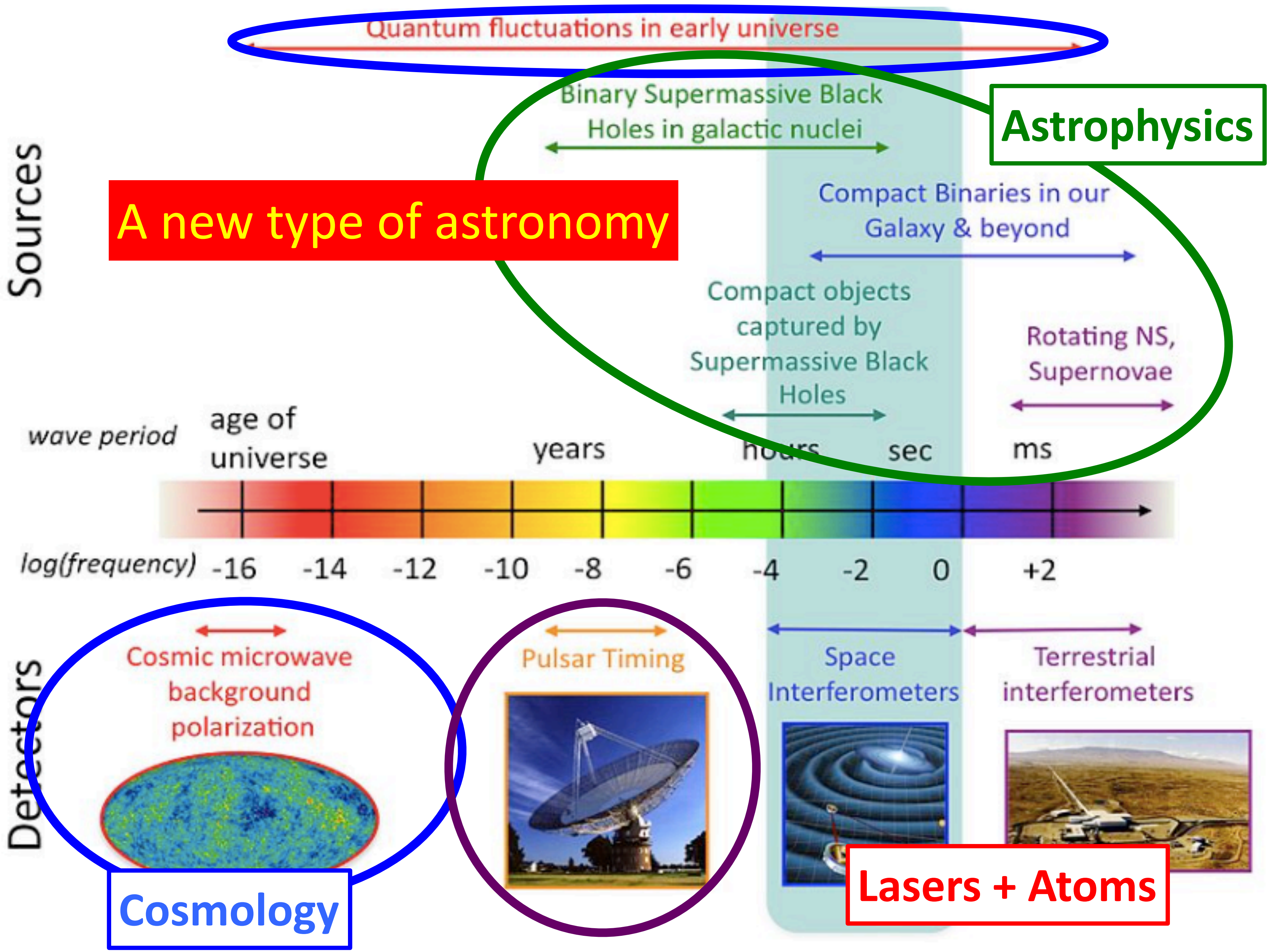
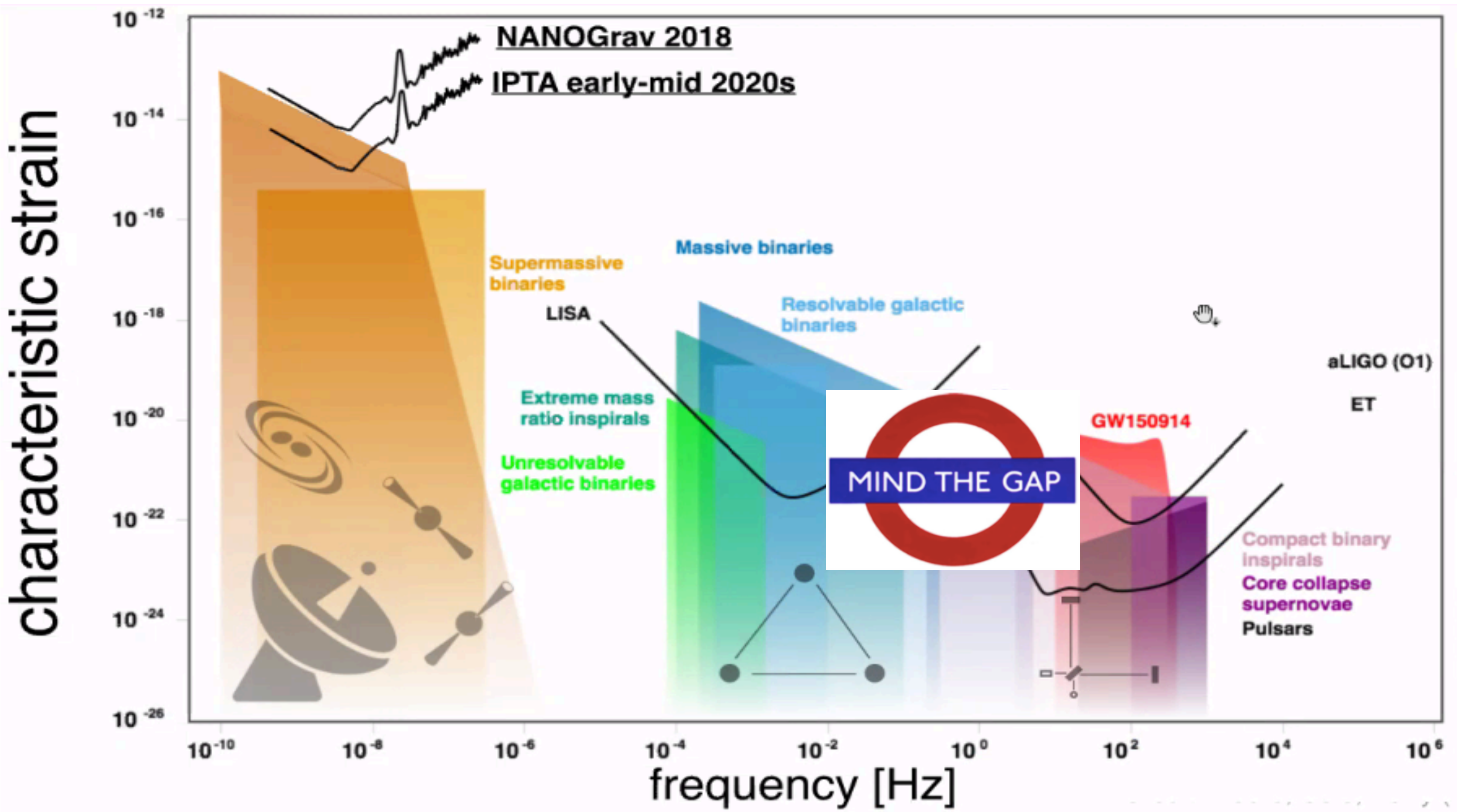
Gravitational Wave Spectrum

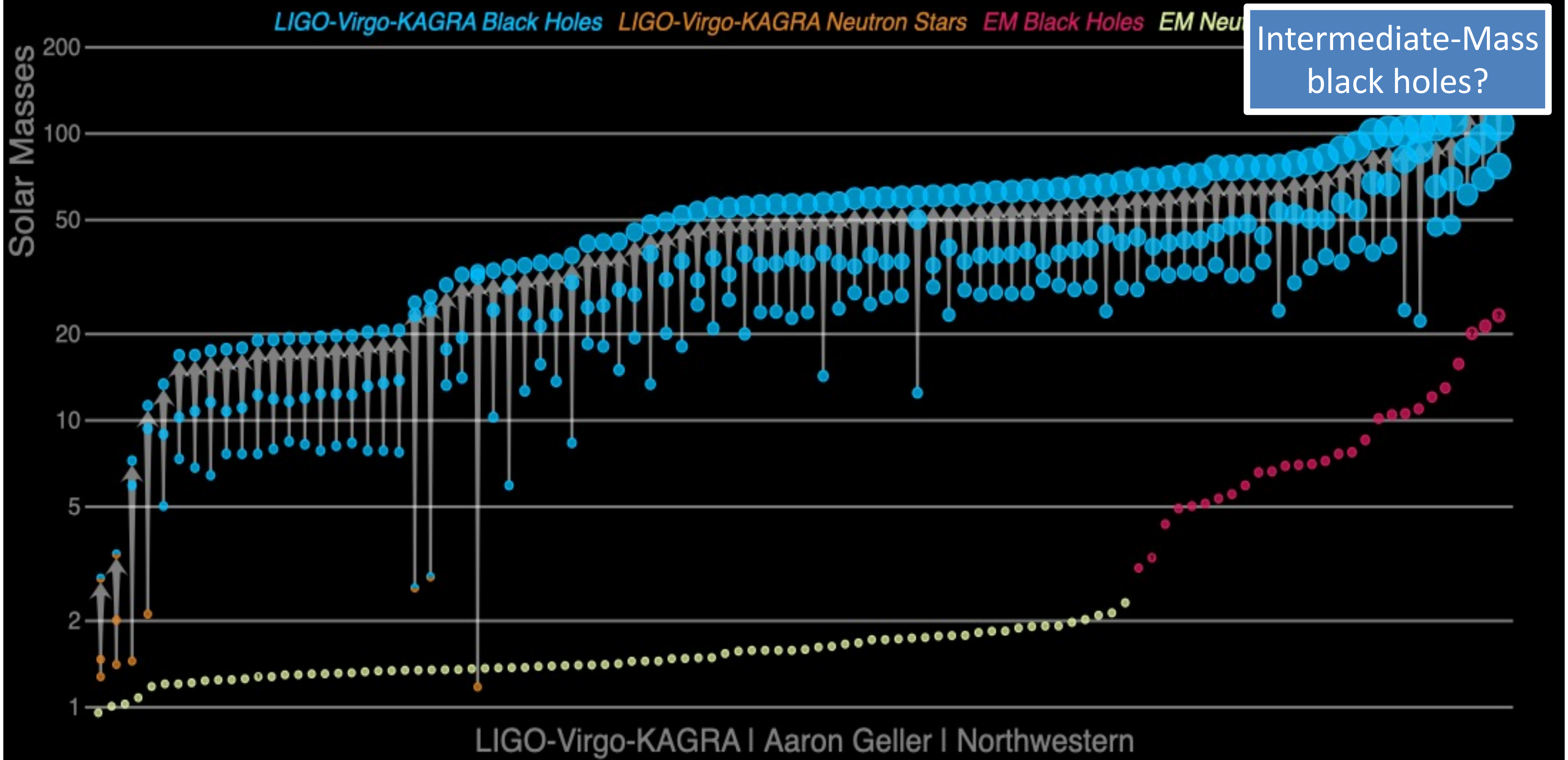


Gravitational Wave Spectrum

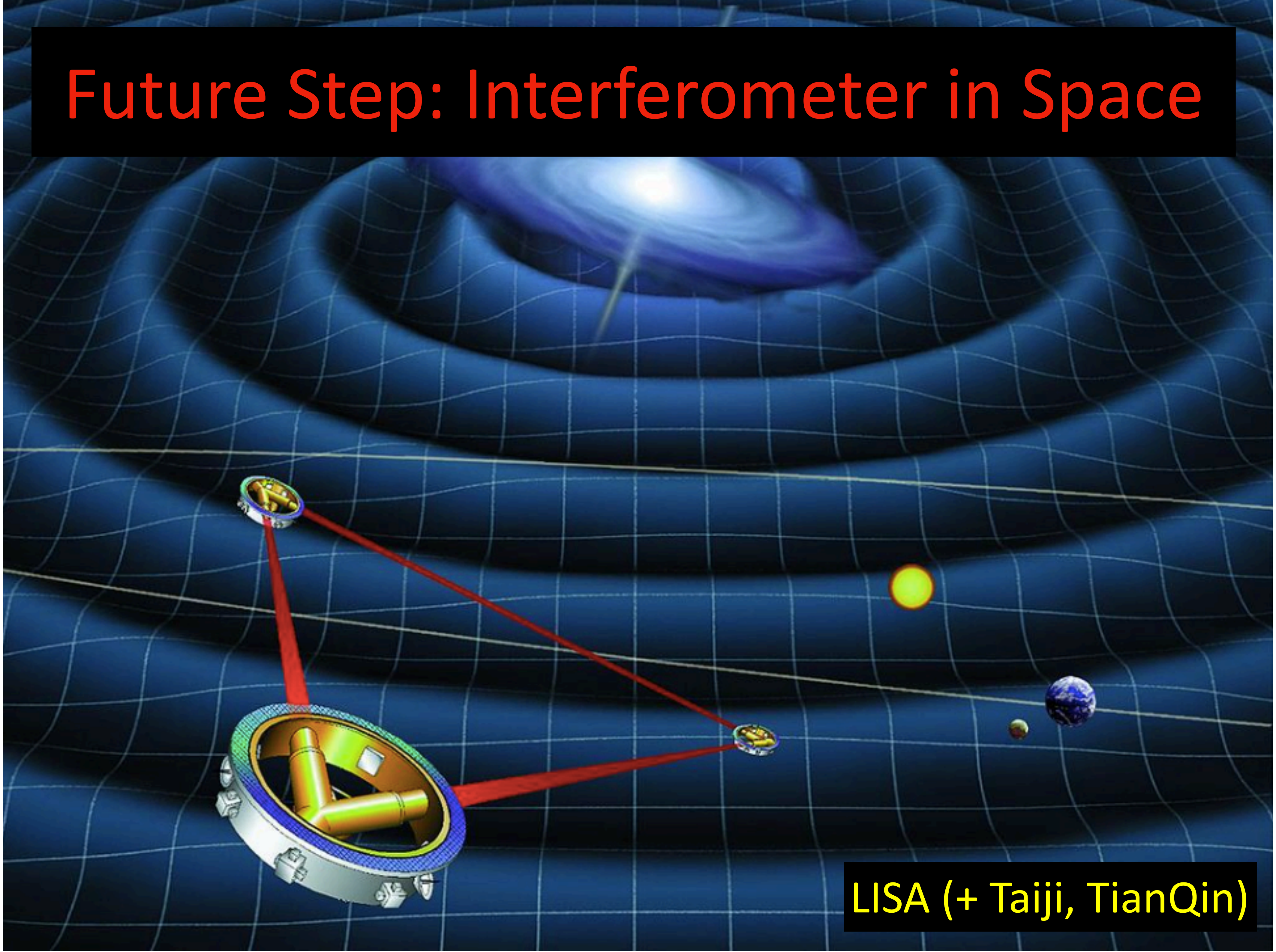


- Gap between ground-based optical interferometers & LISA
  - Formation of supermassive black holes (SMBHs)?
  - Electroweak phase transition? Cosmic strings?
- Gap between LISA & pulsar timing arrays (PTAs)

LIGO-Virgo-KAGRA Black Hole & Neutron Star Masses



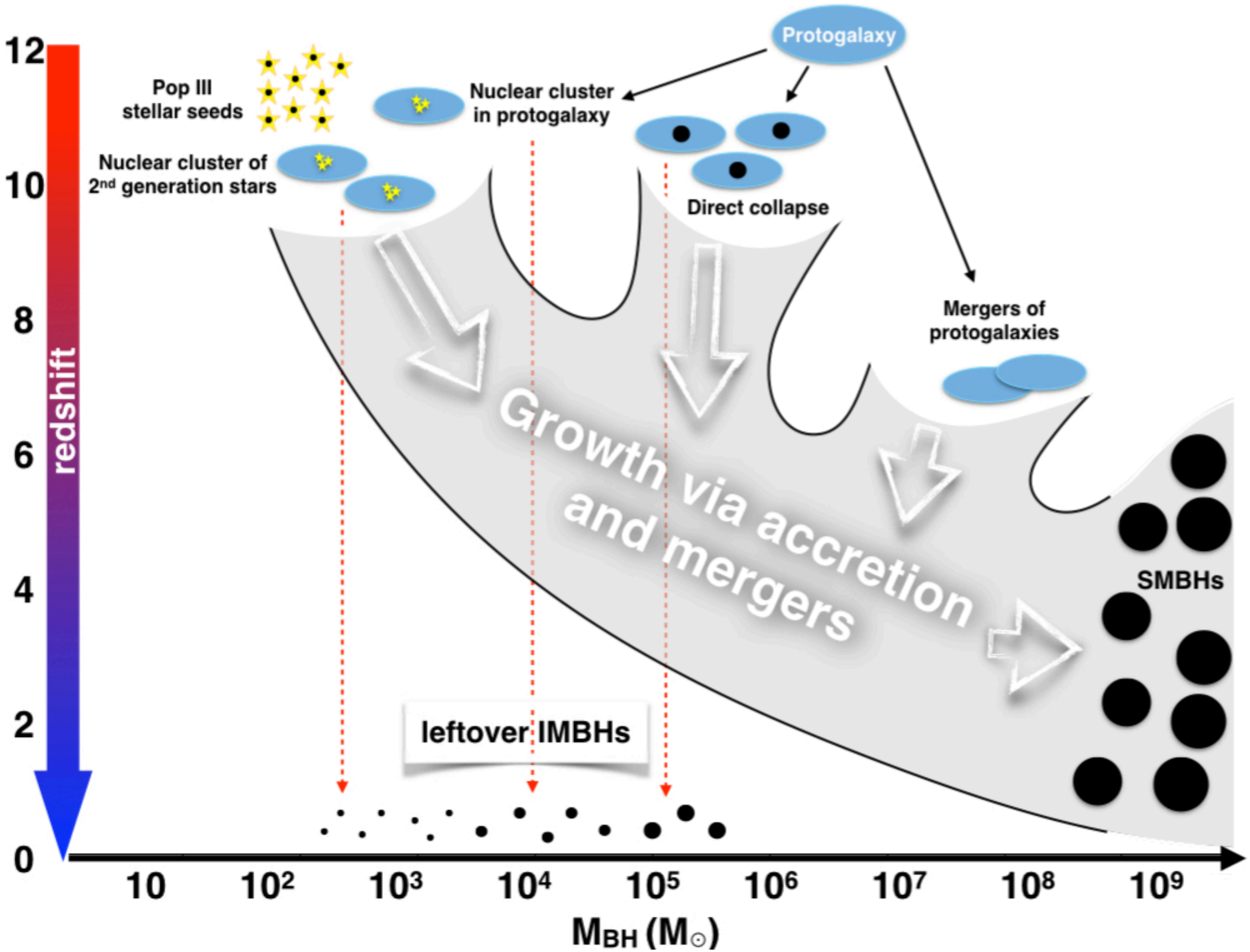
Future Step: Interferometer in Space



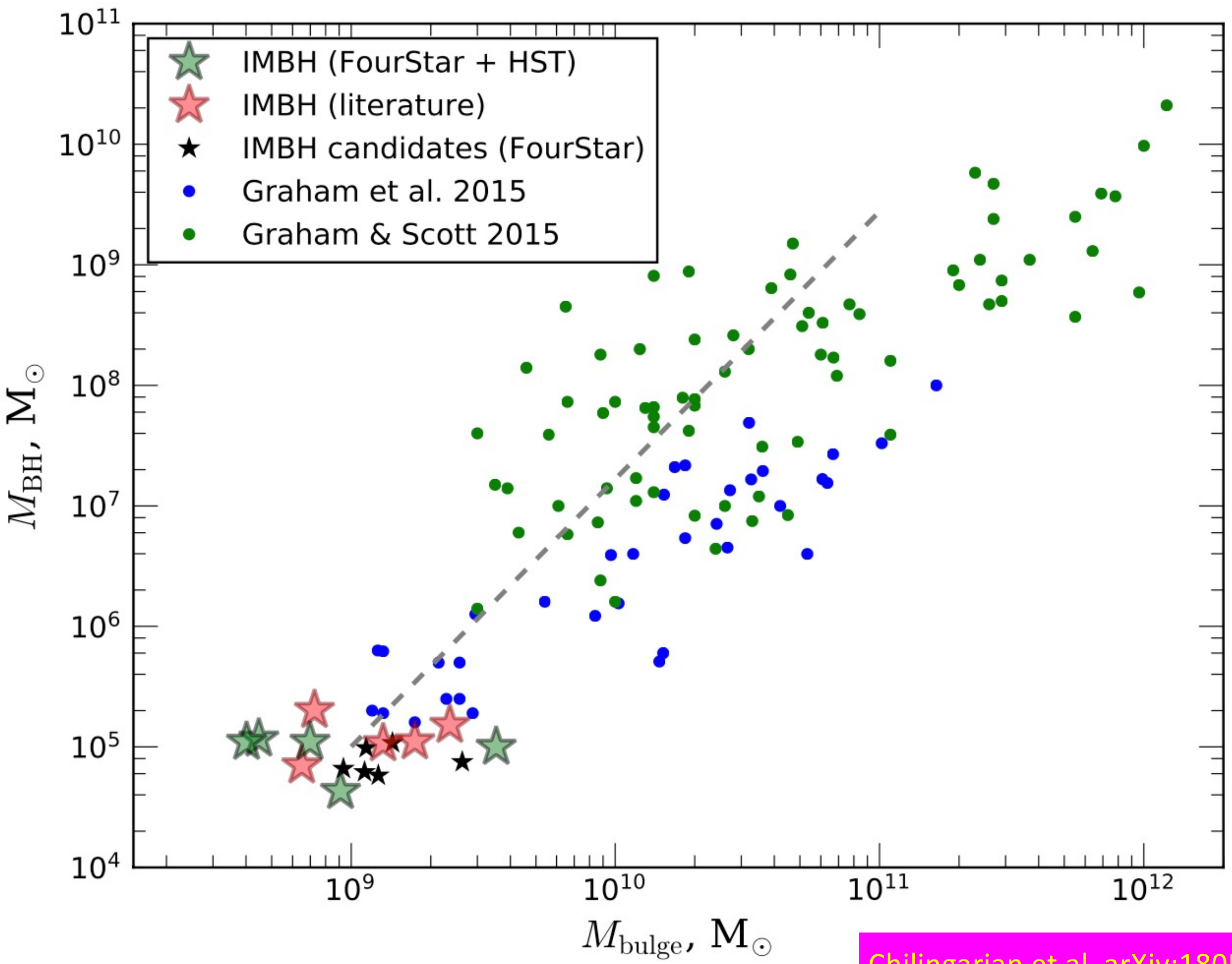
LISA (+ Taiji, TianQin)

How to Make a Supermassive BH?

