Gravitational Waves: Echoes of the Biggest Bangs since the Big Bang

KING'S College LONDON

John Ellis

Outline

- Discovery of black hole binaries
- Measurements of neutron star mergers (kilonovae)
- Supermassive black holes: how to assemble them?
  - Atom interferometry AION
- Discovery of nanoHz GW background by Pulsar Timing Arrays (PTAs)
- Supermassive black hole binaries?
- **BSM scenarios fit NANOGrav data better than BH binaries!**

Gravitational Waves

- General relativity proposed by Einstein 1915
- He predicted gravitational waves in 1916

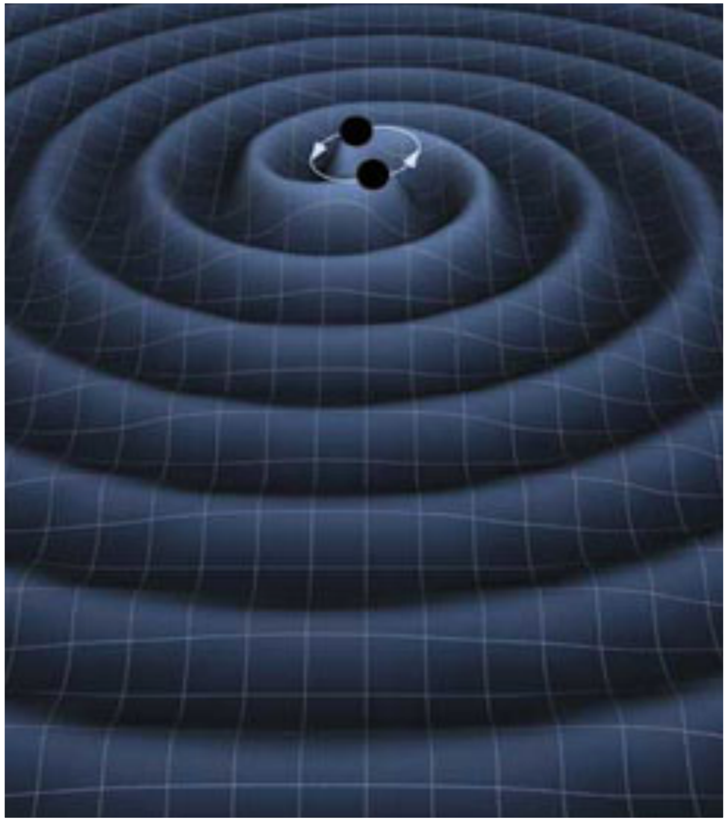
Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Prob
auf dem Gebiete der Gravitationstheorie kann man sich damit begn
die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich
Vorteil der imaginären Zeitvariable x_4 = it aus denselben Gründen
in der speziellen Relativitätstheorie. Unter »erster Näherung« ist d
verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu}$$

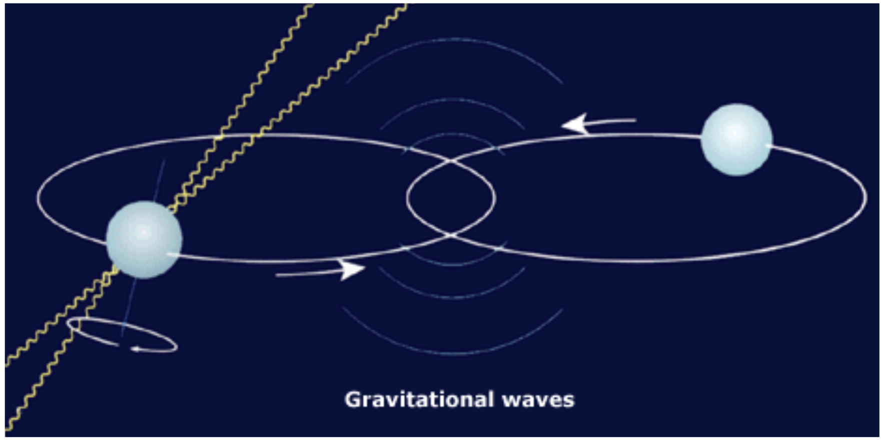
Albert Einstein, *Näherungsweise Integration der Feldgleichungen der Gravitation*, 22.6.Berlin 1916



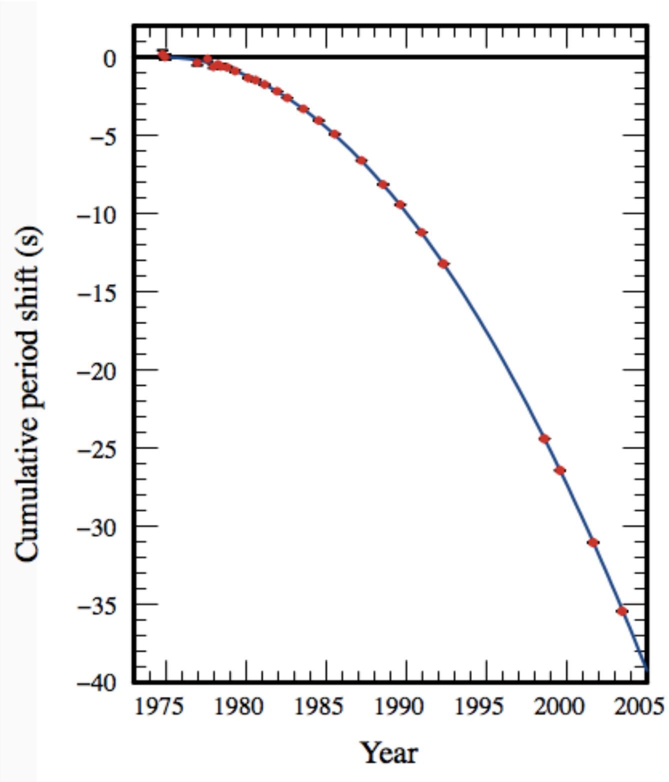
- Tried to retract prediction in 1936!

Indirect Detection

- Binary pulsar discovered 1974 (Hulse & Taylor)
- Emits gravitational waves
- Change in orbit measured



for years

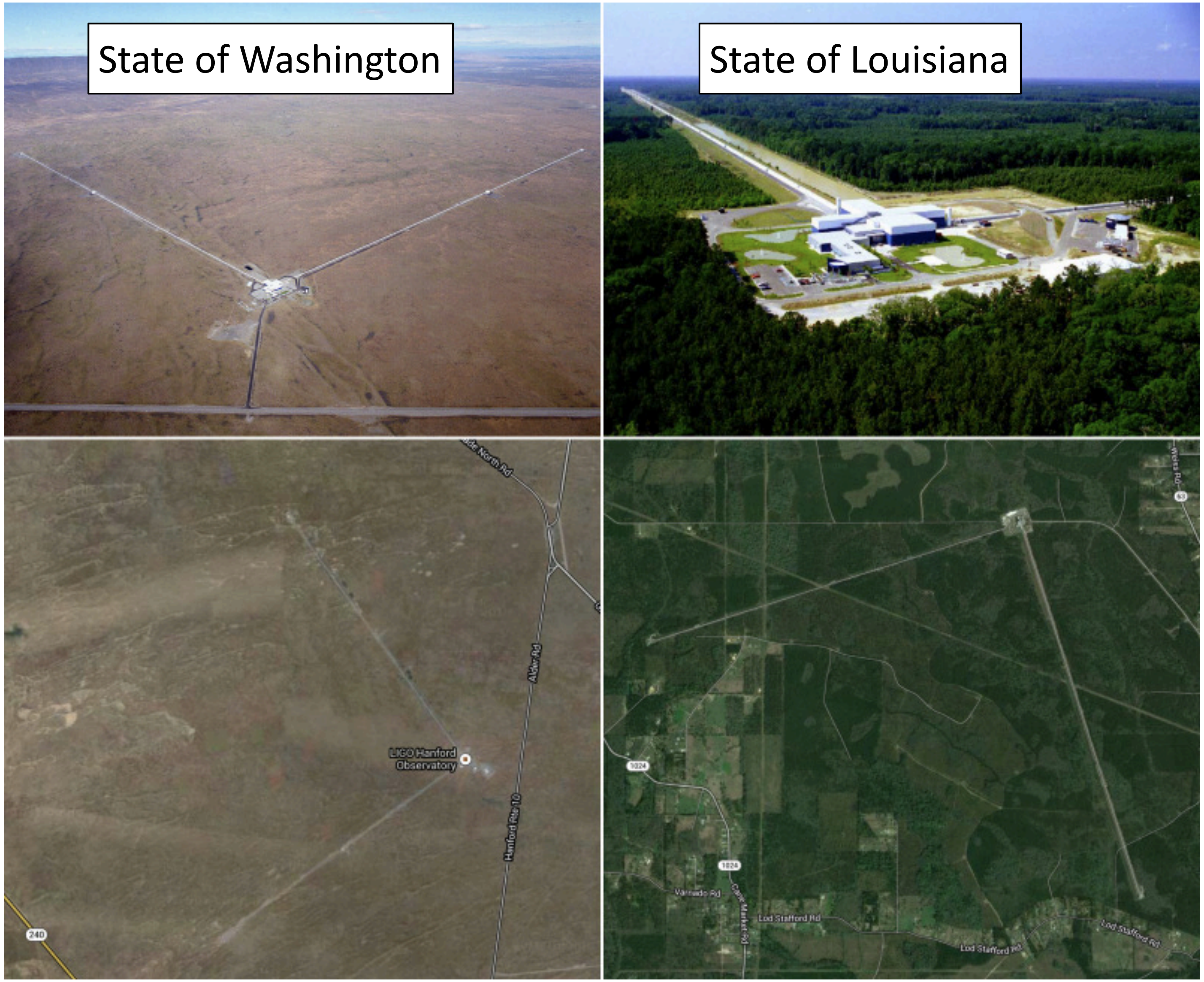


Perfect agreement with Einstein

Nobel Prize 1993

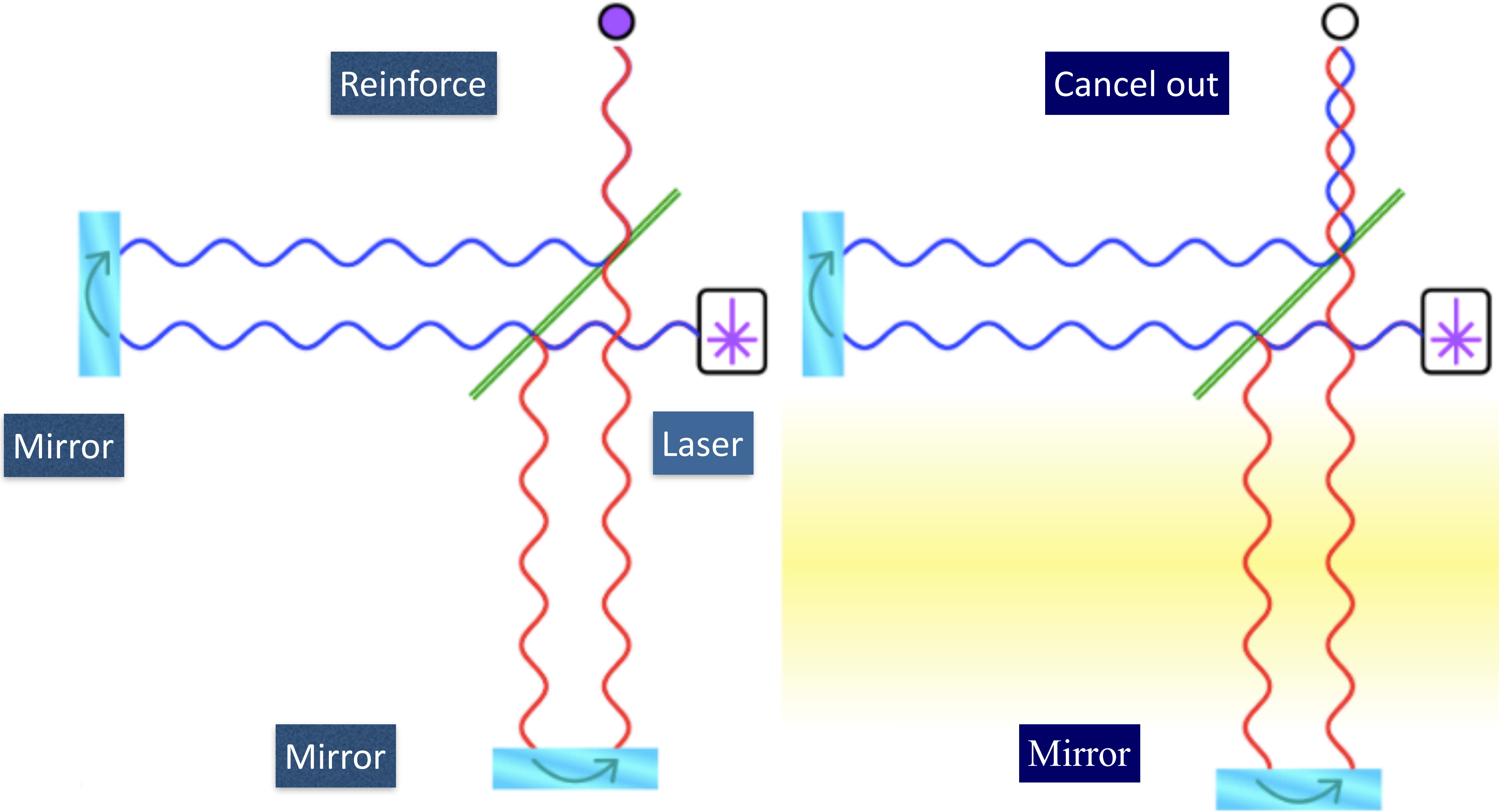
Direct Discovery of Gravitational Waves

- Measured by the LIGO experiment in 2 locations



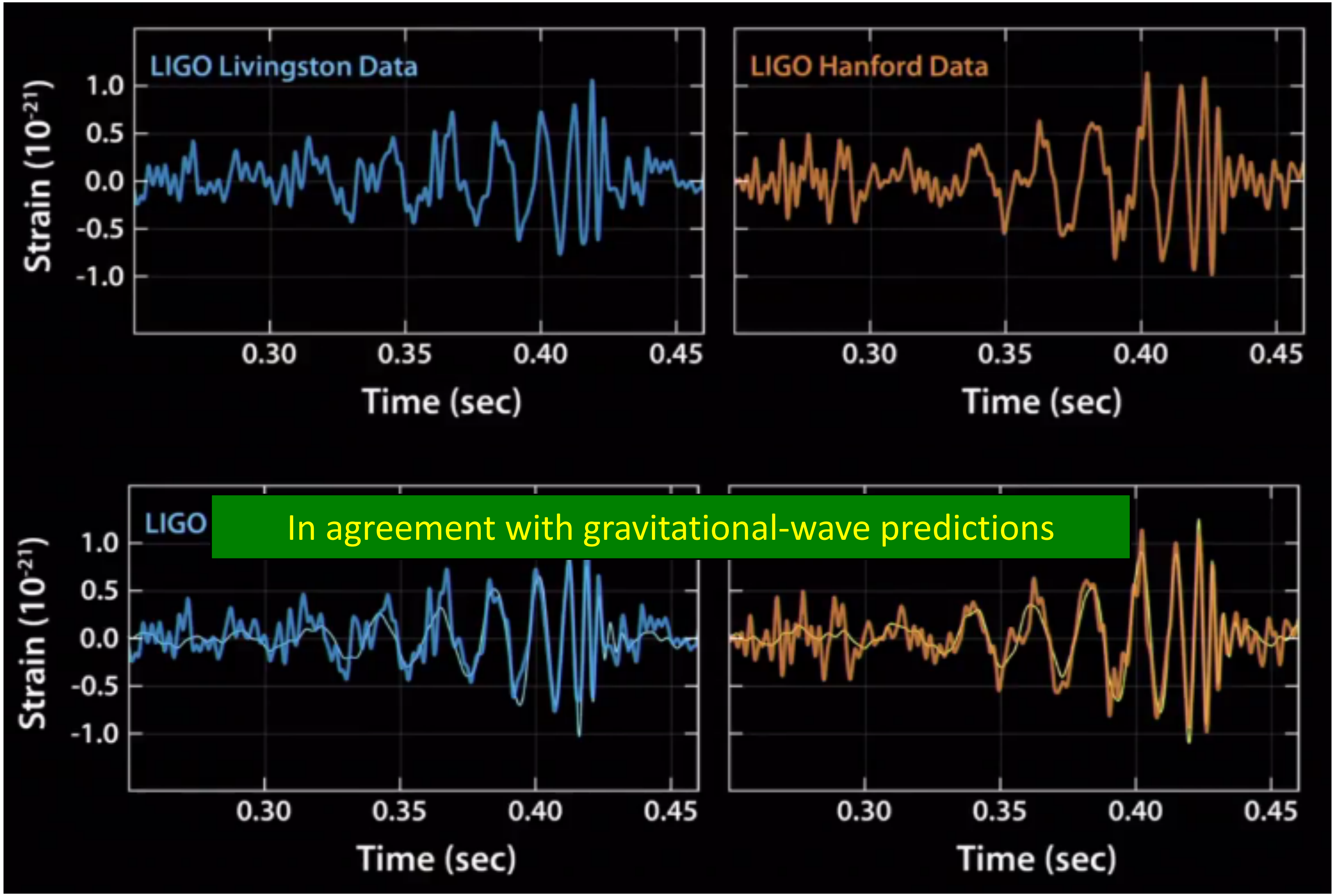
Principle of Laser Interferometers

Interference between 2 laser beams measures the expansion and contraction of space



