Fundamental Physics from Gravitational Waves

The GW spectrum

Probing GW propagation: graviton mass, Lorentz violation

GWs from first-order phase transitions

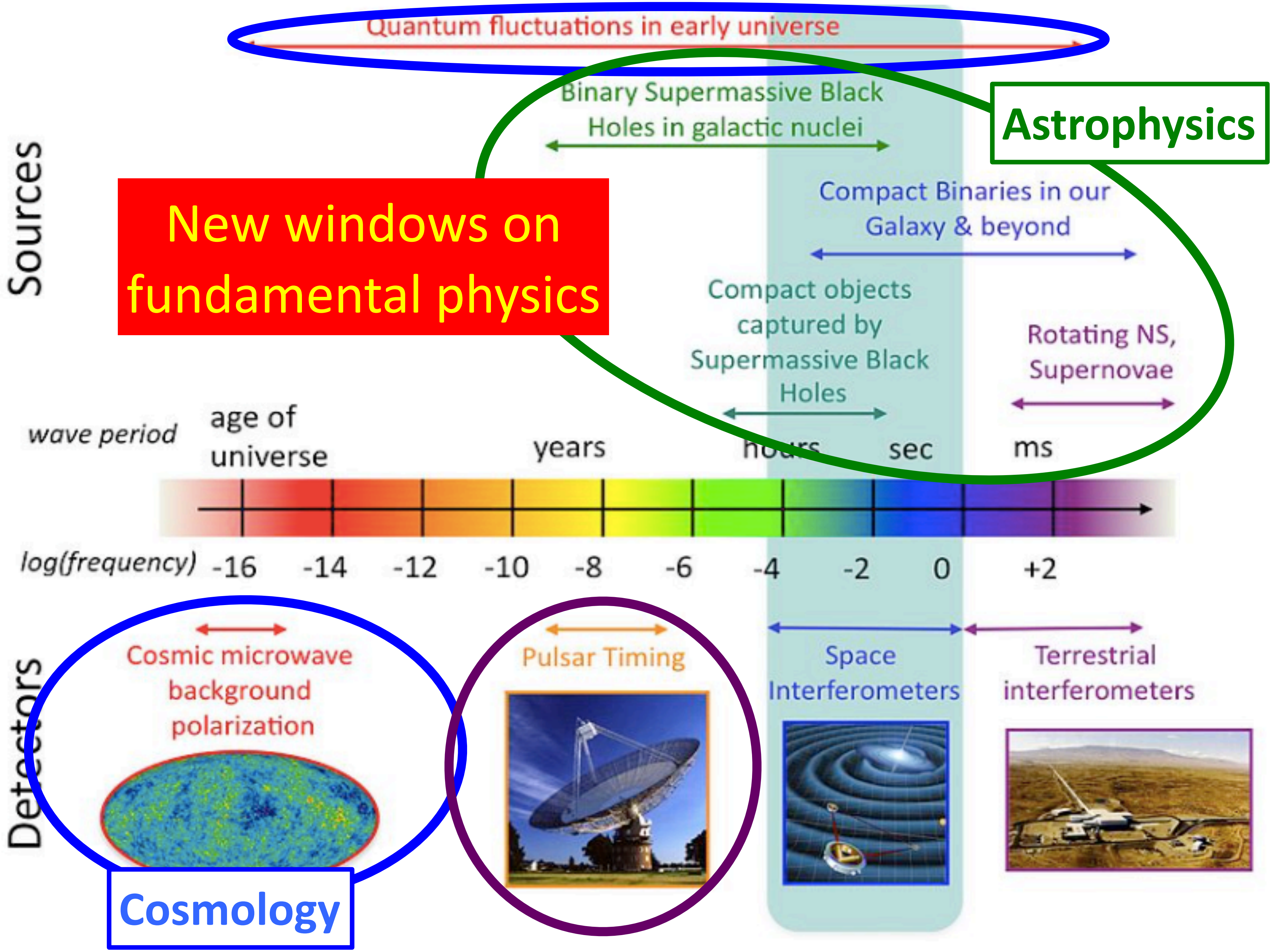
GWs from cosmic strings

Interpreting GW hint from NANOGrav PTA

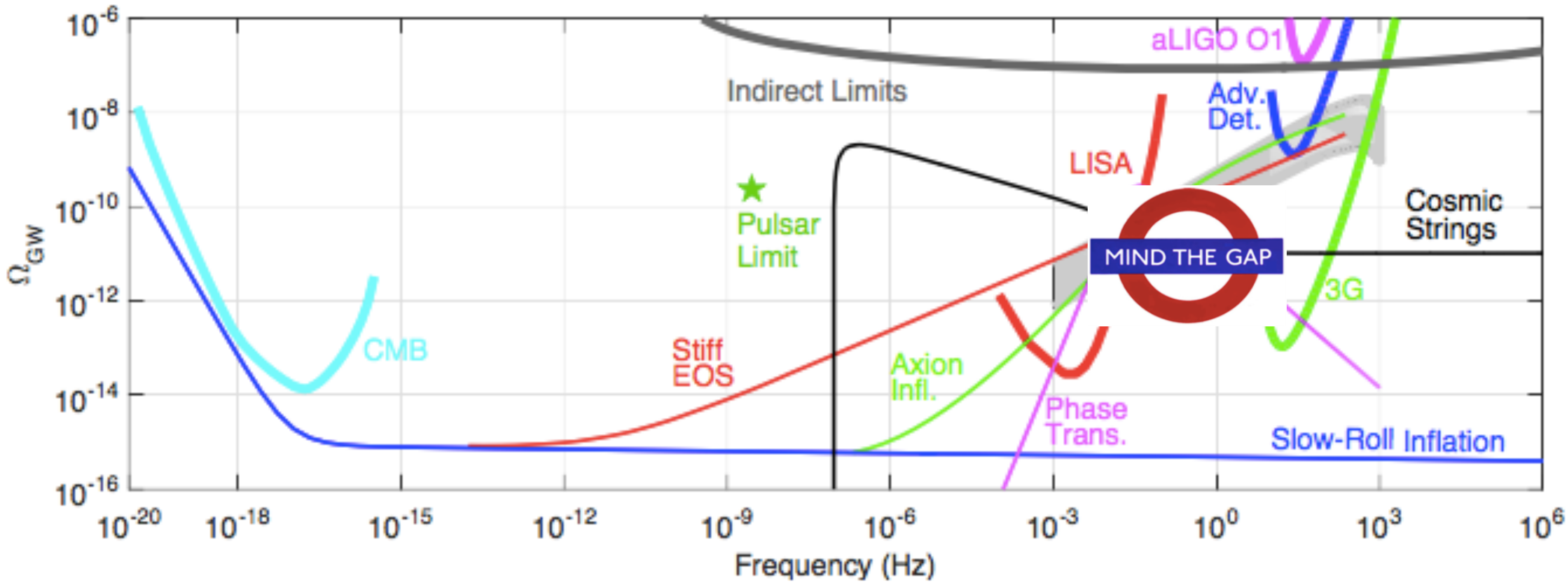
John Ellis

KING'S College LONDON

Gravitational Wave Spectrum



Gravitational Wave Spectrum

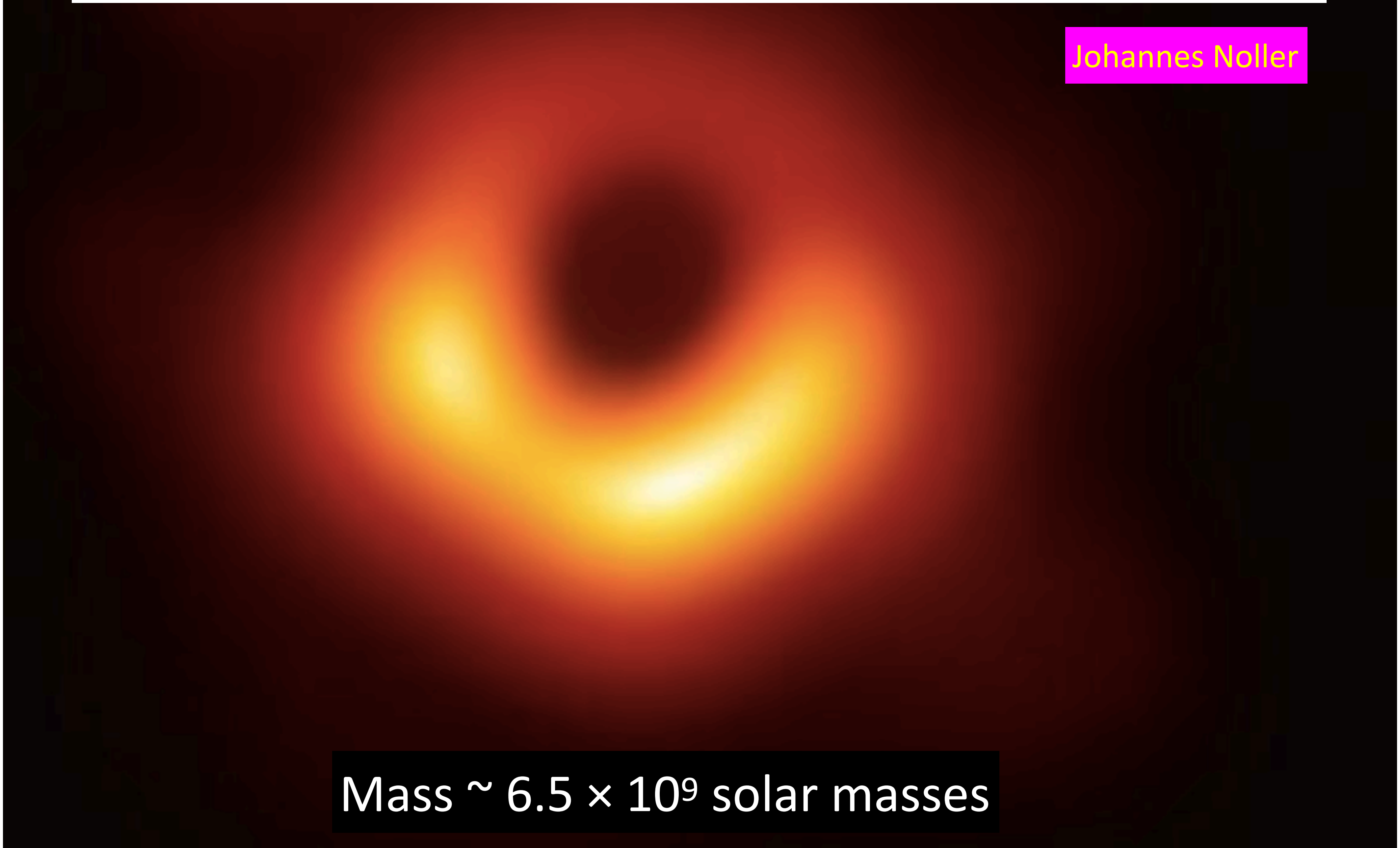


- Gap between ground-based optical interferometers & LISA
  - Formation of supermassive black holes (SMBHs)?
  - Electroweak phase transition? Cosmic strings?
- Also gaps between LISA & pulsar timing arrays (PTAs) and between PTAs and CMB