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

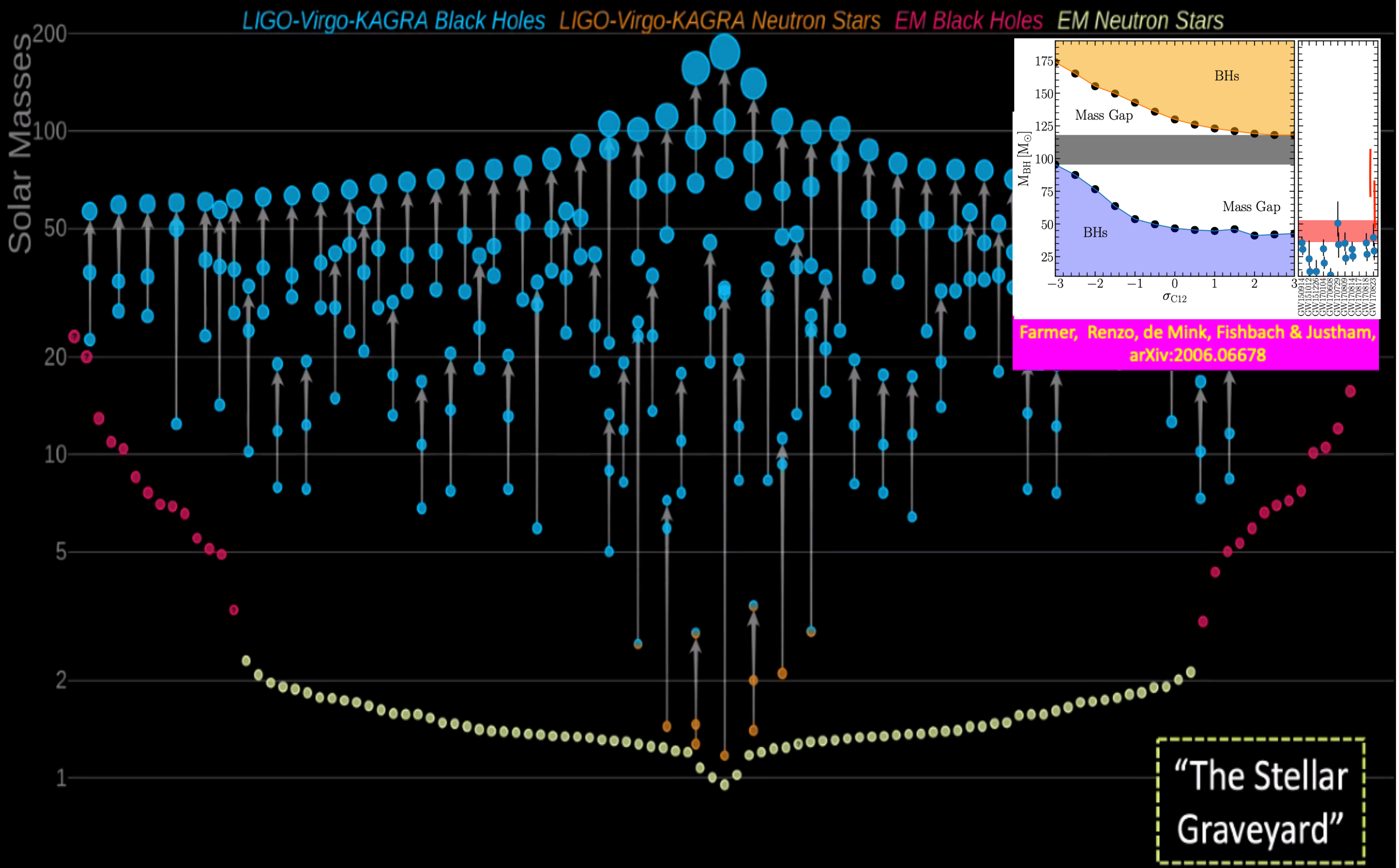


Intermediate Mass Black Holes
Identified as Low-Luminosity Active Galactic Nuclei



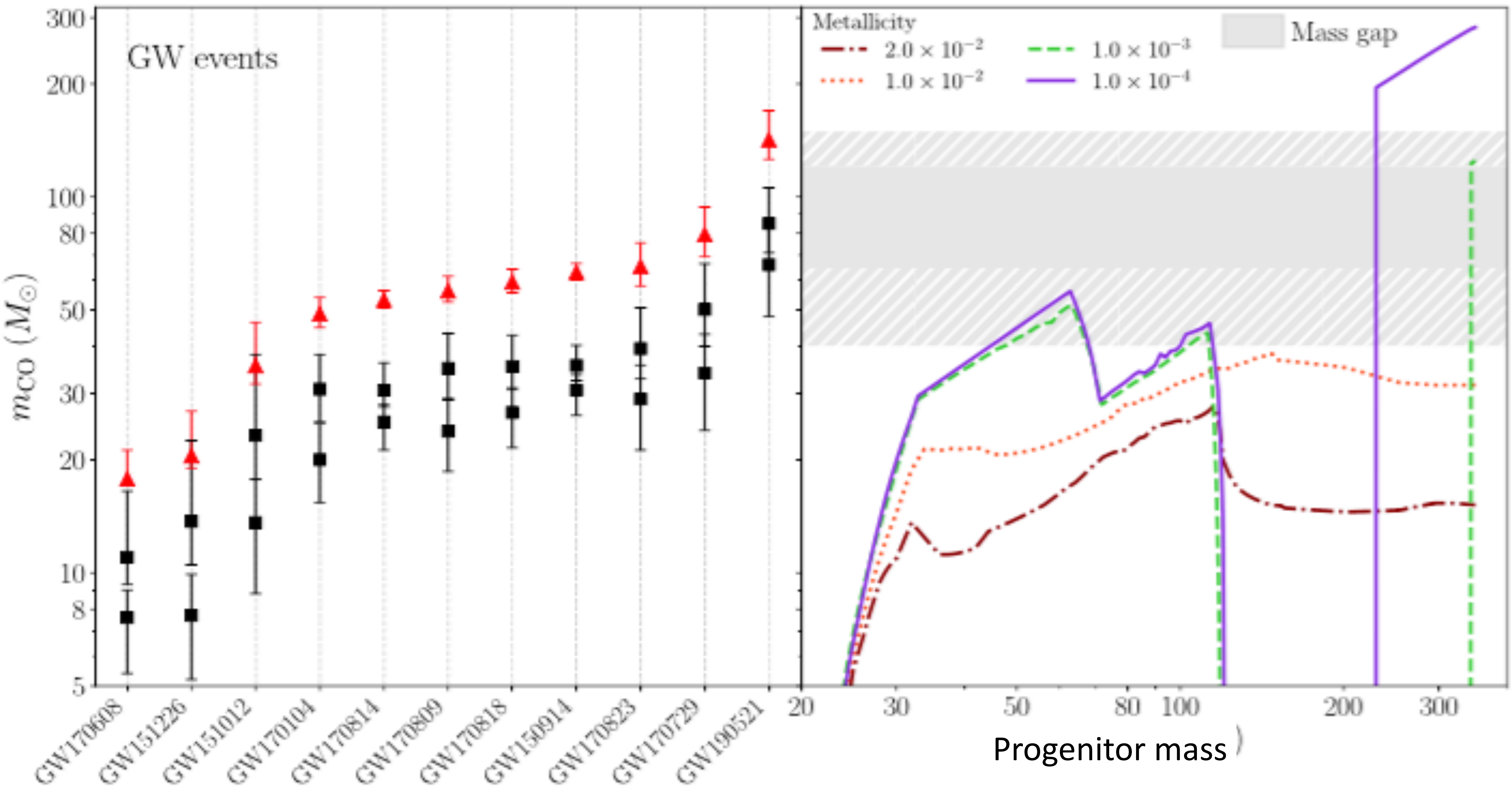
Chilingarian et al, arXiv:1805.01467

LIGO-Virgo-KAGRA Black Hole & Neutron Stars



LIGO & Virgo Collaborations: arXiv:2009.01075, 2009.01190

Predicted Mass Gap



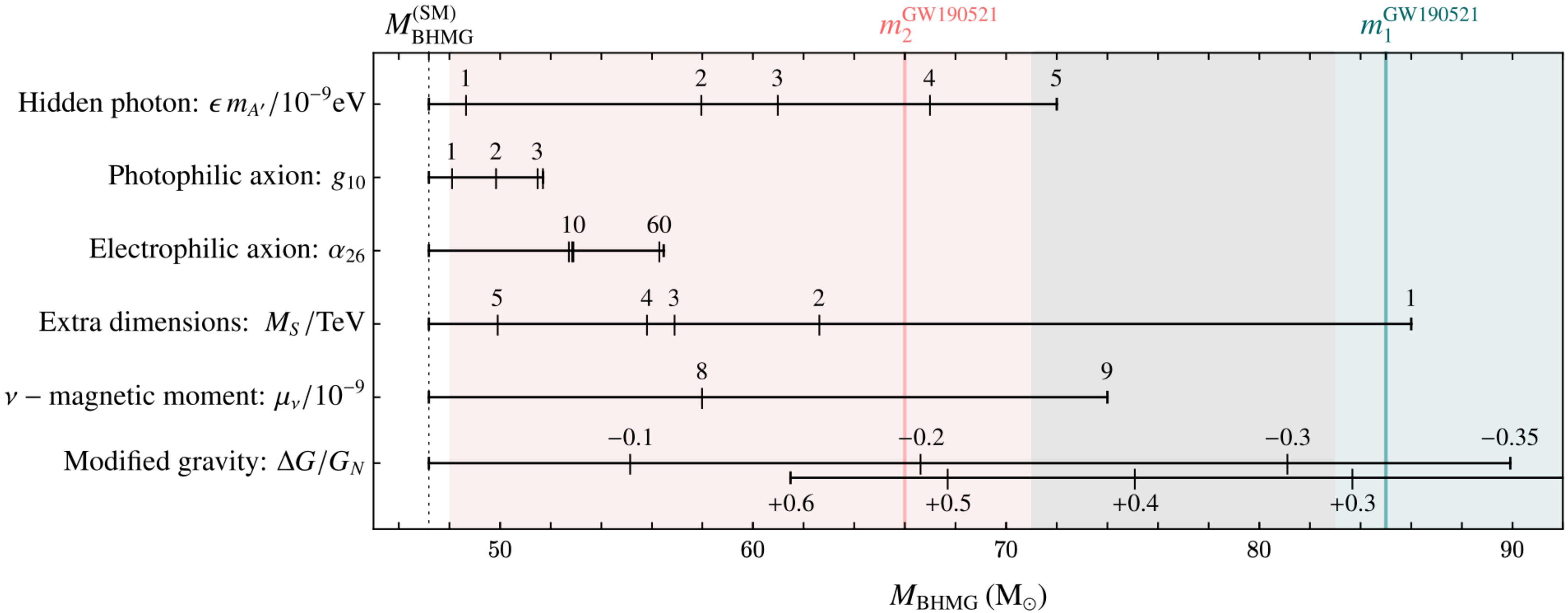
Standard stellar evolution ➔ no black holes between ~70, 120 solar masses

Previous mergers? Primordial black holes? BSM physics to fill in mass gap?

Sakstein, Croon, McDermott, Straight & Baxter, arXiv:2009.01213

Can New Physics Fill the Mass Gap?

- Mass gap due to pair-production instability: $\gamma\gamma \rightarrow e^+e^-$
- Could be (partially) filled in by new physics, BUT …



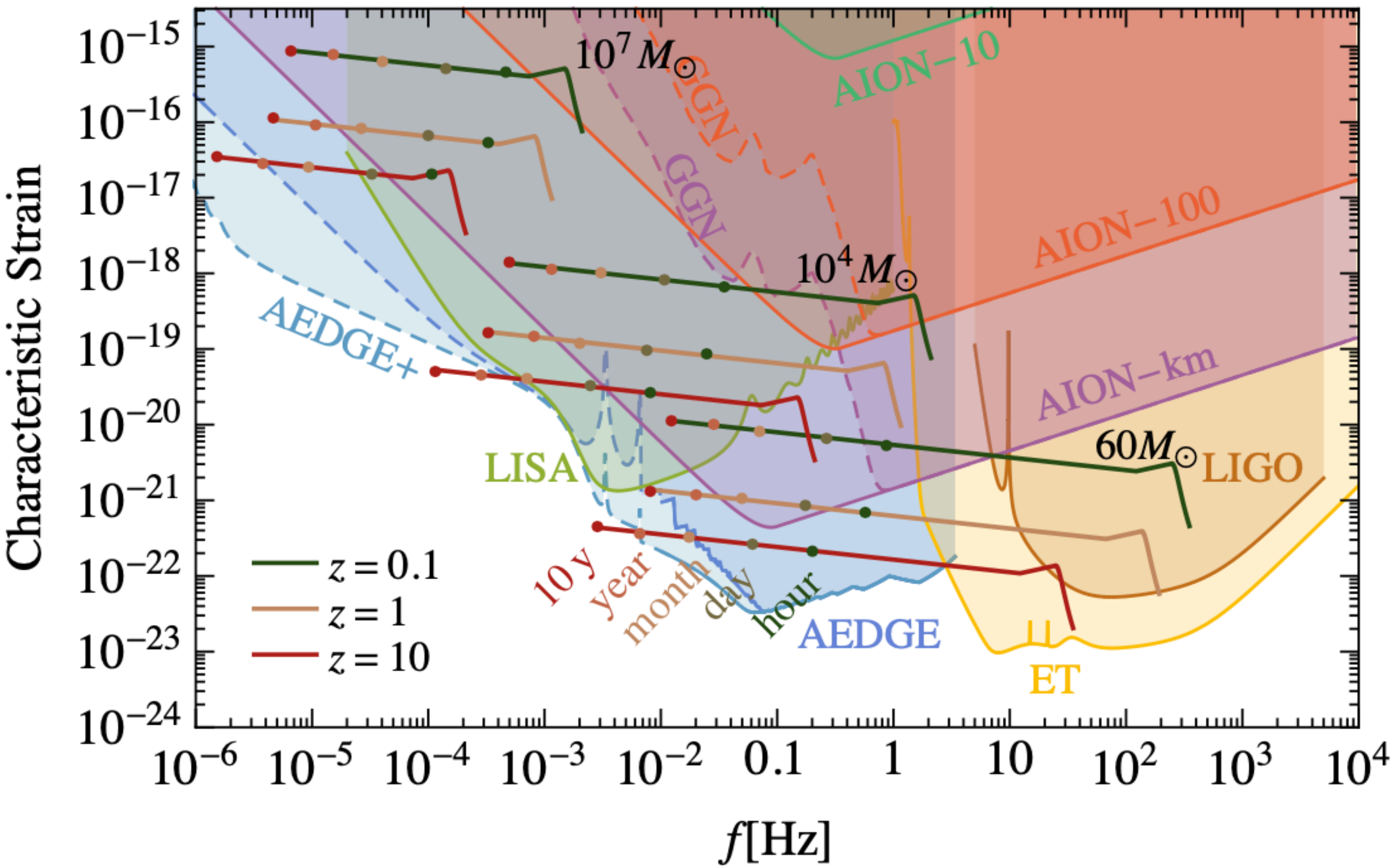
- Location of mass gap subject to nuclear physics uncertainty in the $^{12}C(\alpha,\gamma)^{16}O$ rate, rotation, …

Woosley & Heger, arXiv:2103.07933

- Gap could have been populated by previous mergers

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

Gravitational Waves from IMBH Mergers



Probe formation of SMBHs

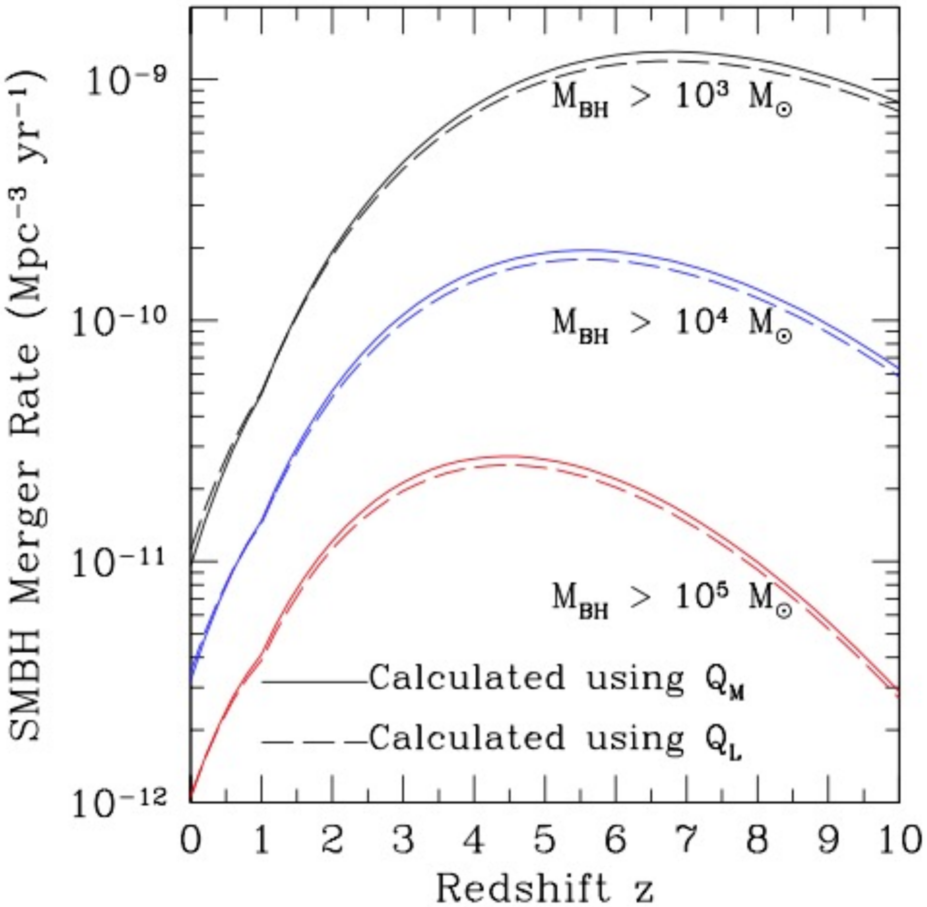
Synergies with other GW experiments (LIGO, LISA), test GR

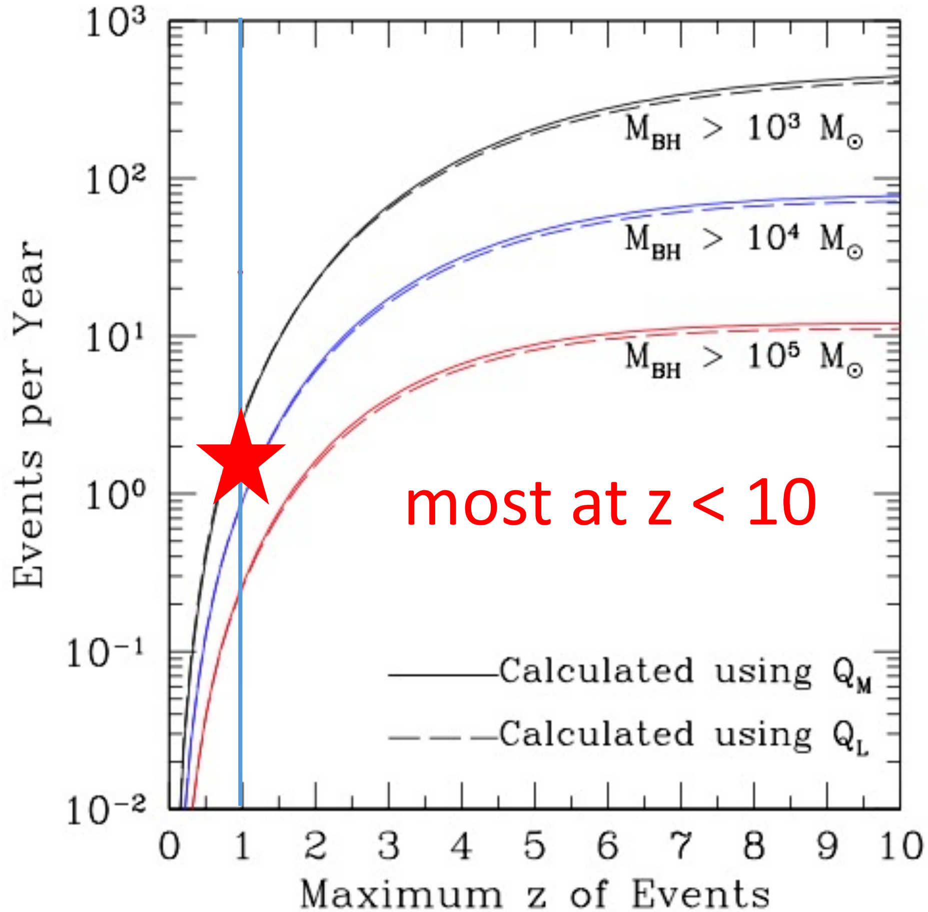
Badurina, Buchmueller, JE, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

How to Make a Supermassive BH?