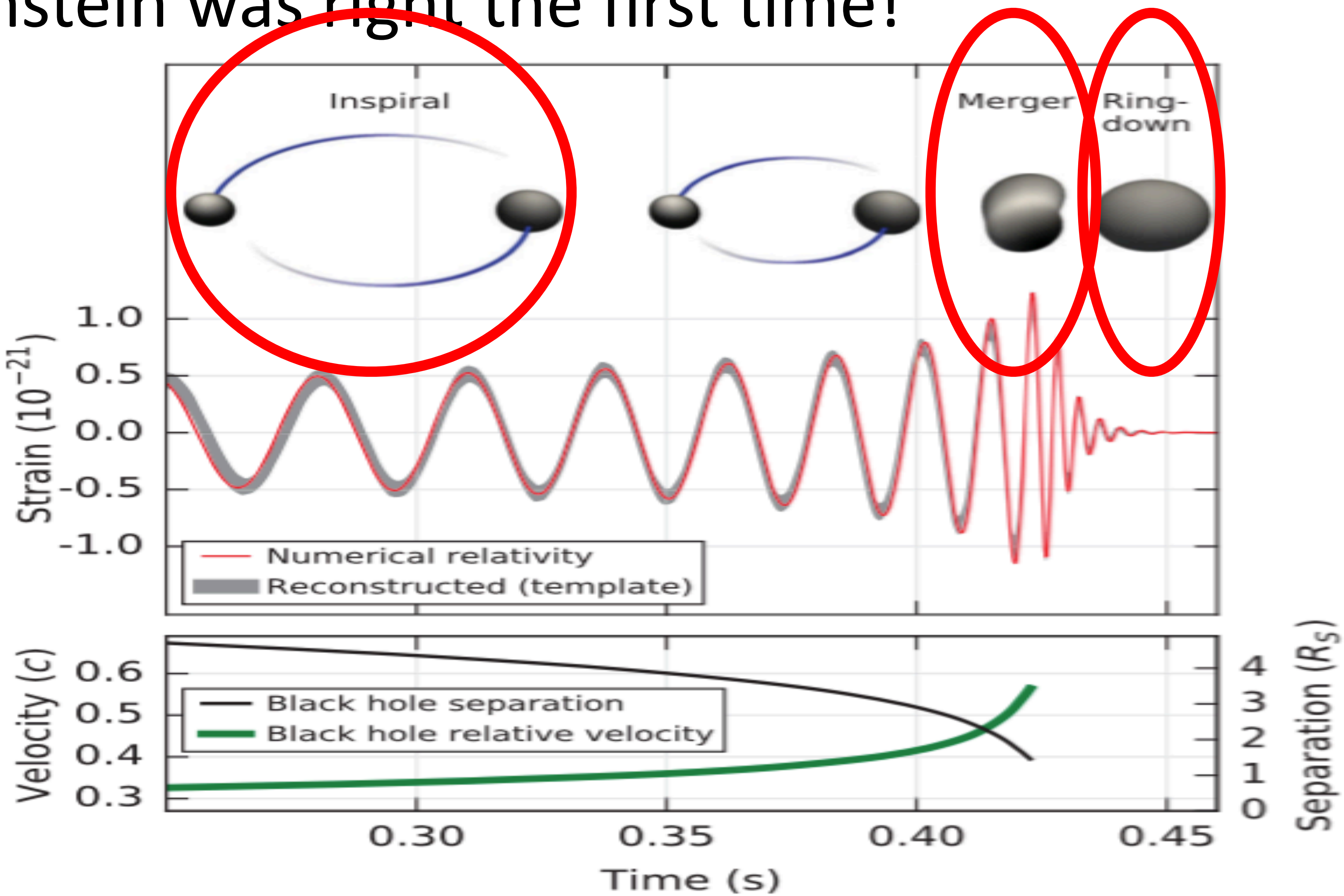
What was observed

- **Very similar signals in the 2 detectors**



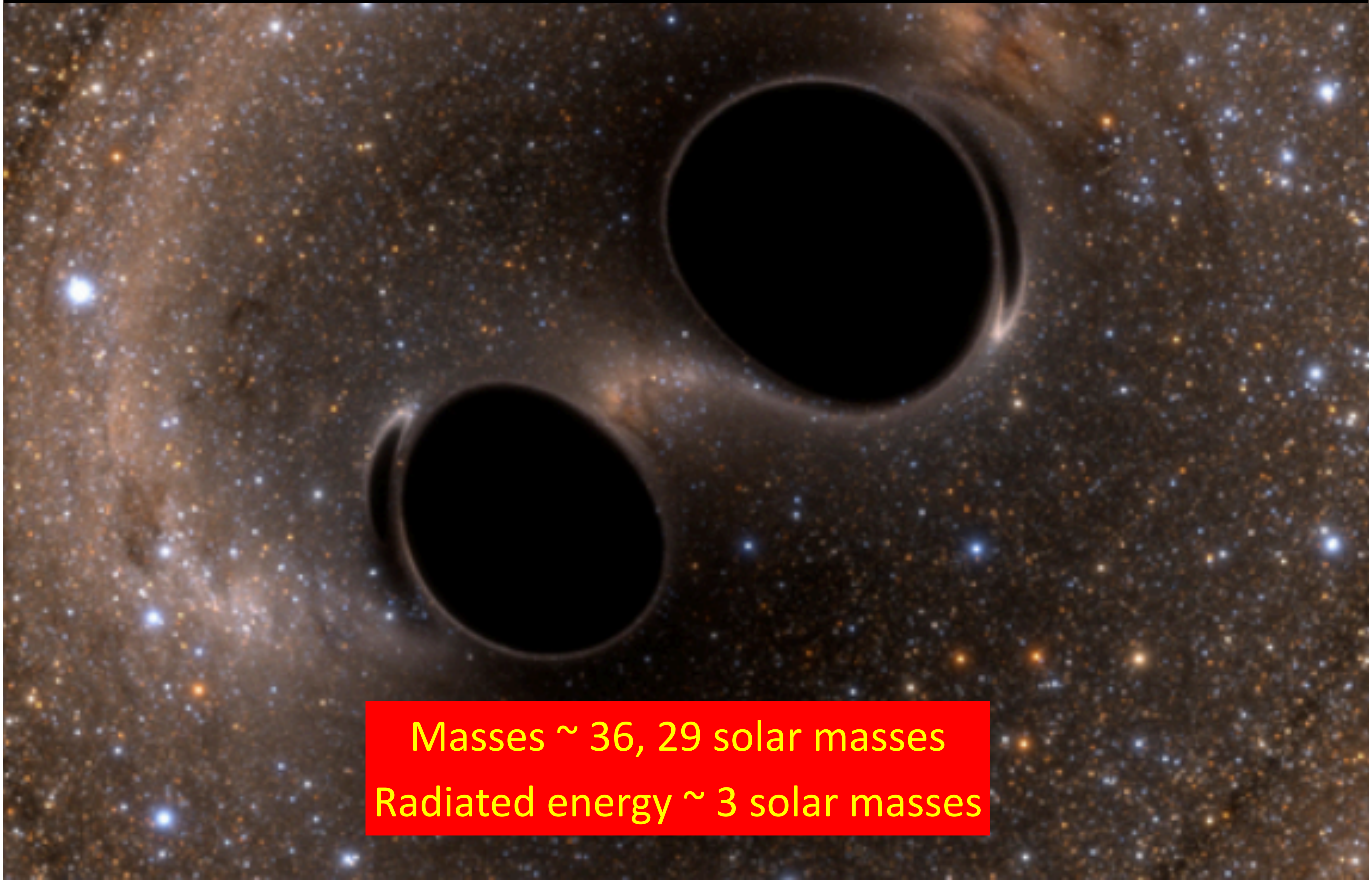
Fusion of two massive black holes

- Einstein was right the first time!



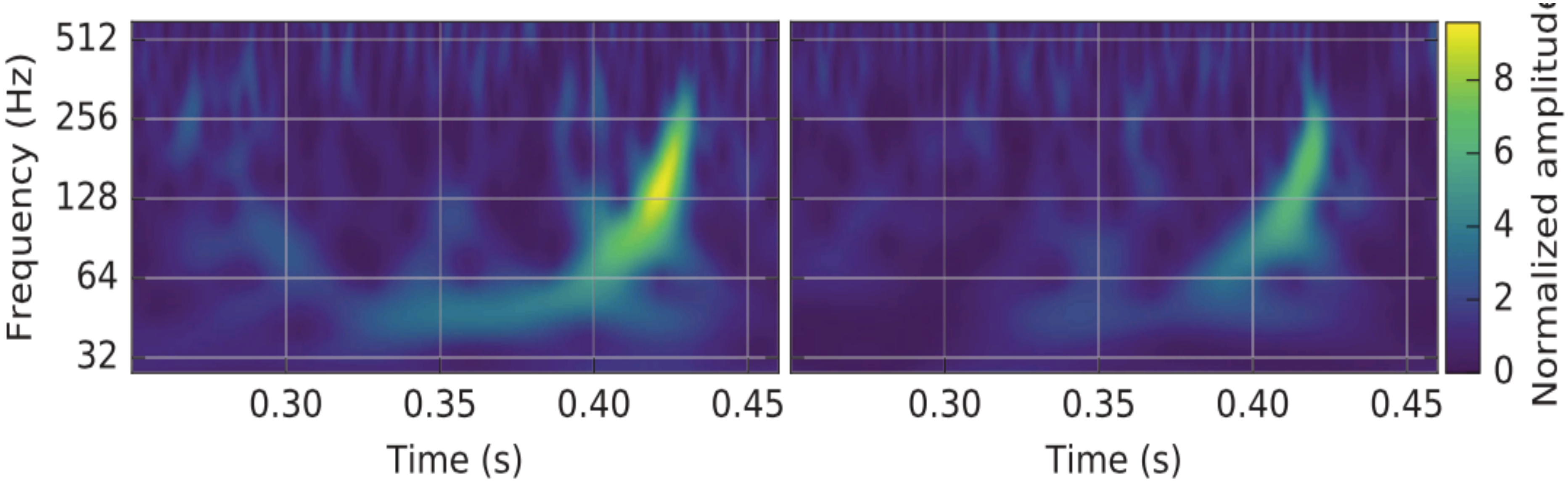
- A new way to study the Universe

Fusion of two massive black holes



The Gravitational Chirp …

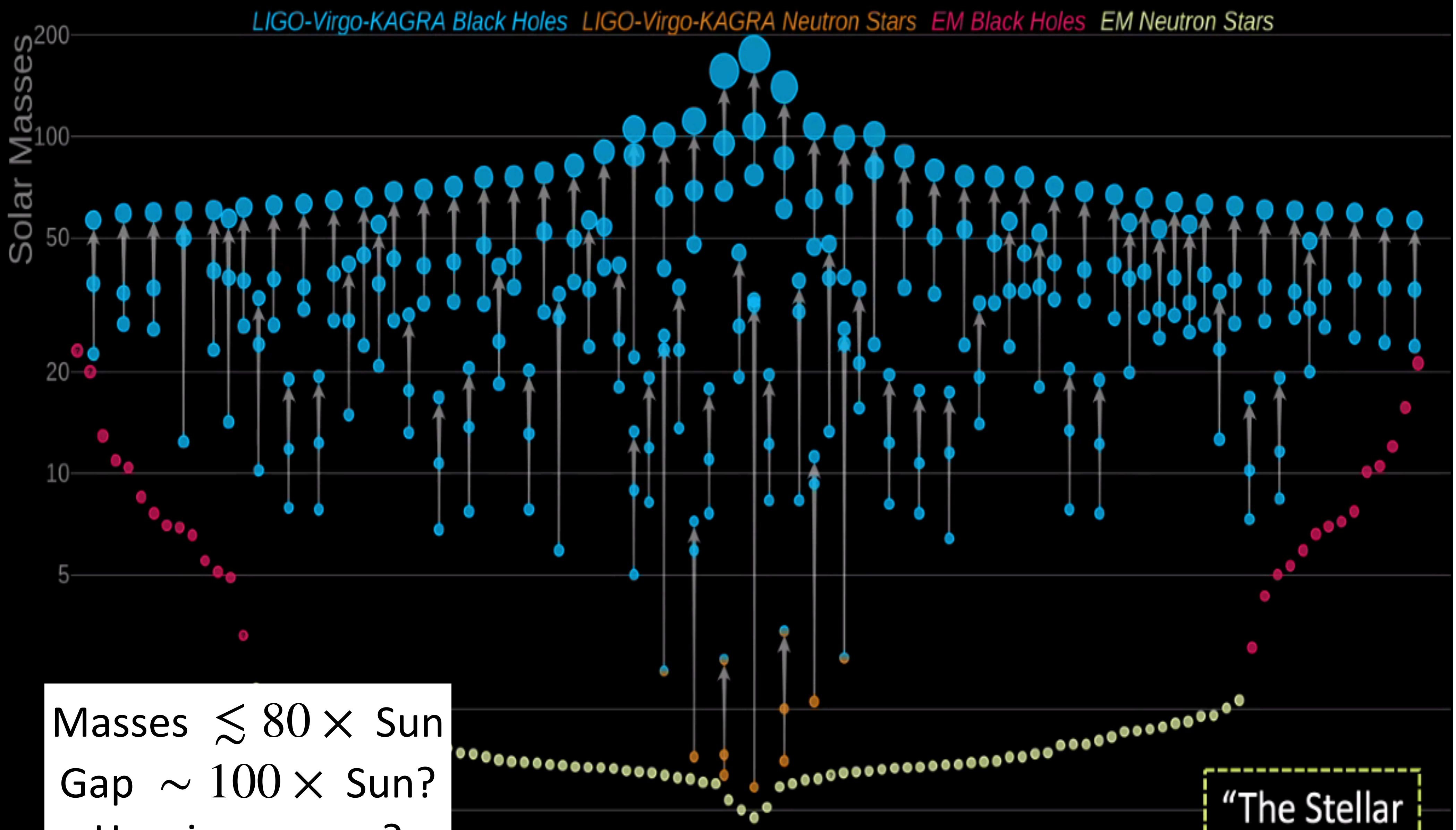
- … heard around the world



- Frequency increases with time during inspiral
- Followed by ringdown of combined black hole
- Graviton mass < 10^{-27} × mass of electron LIGO
- Waves of different frequencies have same speed

JE, Mavromatos & Nanopoulos, arXiv:1602.04764

LIGO-Virgo-KAGRA Black Holes & Neutron Stars

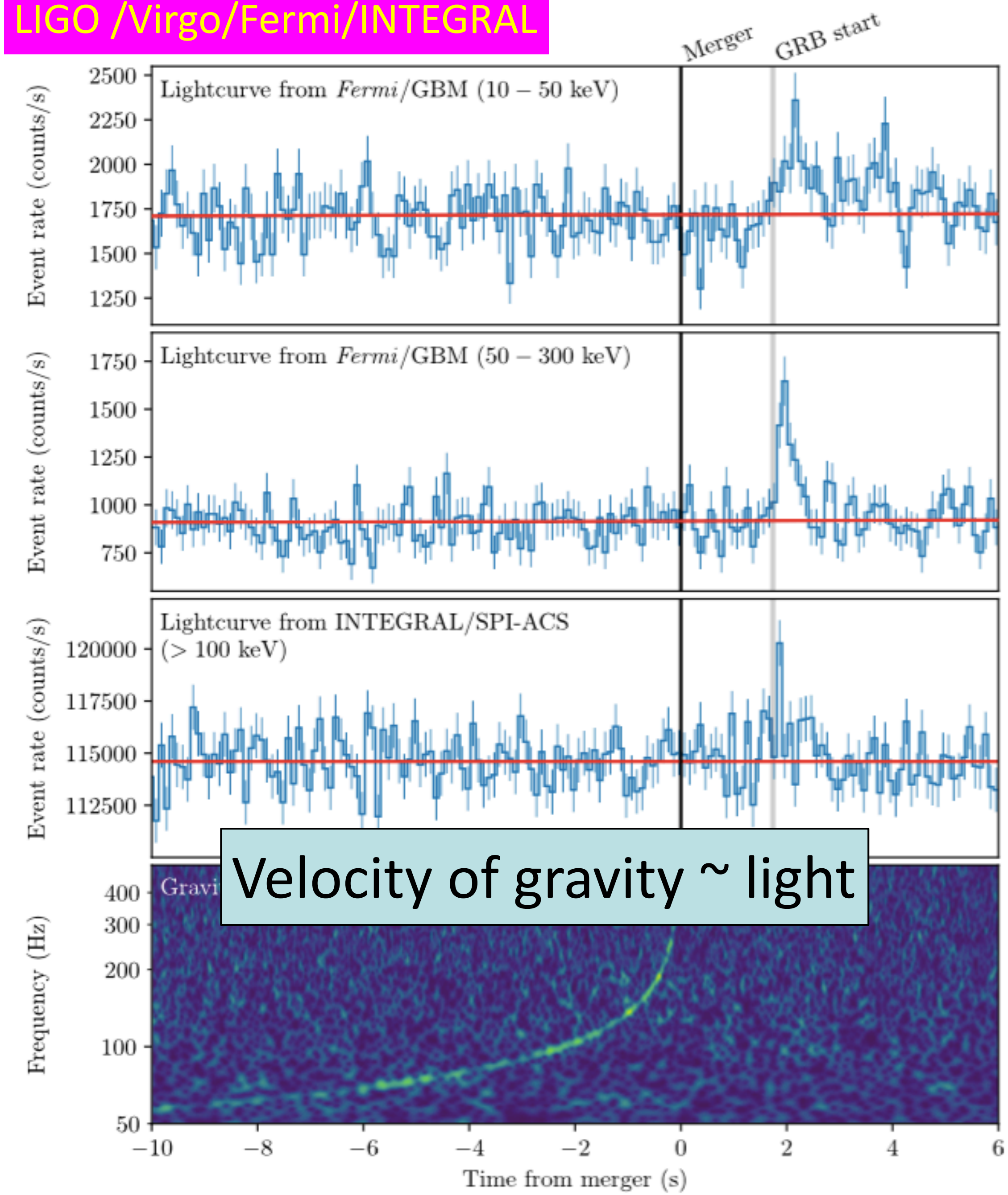


Masses $\lesssim 80 \times$ Sun
Gap $\sim 100 \times$ Sun?
Heavier masses?