Probing General Relativity

Using GWs from Astrophysical Sources

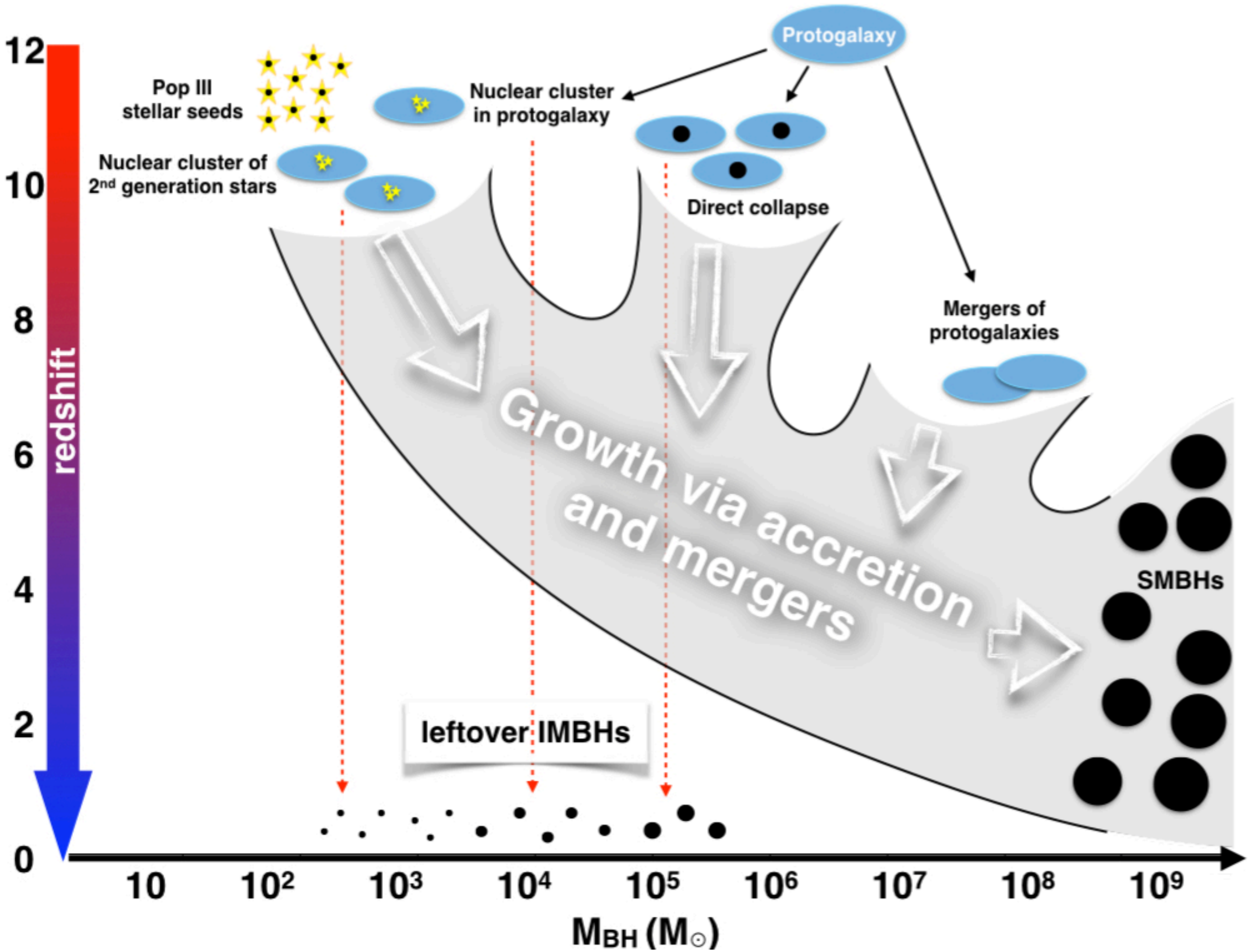
Johannes Noller



Mass ~ 6.5 × 10^9 solar masses

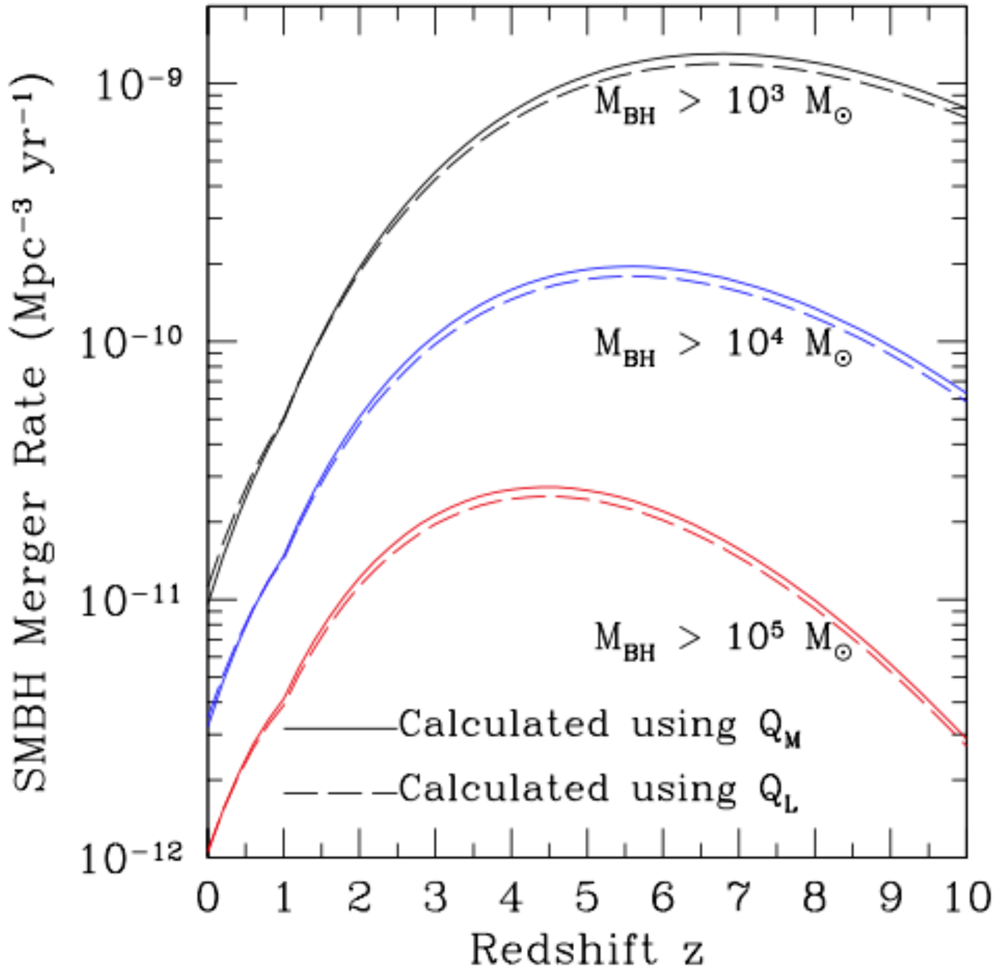
How to Make a Supermassive BH?

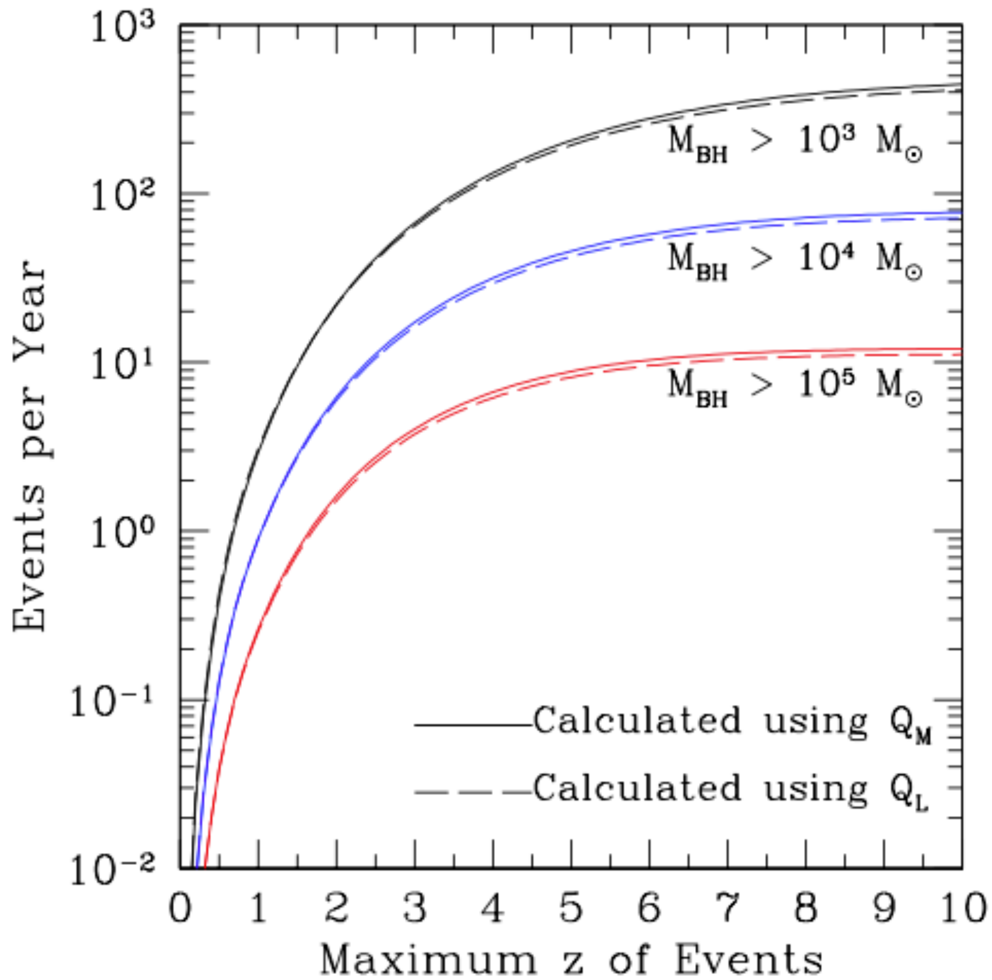
SMBHs from mergers of intermediate-mass BHs (IMBHs)?



How to Make a Supermassive BH?

- SMBHs from mergers of intermediate-mass BHs (IMBHs)?
- Estimated merger rates: most at z < 10