Mergers of intermediate-mass BHs (IMBHs)?

Estimated merger rates:



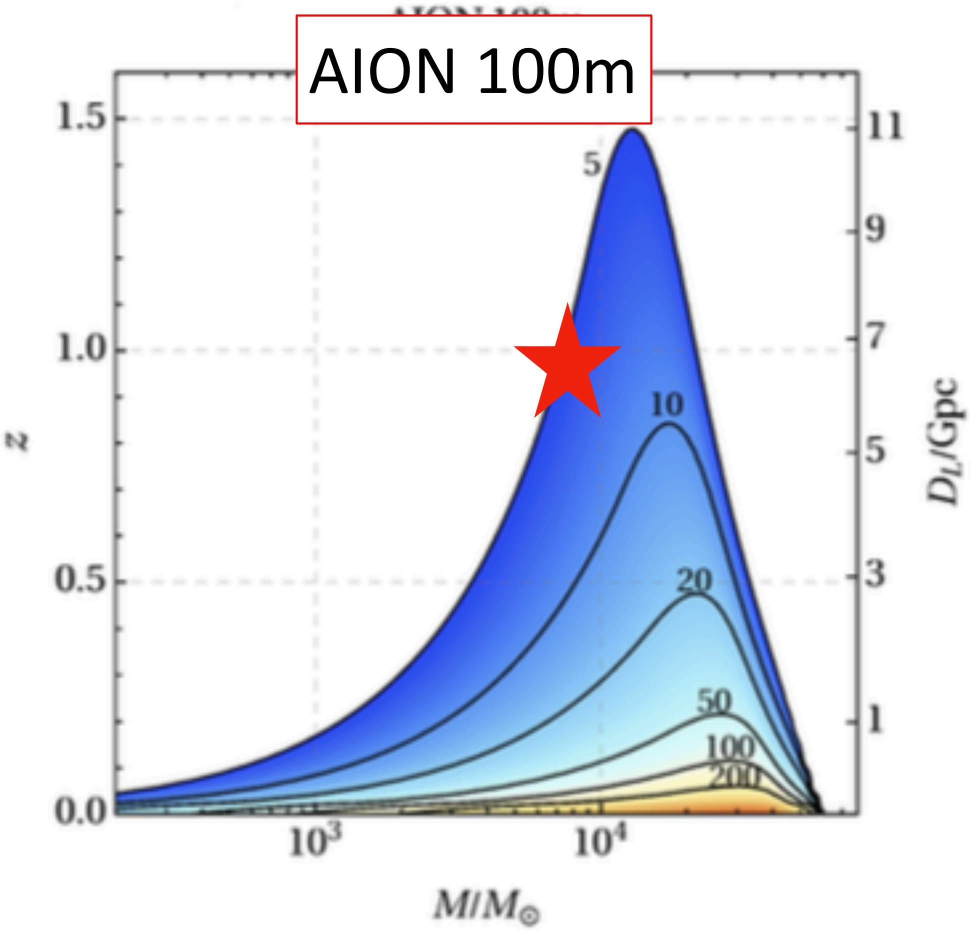


Erickcek, Kamionkowski & Benson, astro- ph/0604281

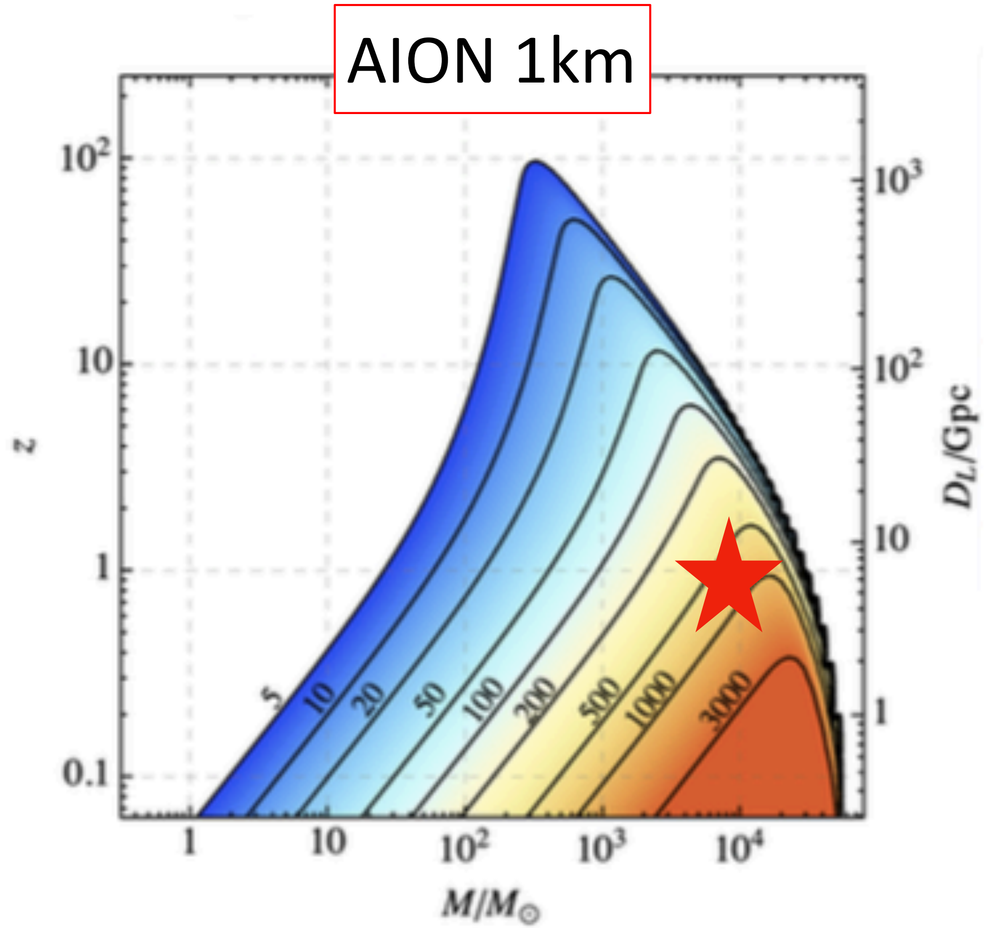
AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755

AION GW SNR from IMBH Mergers

Map assembly of SMBHs



SNR > 5 out to z > 1
for masses ~ 10^4 solar

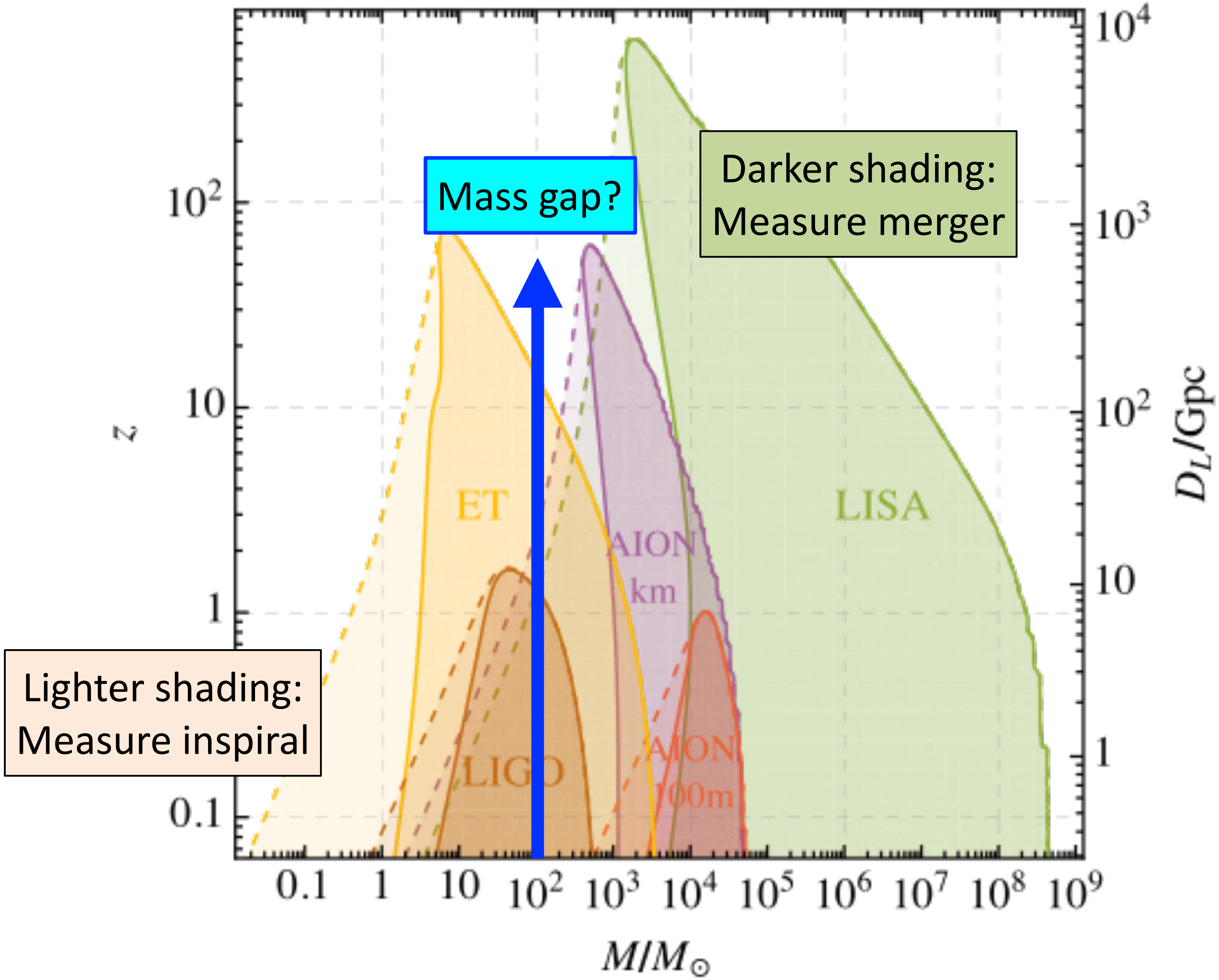


SNR > 10 out to z ~ 10
for masses ~ 10^3 solar

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

GWs from IMBH Mergers: SNR = 8

AION



AION complementary to LIGO, Einstein Telescope (ET)

Operation before LISA

Gravitational Memory

- GR predicts that the passage of matter or radiation from an asymmetrically-emitting source causes a permanent change in the local space-time metric - the Gravitational Memory effect

$$h_{\mu\nu}(\mathbf{x},t) = 4G\int d^3\mathbf{x}' \left(\frac{S_{\mu\nu}(\mathbf{x}', t - |\mathbf{x}-\mathbf{x}'|)}{|\mathbf{x}-\mathbf{x}'|} \right)$$

Zel'dovich & Polnarev, 1974
Braginskii & Thorne, 1987

- Sourced, e.g., by SN neutrinos

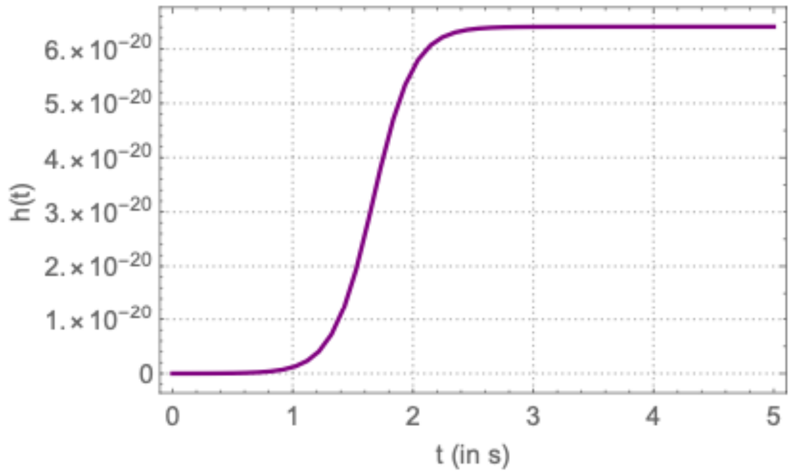
$$h(t) = \frac{2G}{r}\int_{-\infty}^{t-r} dt' L_\nu(t')\alpha(t')$$

Epstein, 1978

- Where $L_\nu(t)$ is neutrino luminosity,

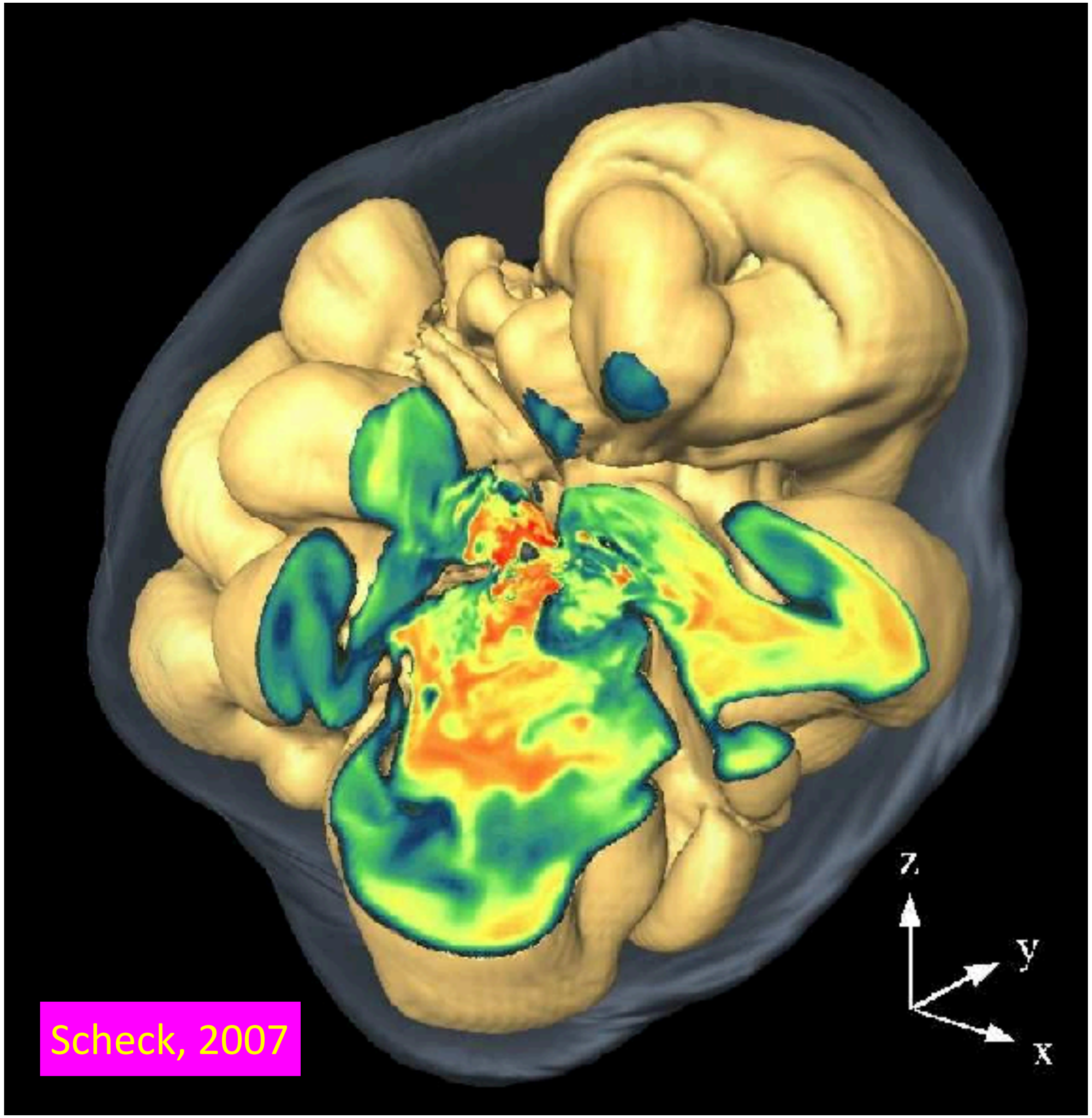
  $\alpha(t)$ its anisotropy

- Sketch of typical strain profile
- NB: also nonlinear memory from GWs



Anisotropic Supernova Explosions

- Three-dimensional simulations of supernovae typically exhibit anisotropies
- Anisotropy of neutrino emissions is supported by high velocities of supernova remnants



