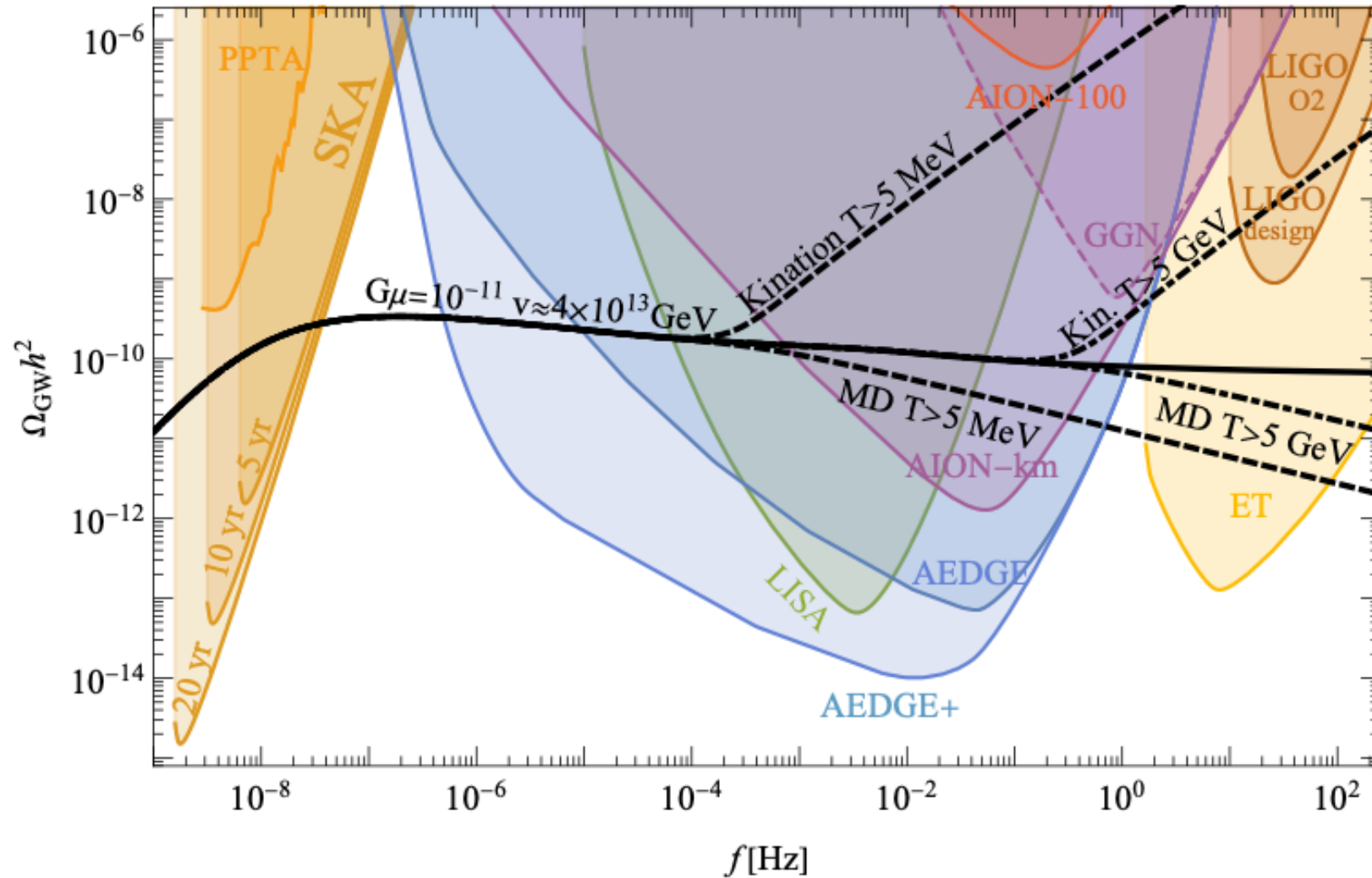
# AEDGE: GWs from IMBH, BH-NS Mergers



AEDGE complementary to LIGO, LISA, Einstein Telescope (ET)