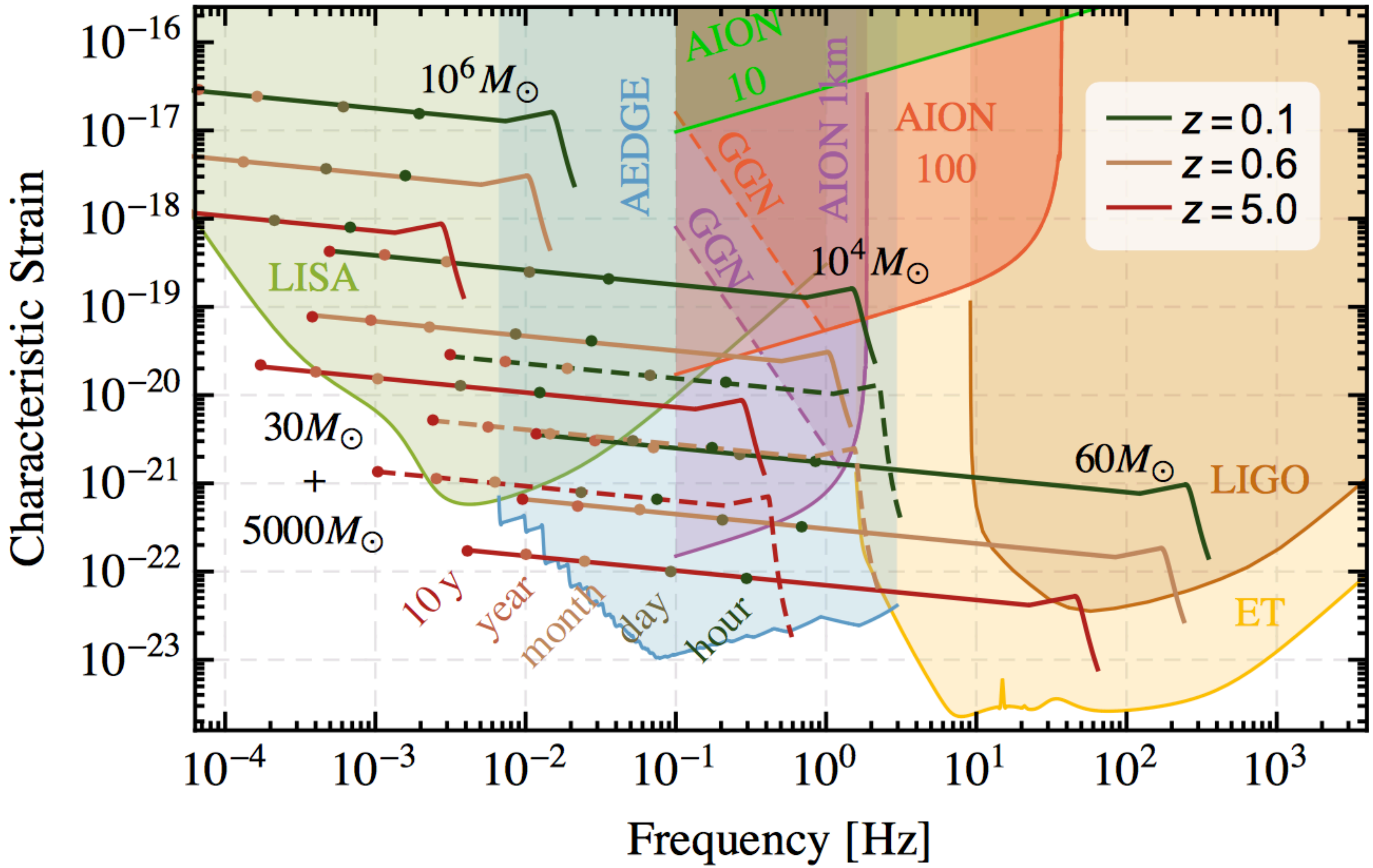




Erickcek, Kamionkowski & Benson, astro-ph/0604281

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

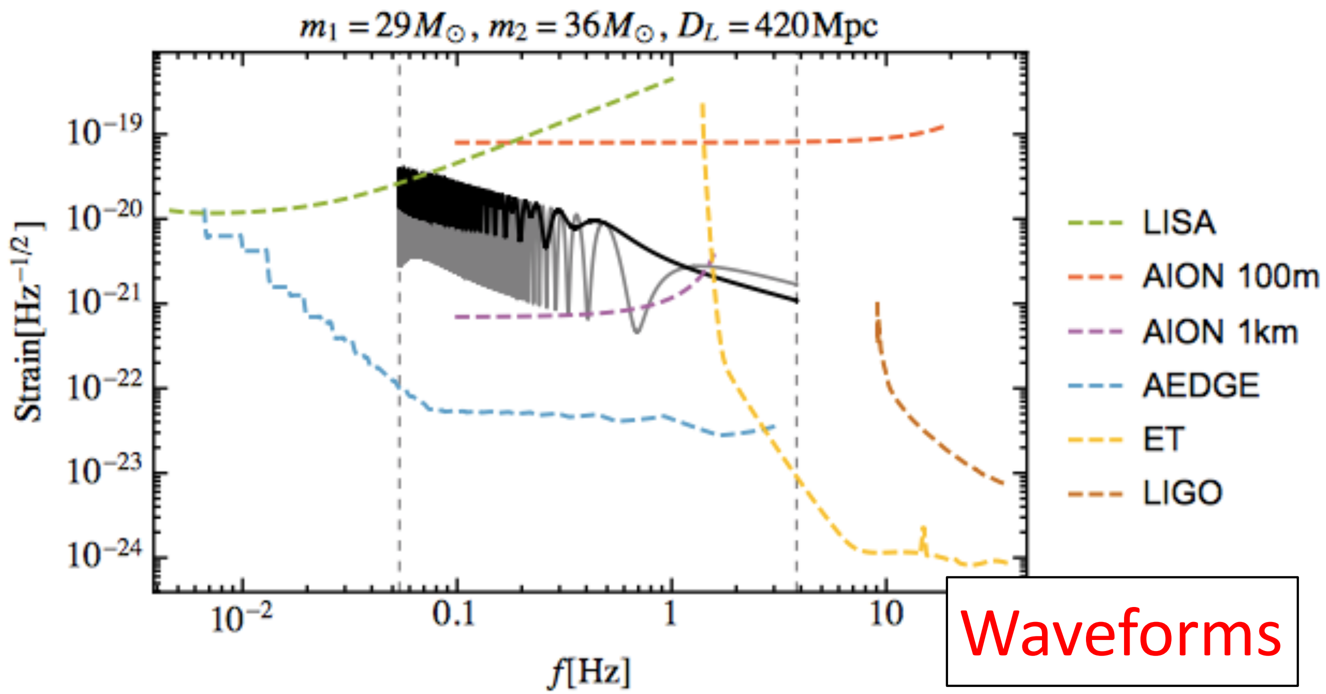
Gravitational Waves from IMBH Mergers



Probe formation of SMBHs

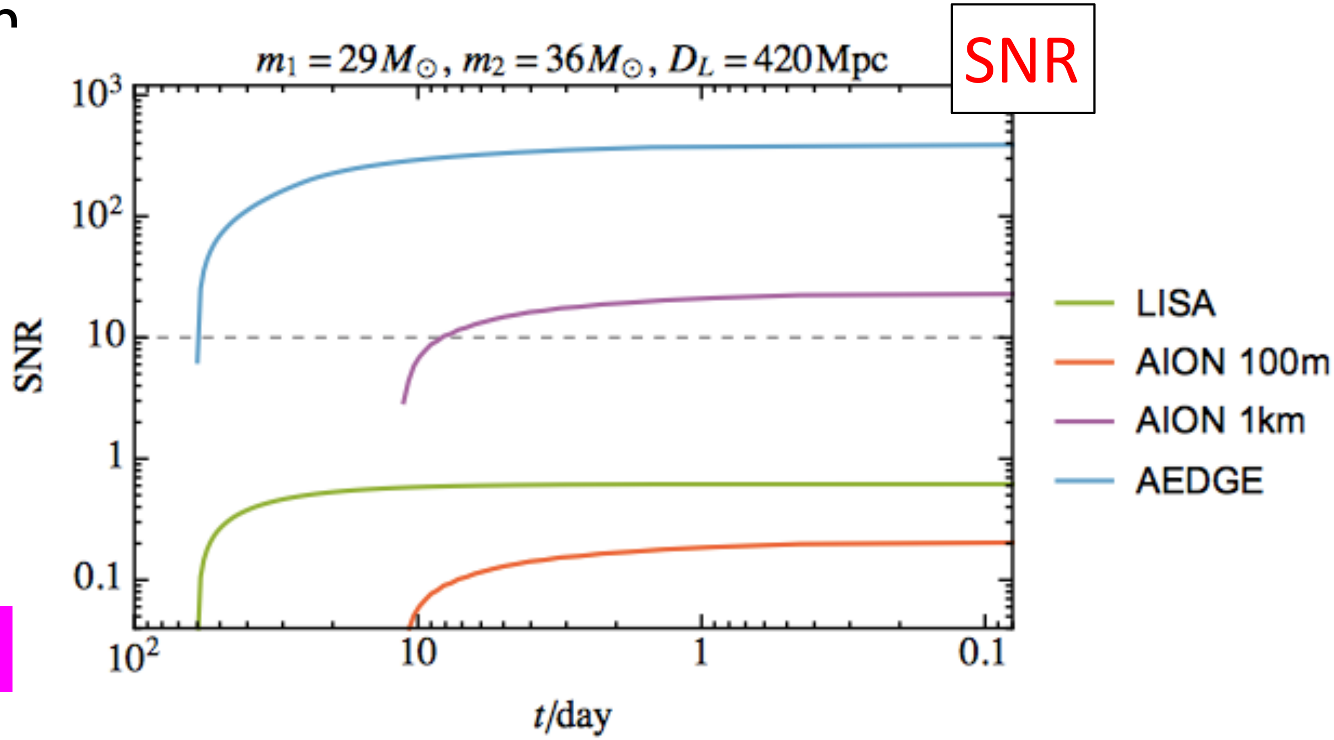
Synergies between GW experiments (LIGO, AION, LISA), test GR

Constraints on Graviton Mass



LIGO/Virgo: arXiv:2010.14529

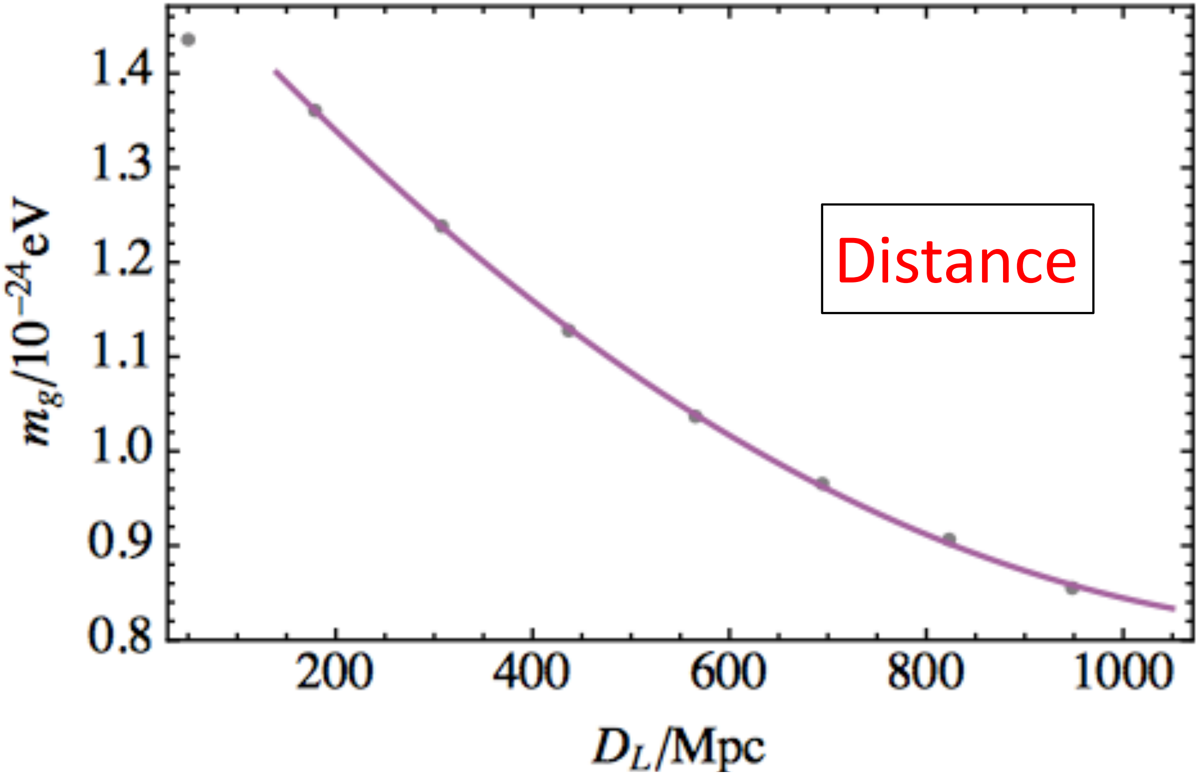
- Current LIGO/Virgo limit: 1.76×10^{-23} eV
- Future sensitivity with LIGO/Virgo-like event?
  Longer observations
- With merger of heavier BHs?
  Lower frequencies

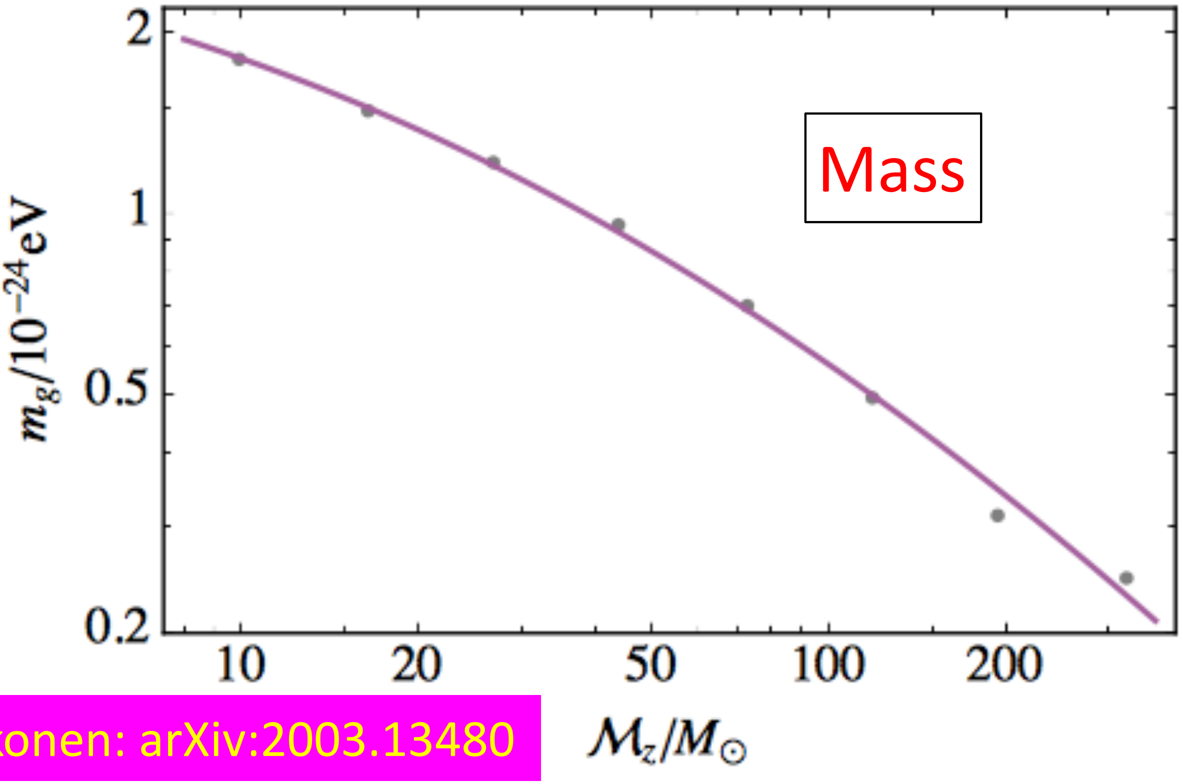


JE & Vaskonen: arXiv:2003.13480

Constraints on Graviton Mass

- AION 1-km:
- 10^{-24} eV with LIGO/Virgo-like event
- 2×10^{-25} eV with heavier BHs
- AEDGE:
- Order of magnitude more sensitive