Supernova Neutrino Emission

- Neutrino luminosity:

typical duration of

accretion phase $\mathcal{O}(1)$ sec

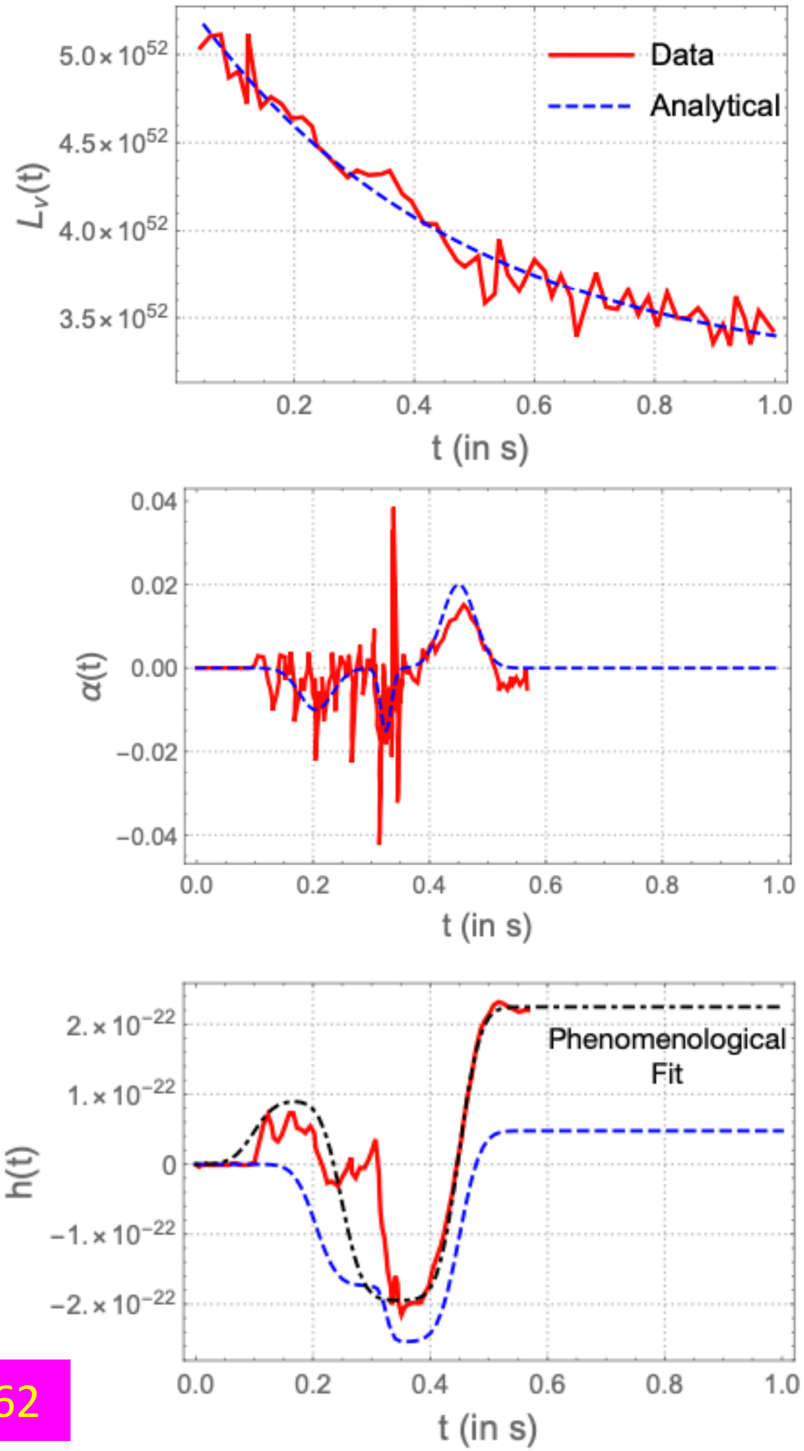
- Anisotropy of neutrino emissions:

fluctuating, % level,

typical duration $\mathcal{O}(0.5)$ sec

- Gives order-of-magnitude estimate

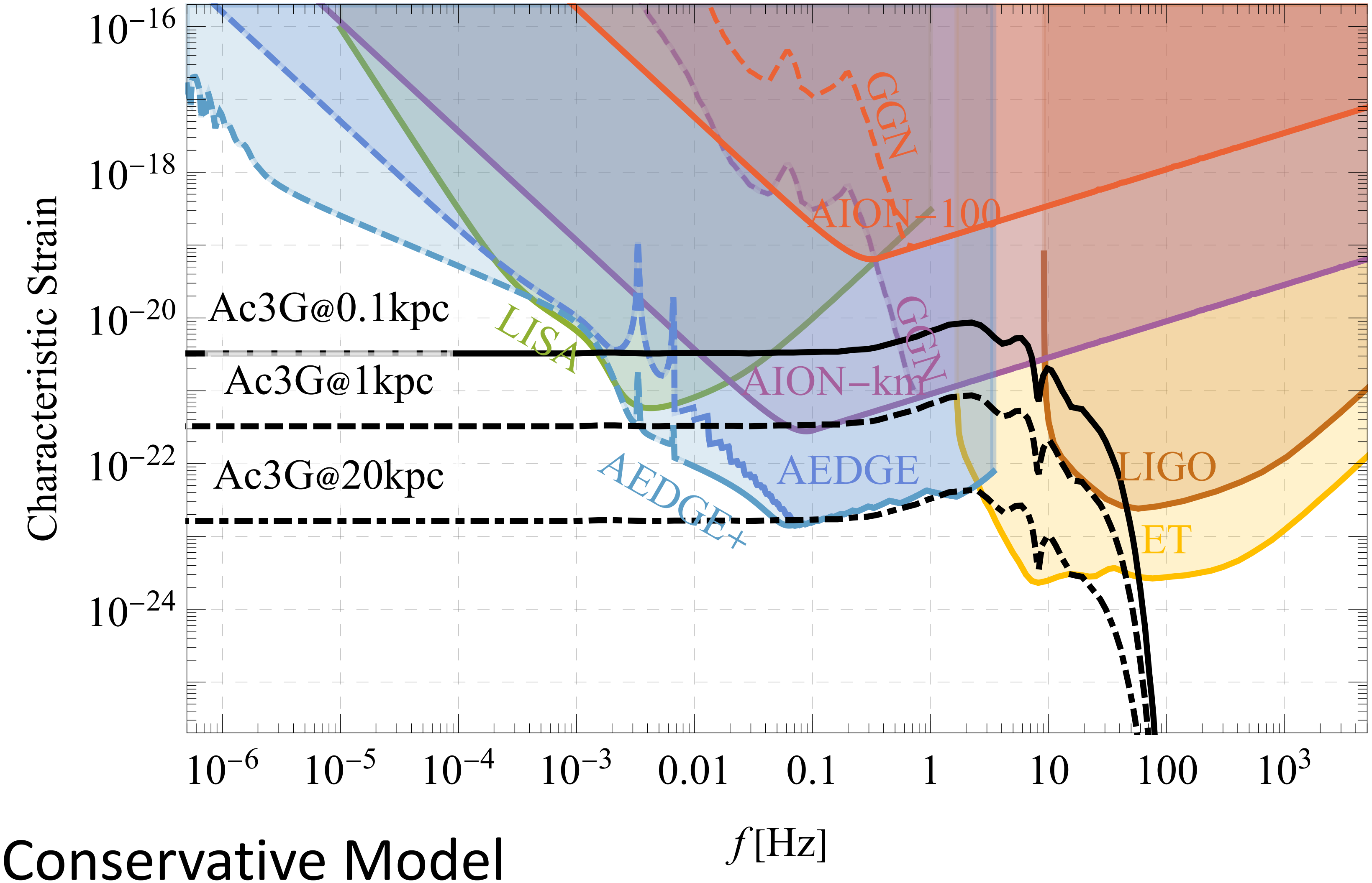
of frequency support $\mathcal{O}(1)$ Hz



Mukhopadhyay, Cardona & Lunardini, arXiv:2105.05862

AION/AEDGE Sensitivities to Gravitational Memory of Supernova Neutrinos

AION



Conservative Model

Sensitivity to SN within the Milky Way

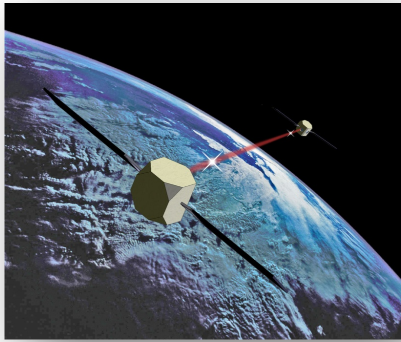
Badurina, Buchmueller, JE, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

And then?

AEDGE:
Atomic Experiment for Dark Matter and Gravity Exploration in Space

Beyond LISA

Yousef Abou El-Neaj,[1] Cristiano Alpigiani,[2] Sana Amairi-Pyka,[3] Henrique Araújo,[4] Antun Balaž,[5] Angelo Bassi,[6] Lars Bathe-Peters,[7] Baptiste Battelier,[8] Aleksandar Belić,[5] Elliot Bentine,[9] José Bernabeu,[10] Andrea Bertoldi,[8,*] Robert Bingham,[11] Diego Blas,[12] Vasiliki Bolpasi,[13] Kai Bongs,[14,*] Sougato Bose,[15] Philippe Bouyer,[8,*] Themis Bowcock,[16] William Bowden,[17] Oliver Buchmueller,[4,@] Clare Burrage,[18] Xavier Calmet,[19] Benjamin Canuel,[8,*] Laurentiu-Ioan Caramete,[20,*] Andrew Carroll,[16] Giancarlo Cella,[21,22] Vassilis Charmandaris,[23] Swapan Chattopadhyay,[24,25] Xuzong Chen,[26] Maria Luisa Chiofalo,[21,22] Jonathon Coleman,[16,*] Joseph Cotter,[4] Yanou Cui,[27] Andrei Derevianko,[28] Albert De Roeck,[29,30,*] Goran Djordjevic,[31] Peter Dornan,[4] Michael Doser,[30] Ioannis Drougkakis,[13] Jacob Dunningham,[19] Ioana Dutan,[20] Sajan Easo,[11] Gedminas Elertas,[16] John Ellis,[12,32,33,*] Mai El Sawy,[34] Farida Fassi,[35] Daniel Felea,[20] Chen-Hao Feng,[8] Robert Flack,[15] Chris Foot,[9] Ivette Fuentes,[18] Naceur Gaaloul,[36] Alexandre Gauguet,[37] Remi Geiger,[38] Valerie Gibson,[39] Gian Giudice,[33] Jon Goldwin,[14] Oleg Grachov,[40] Peter W. Graham,[41,*] Dario Grasso,[21,22] Maurits van der Grinten,[11] Mustafa Gündogan,[3] Martin G. Haehnelt,[42,*] Tiffany Harte,[39] Aurélien Hees,[38,*] Richard Hobson,[17] Bodil Holst,[43] Jason Hogan,[41,*] Mark Kasevich,[41] Bradley J. Kavanagh,[44] Wolf von Klitzing,[13,*] Tim Kovachy,[45] Benjamin Krikler,[46] Markus Krutzik,[3,*] Marek Lewicki,[12,47,*] Yu-Hung Lien,[15] Miaoyuan Liu,[26] Giuseppe Gaetano Luciano,[48] Alain Magnon,[49] Mohammed Mahmoud,[50] Sarah Malik,[4] Christopher McCabe,[12,*] Jeremiah Mitchell,[24] Julia Pahl,[3] Debapriya Pal,[13] Saurabh Pandey,[13] Dimitris Papazoglou,[51] Mauro Paternostro,[52] Bjoern Penning,[53] Achim Peters,[3,*] Marco Prevedelli,[54] Vishnupriya Puthiya-Veettil,[55] John Quenby,[4] Ernst Rasel,[36,*] Sean Ravenhall,[9] Haifa Rejeb Sfar,[29] Jack Ringwood,[16] Albert Roura,[56,*] Dylan Sabulsky,[8,*] Muhammed Sameed,[57] Ben Sauer,[4] Stefan Alaric Schäffer,[58] Stephan Schiller,[59,*] Vladimir Schkolnik,[3] Dennis Schlippert,[36] Christian Schubert,[3,*] Armin Shayeghi,[60] Ian Shipsey,[9] Carla Signorini,[21,22] Marcelle Soares-Santos,[53] Fiodor Sorrentino,[61,*] Yajpal Singh,[14,*] Timothy Sumner,[4] Konstantinos Tassis,[13] Silvia Tentindo,[62] Guglielmo Maria Tino,[63,64,*] Jonathan N. Tinsley,[63] James Unwin,[65] Tristan Valenzuela,[11] Georgios Vasilakis,[13] Ville Vaskonen,[12,32,*] Christian Vogt,[66] Alex Webber-Date,[16] André Wenzlawski,[67] Patrick Windpassinger,[67] Marian Woltmann,[66] Michael Holynski,[14] Efe Yazgan,[68] Ming-Sheng Zhan,[69,*] Xinhao Zou,[8] Jure Zupan[70]



White paper submitted to ESA Voyage 2050 Call

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

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

Conceptual Design of Space Experiment

Two satellites in Medium Earth Orbit

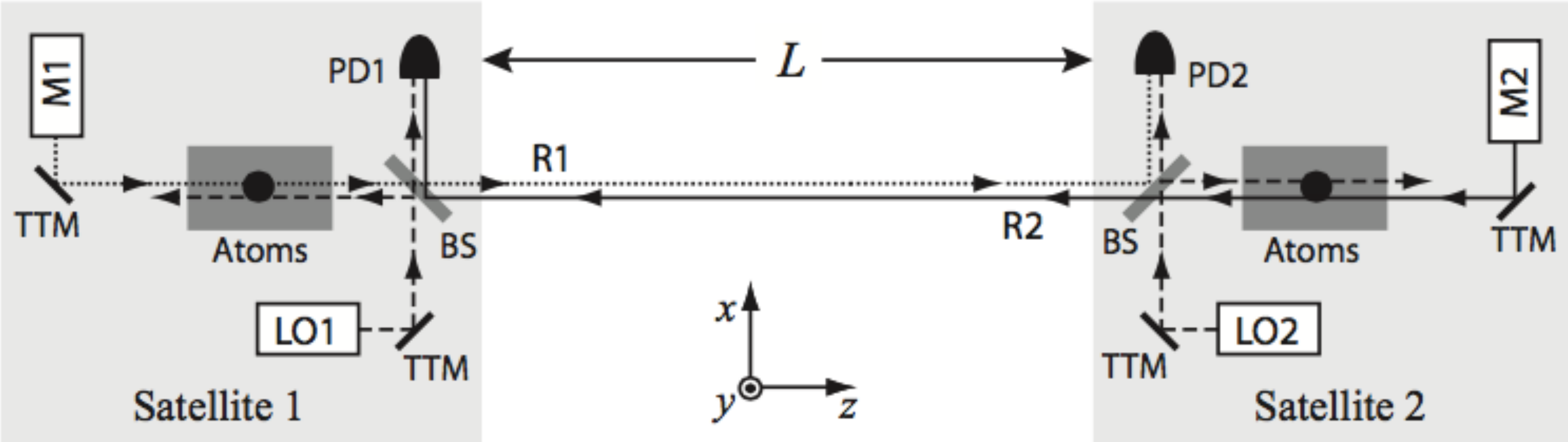


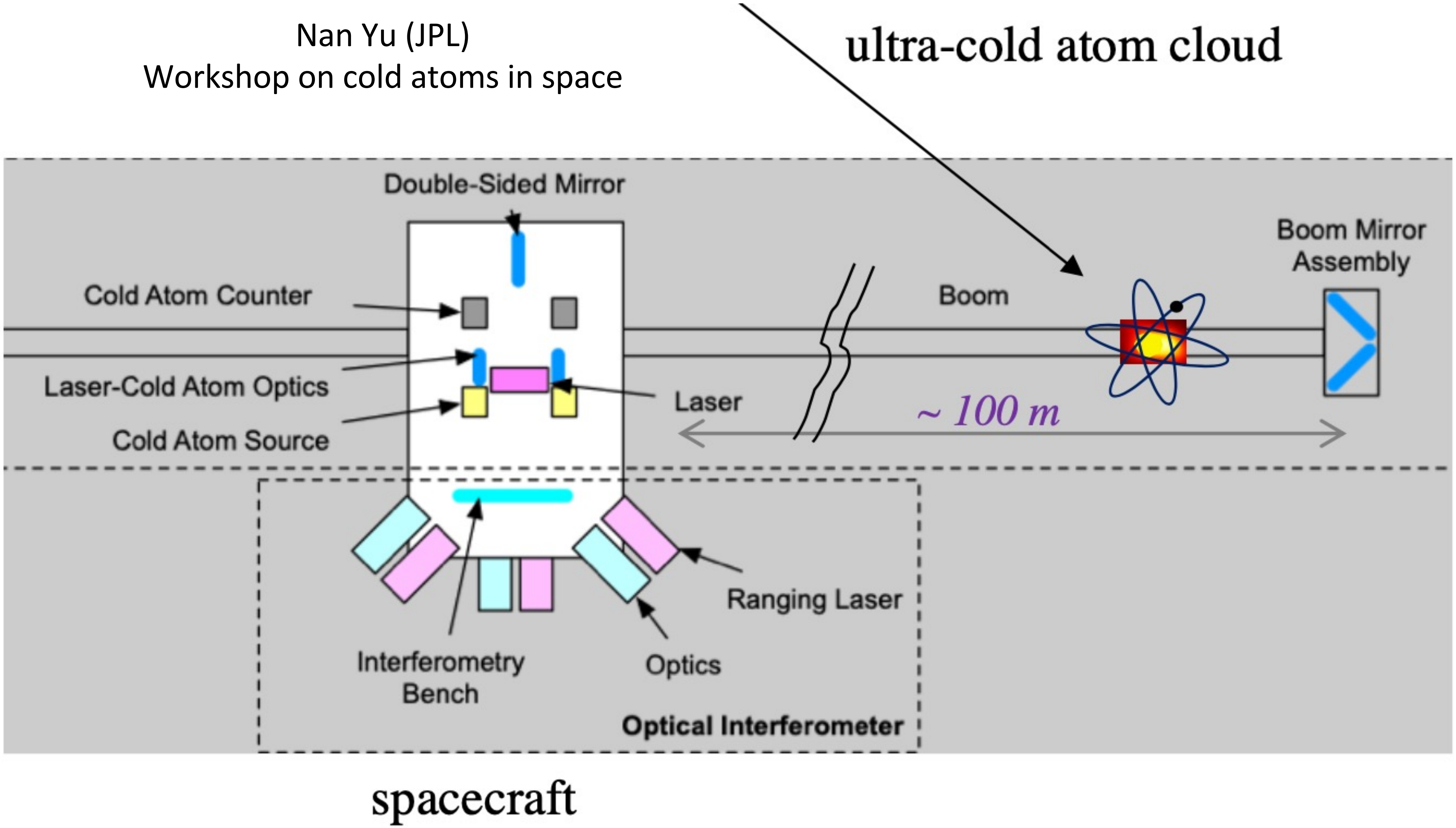
Table 1. List of basic parameters of strontium atom interferometer designs for AEDGE and a benchmark 1-km terrestrial experiment using similar technologies: length of the detector L; interrogation time of the atom interferometer T_{int}; phase noise $\delta\phi_{\text{noise}}$; and the total number of pulses $n_p^{\max}$, where n is the large momentum transfer (LMT) enhancement and Q the resonant enhancement. The choices of these parameters predominately define the sensitivity of the projection scenarios[45].

Sensitivity Scenario	L [m]	T_{int} [sec]	$\delta\phi_{\text{noise}}$ $[1/\sqrt{\text{Hz}}]$	$n_p^{\max} = 2Q(2n-1)+1$ [number]
Earth-km	2000	5	0.3×10^{-5}	40000
AEDGE	4.4×10^7	300	10^{-5}	1000

AEDGE+

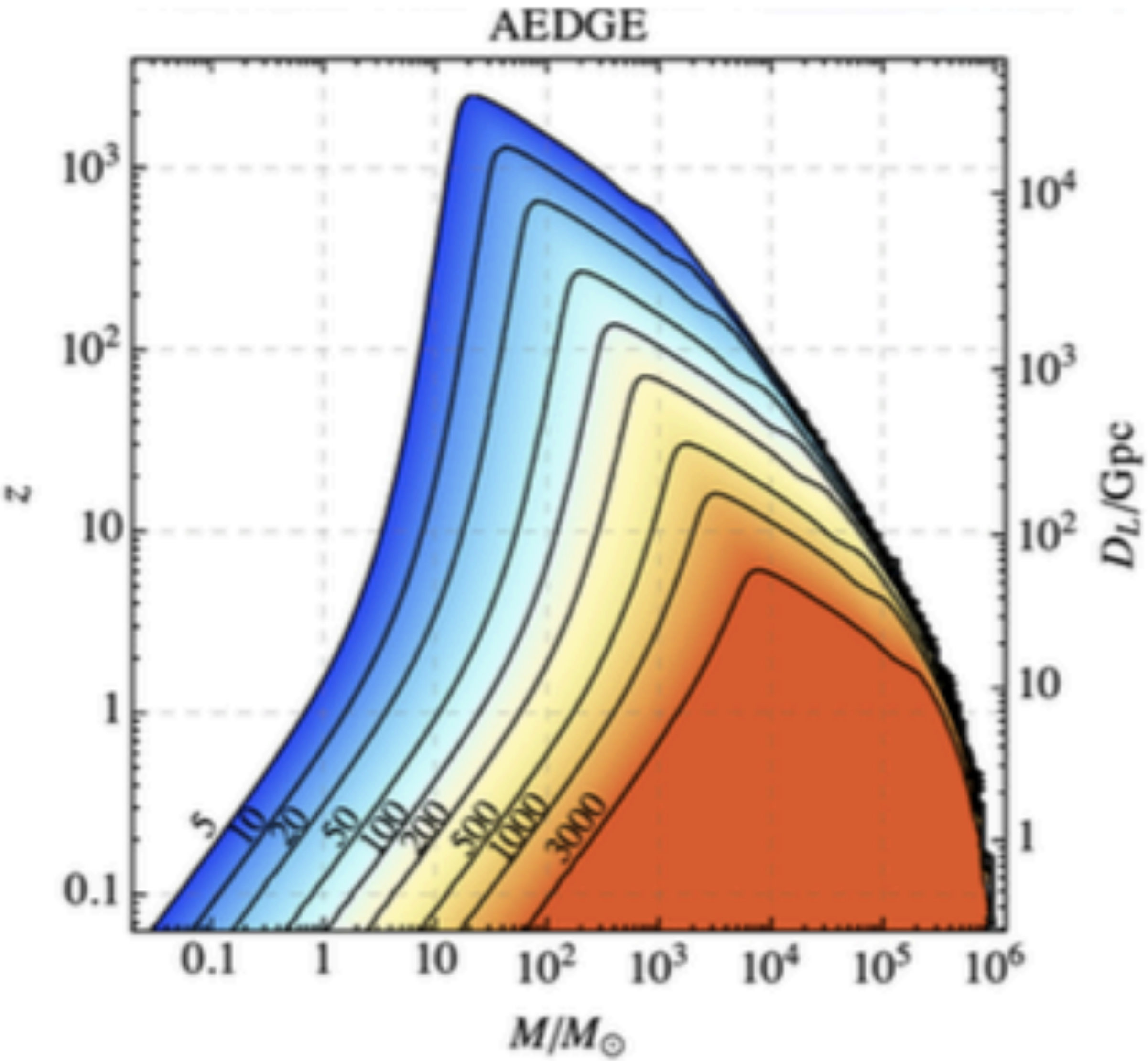
External Atom Cloud?