"The Stellar Graveyard"

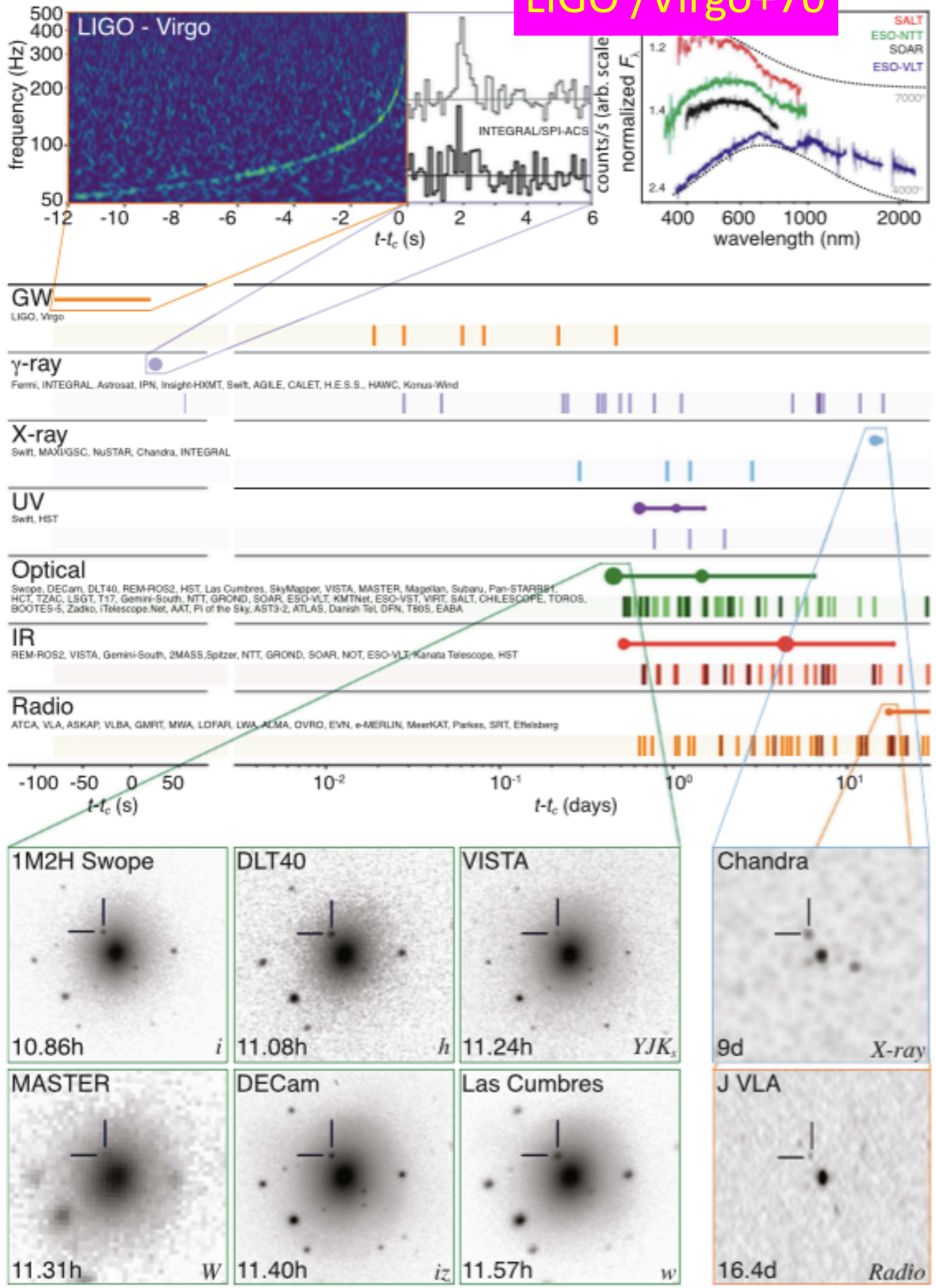
Observations of Neutron Star Merger (Kilonova)

LIGO /Virgo/Fermi/INTEGRAL

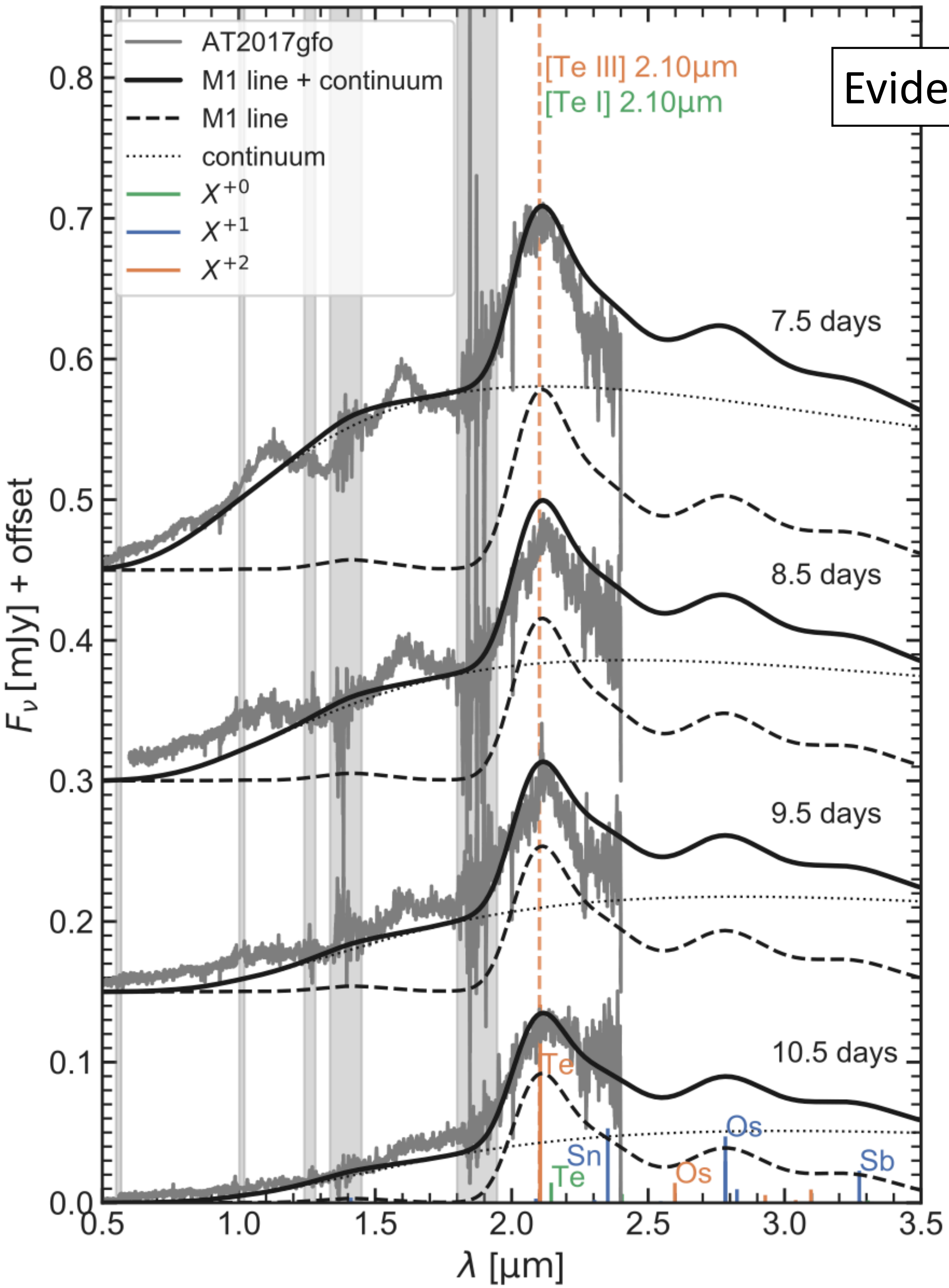


Velocity of gravity ~ light

LIGO /Virgo+70

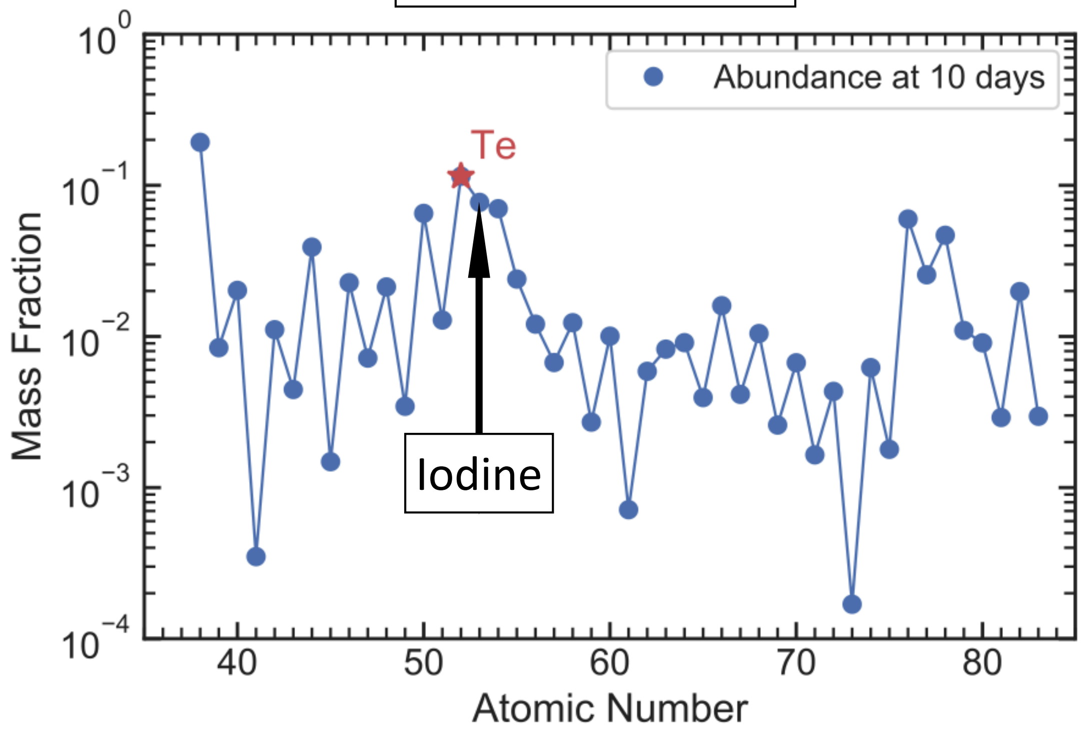


Heavy-Element Production in Kilonovae



Evidence for tellurium production

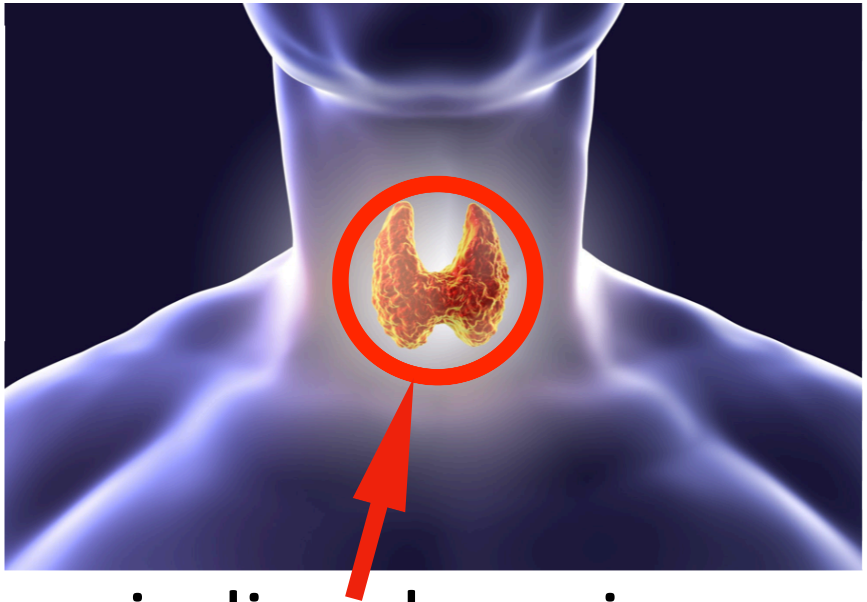
Model calculations



Iodine

Iodine production predicted to be similar:
Essential for human life!

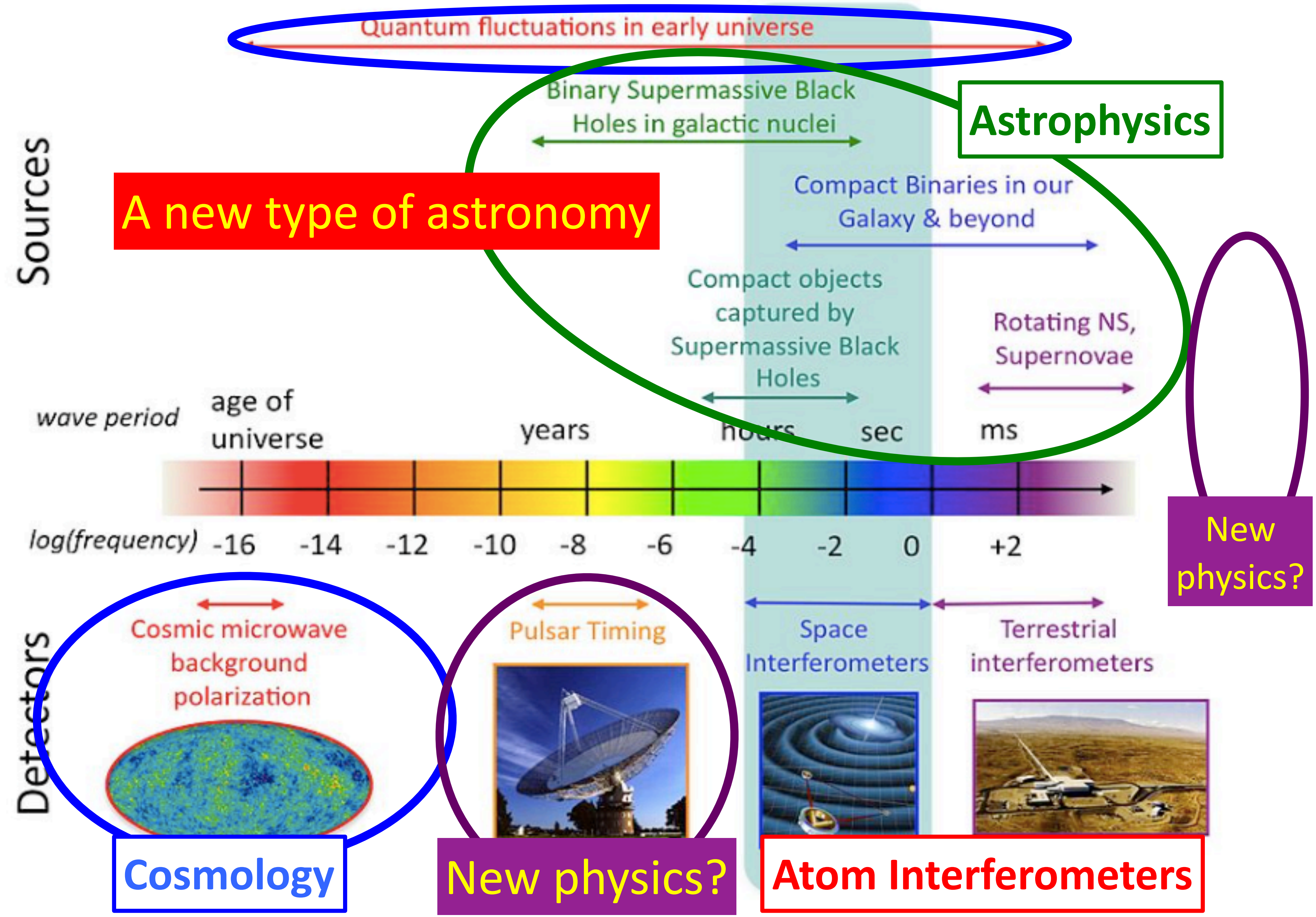
Do we Owe our Lives to Gravitational Waves?