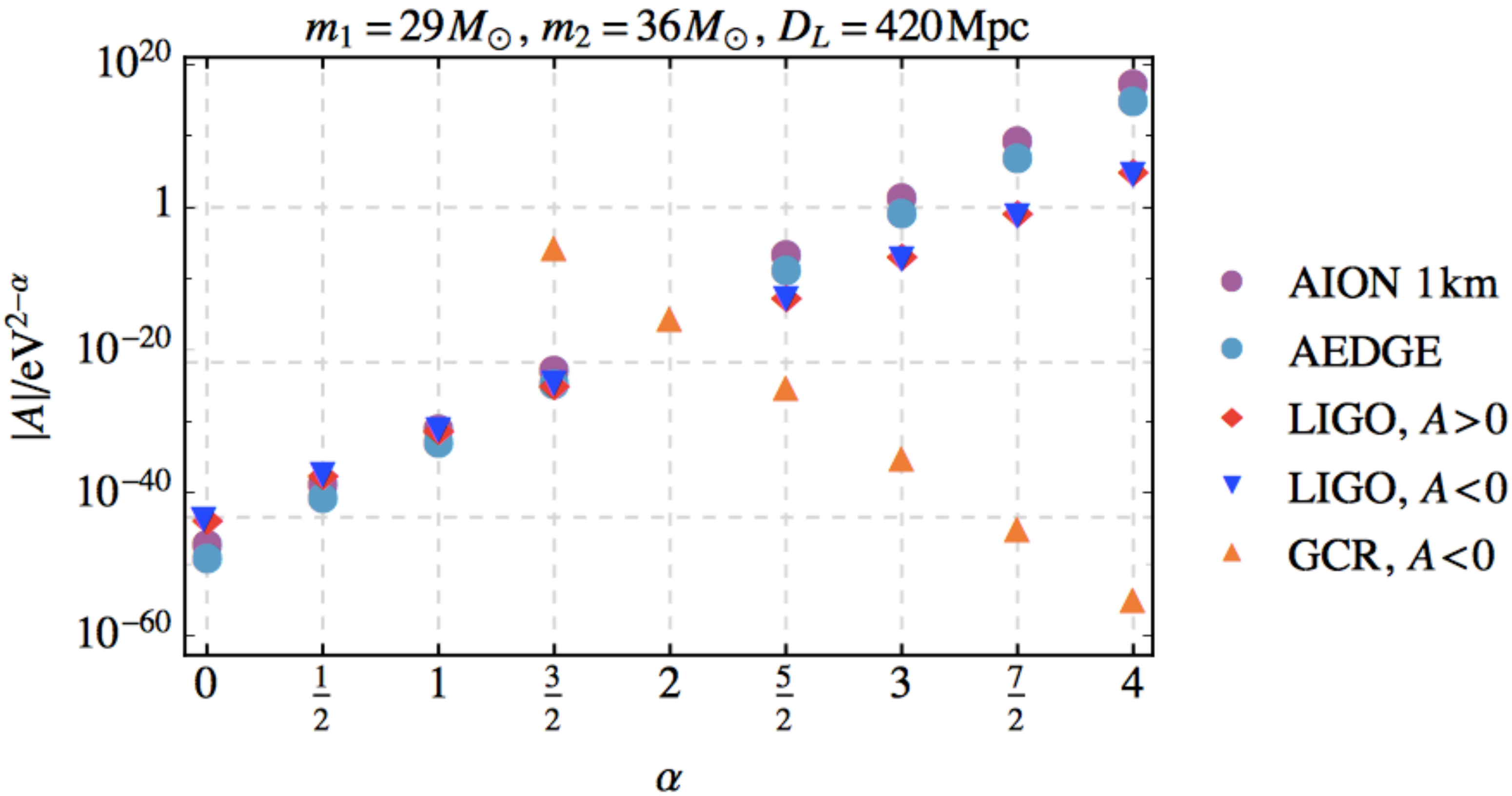




JE & Vaskonen: arXiv:2003.13480

Lorentz Violation

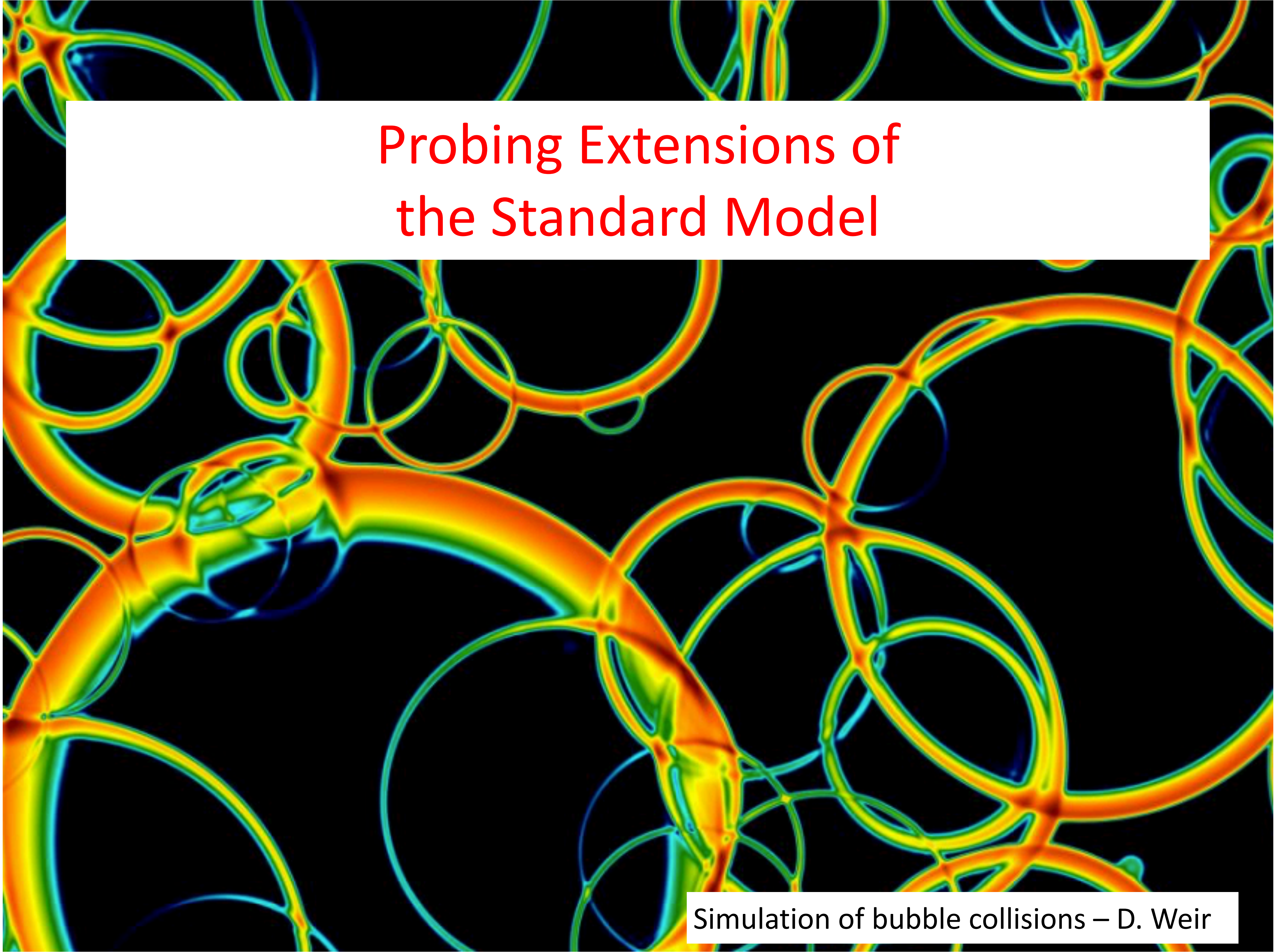
- Modified dispersion relation: $E^2 = p^2 + Ap^\alpha$



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

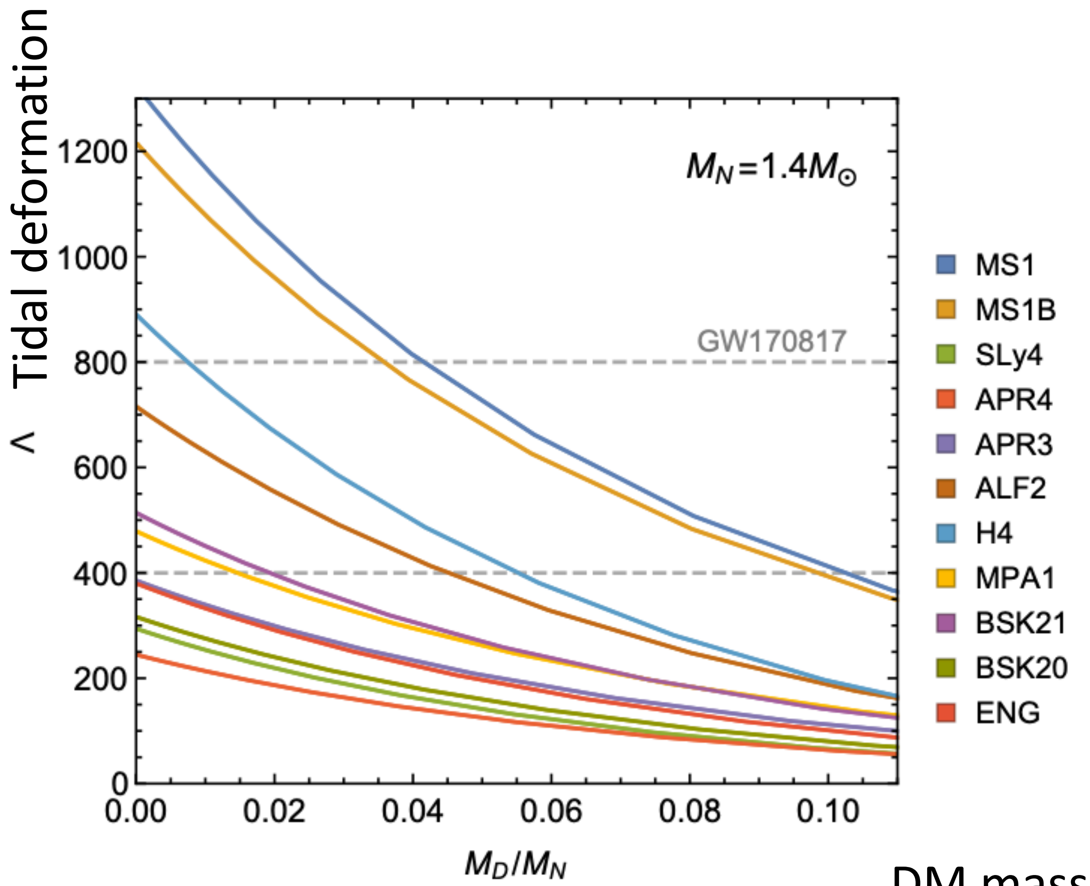
JE & Vaskonen: arXiv:2003.13480

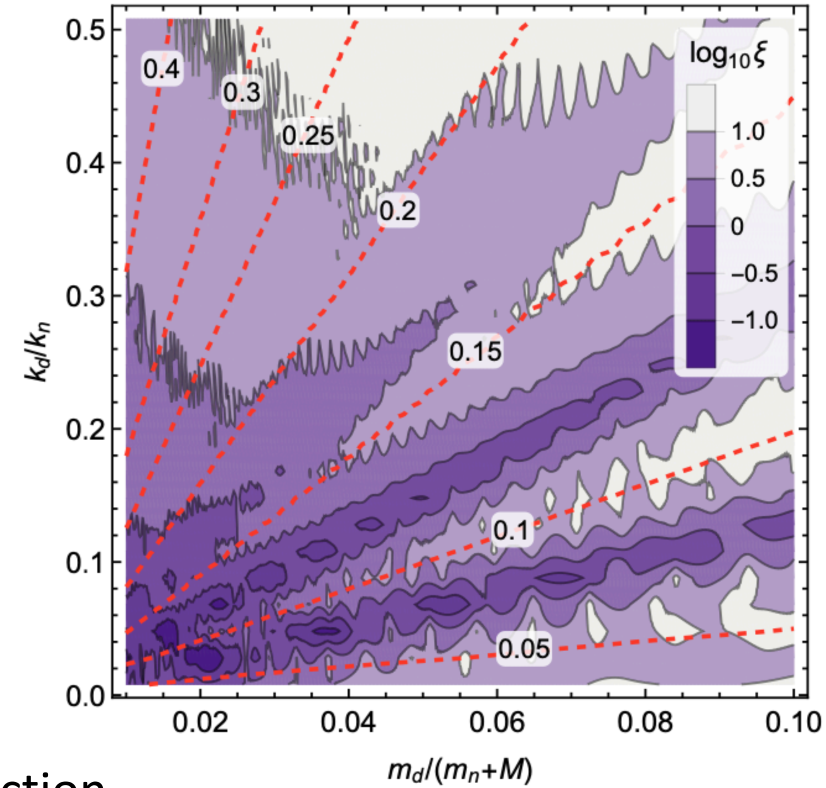
Probing Extensions of the Standard Model



Simulation of bubble collisions – D. Weir

Dark Matter Effects in Neutron-Star Mergers?





DM mass fraction

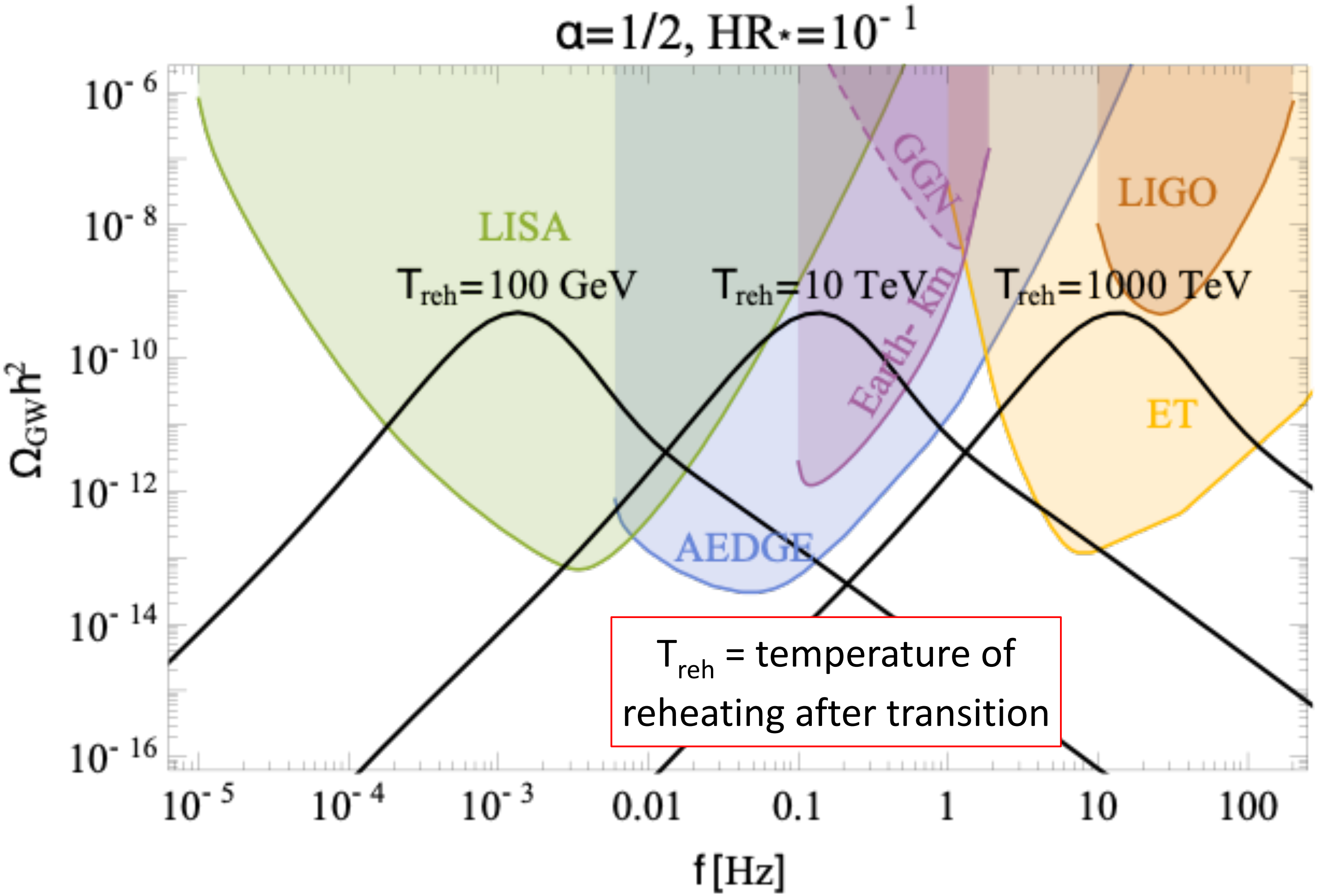
(Very) large DM fraction could have measurable effect on equation of state, give additional feature in GW spectrum

JE, Hektor, Hütsi, Kannike, Marzola, Raidal & Vaskonen: arXiv:1710.05540, arXiv:1804.01418

GWs from a First-Order Phase Transition

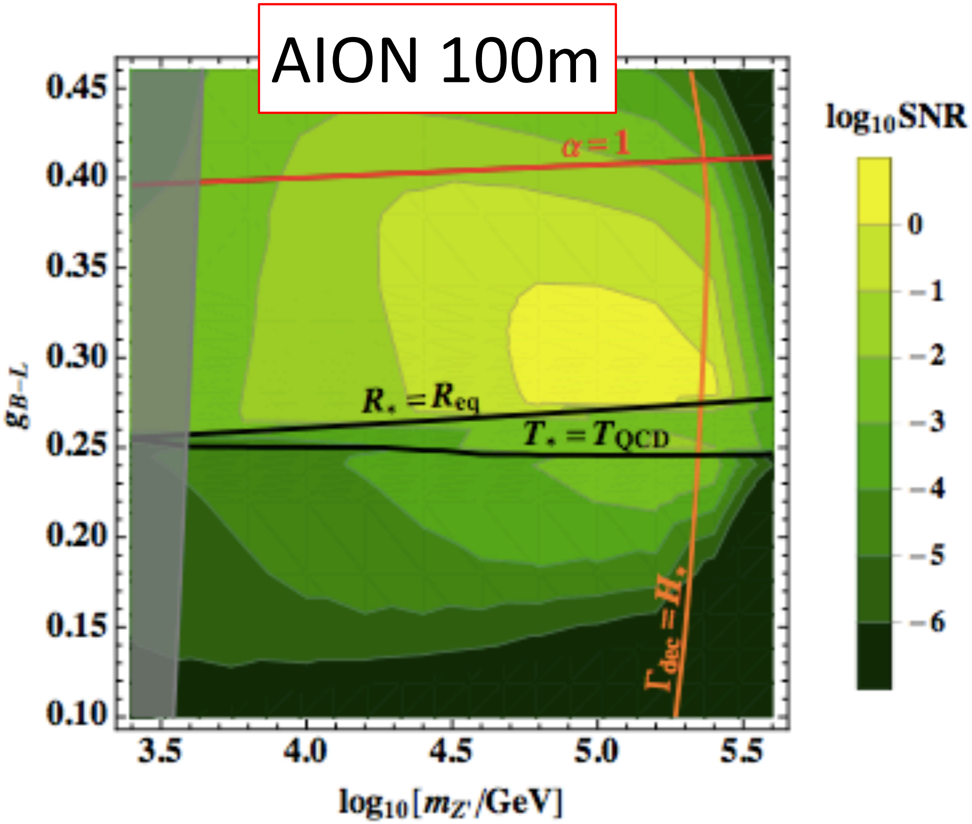
- Transition by percolation of bubbles of new vacuum
- Bubbles grow and collide
- Possible sources of GWs:
  - Bubble collisions
  - Turbulence and sound waves in plasma
- Models studied:
  - Standard Model + H^6/Λ^2 interaction
  - Standard Model + $U(1)_{B-L}$ Z'
- These also have prospective collider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