Nan Yu (JPL)
Workshop on cold atoms in space



AEDGE: Abou El-Neaj, …, JE et al: arXiv:1908.00802

Gravitational Waves from IMBHs



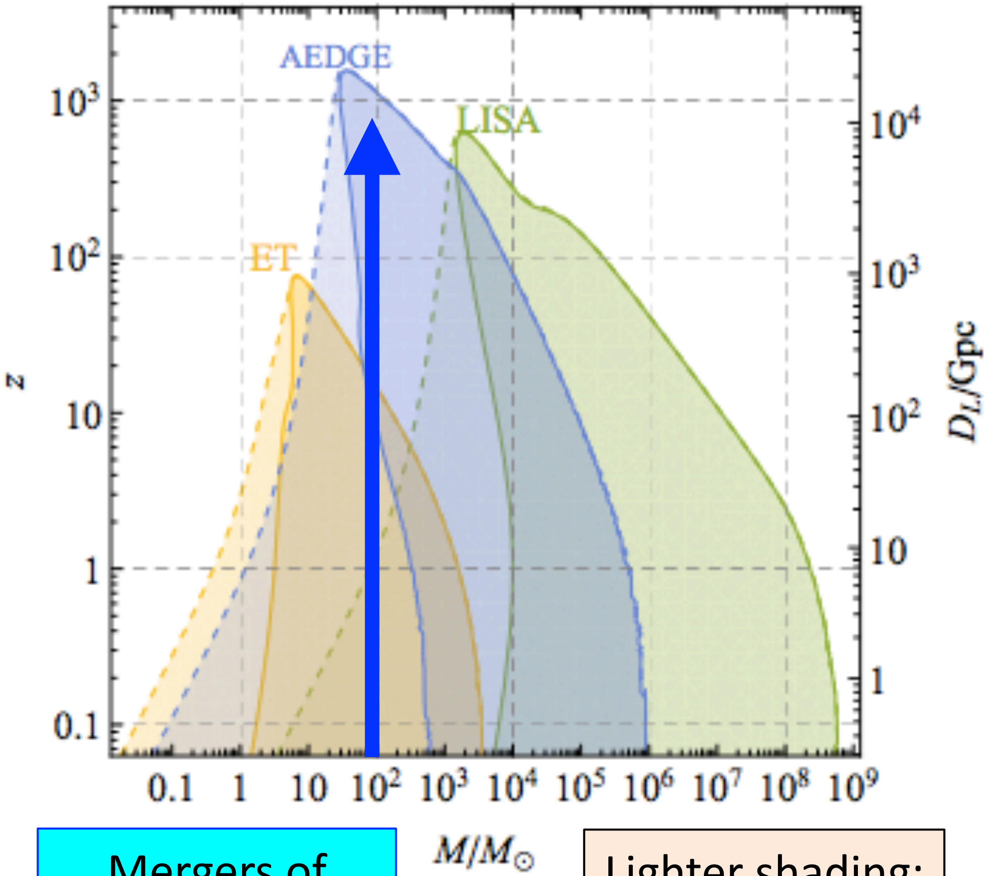
Detect mergers of ~ 10^4 solar-mass BHs with SNR 1000 out to z ~ 10,

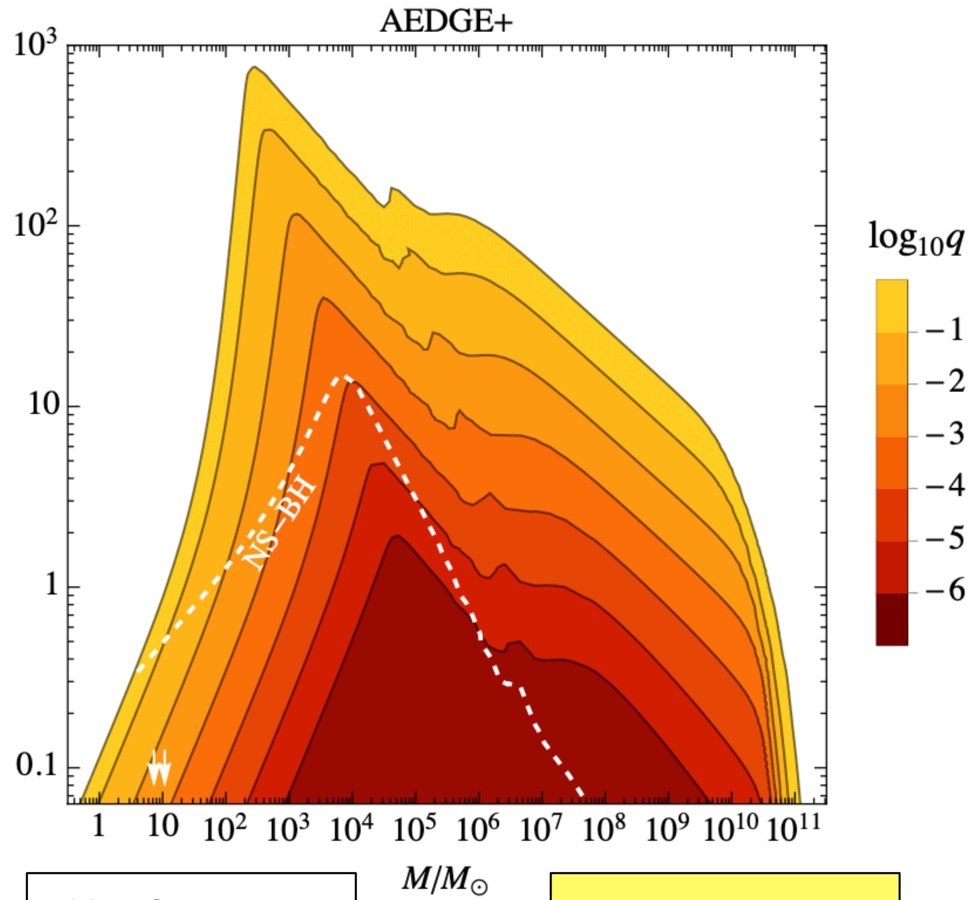
Mergers of ~ 10^3 solar-mass BHs with SNR 100 out to z ~ 100

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

GWs from IMBH, BH-NS Mergers

AION





Mergers of BHs in mass gap

Lighter shading: Measure inspiral

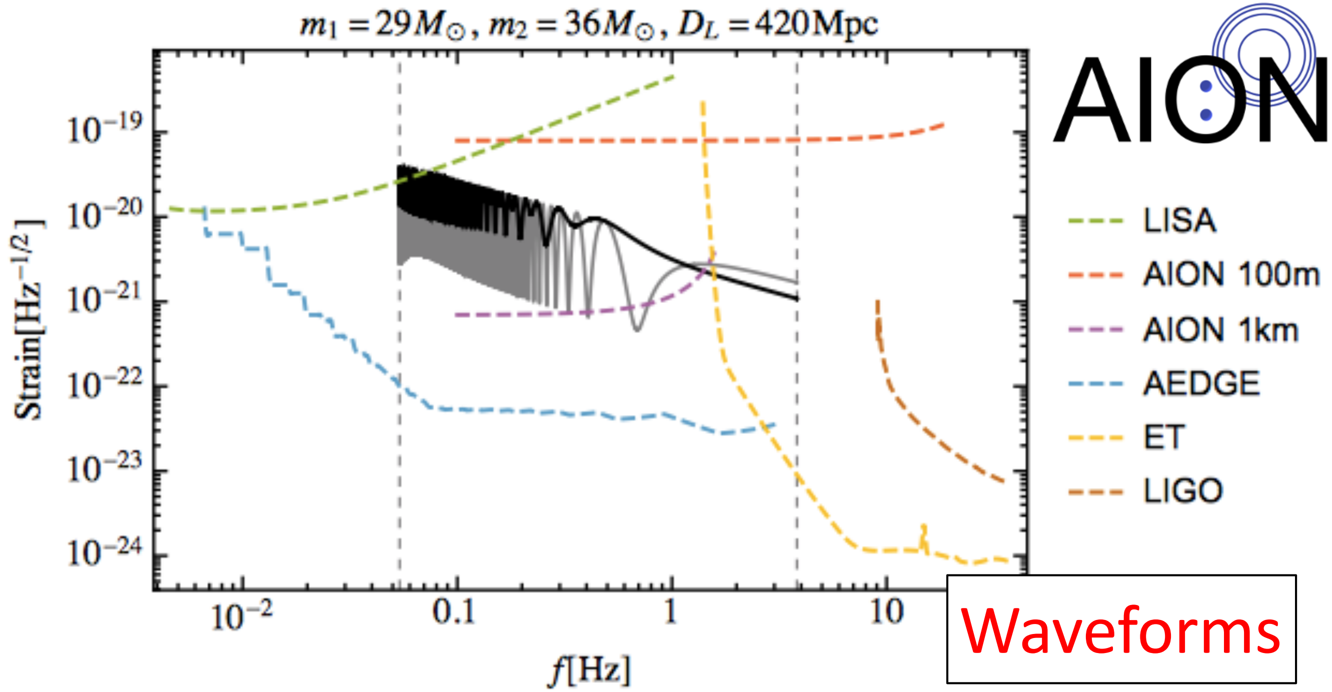
BH-NS mergers out to large z

Detect ultramassive BH

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

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

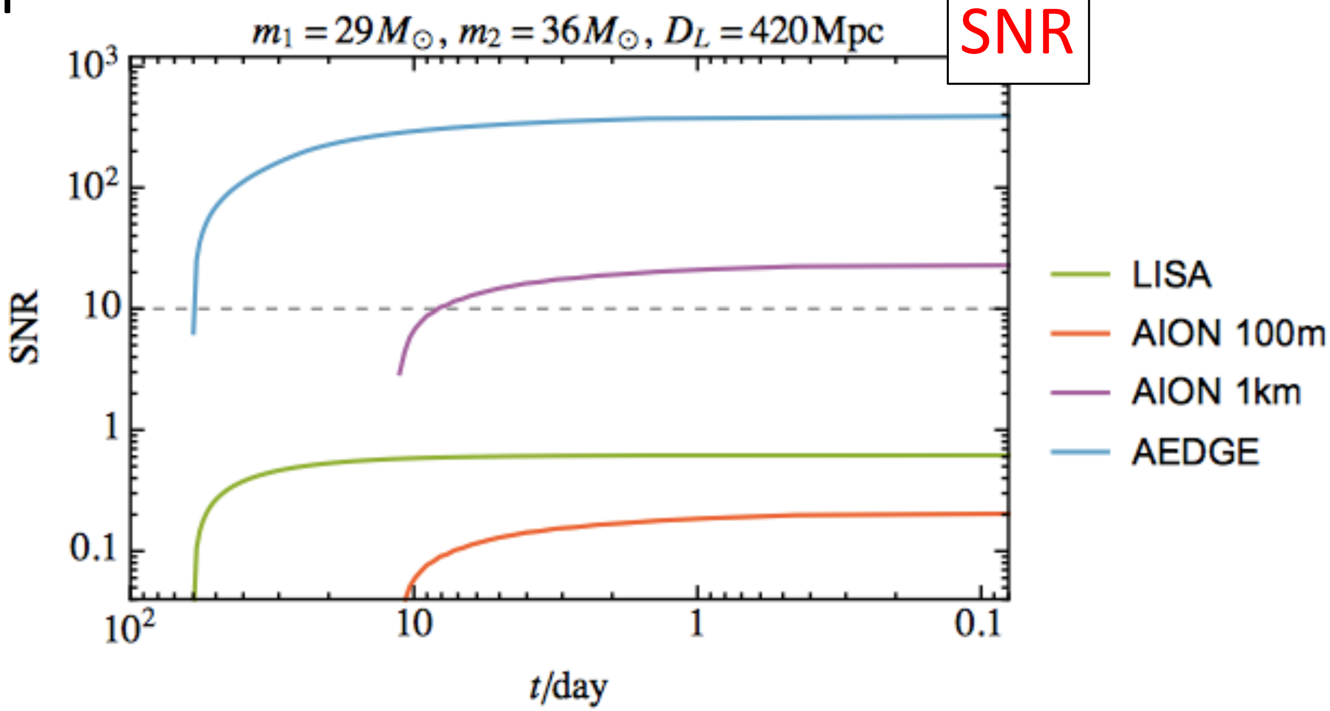
Constraints on Graviton Mass



Waveforms

LIGO/Virgo: arXiv:2010.14529

- Current LIGO/Virgo limit: 1.76 × 10^{-23} eV
- Future sensitivity with LIGO/Virgo-like event?
  Longer observations
- With merger of heavier BHs?
  Lower frequencies

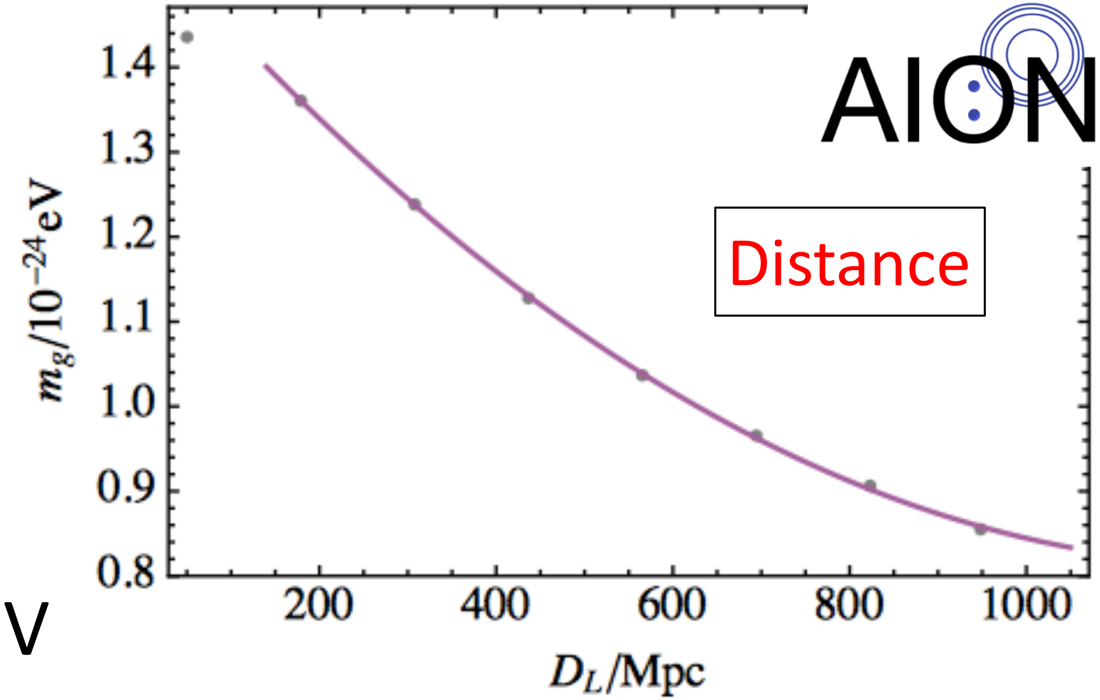


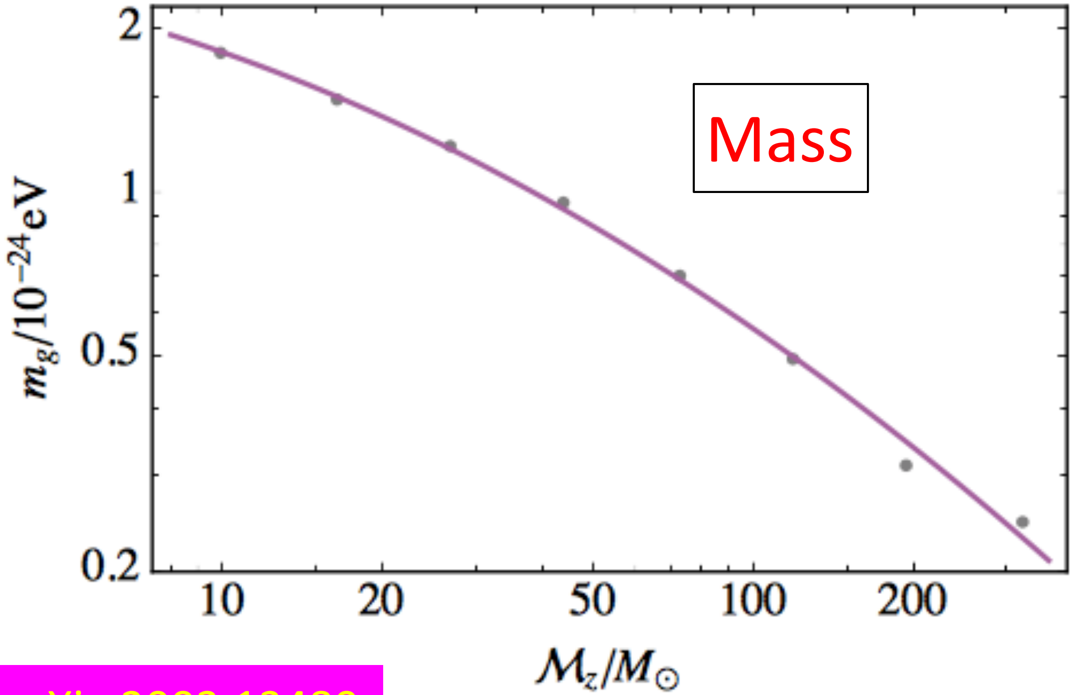
SNR

JE & Vaskonen: arXiv:2003.13480

Constraints on Graviton Mass

- LIGO/Virgo: <1.76 × 10^{-23} eV
- AION 1-km: sensitive to 10^{-24} eV with LIGO/Virgo-like event
- Sensitive to 2 × 10^{-25} eV with heavier BHs
- AEDGE: 8 × 10^{-27} eV with BHs 5600 + 4400 solar masses