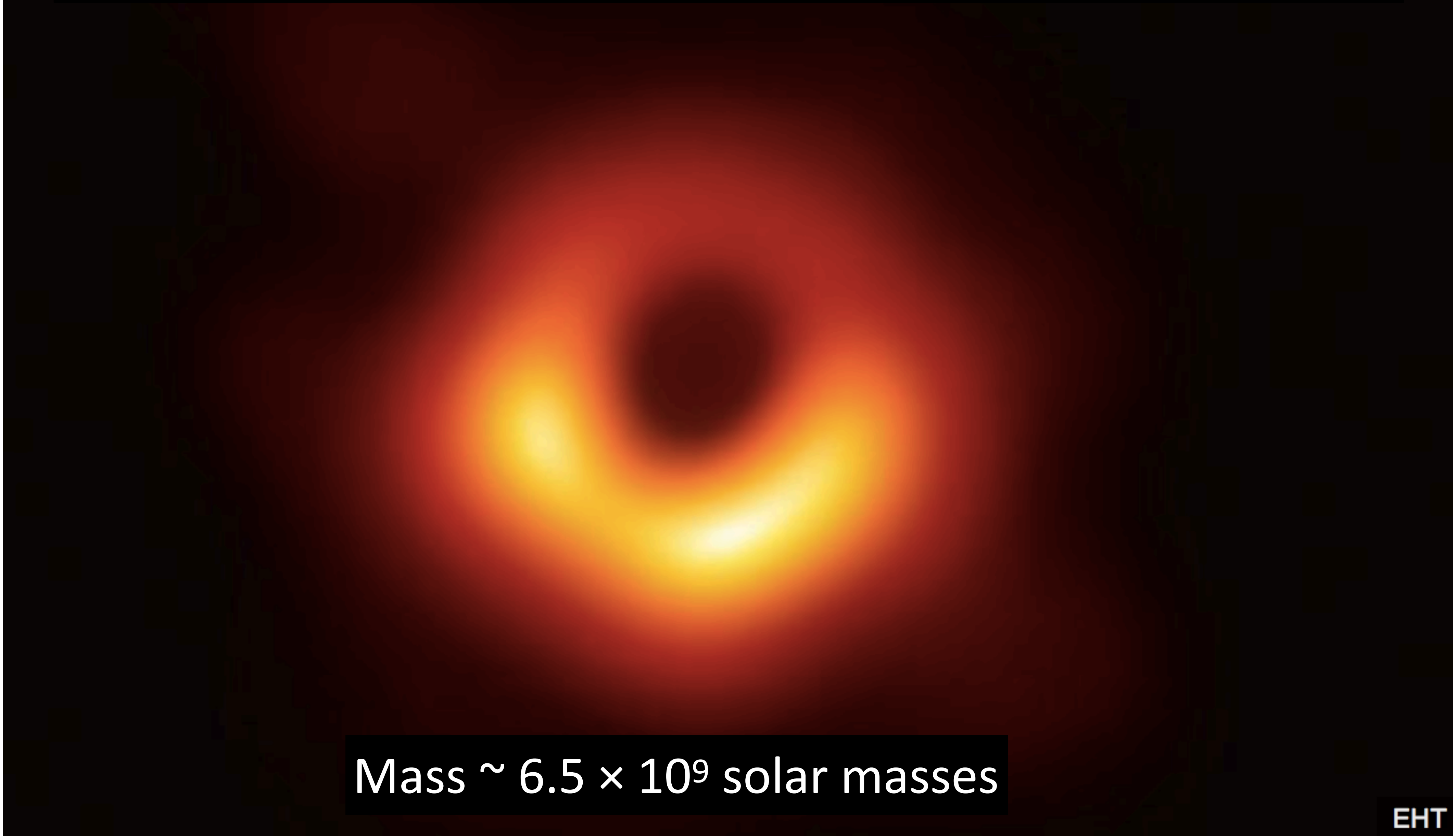
- Some heavy elements are essential in human biology, e.g., iodine, bromine
- Produced by the nuclear r-process in neutron-rich environments
- Probably not most supernovae, certainly (mainly?) in kilonovae (collisions of neutron stars)
- Why do neutron stars collide?
- **Because they lose energy via gravitational waves!**

JE, Fields & Surman, arXiv:2402.xxxxx

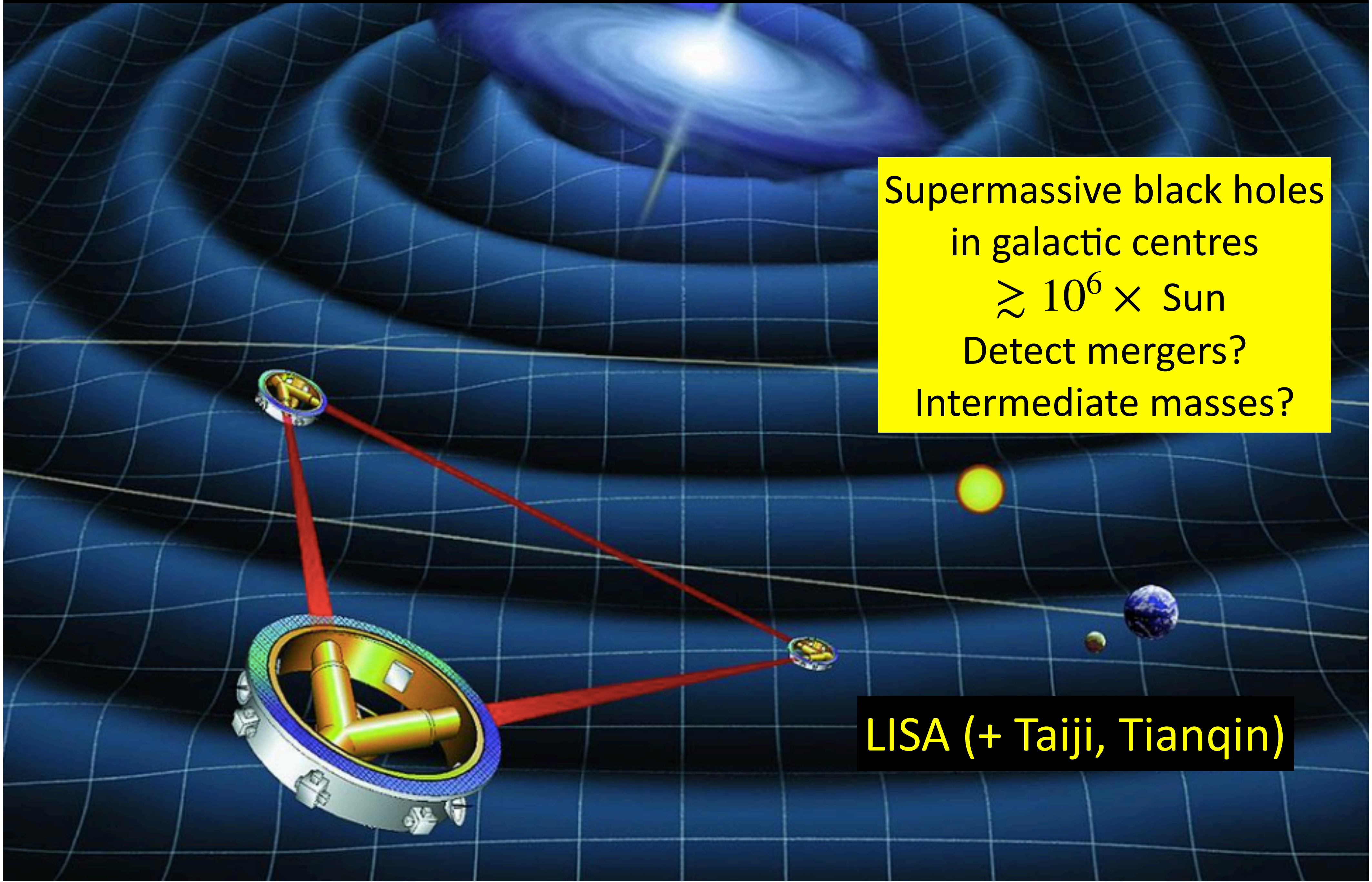
Gravitational Wave Spectrum



Supermassive Black Holes in Active Galactic Nuclei: Image of M87

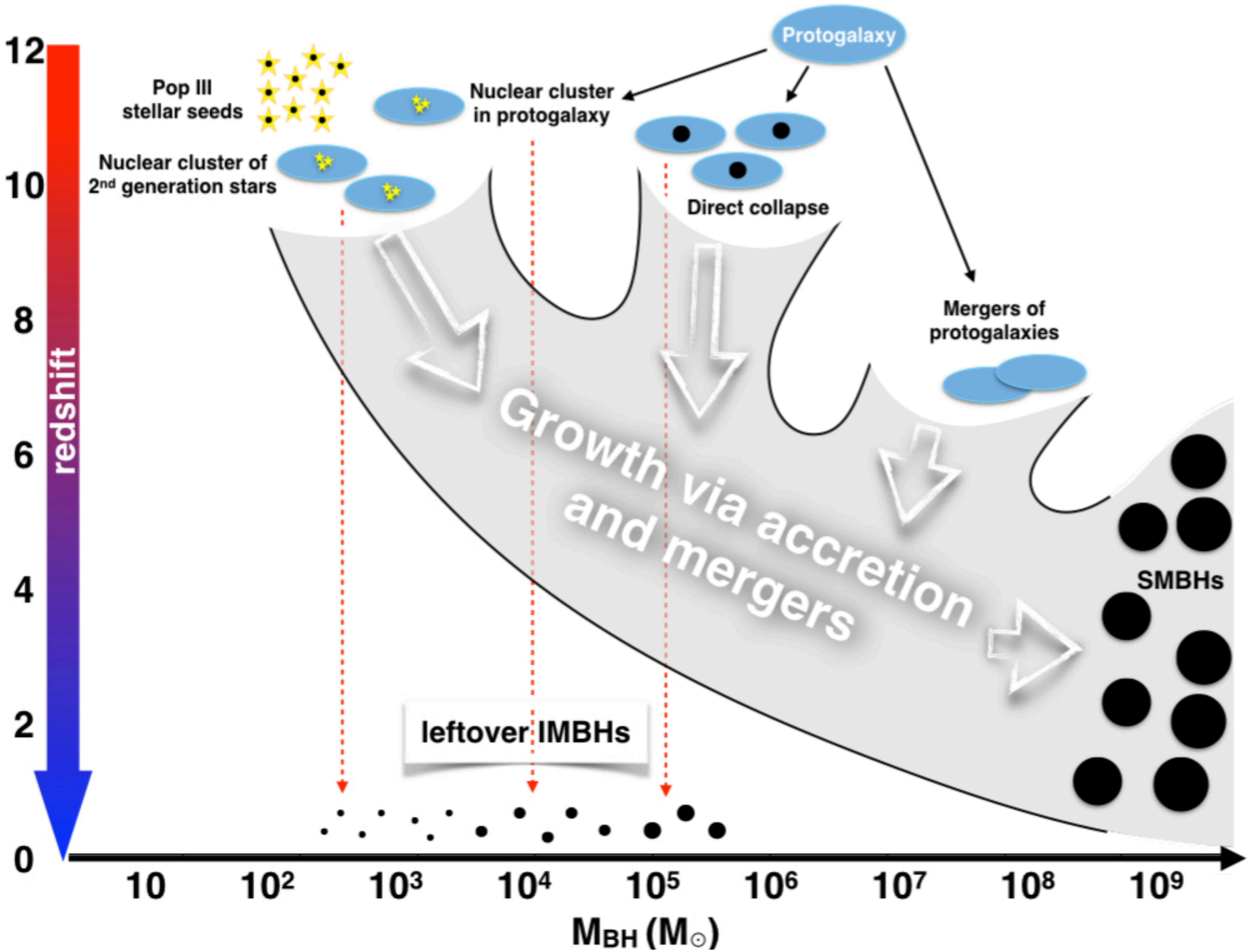


Future Step: Interferometer in Space

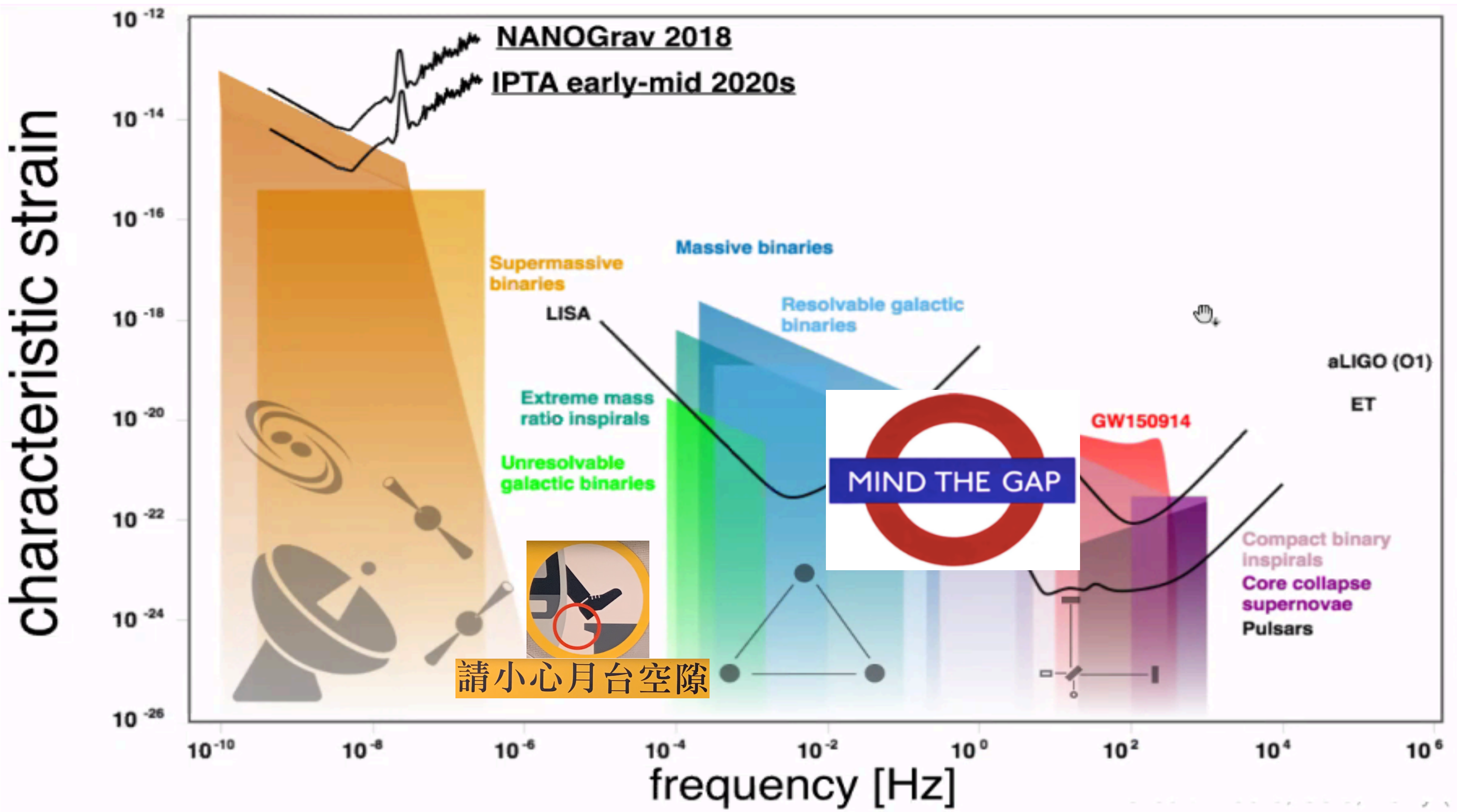


How to Make a Supermassive BH?

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

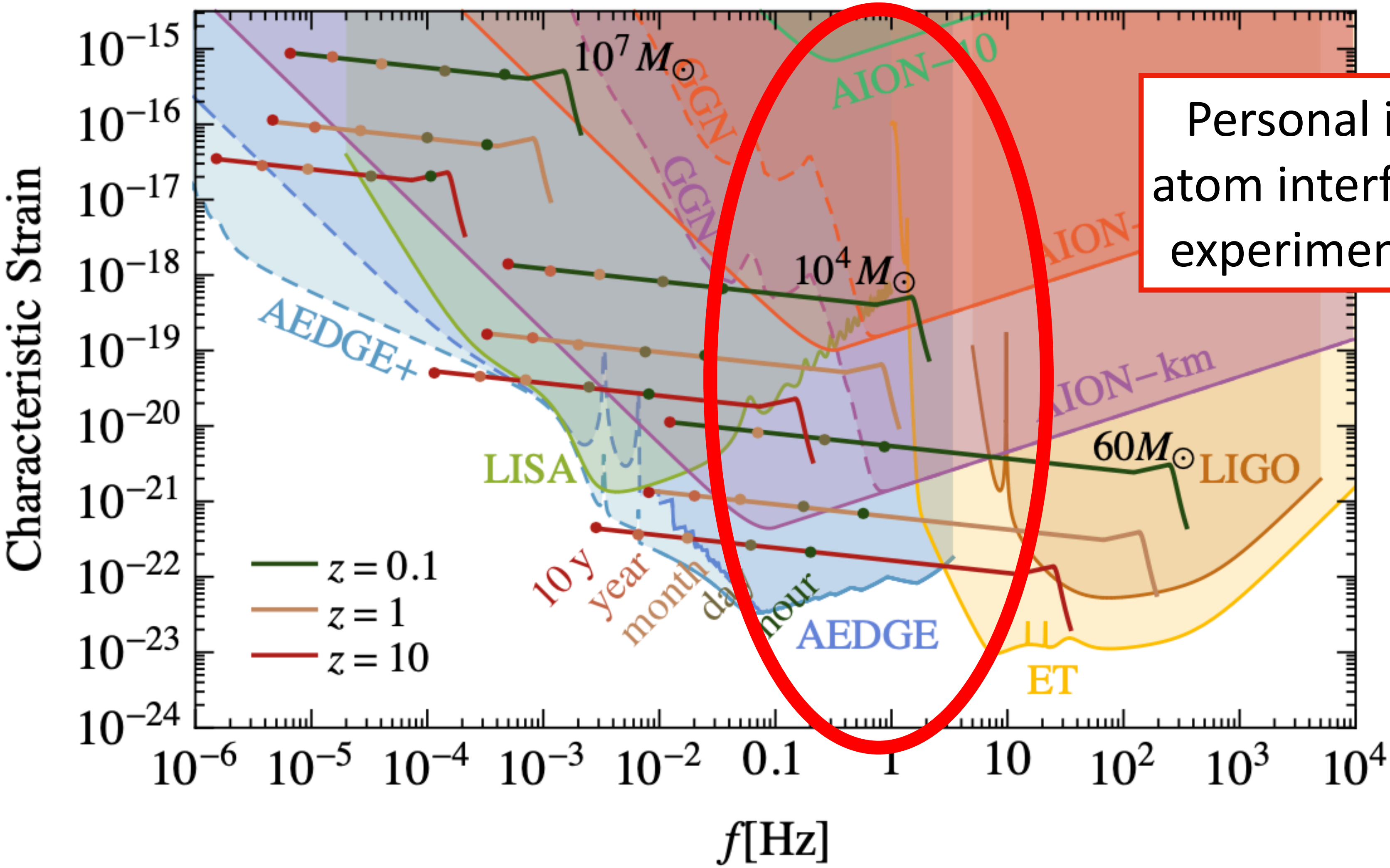


Gravitational Wave Spectrum



- Gap between ground-based optical interferometers & LISA
  - Formation of supermassive black holes (SMBHs)
  - Supernovae? Phase transitions? …
- **Atom interferometry?**