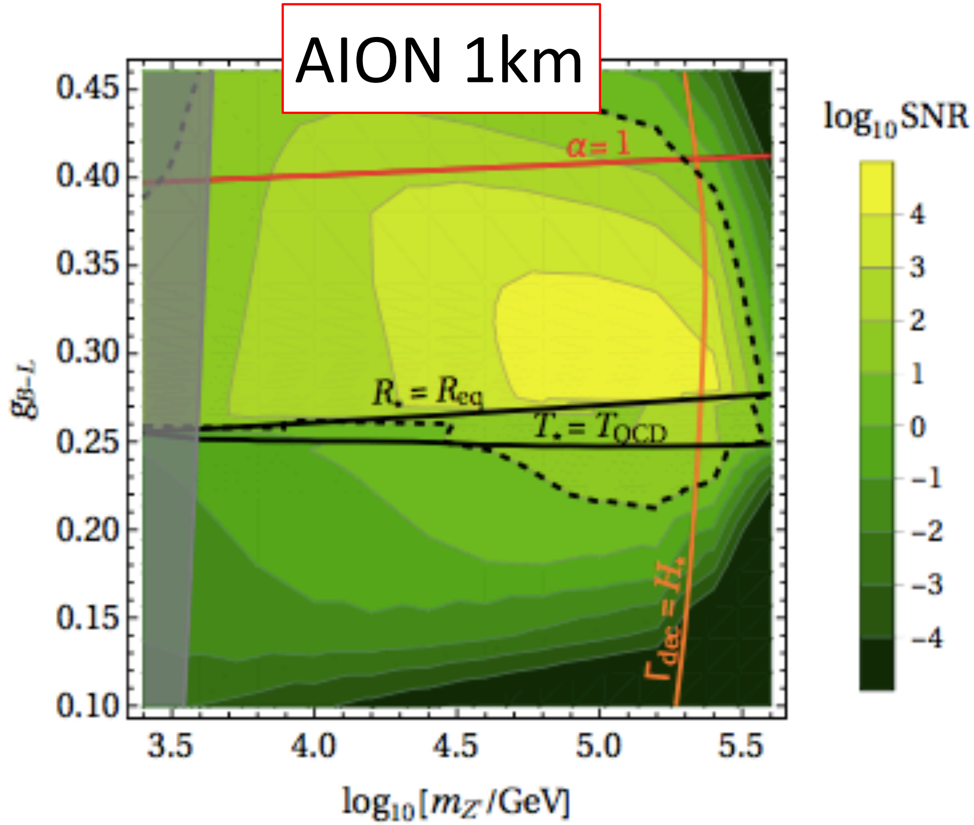
Gravitational Waves from $U(1)_{B-L}$ Phase Transition



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

AION GW SNR in $U(1)_{B-L}$ Model





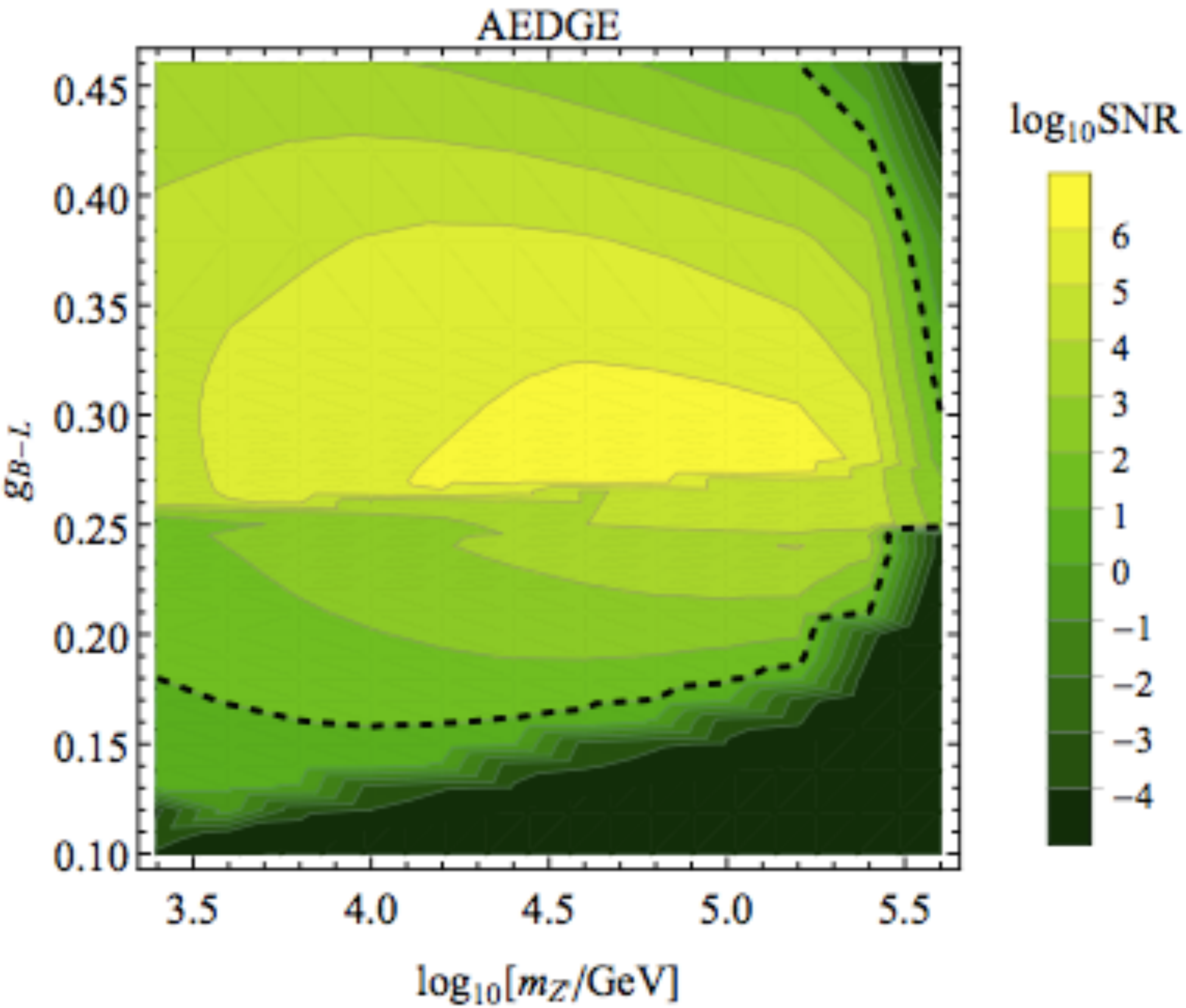
Discovery of GW possible with AION 1km

Above red line: transition before vacuum energy dominates
Right of orange line: period of matter domination

JE, Lewicki, No & Vaskonen, arXiv:1903.09642

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

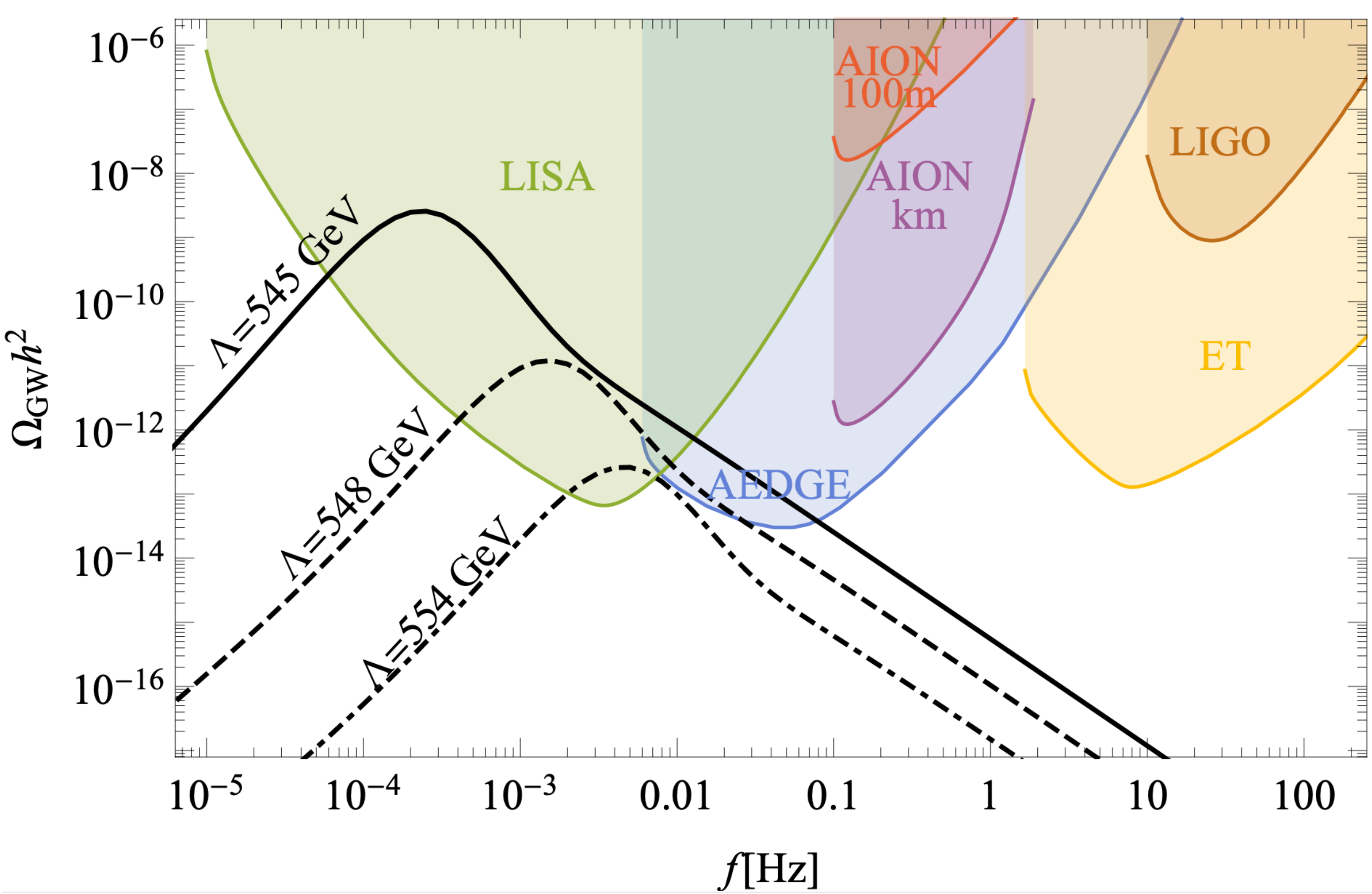
Sensitivity to $U(1)_{B-L}$ Z'



GW discovery sensitivity beyond $m_{Z'}$ = 100 TeV

GW Signal in H^6 Model

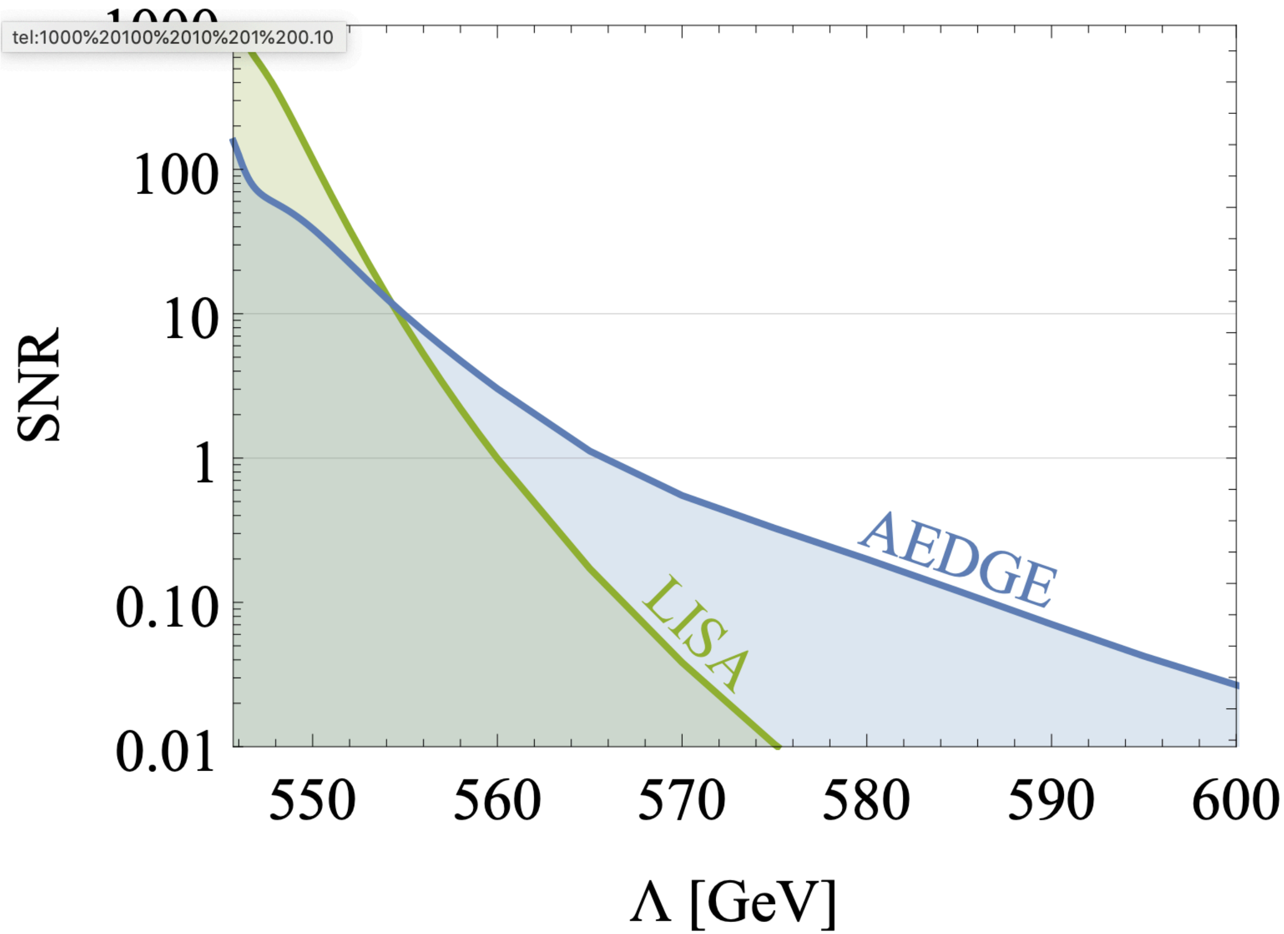
- Strongest signal for which percolation is assured