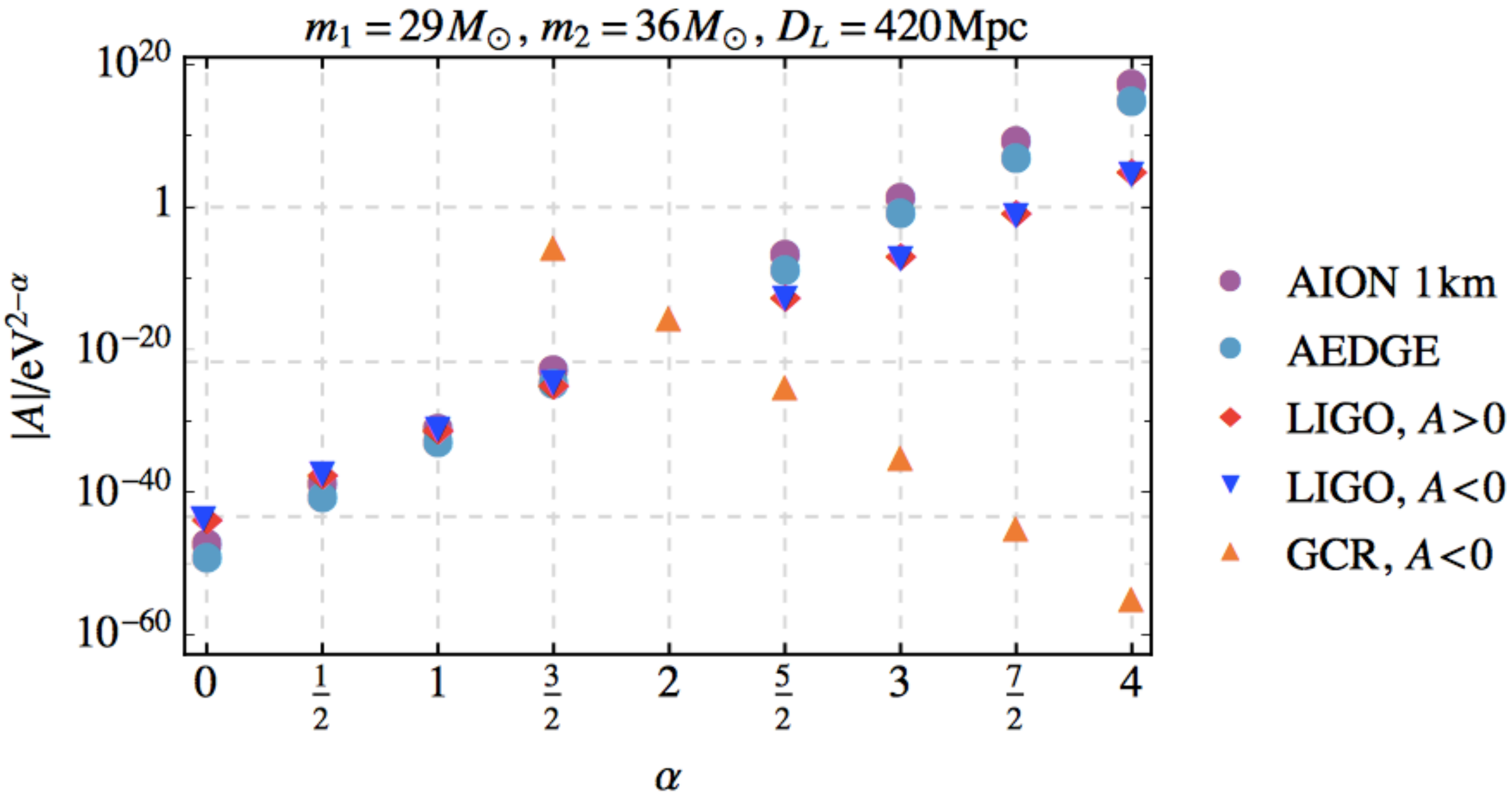


JE & Vaskonen: arXiv:2003.13480

Lorentz Violation

AION

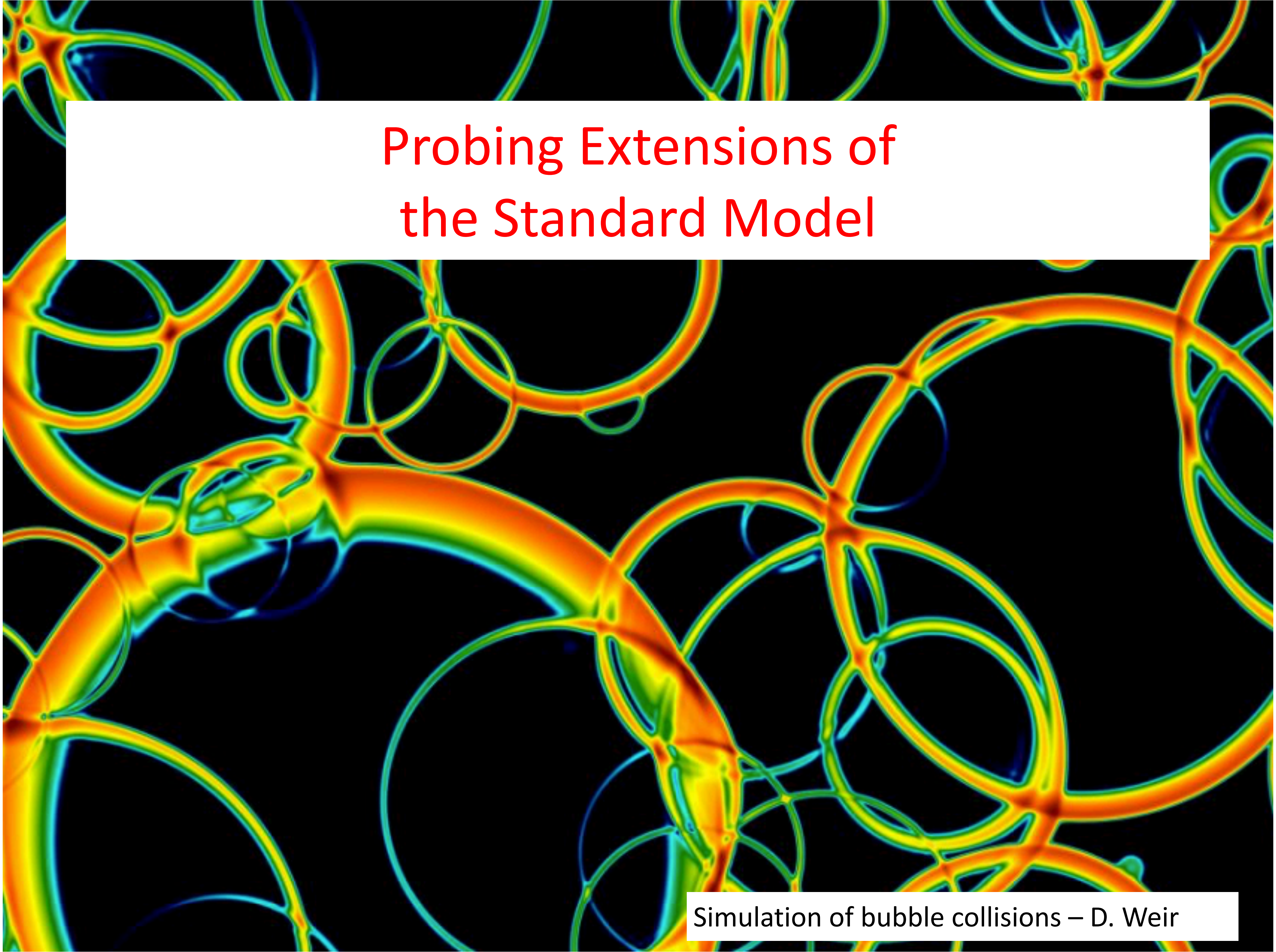
- Modified dispersion relation: $E^2 = p^2 + Ap^\alpha$



- AION 1-km: sensitivity 10 × LIGO for α = ½
- AEDGE: sensitivity 1000 × LIGO for α = ½

JE & Vaskonen: arXiv:2003.13480

Probing Extensions of the Standard Model



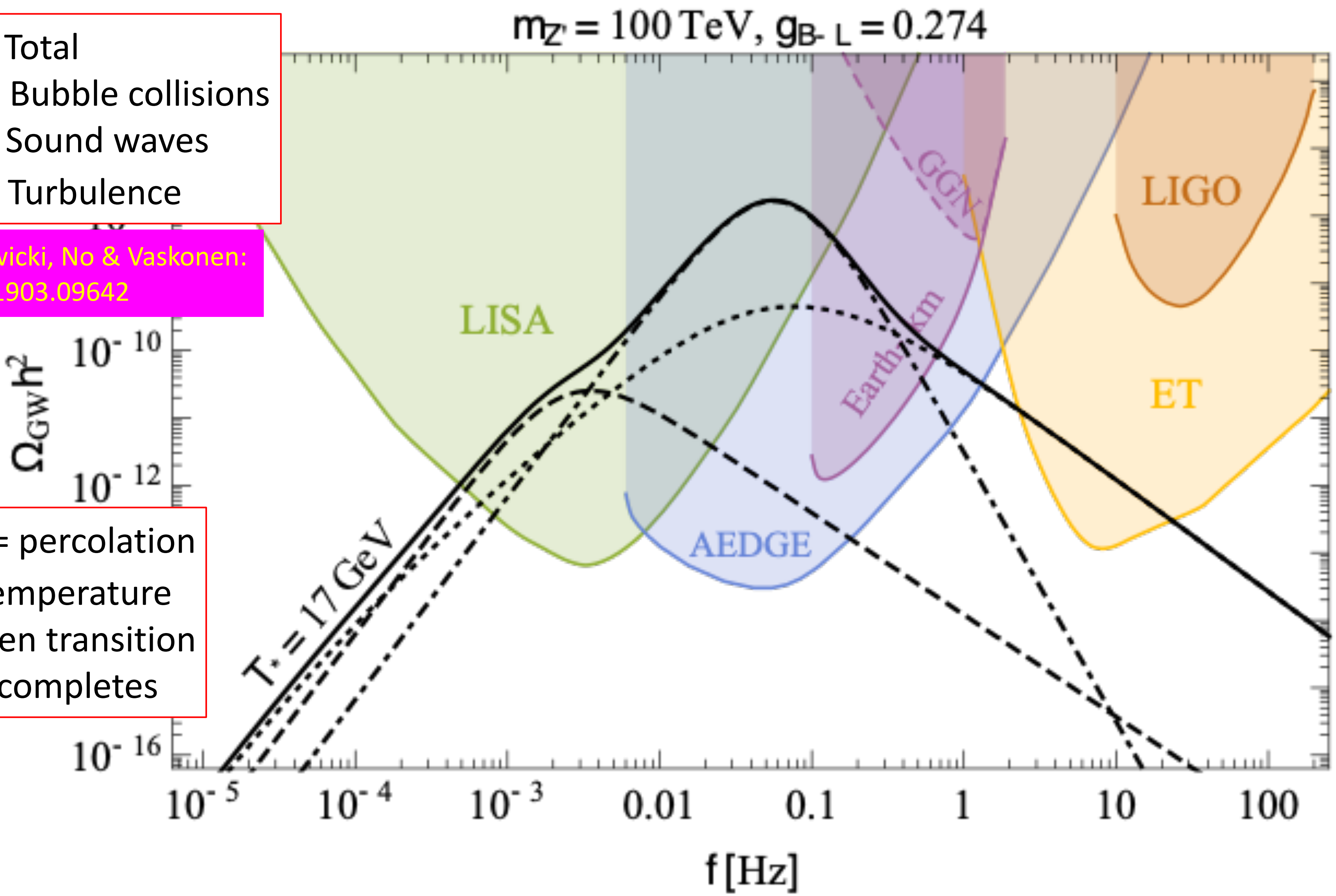
Simulation of bubble collisions – D. Weir

GWs from a First-Order Phase Transition

- Transition by percolation of bubbles of new vacuum
- Bubbles grow and collide
- Possible sources of GWs:
  - Bubble collisions
  - Turbulence and sound waves in plasma
- Models studied:
  - Standard Model + H^6/Λ^2 interaction
  - Standard Model + $U(1)_{B-L}$ Z'
- These also have prospective collider signatures

Gravitational Waves from $U(1)_{B-L}$ Phase Transition

AION



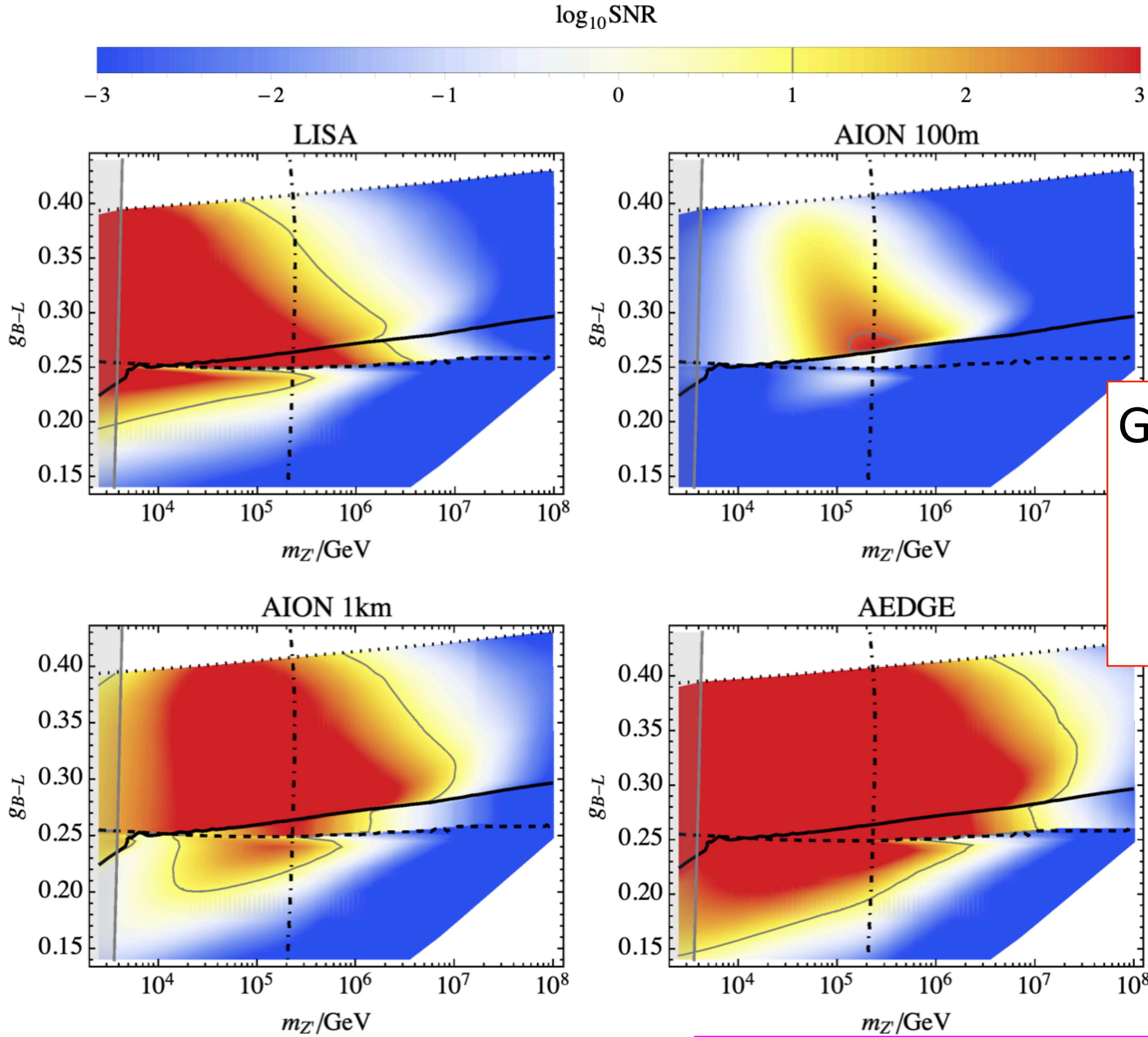
JE, Lewicki, No & Vaskonen: arXiv:1903.09642

T_* = percolation temperature when transition completes

AEDGE: Bertoldi, …, JE et al: arXiv:1908.00802

Sensitivities to U(1)$_{B-L}$ Z'

AION

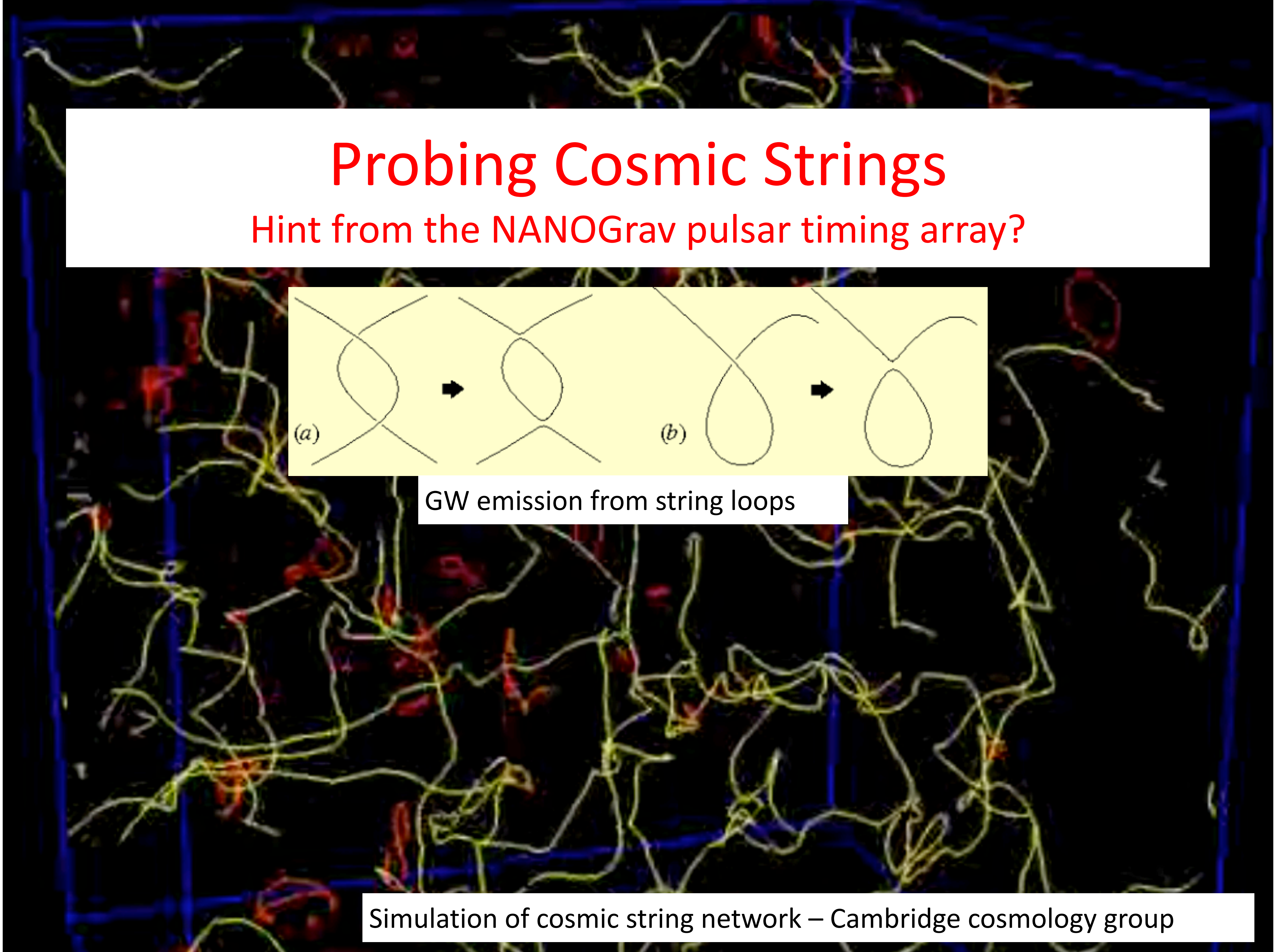


GW discovery sensitivity far beyond colliders

JE, Lewicki & Vaskonen, arXiv:2007.15586

Probing Cosmic Strings

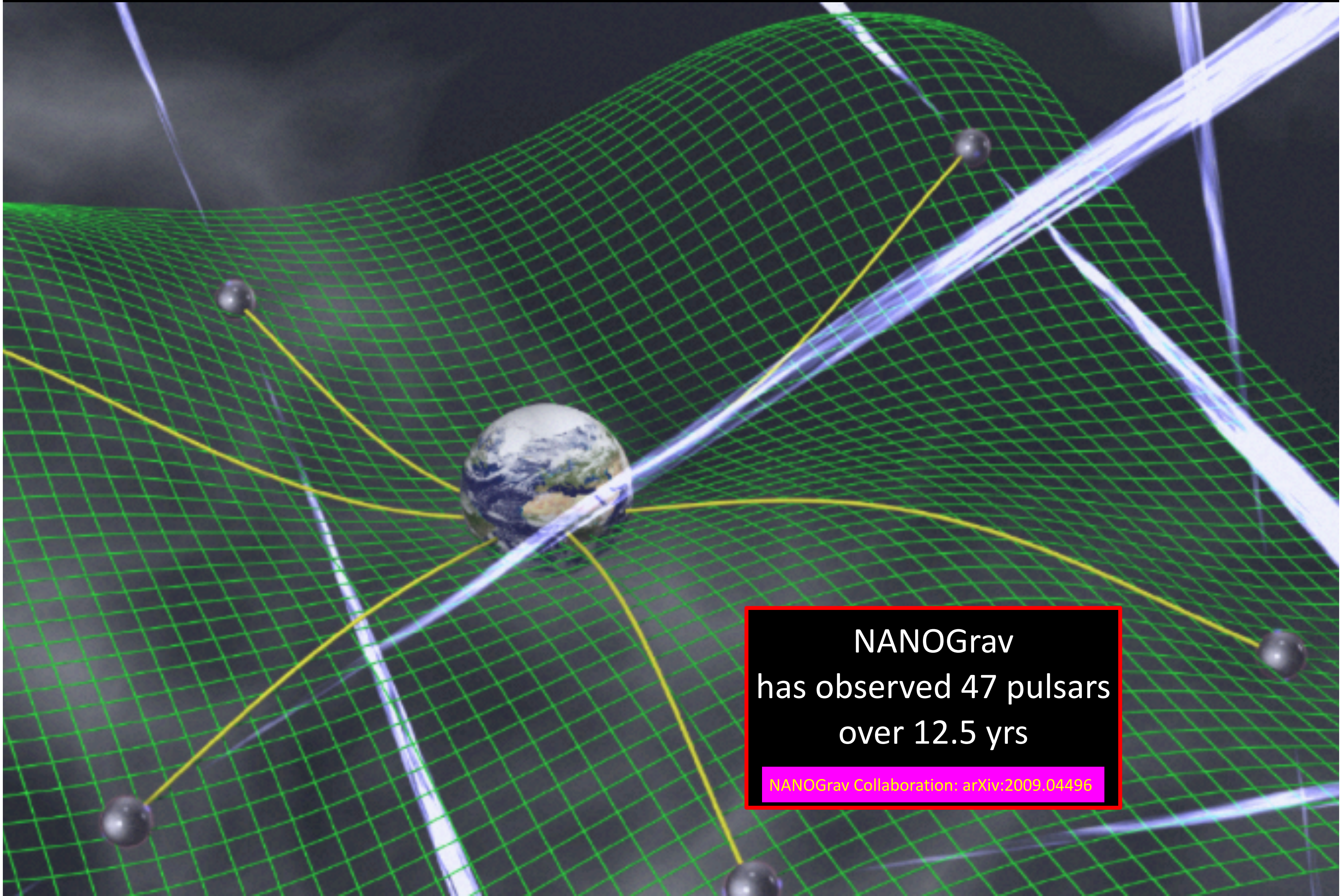
Hint from the NANOGrav pulsar timing array?