Gravitational Waves from IMBH Mergers



Personal interest: atom interferometer experiments: AION

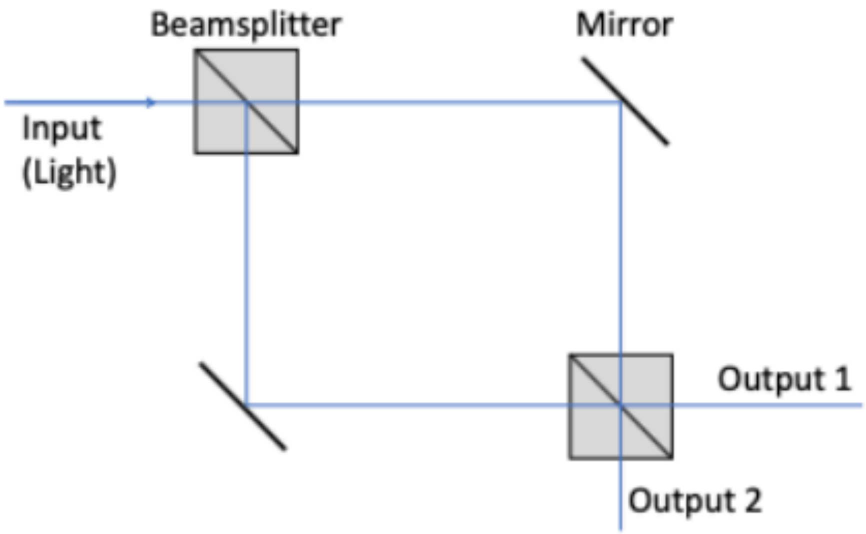
Probe formation of SMBHs

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

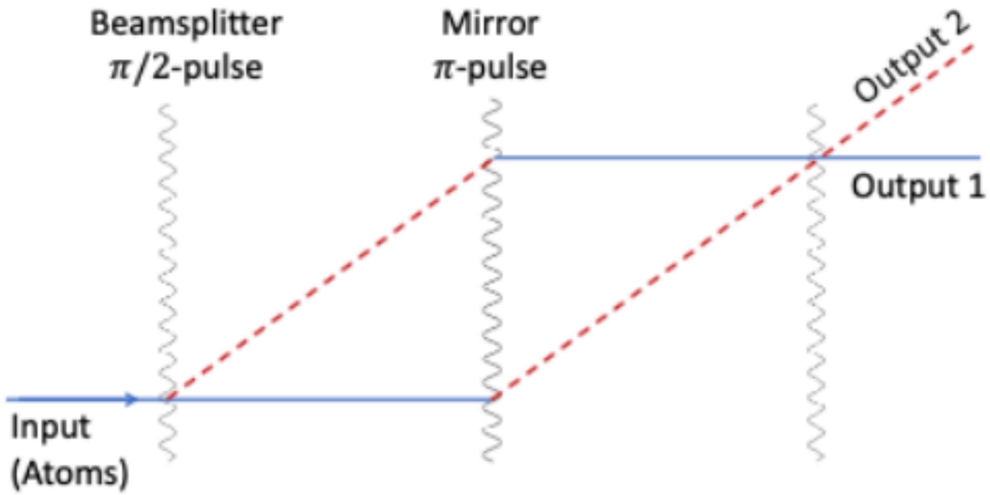
Badurina, Buchmueller, JE, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

Principle of Atom Interferometry

Mach-Zehnder Laser Interferometer

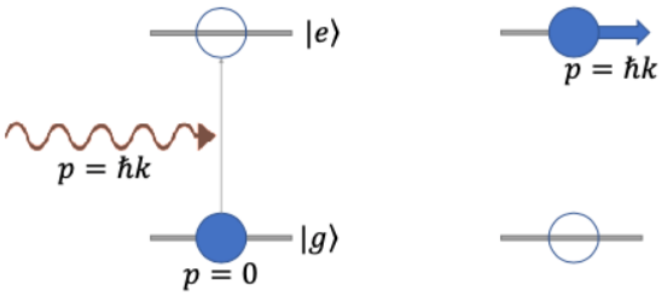


Atom Interferometer

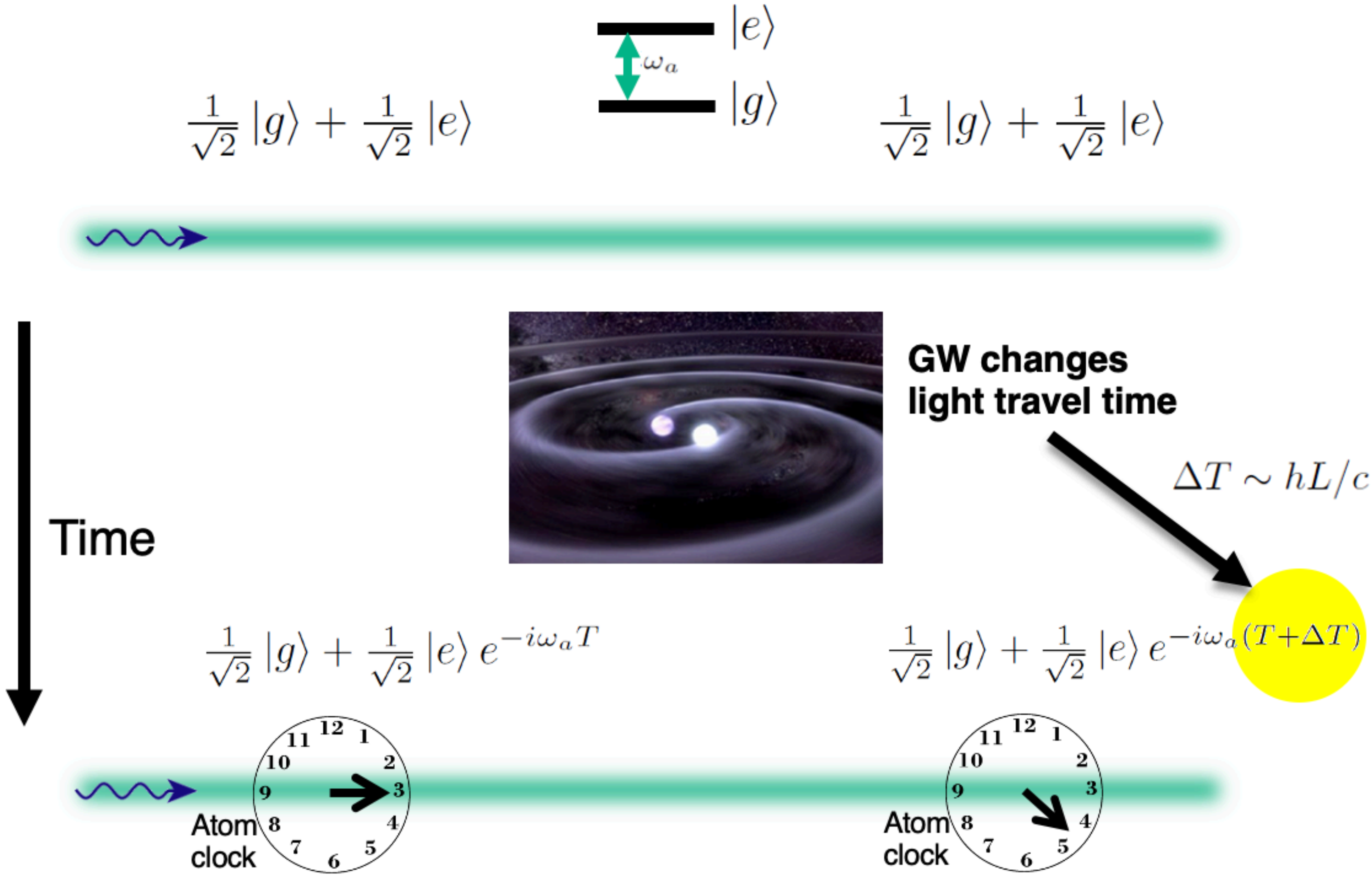


Laser excitation gives momentum kick to excited atom, which follows separated space-time path

Interference between atoms following different paths



Effect of Gravitational Wave on Atom Interferometer



AION Collaboration

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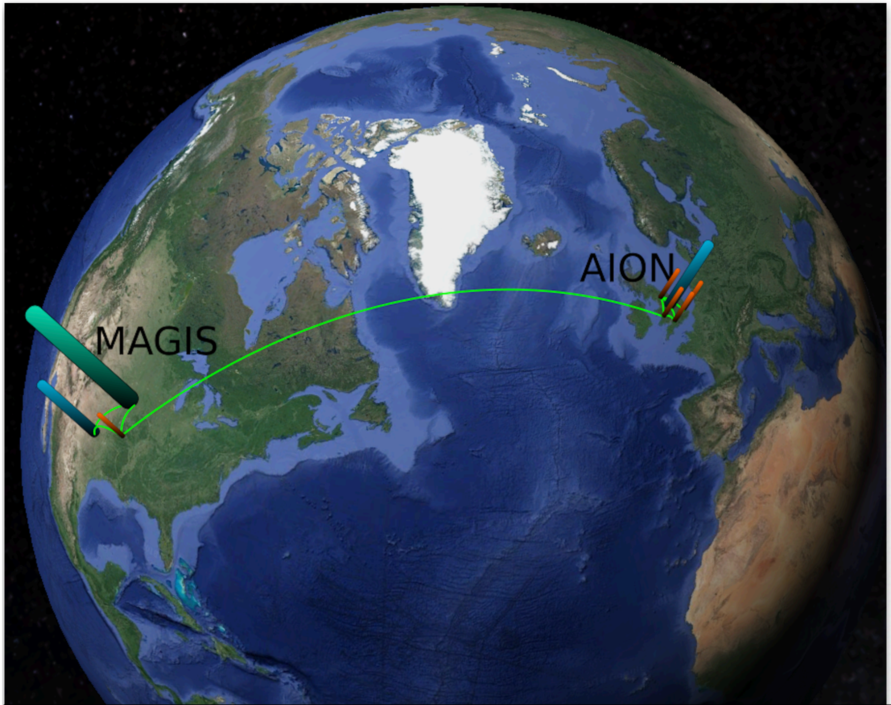
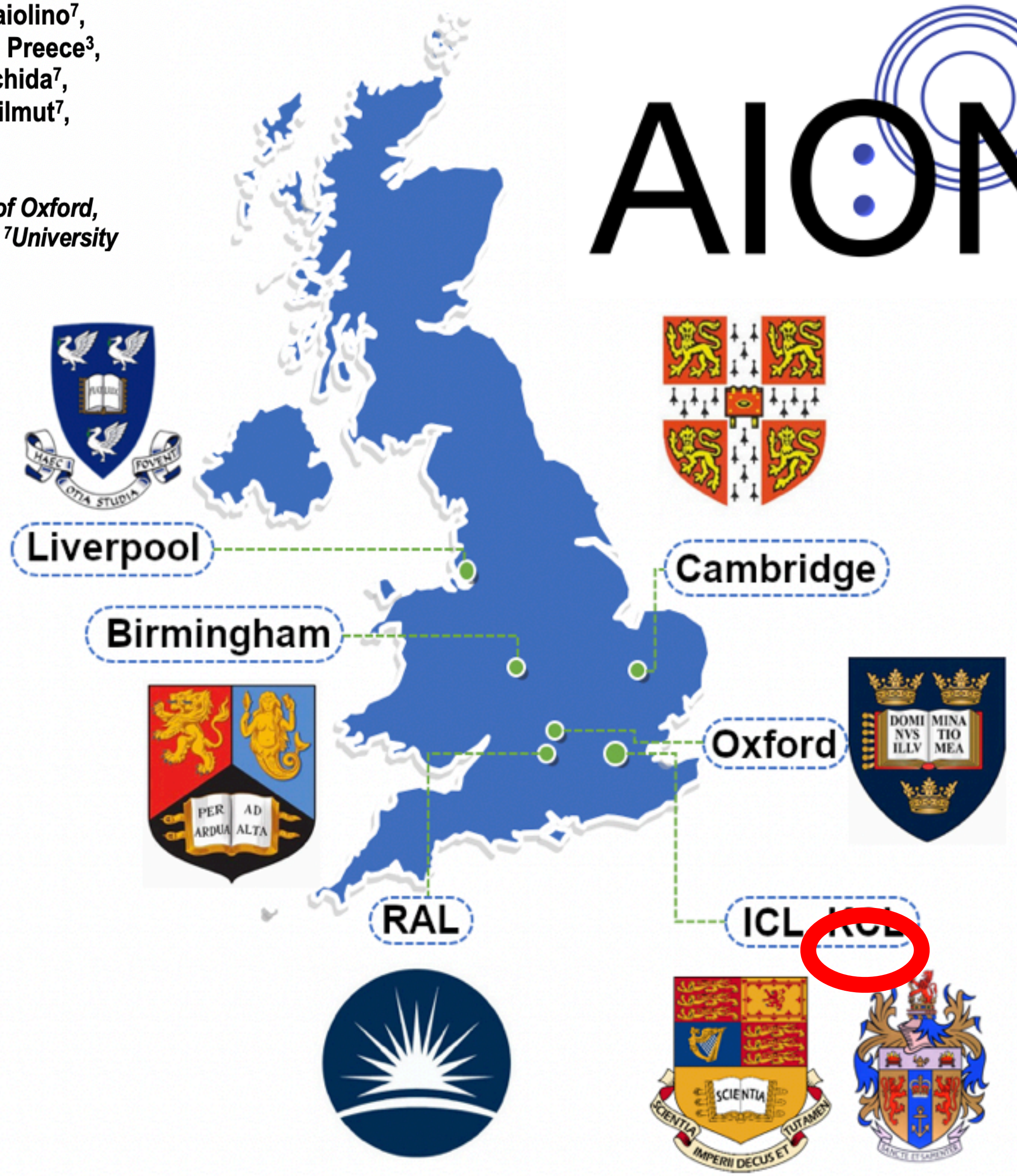


Network with MAGIS project in US

MAGIS Collaboration (Abe et al): arXiv:2104.02835

Also MIGA (France), ZAIGA (China)



AION – Proposed Programme

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

Oxford

Initial funding from UK STFC

- AION-100: Stage 2 [year 3 to 6]
  - 100m Construction & commissioning

Boulby? CERN?

- AION-KM: Stage 3 [> year 6]
  - Operating AION-100 and planning for 1 km & beyond
- AION-SPACE (AEDGE): Stage 4
  - Space-based version