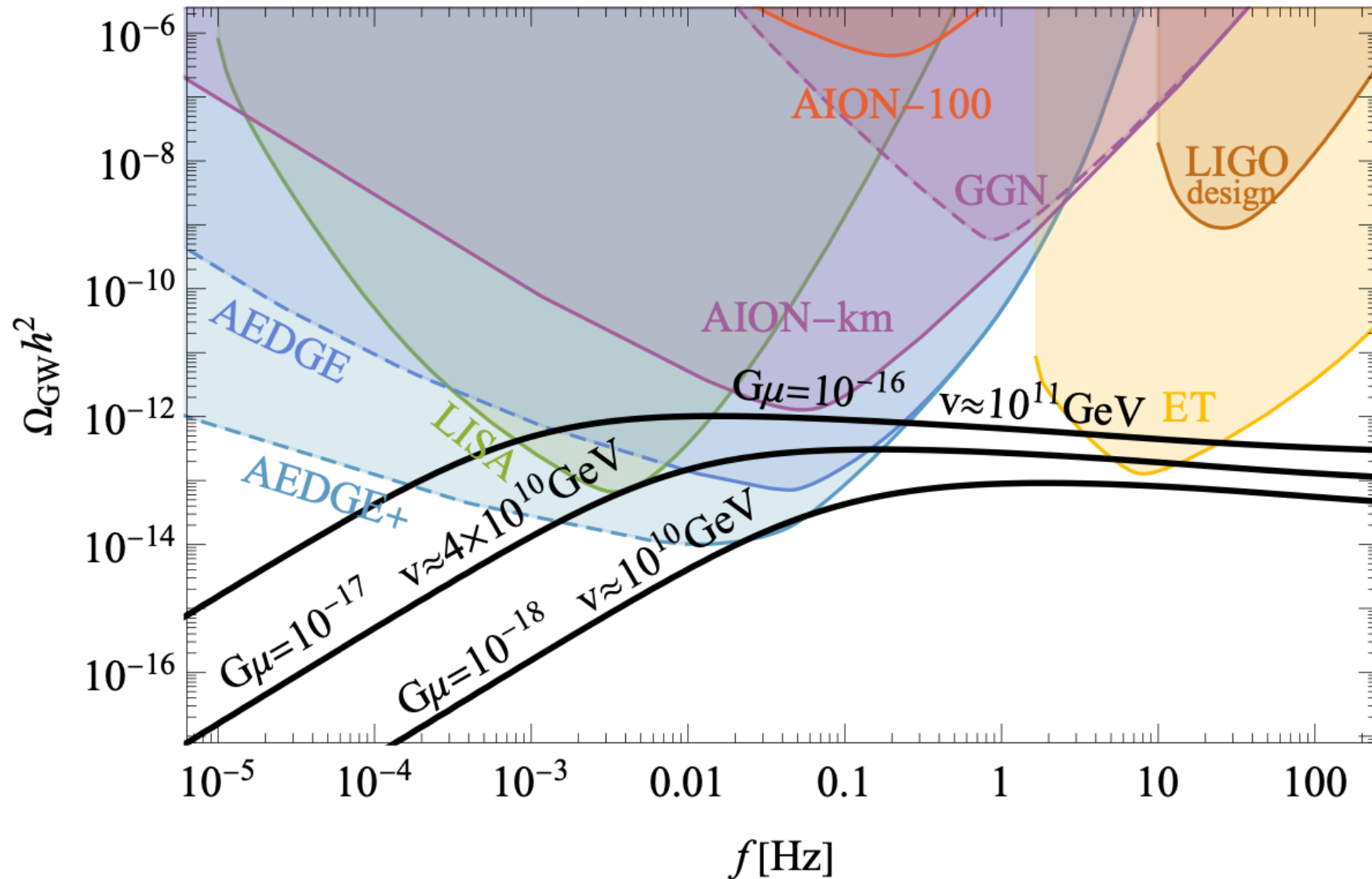


# AEDGE: Gravitational Waves from Cosmic Strings



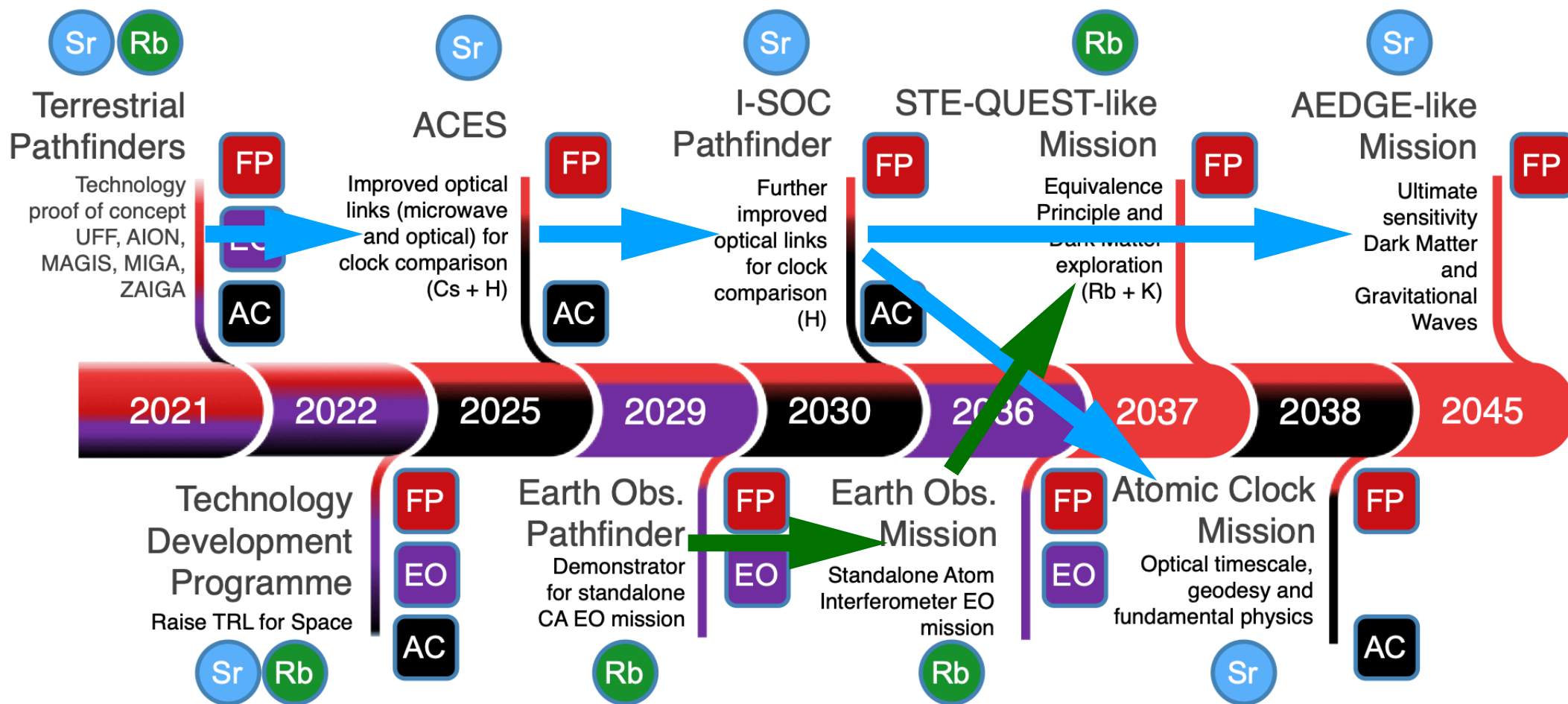
Spectrum  $\sim$  flat from PTA/SKA to LIGO/ET  
 Tension  $G\mu < 10^{-11}$  from PTA limit

# AEDGE: Gravitational Waves from Cosmic Strings



Different experiments sensitive to different values of cosmic string tension

# Community Proposal for ESA Road-Map for Cold Atoms in Space



Main Cold Atom Species



Areas of Relevance



Main Milestone Area (colour coded)



# Towards the Definition of an Earth Observation (Pathfinder) Mission

- The EU has committed itself to a pathfinder EO mission in collaboration with ESA
- What should be its objectives?
- What should be the long-term satellite EO objectives
- Wishlist?
  - What sensitivity on what time-scale, with what spatial resolution?
  - C/should it be sensitive to moisture, biomass, infrastructure, ...?