GW emission from string loops

Simulation of cosmic string network – Cambridge cosmology group

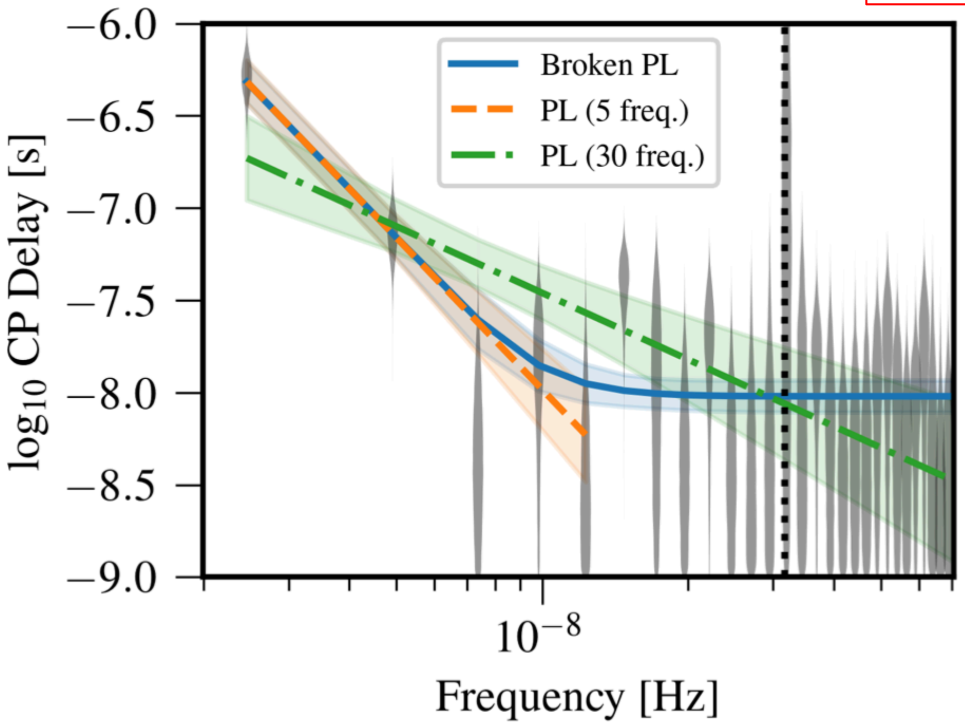
Pulsar Timing Arrays

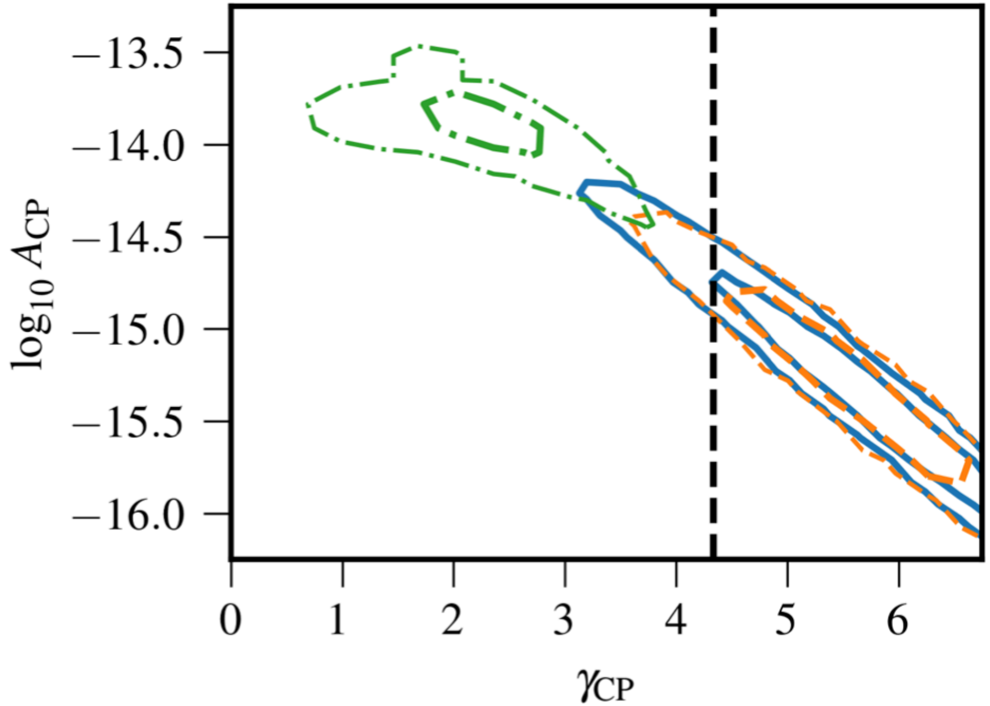


NANOGrav Collaboration: arXiv:2009.04496

Pulsar Timing Data from NANOGrav

12.5-year data





"Strong evidence for a stochastic common-spectrum process" at frequencies < 10^{-8} Hz

No dipole or quadrupole signal detected

Focus on simple power law

Amplitude A ~ 10^{-15}

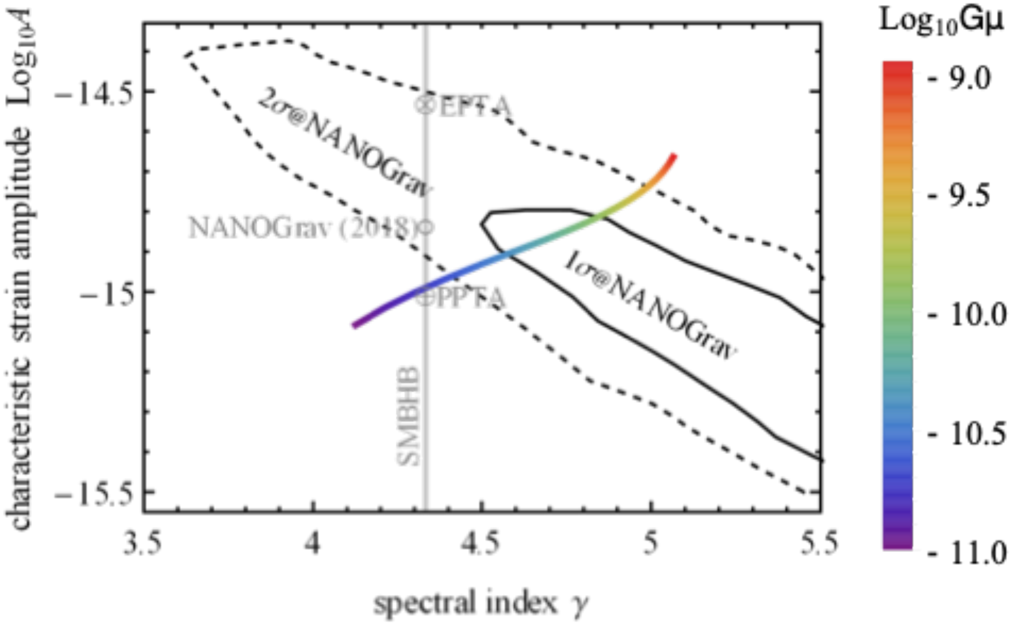
Slope γ ~ 5

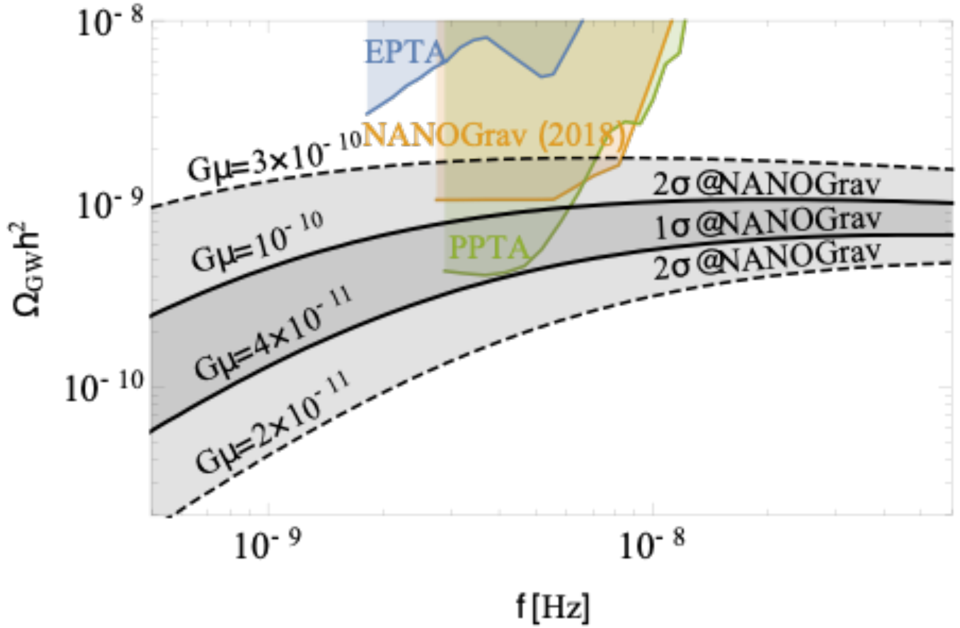
Vertical dashed line: mergers of supermassive BHs

"the amplitude … may imply that the black hole mass function is underestimated, specifically when extrapolated from observations of the local supermassive black hole population"

JE & Lewicki: arXiv:2009.06555

Cosmic String Interpretation of NANOGrav



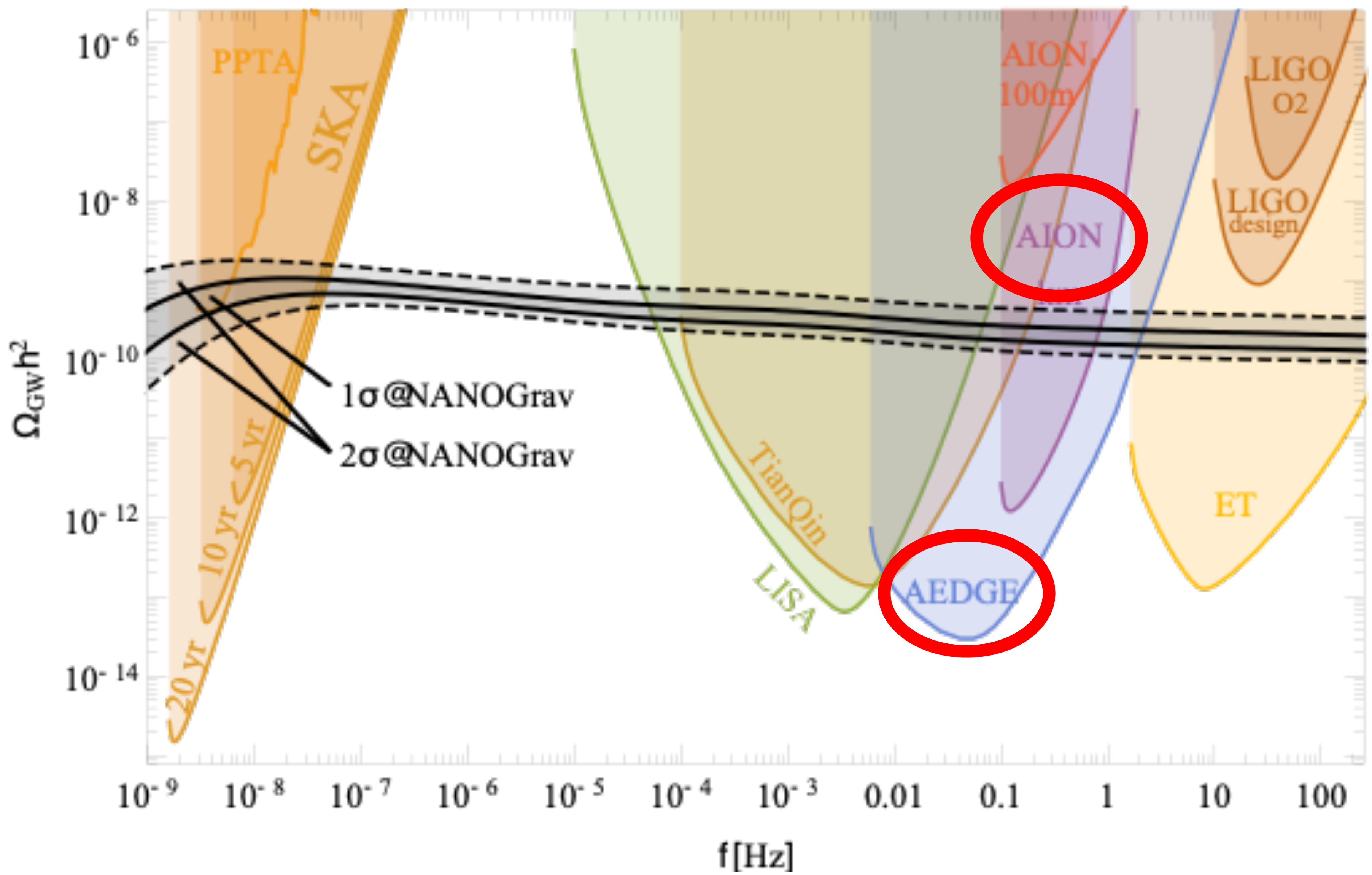


"Rainbow curve"
is cosmic string prediction as a
function of the cosmic string tension Gμ
Vertical line is SMBH merger prediction
Previous PTA upper limits for
this value of γ

Fits to NANOGrav signal
at 1σ (68%), 2σ (95%) levels
Compared to previous
upper limits
(previous NANOGrav superseded)

JE & Lewicki: arXiv:2009.06555

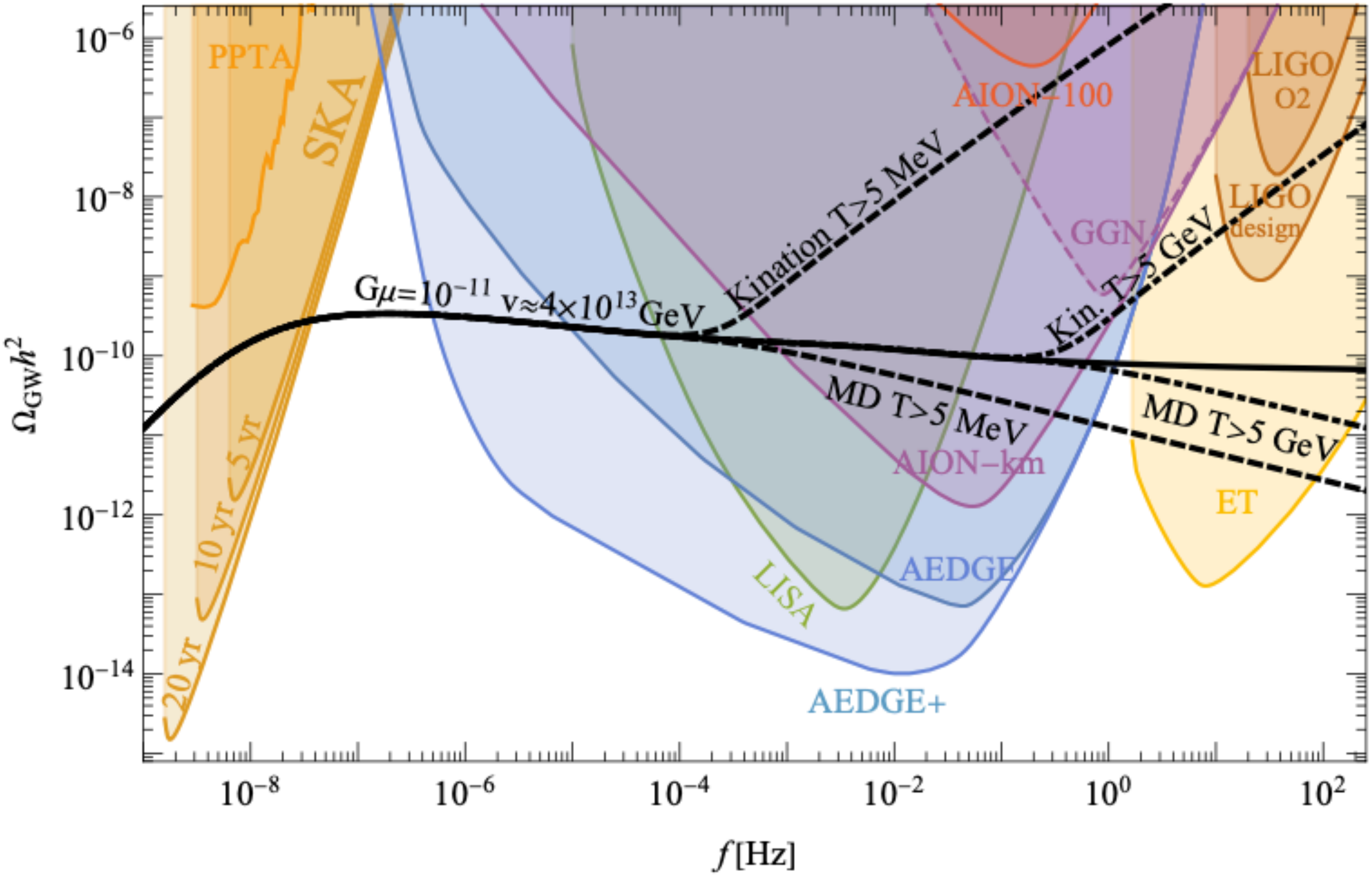
Cosmic String Interpretation of NANOGrav



Cosmic string prediction can be tested in several upcoming experiments (not LIGO)

AEDGE: Bertoldi, ..., JE et al: arXiv:1908.00802

Gravitational Waves from Cosmic Strings



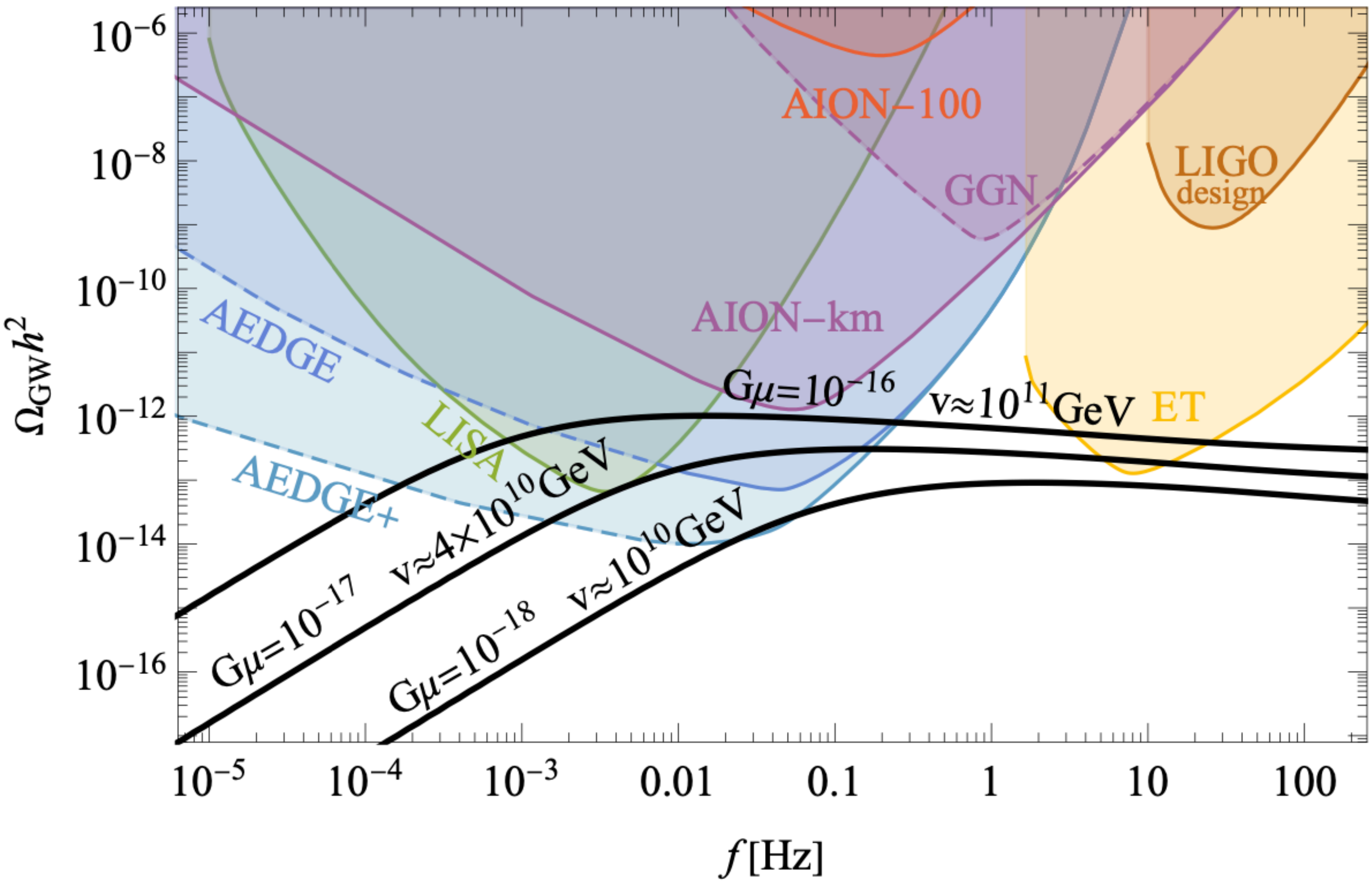
Effects of modified expansion: Kination, Matter Dominance