- AEDGE and LISA sensitivities very similar

JE, Lewicki, No & Vaskonen, arXiv:1903.09642

Gravitational Wave Sensitivity to Scale of H^6 Interaction

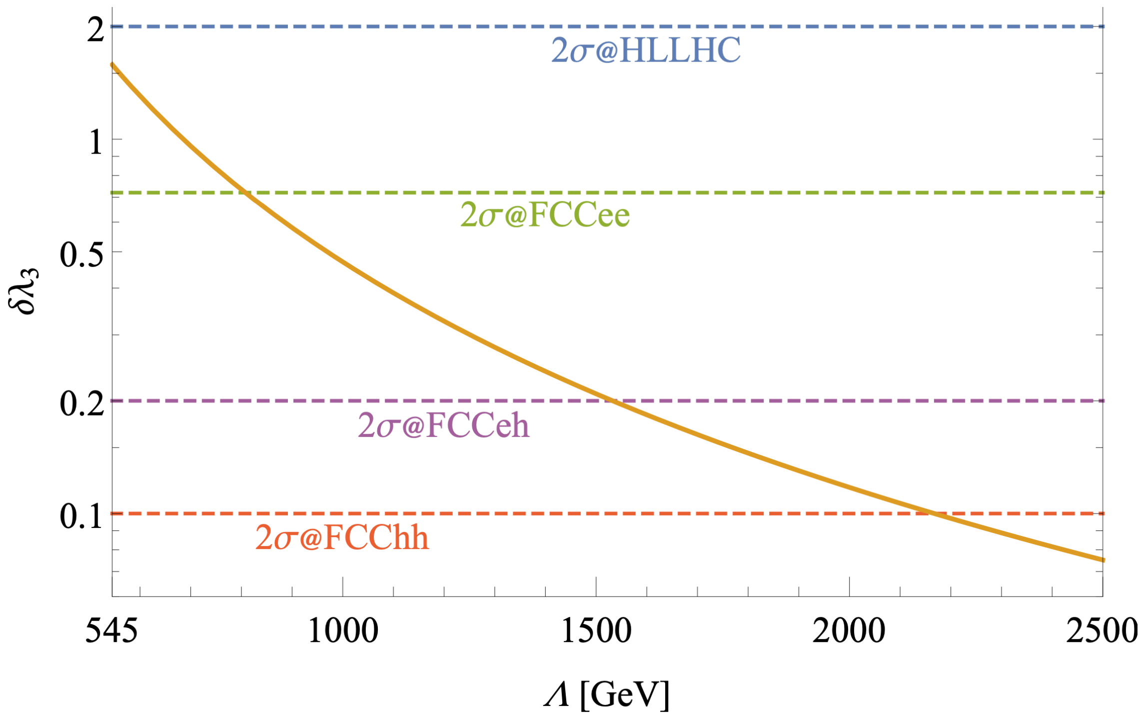


Gravitational wave sensitivity to Λ

JE, Lewicki & No, arXiv:1809.08242

Modification of Triple-H Coupling

- Current LHC data insensitive to H^6/Λ^2 coupling
- Future collider sensitivity via modification of triple-Higgs coupling λ_3

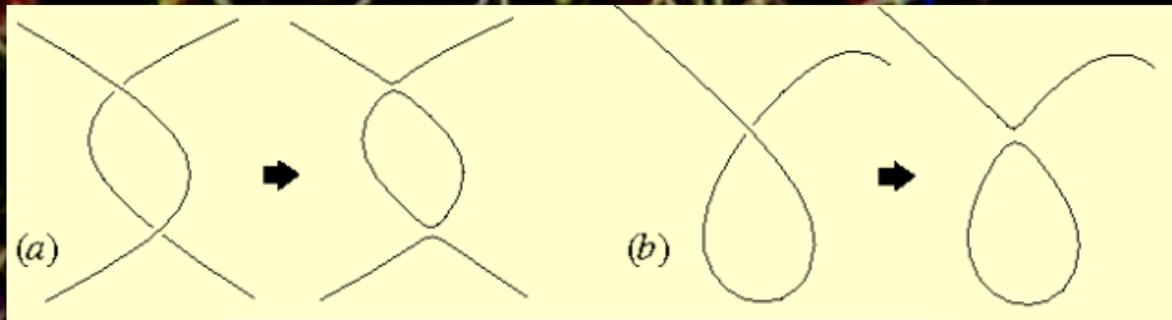


Collider sensitivity will be > gravitational waves

JE, Lewicki & No, arXiv:1809.08242

Probing Cosmic Strings

Hint from the NANOGrav pulsar timing array?