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

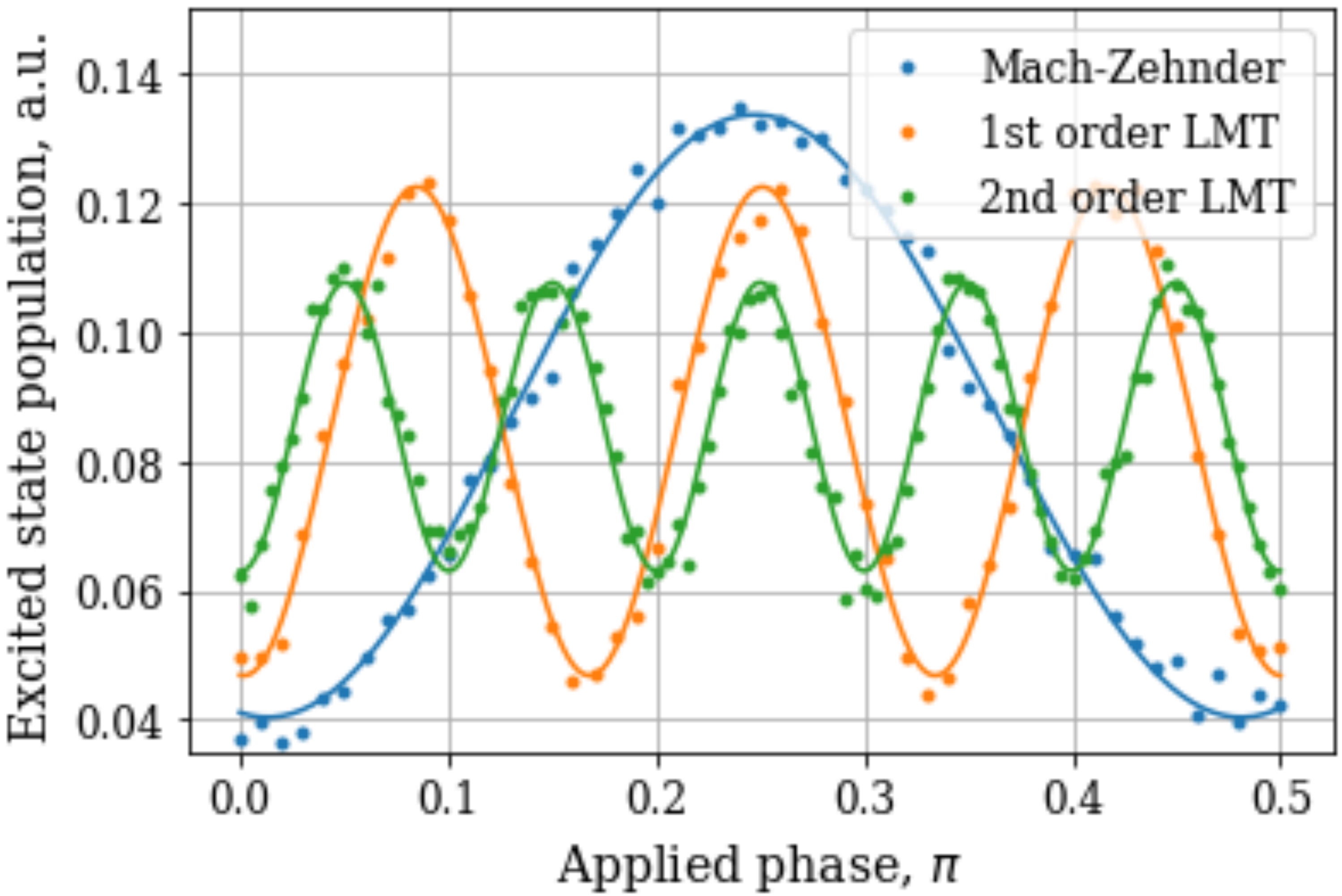
Interference Fringes

Mach-Zehnder

1st order

2nd order

Larger momentum transfers



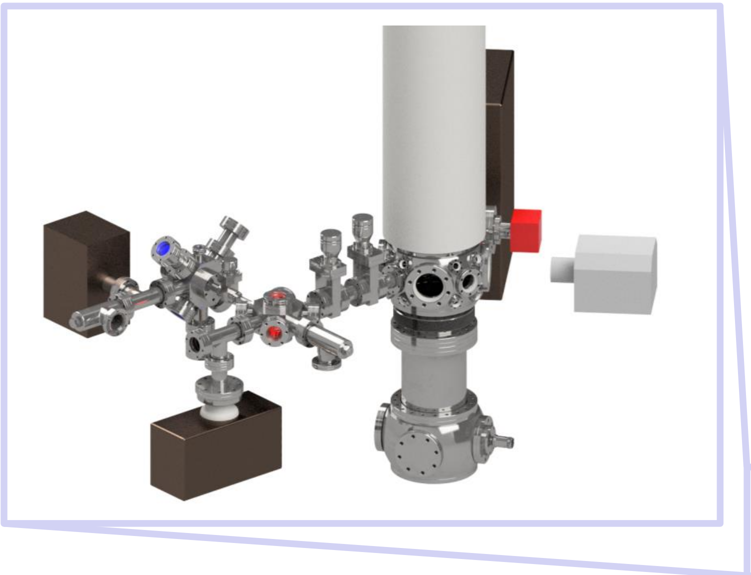
Using 689 nm transition in Sr

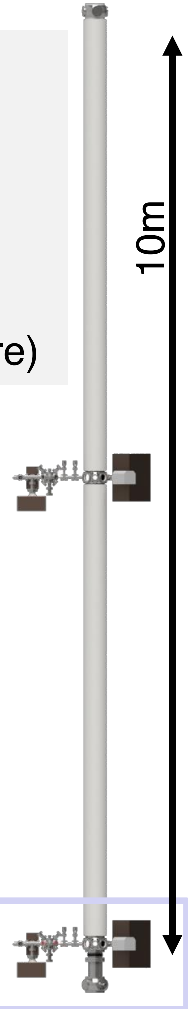
AION Collaboration

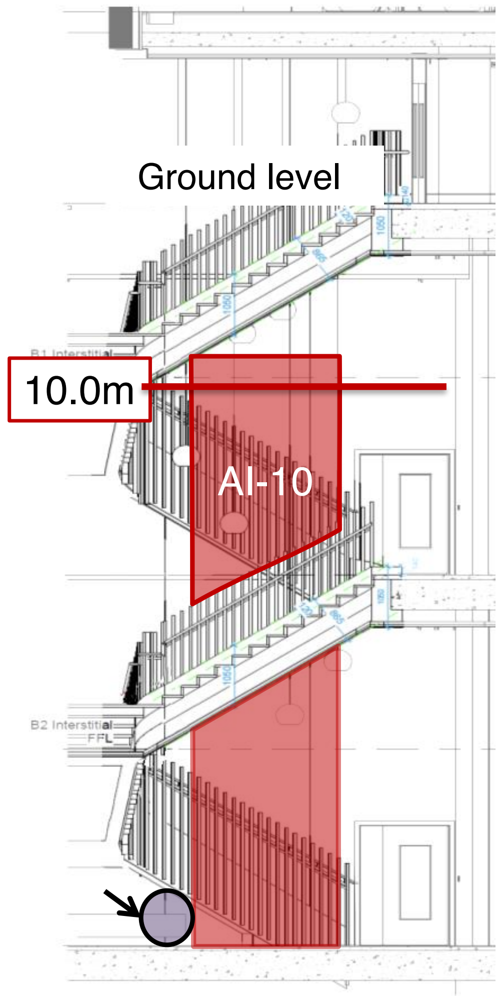
Planned Location of AION-10m

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)

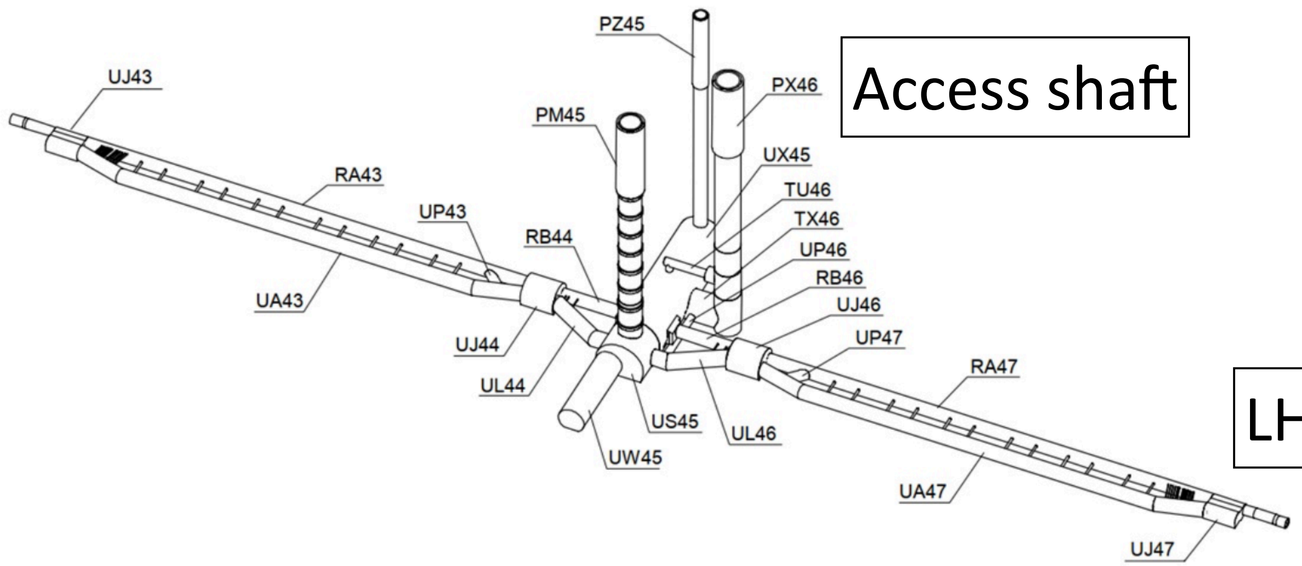






Possible CERN Location

AION

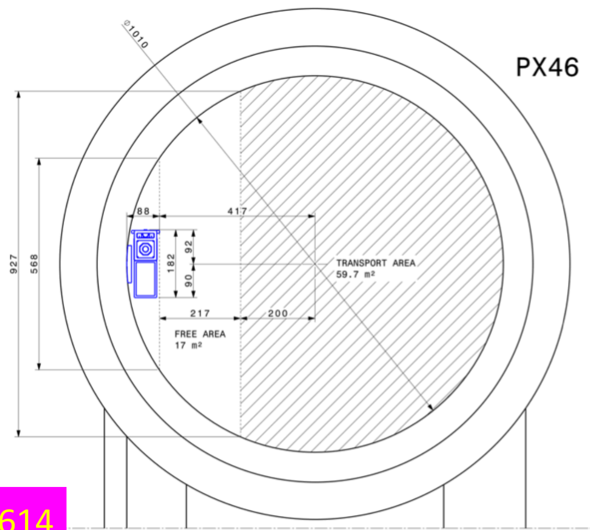


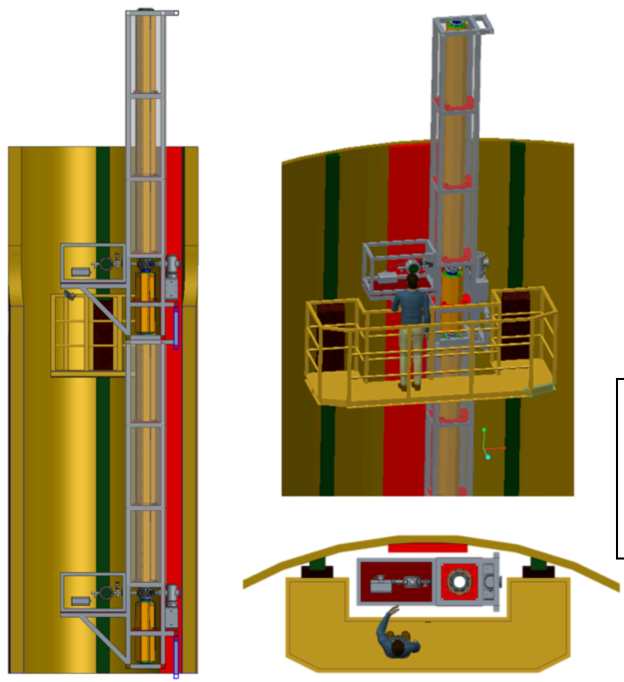
LHC

Access shaft

LHC

Cross-section of access shaft

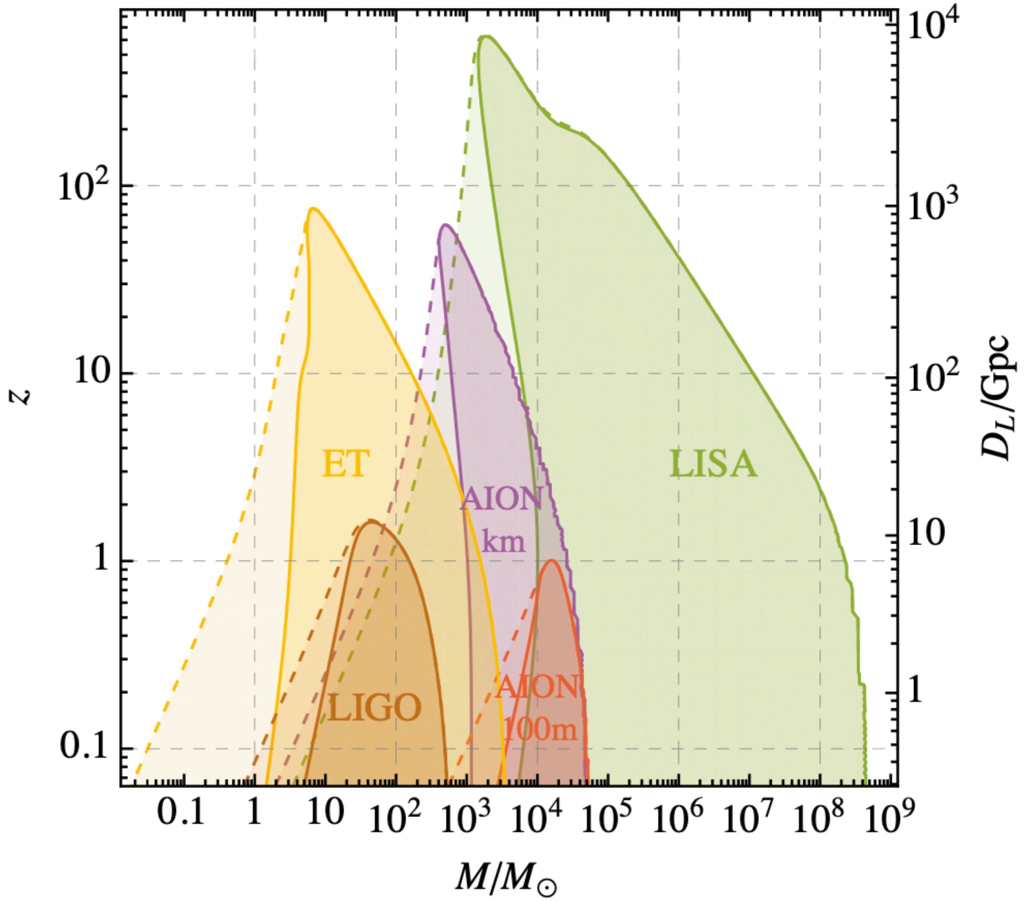


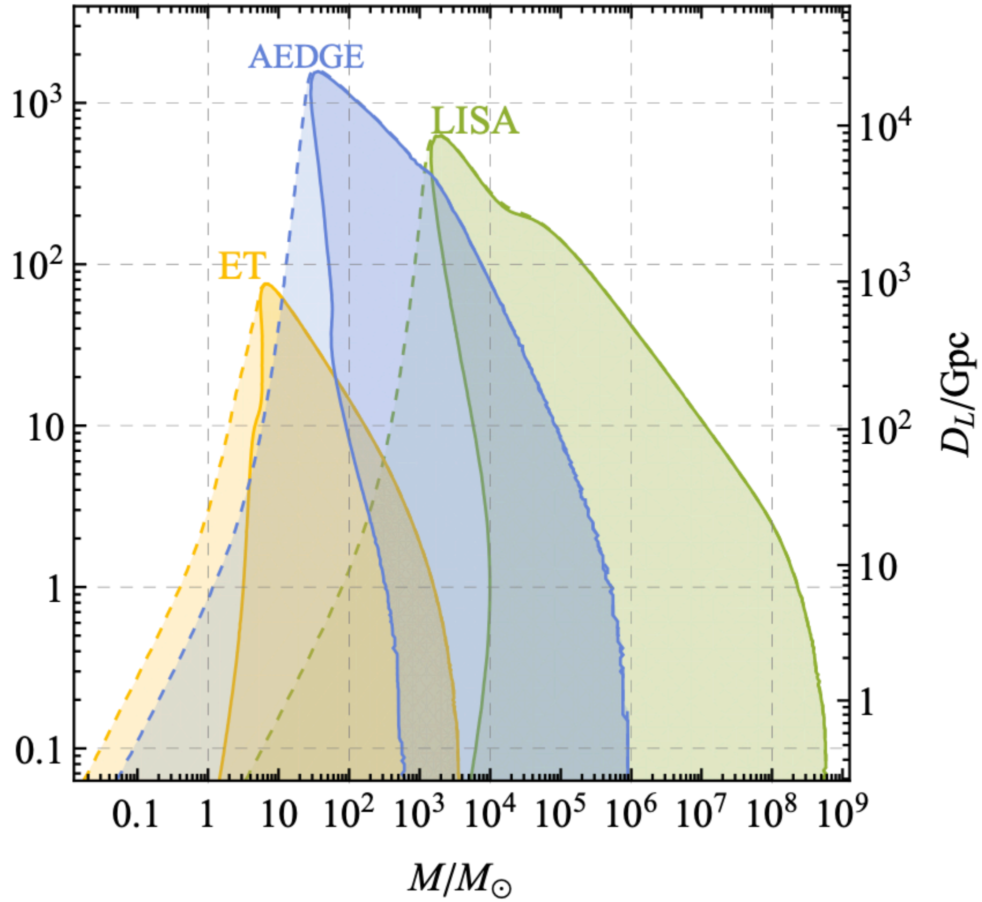


Layout of experiment

Arduini et al: arXiv:2304.00614

SNR = 8 Sensitivities to GWs from Mergers



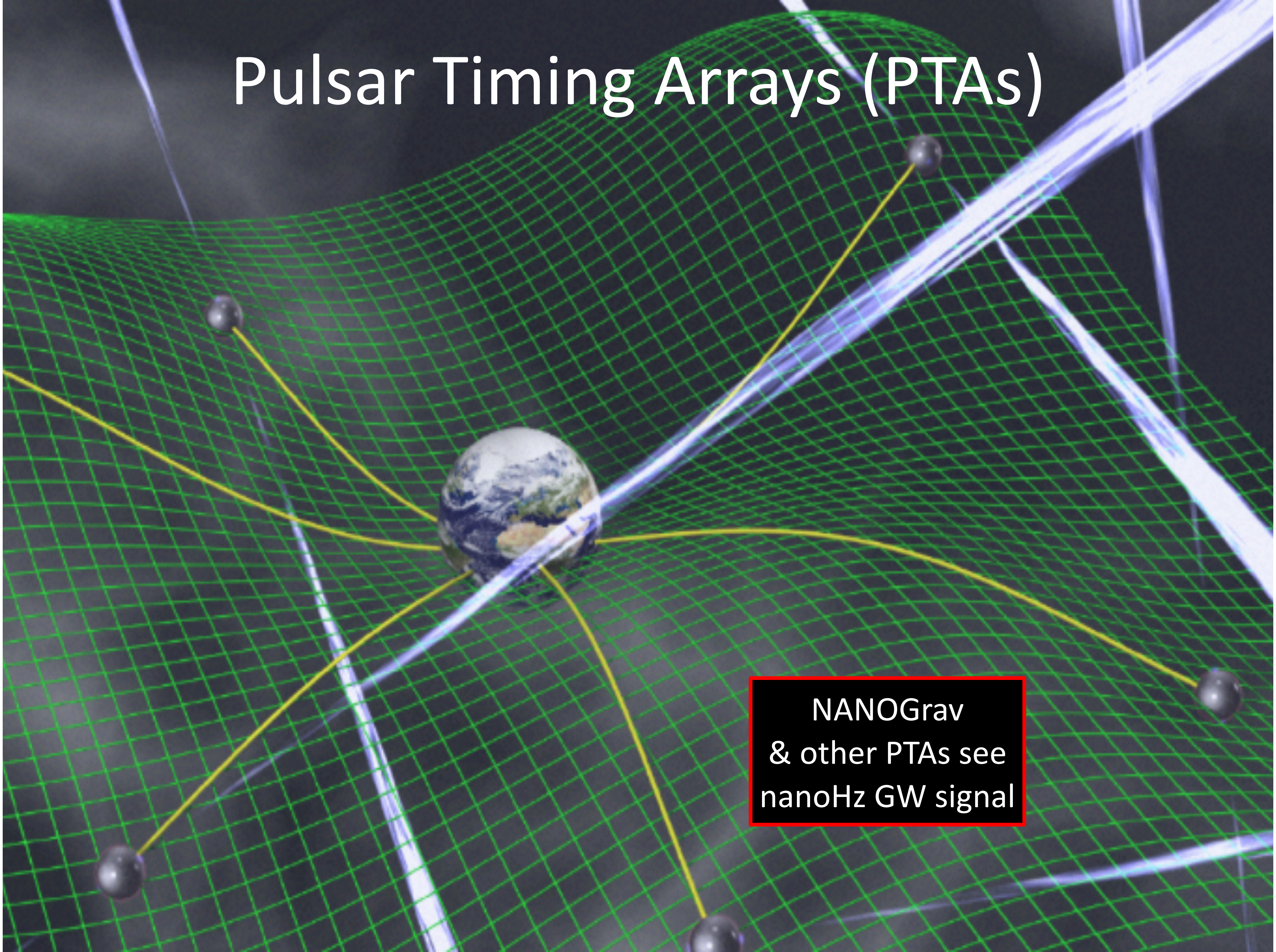


In the lighter regions between the dashed and solid lines the corresponding detector observes only the inspiral phase.