Spectrum ~ flat from PTA/SKA to LIGO/ET

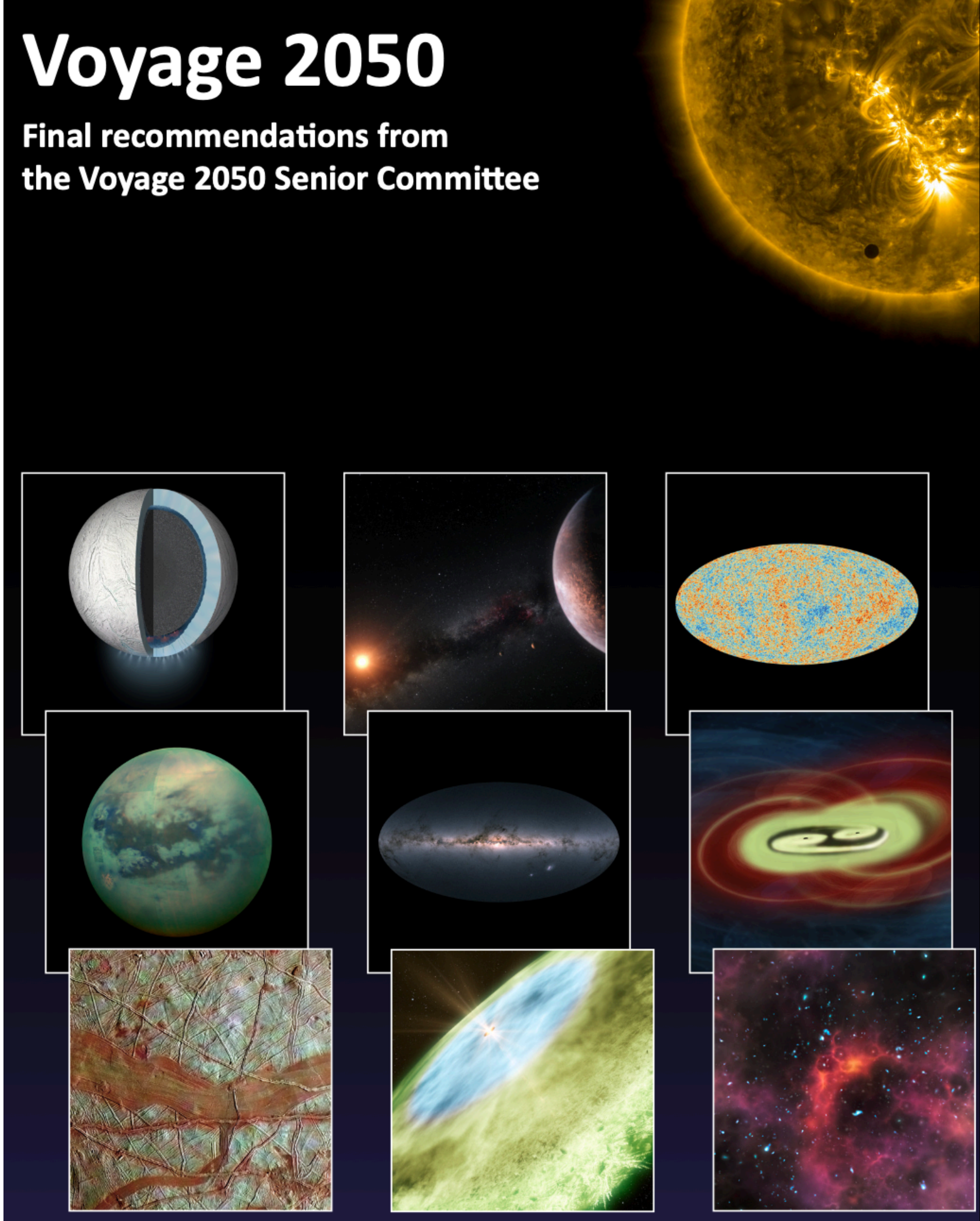
Tension $G\mu < 10^{-11}$ from PTA limit

Badurina, Buchmueller, JE et al: arXiv:2108.02468

Gravitational Waves from Cosmic Strings



Different experiments sensitive to different values of cosmic string tension



Large missions:

- Moons of the Giant Planets
- Exoplanets
- New Physical Probes of the Early Universe: Fundamental physics and astrophysics

Possible Medium missions:

- … QM & GR (cold atoms?)

Technology development recommendations for Cold Atom Interferometry

- for gravitational wave detectors in new wavebands …, detectors for dark matter candidates, sensitive clock tests of general relativity, tests of wave function collapse ….
- must reach high technical readiness level, be superior to classical technologies
- start with atomic clocks, on free-flyer or ISS?
- M-mission?

Cold Atoms in Space: Community Report & Road-Map

Cold Atoms in Space:

Community Workshop Summary and Proposed Road-Map

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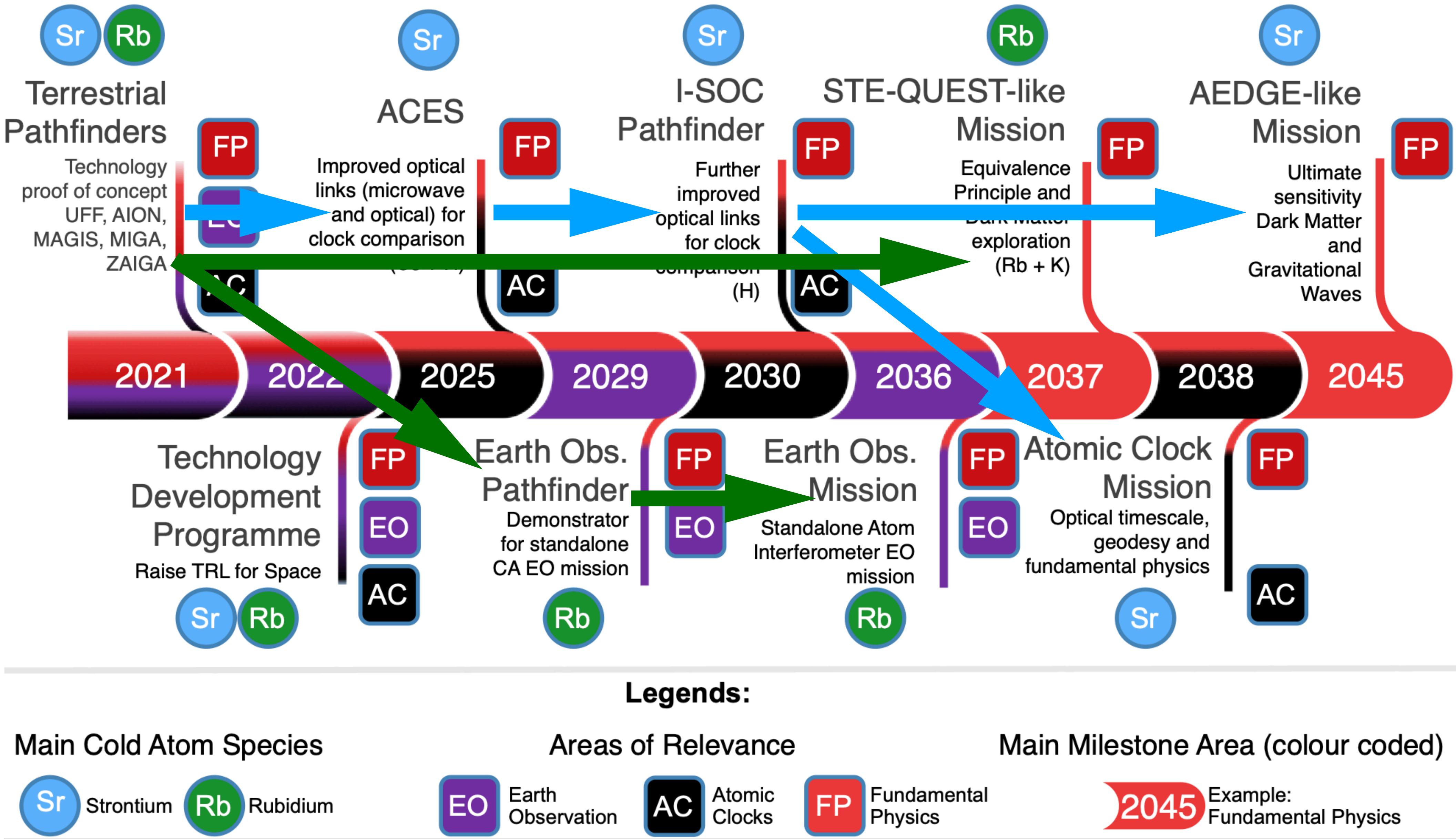
Alonso, …, Badurina, …, JE, …, McCabe et al, arXiv:2201.07789

Proposed ESA Road-Map for Cold Atoms in Space



STE-QUEST Phase 1 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

Lead proposer: Peter Wolf
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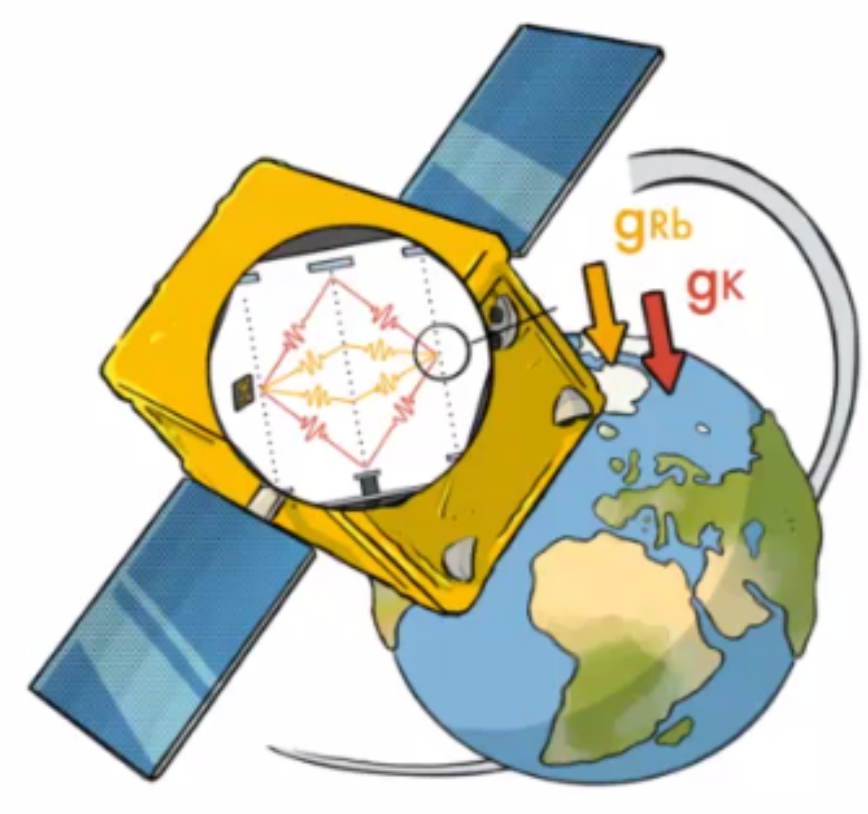
February 15, 2022



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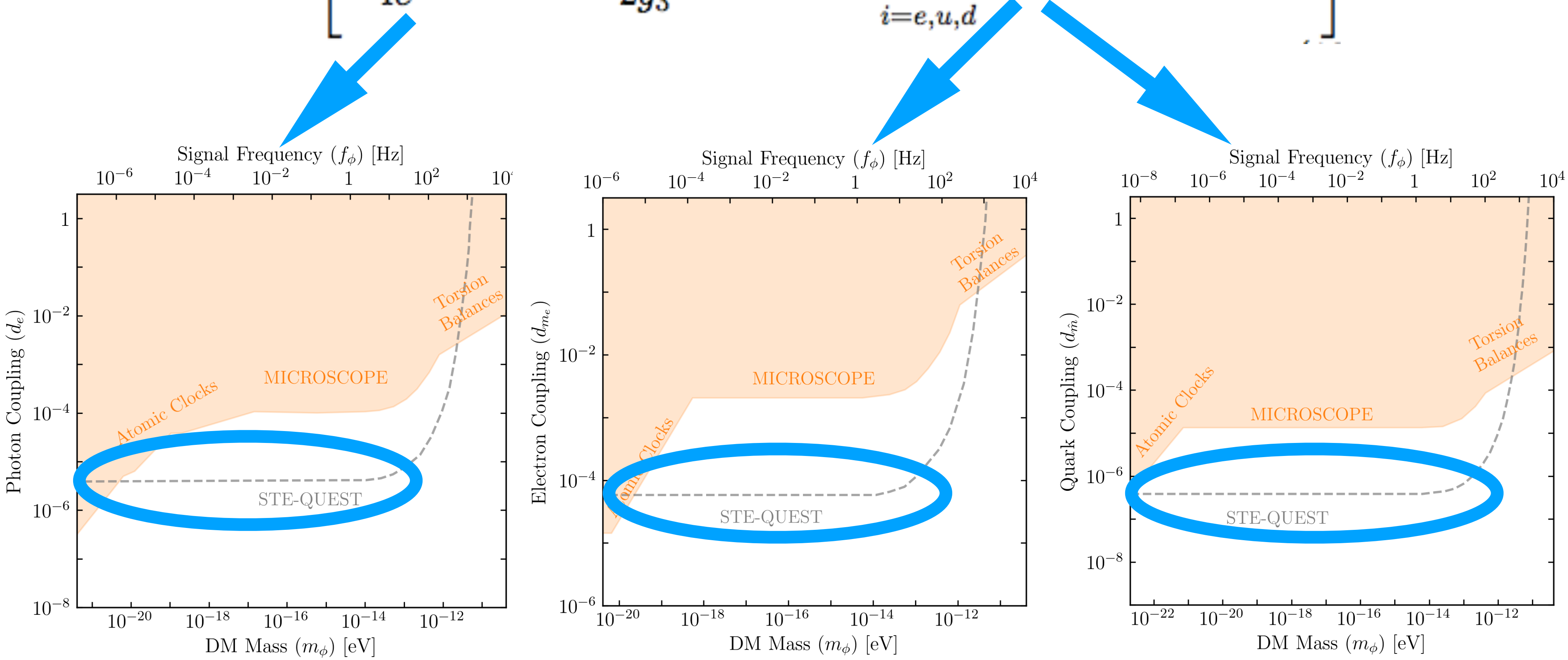
STE-QUEST Science:
Testing the Equivalence Principle

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

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



Wave-Function Collapse?

- Transition from quantum to classical behaviour?
- Black holes: information loss across horizon causes pure states → mixed states

Hawking, 1975

- Non-factorising scattering matrix $\rho_{out} = \$ \rho_{in} : \$ \neq SS^\dagger$
- Non-Hamiltonian evolution: $\partial_t \rho = i[\rho, H] + \mathscr{H} \rho$ due to information loss via microscopic black holes?

JE, Hagelin, Nanopoulos, Olive & Srednicki, 1984

- e.g., 2-state system with equal energies:

$$\rho = \frac{1}{2} \begin{pmatrix} 1 & e^{-\lambda t} \\ e^{-\lambda t} & 1 \end{pmatrix}$$

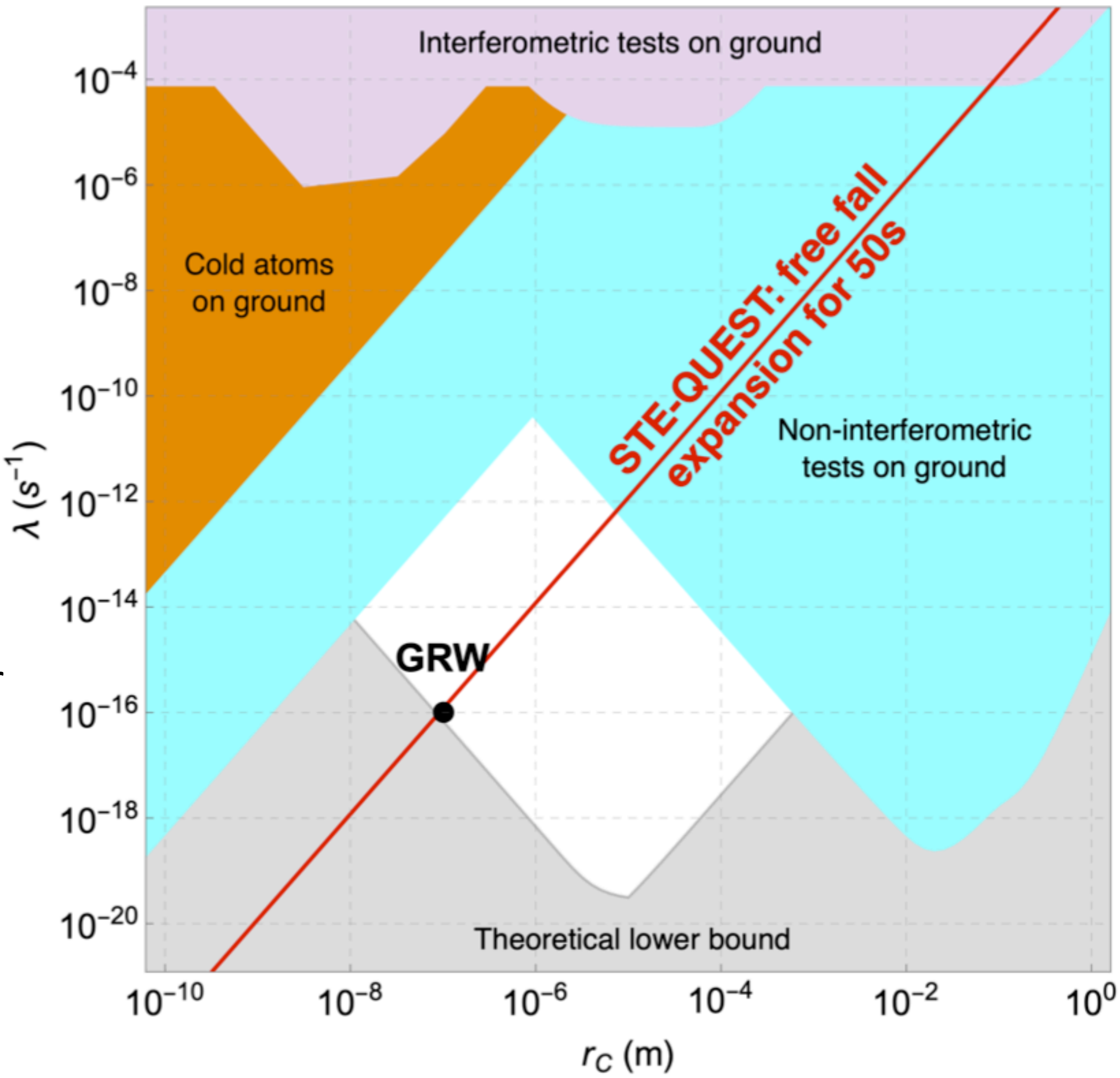
- General parametrisation: $e^{-\frac{d}{r_c}}, e^{-\lambda t}$

Ghirardi, Rimini & Weber, 1986

STE-QUEST Science:
Probe of Quantum Mechanics

Models for
wave-function collapse
parameterised by
time-scale λ
and range r_c

GRW = parameters
proposed by
Ghirardi, Rimini, Weber



STE-QUEST Science Programme

Probe the boundaries of our fundamental theories
& interfaces between them