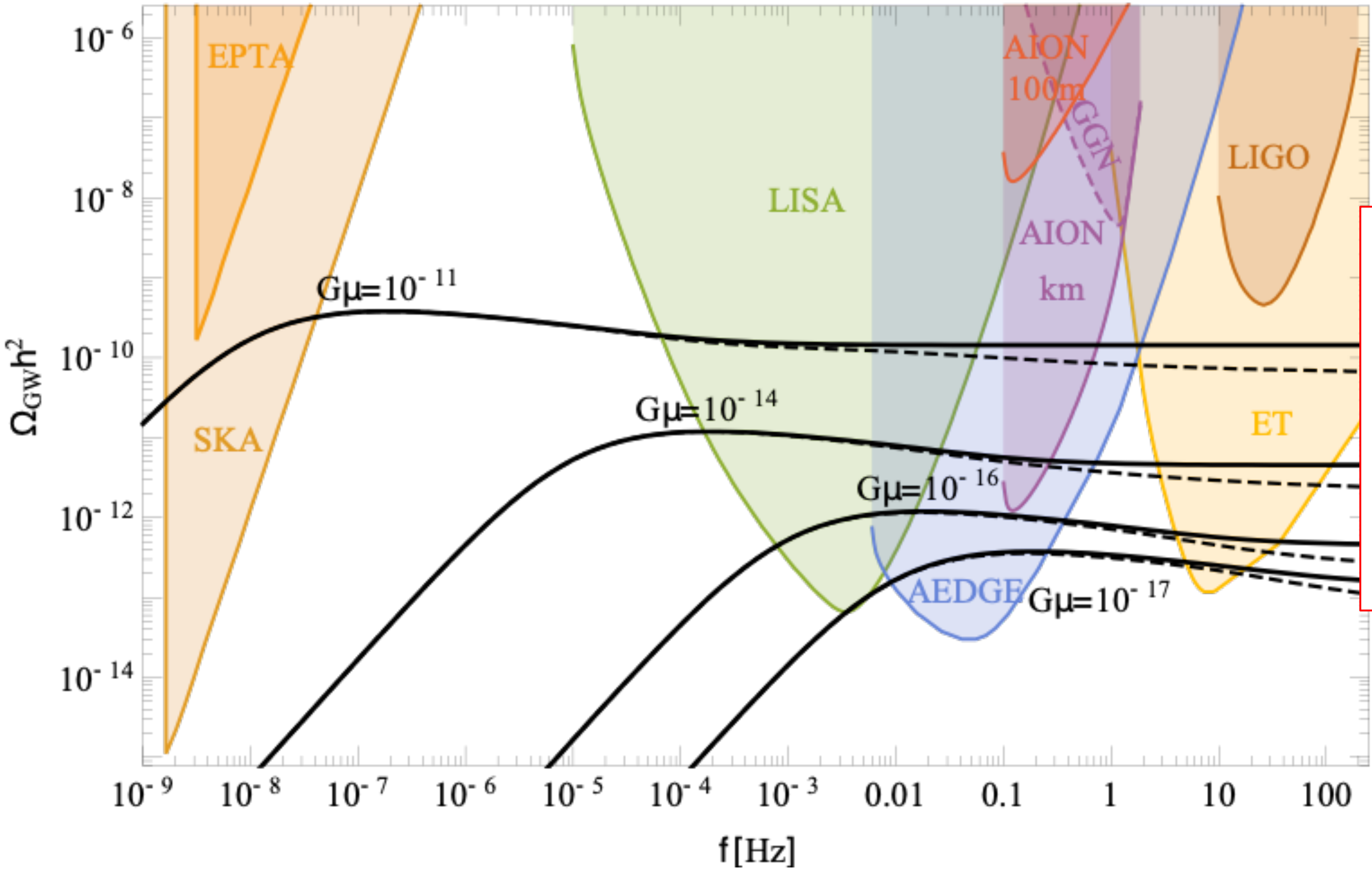


GW emission from string loops

Simulation of cosmic string network – Cambridge cosmology group

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

Gravitational Waves from Cosmic Strings



Effect of change in degrees of freedom In SM

——

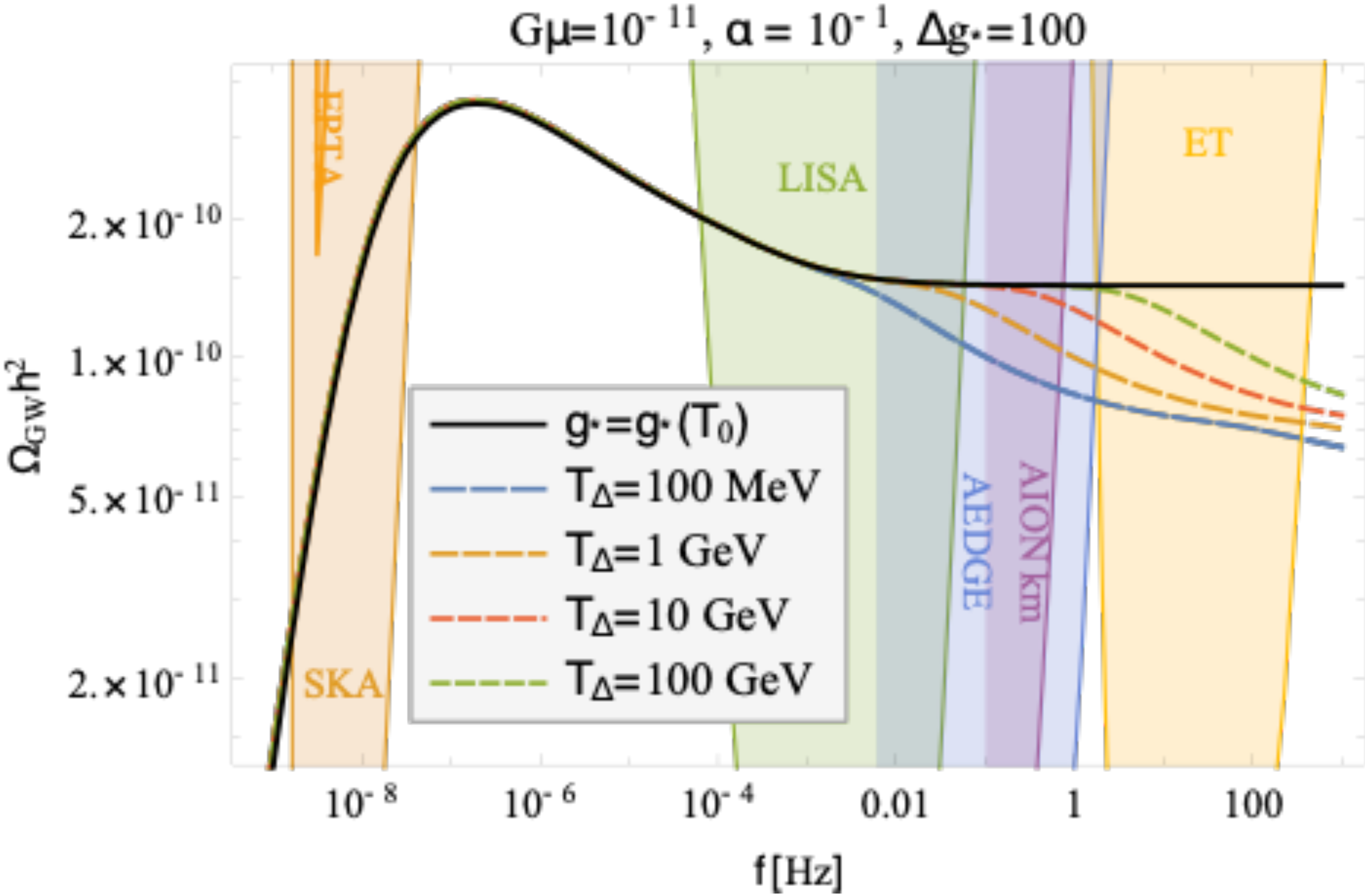
- - -

Spectrum ~ flat from PTA/SKA to LIGO/ET

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

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

Gravitational Waves from Cosmic Strings

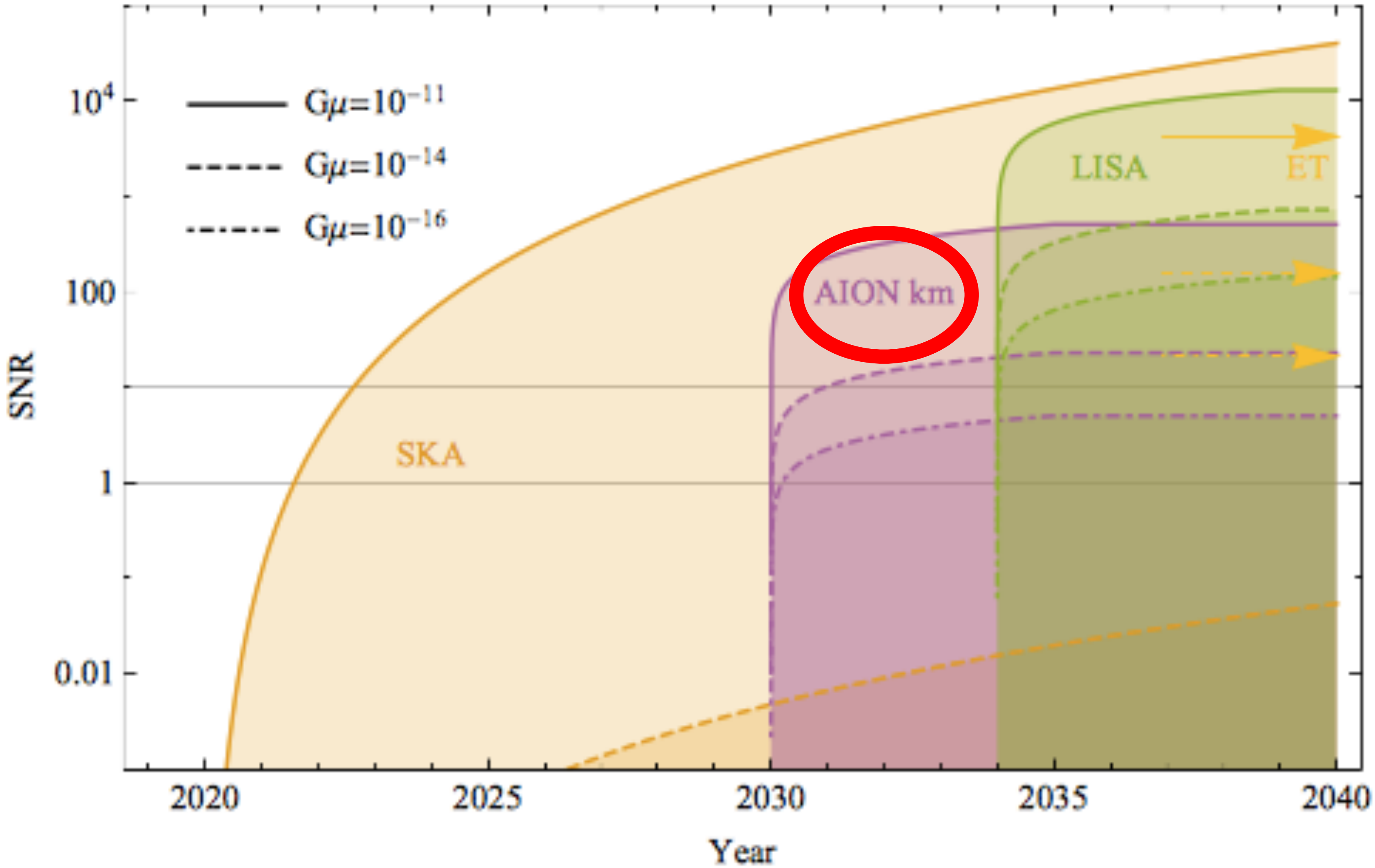


Sensitive to changes in # of degrees of freedom

1% measurement of spectrum = Δ# d.o.f. = 2

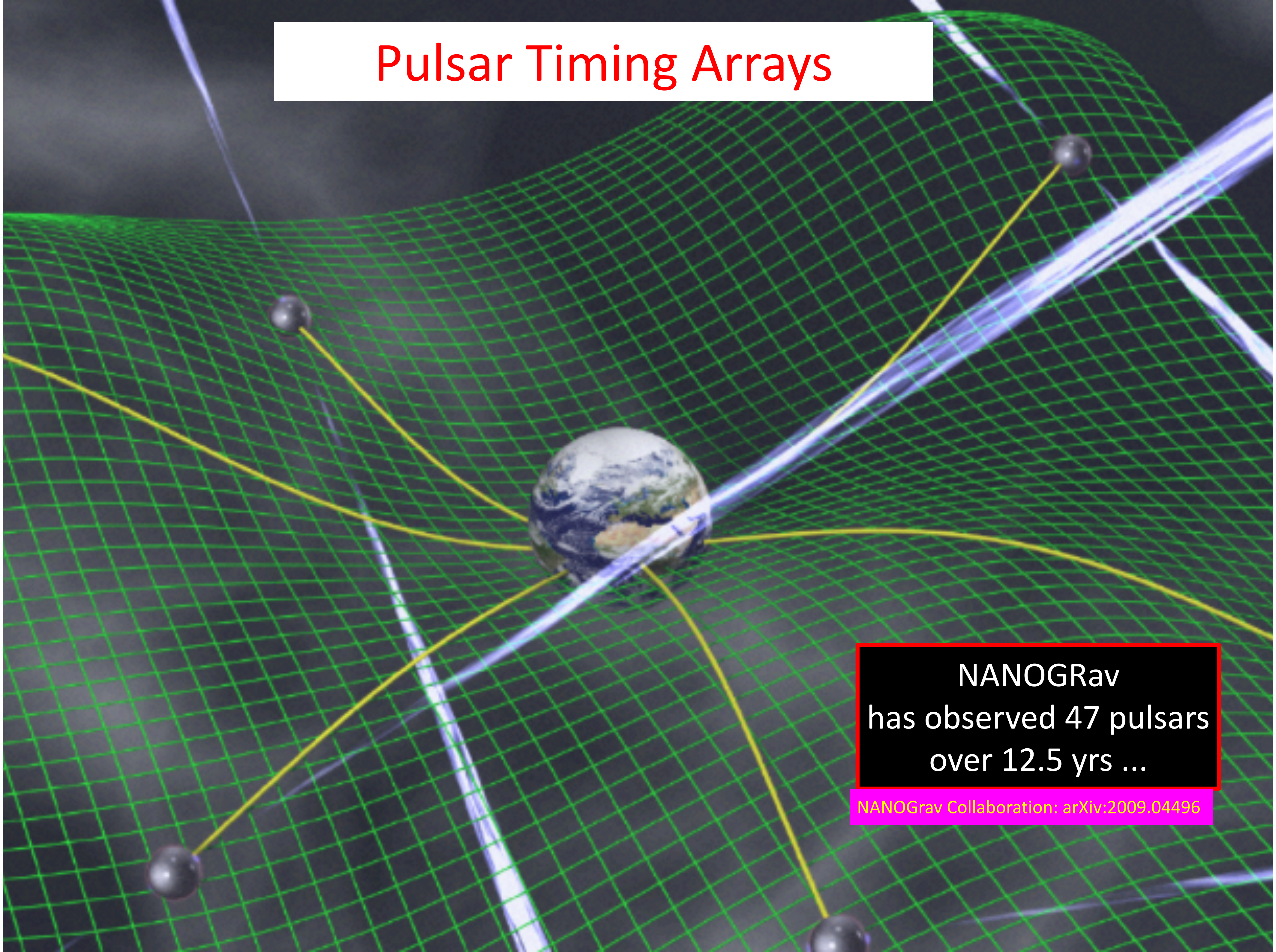
Probe expansion history of early universe

Perspectives for Future Experiments



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

Pulsar Timing Arrays



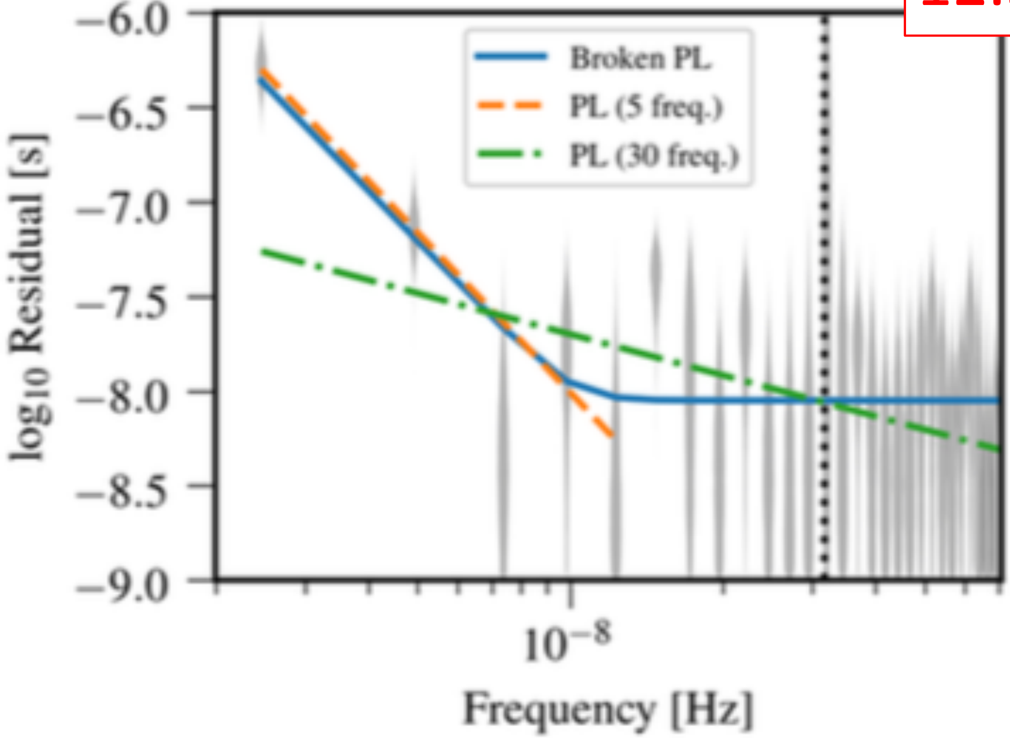
NANOGRav
has observed 47 pulsars
over 12.5 yrs ...

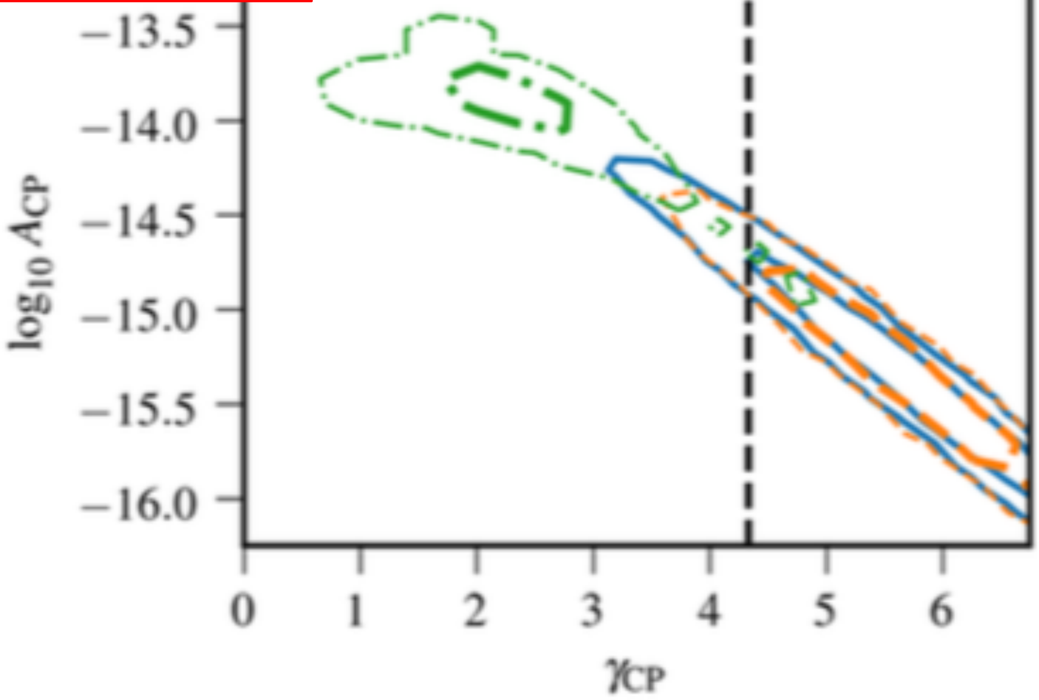
NANOGrav Collaboration: arXiv:2009.04496

NANOGrav Collaboration: arXiv:2009.04496

Pulsar Timing Data from NANOGrav

12.5-year data





NANOGrav reports
"strong evidence for a stochastic common-spectrum process"
at frequencies < 10^{-8} Hz
No dipole or quadrupole signal detected