AION, arXiv:1911.11755

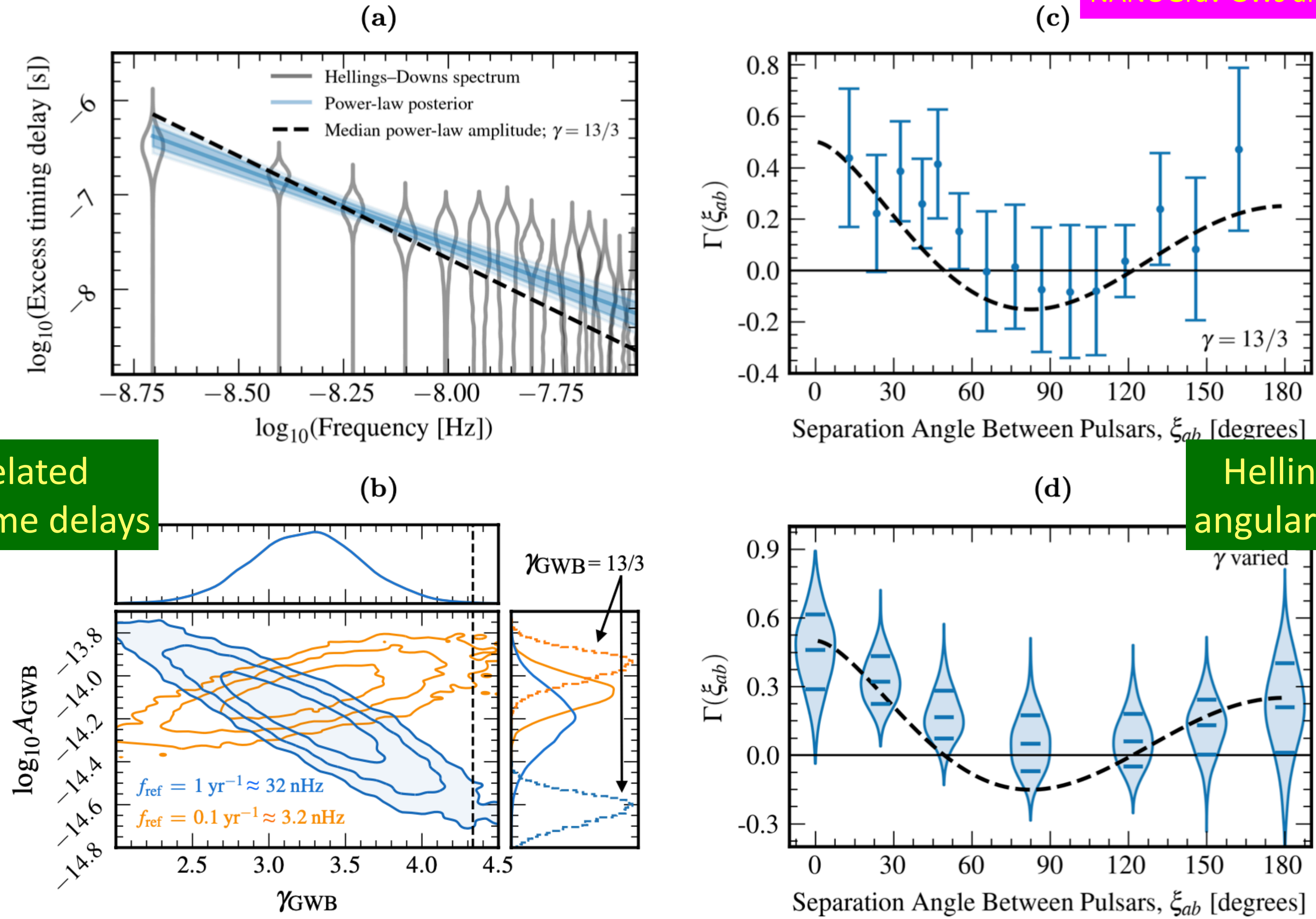
AEDGE, arXiv:1908.00802

Pulsar Timing Arrays (PTAs)



NANOGrav 15-Year Data

NANOGrav GWs arXiv:2306.16213

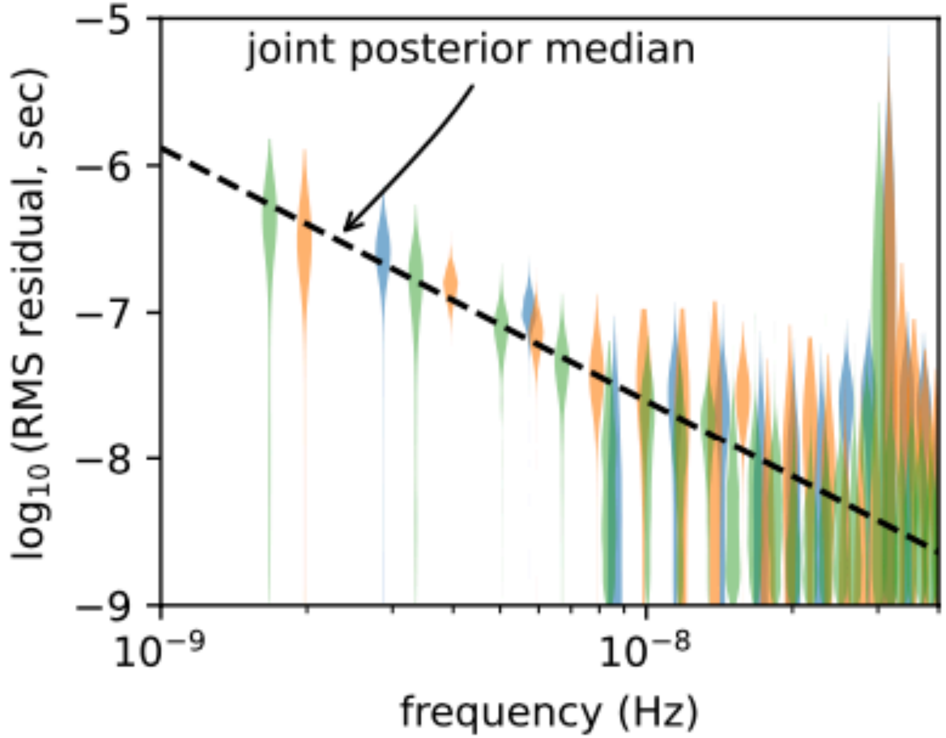


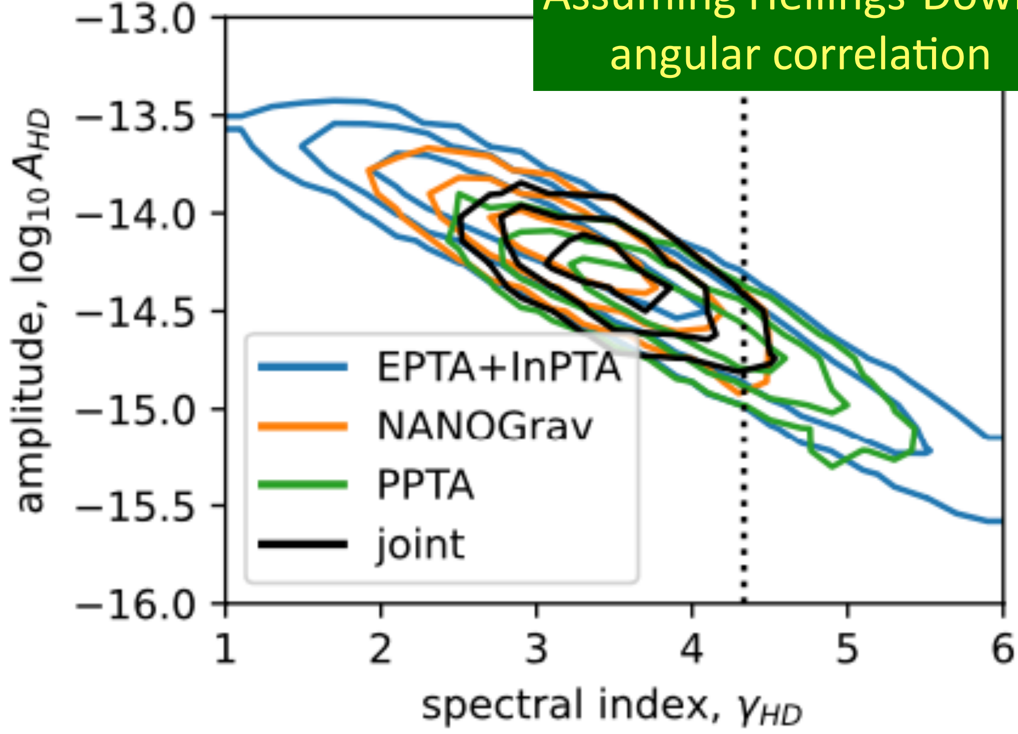
Correlated pulsar time delays

Hellings-Downs angular correlation

Evidence for GWs: Hellings-Downs angular correlation Bayes factor ~ 200

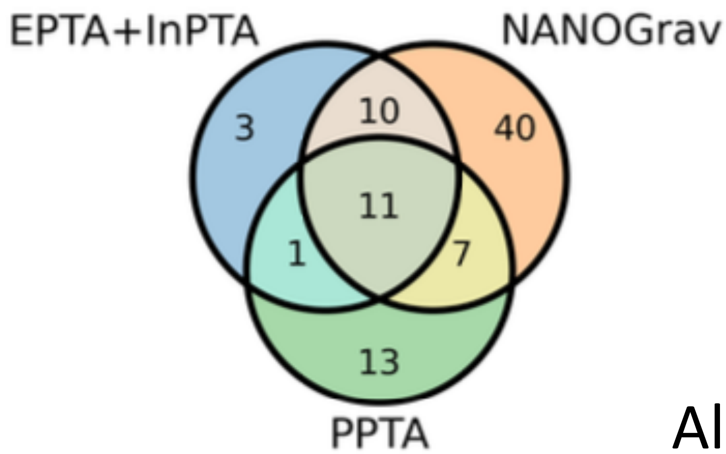
IPTA Data Compilation





Assuming Hellings-Downs angular correlation

Venn diagram of PTA data sets



IPTA Collaboration, arXiv:2309.00693

Also Chinese PTA

The Biggest Bangs since the Big Bang?

BH Merger Rate Estimate

BH merger rate $R_{\rm BH}$

$$\frac{{\rm d}R_{\rm BH}}{{\rm d}m_1{\rm d}m_2} \approx p_{\rm BH}\frac{{\rm d}M_1}{{\rm d}m_1}\frac{{\rm d}M_2}{{\rm d}m_2}\frac{{\rm d}R_h}{{\rm d}M_1{\rm d}M_2}$$

where R_h is halo merger rate calculated using Extended Press-Schechter formalism,

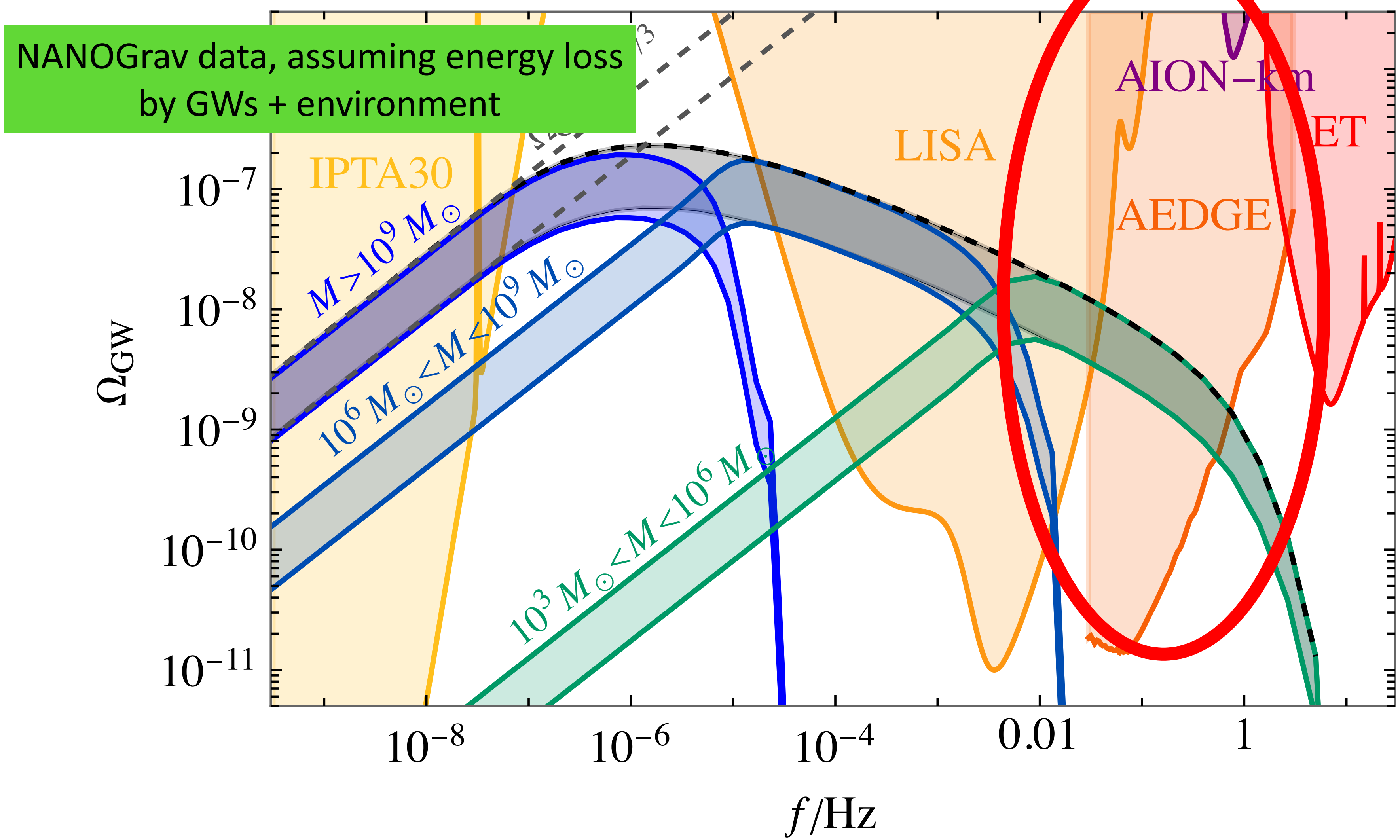
$$p_{\rm BH} \equiv p_{\rm occ}(m_1)p_{\rm occ}(m_2)p_{\rm merg}$$

is merger probability, and

strength of PTA signal can be fitted by constant $p_{\rm BH}$

JE, Fairbairn, Hütsi, Raidal, Urrutia, Vaskonen & Veermäe: arXiv:2301.13854

Stochastic GW Background from BH Mergers



Black dashed line is maximum possible Ω_{GW}, i.e., $p_{BH} = 1$

JE, Fairbairn, Hütsi, Raidal', Urrutia, Vaskonen & Veermäe: arXiv:2306.17021

Environmental energy loss AION

- Interactions with gas, stars, dark matter?
- Total energy loss rate: $\dot{E} = -\dot{E}_{\rm GW} - \dot{E}_{\rm env}$
- Characteristic time scales: $t_{\rm GW} \equiv E/\dot{E}_{\rm GW} = 4\tau\,,\ t_{\rm env} \equiv E/\dot{E}_{\rm env}$
- Where $\tau = \frac{5}{256}(\pi f_r)^{-8/3}\mathcal{M}^{-5/3}$
- Energy radiated in GWs reduced because of accelerated evolution:

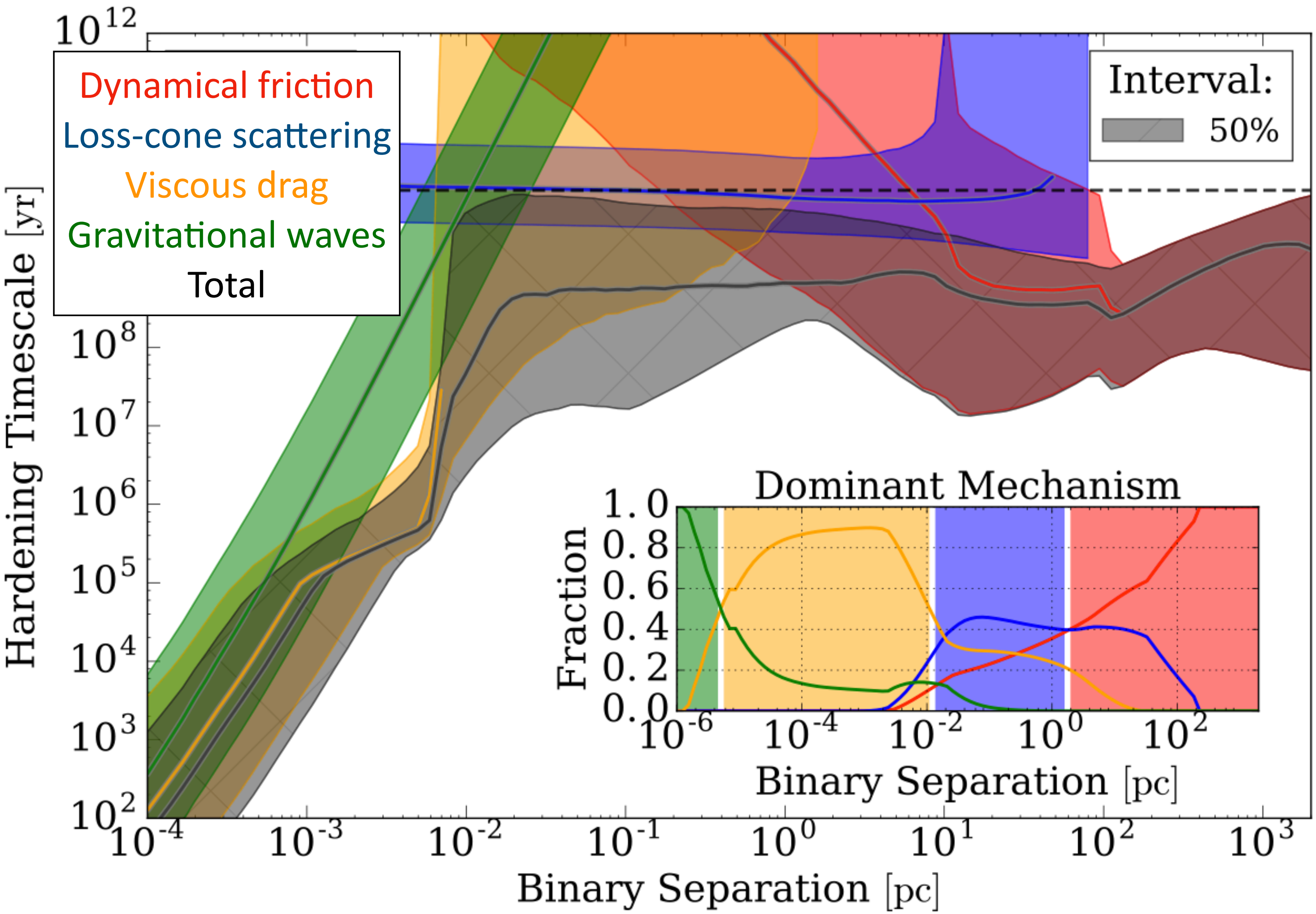
$$\frac{\mathrm{dE_{GW}}}{\mathrm{d\ln f_r}} = \frac{1}{3}\frac{(\pi f_r)^{\frac{2}{3}}\mathcal{M}^{\frac{5}{3}}}{1 + t_{\rm GW}/t_{\rm env}}$$