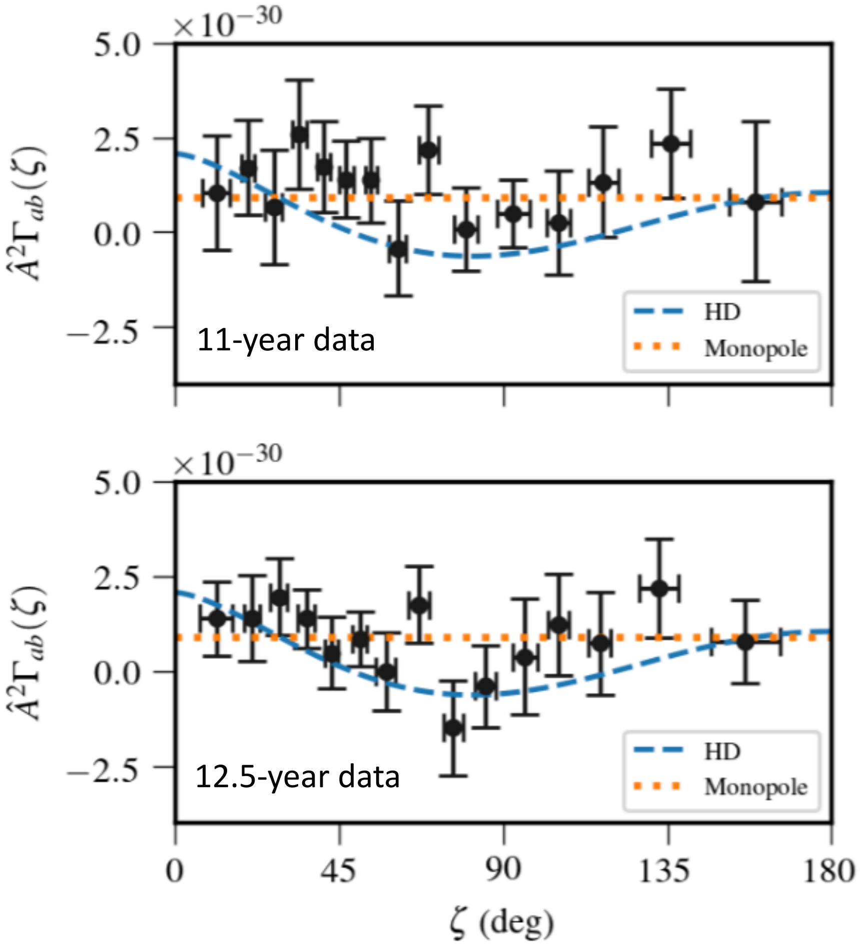
Fits to amplitude of signal
Focus on simple power law
Amplitude A ~ 10^{-15}
Slope γ ~ 5

Default model

Vertical dashed line: simple model of mergers of supermassive BHs

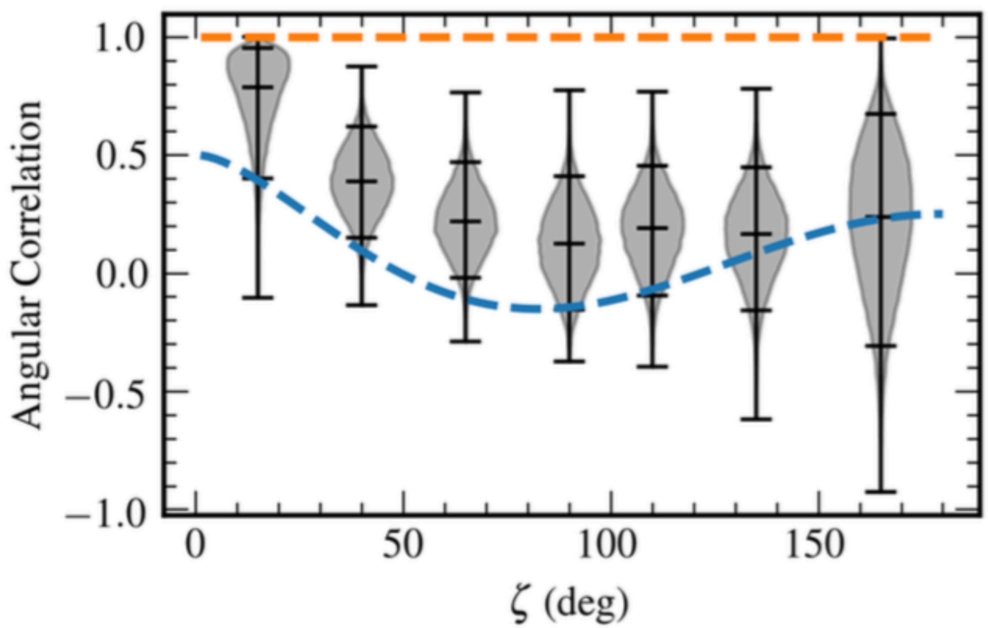
NANOGrav Collaboration: arXiv:2009.04496

Pulsar Timing Data from NANOGrav



Average angular distribution of cross-correlated power

Improved treatment of intrinsic pulsar red noise in 12.5-yr data compared to 11-yr data



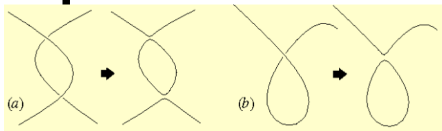
Reconstruction of inter-pulsar angular correlations compared with GWs

JE & Lewicki: arXiv:2009.06555

Calculation of GWs from Cosmic Strings

- Network of strings produces small loops:

$$\ell = \alpha_\ell t_i - \Gamma G\mu (t - t_i)$$



- Loops emit at normal mode frequencies:

$$f = \frac{a(\tilde{t})}{a(t_0)} \frac{2k}{\alpha_\ell t_i - \Gamma G\mu(\tilde{t} - t_i)}$$

- Density of GWs: $\Omega_{GW}^{CS}(f) = \sum_k \Omega_{GW}^{(k)}(f)$ where

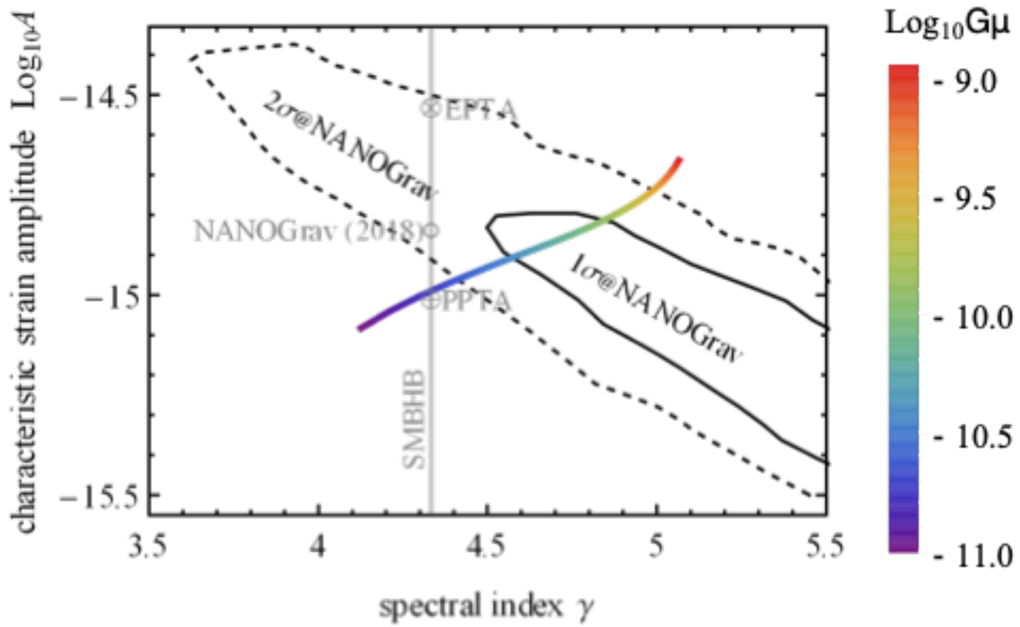
$$\Omega_{GW}^{(k)}(f) = \frac{16\pi k}{3H_0^2 f} \frac{(0.1)\,\Gamma_k (G\mu)^2}{\alpha_\ell(\alpha_\ell + \Gamma G\mu)} \int_{t_F}^{t_0} d\tilde{t}\, \frac{C_{eff}(t_i)}{t_i^4} \left(\frac{a(\tilde{t})}{a(t_0)}\right)^5 \left(\frac{a(t_i)}{a(\tilde{t})}\right)^3 \Theta(t_i - t_F)$$

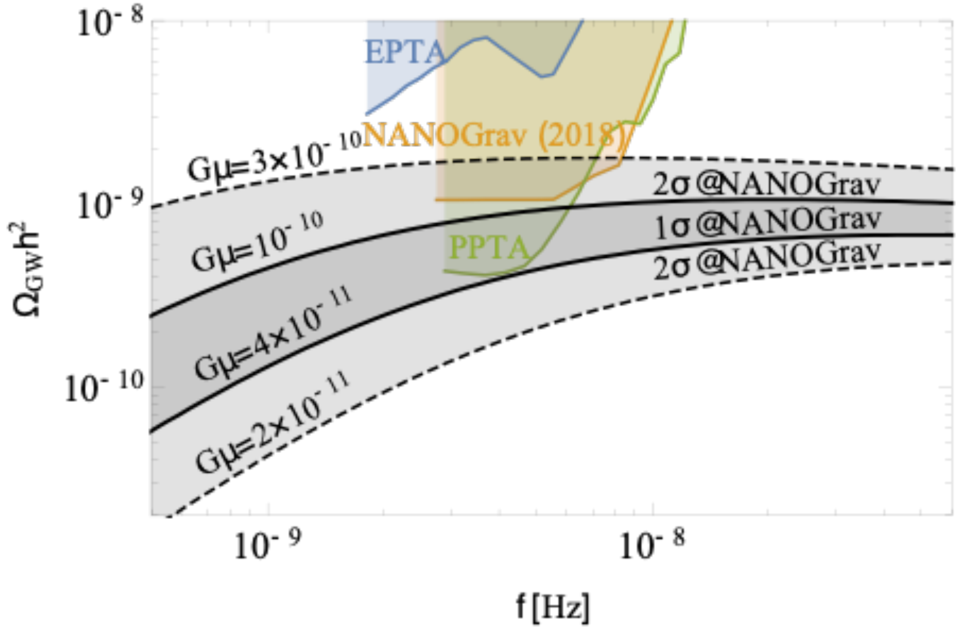
and $\Gamma^{(k)} = \Gamma k^{-\frac{4}{3}} / (\sum_{m=1}^{\infty} m^{-\frac{4}{3}})$ with $\Gamma = 50$ & where

- $C_{eff} = 5.4$ and 0.39 during radiation and matter domination (from Velocity-dependent One-Scale Model), factor 0.1 from simulations

JE & Lewicki: arXiv:2009.06555

Cosmic String Interpretation of NANOGrav



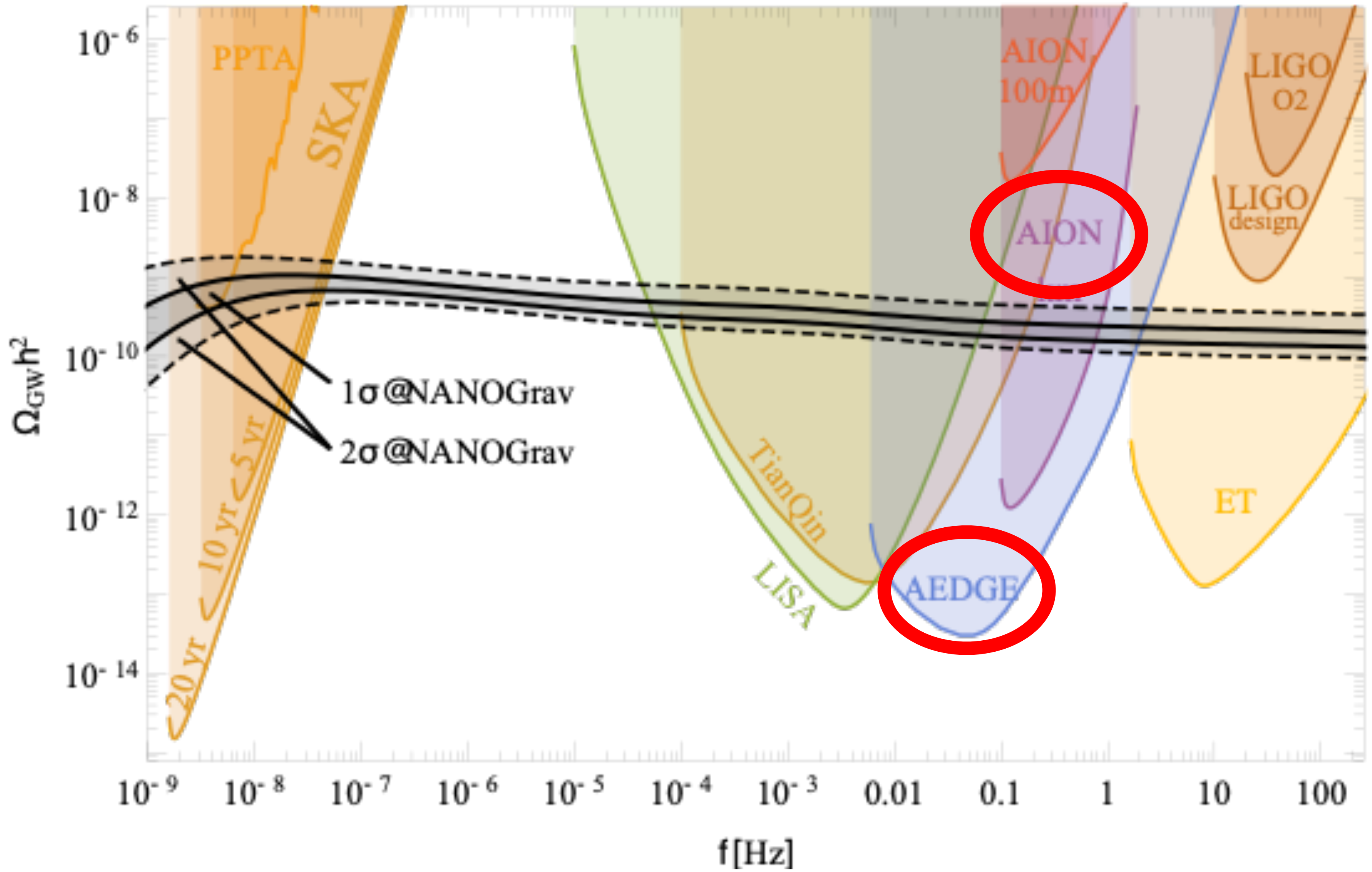


"Rainbow curve"
is cosmic string prediction as a
function of the cosmic string tension Gμ
Vertical line is naïve SMBH merger prediction
Previous PTA upper limits for
this value of γ

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)

See also Blasi, Vrdar & Schmitz: arXiv:2009.06607v2

Fundamental Physics
Beyond Gravitational Waves

- Atom interferometers can search for ultralight dark matter
- High-precision measurement of the gravitational redshift, probes of Bell inequalities and the equivalence principle
- Probing fundamental "constants", chameleons, dark energy
- Fundamental (≠ environmental) decoherence?
- .....