- Phenomenological parametrization:

$$\frac{t_{\rm env}}{t_{\rm GW}} = \left(\frac{f_r}{f_{\rm GW}}\right)^{\alpha}, \quad f_{\rm GW} = f_{\rm ref}\left(\frac{\mathcal{M}}{10^9 M_{\rm sun}}\right)^{-\beta}$$

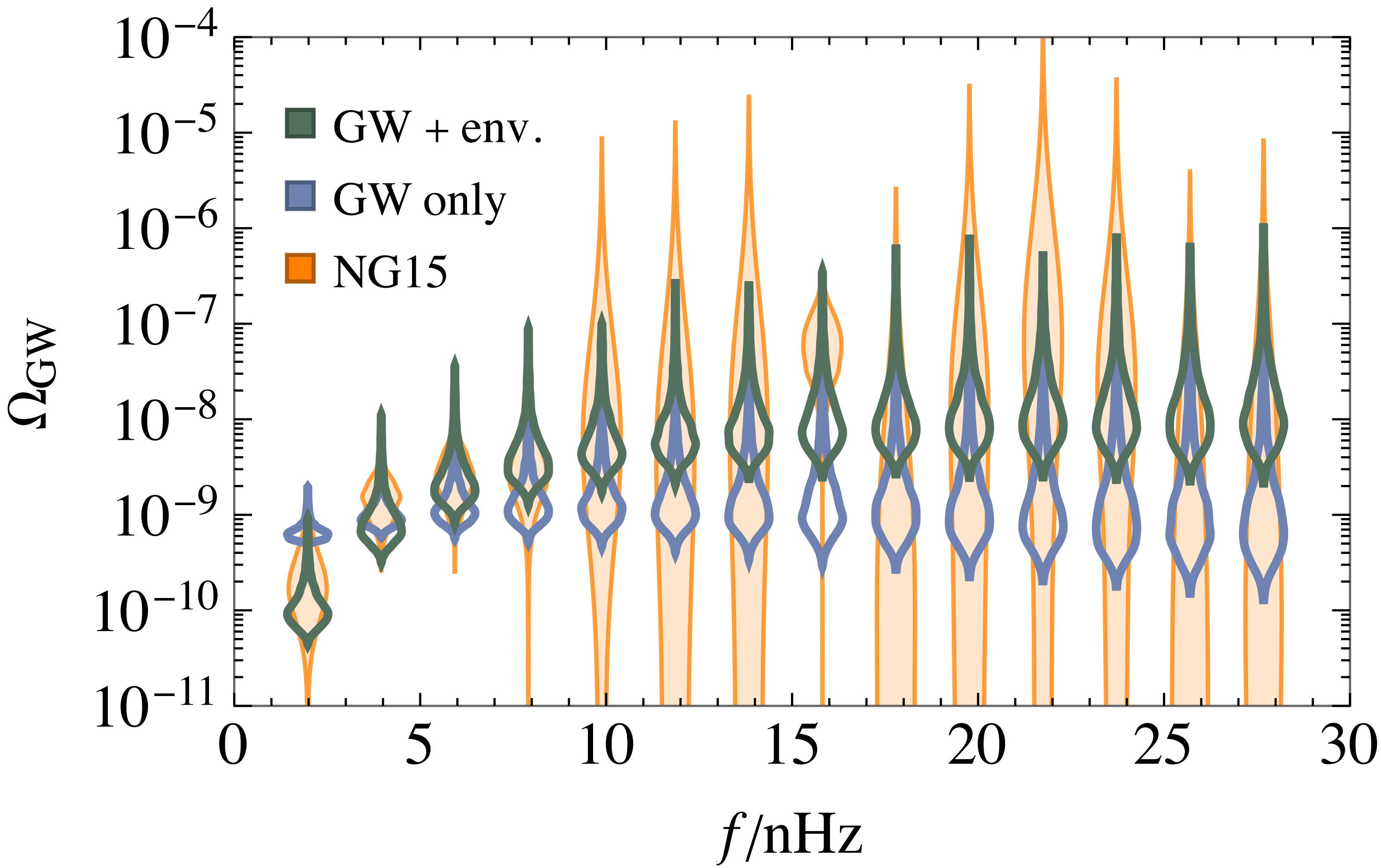
JE, Fairbairn, Hütsi, Raidal', Urrutia, Vaskonen & Veermäe: arXiv:2306.17021

Mechanisms for Energy Loss



Kelley, Blecha & Hernquist, arXiv:1606.01900

Astrophysical Interpretations

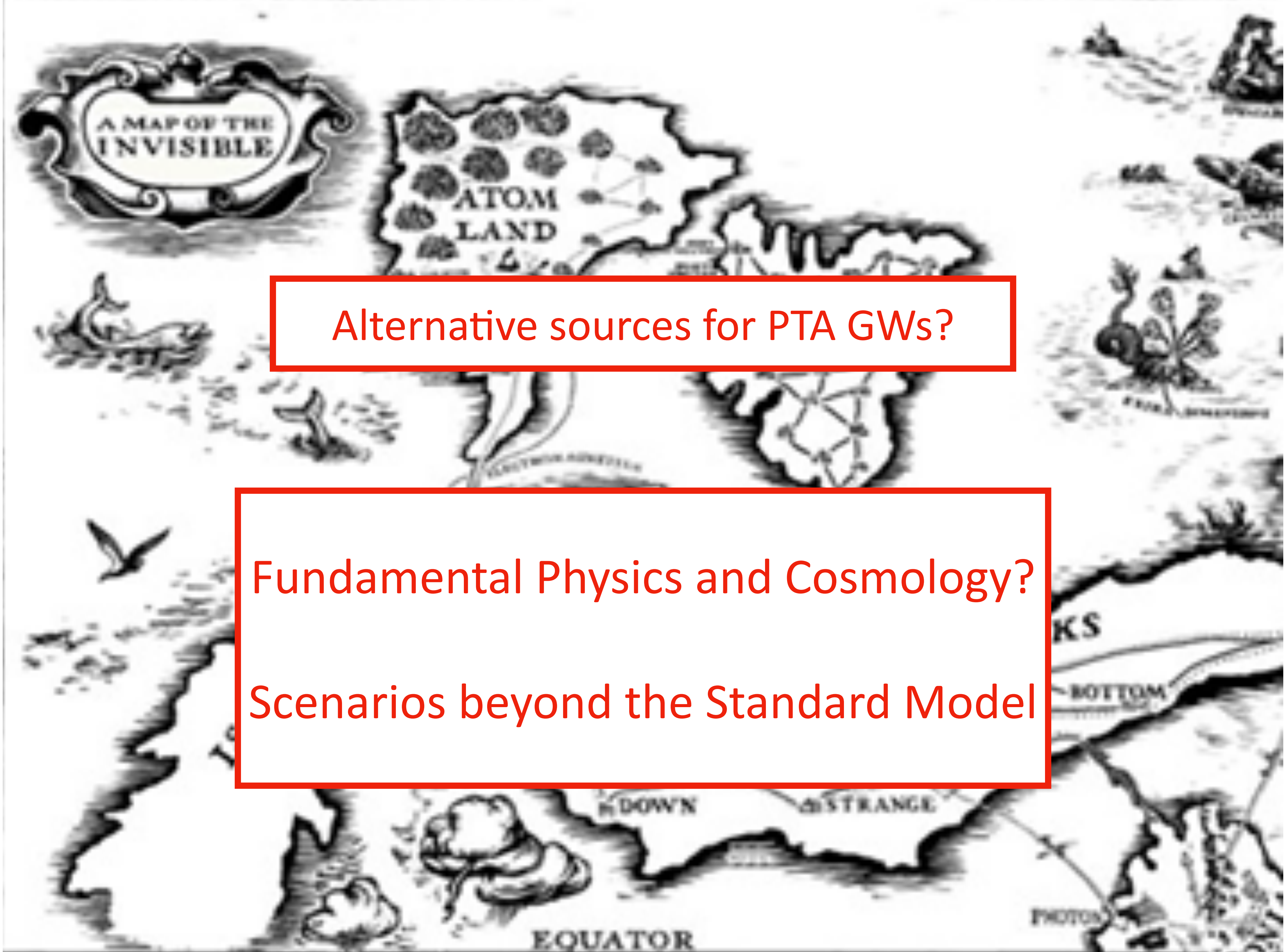


Fits use overlaps of data and model violins in each bin

NB: Fits go beyond simple power-law approximations

Better fit to spectrum if evolution driven by both environment & GWs

JE, Fairbairn, Hütsi, Raidal', Urrutia, Vaskonen & Veermäe: arXiv:2306.17021

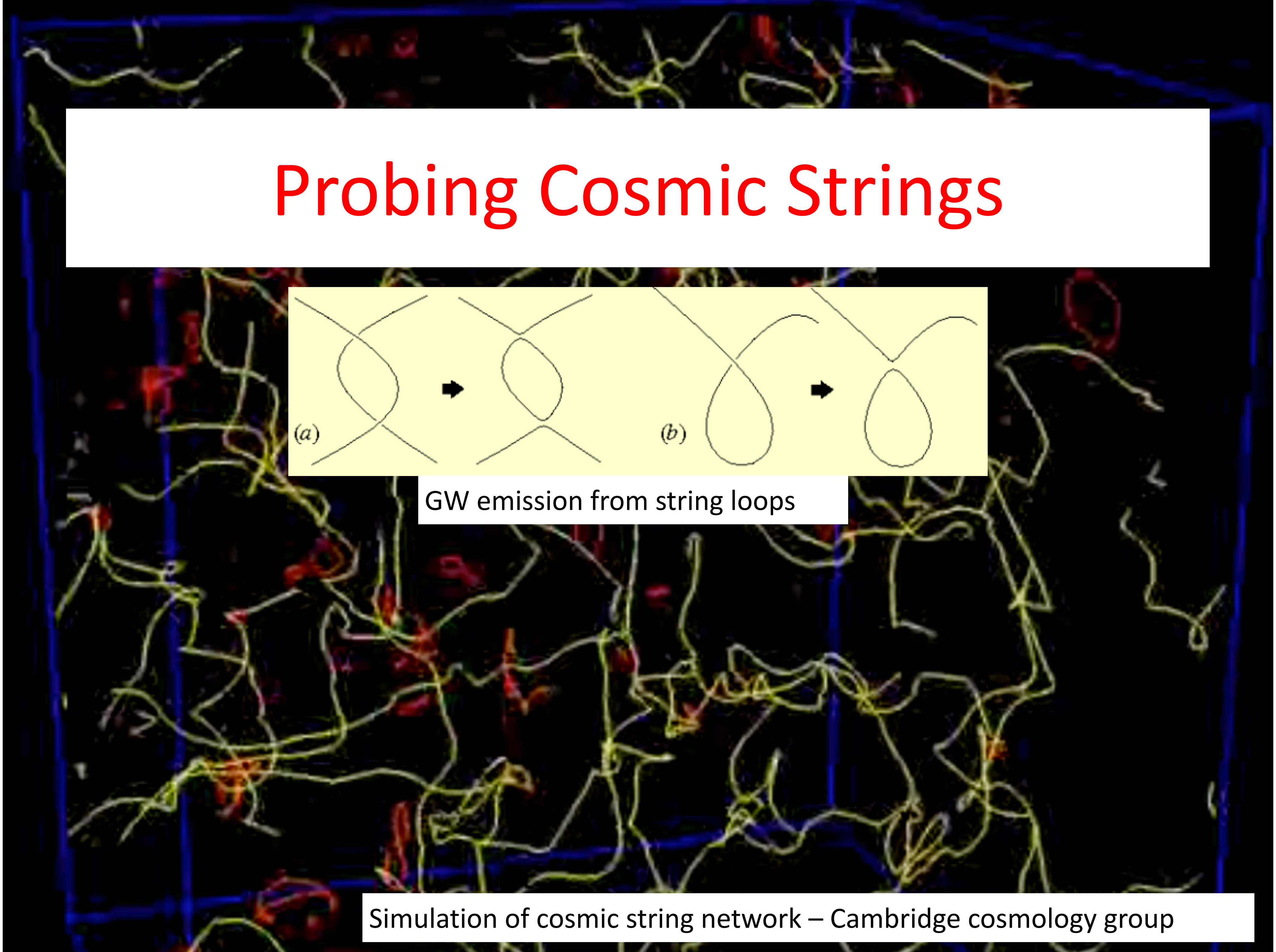


Alternative sources for PTA GWs?

Fundamental Physics and Cosmology?

Scenarios beyond the Standard Model

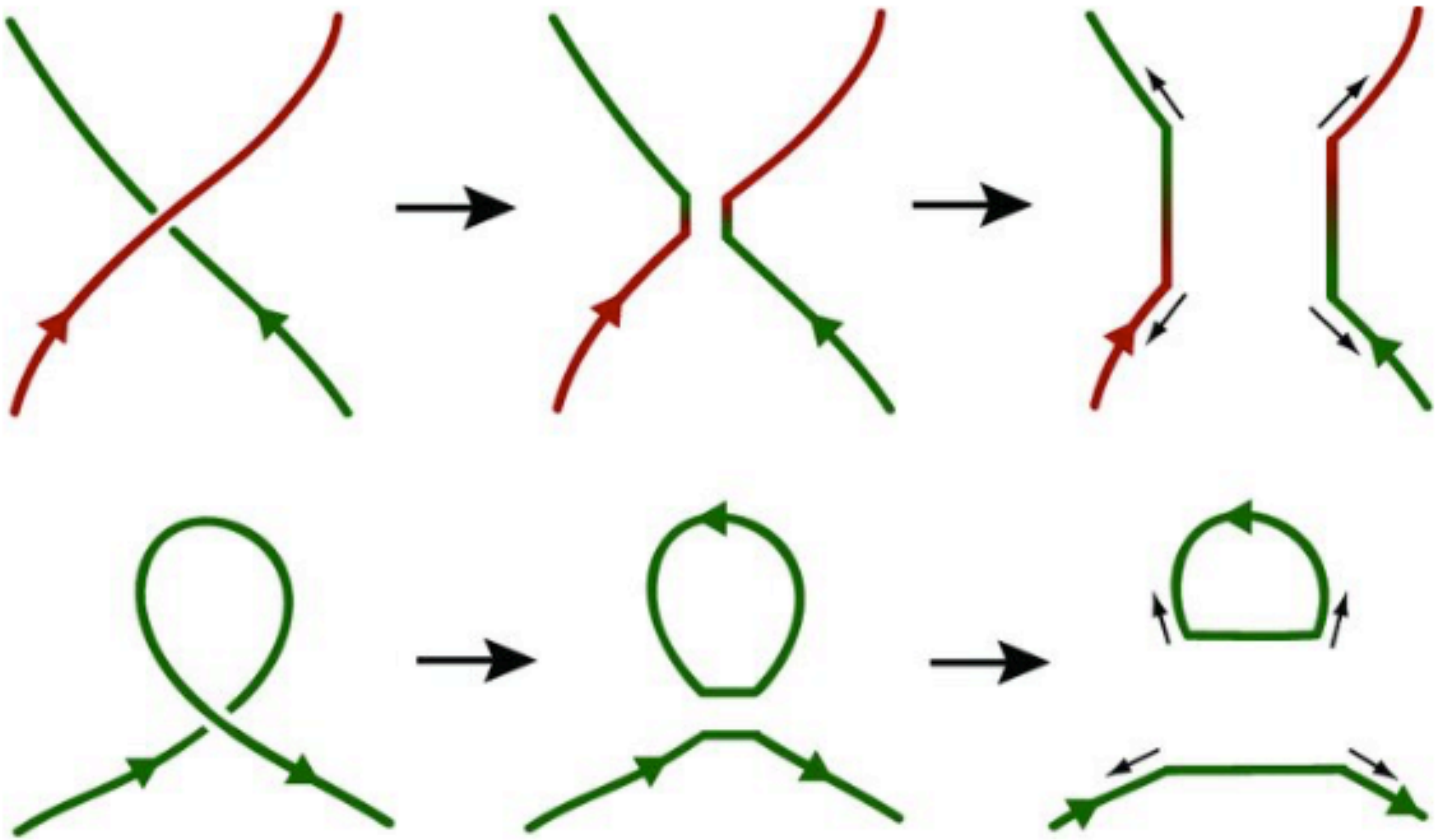
Probing Cosmic Strings



GW emission from string loops

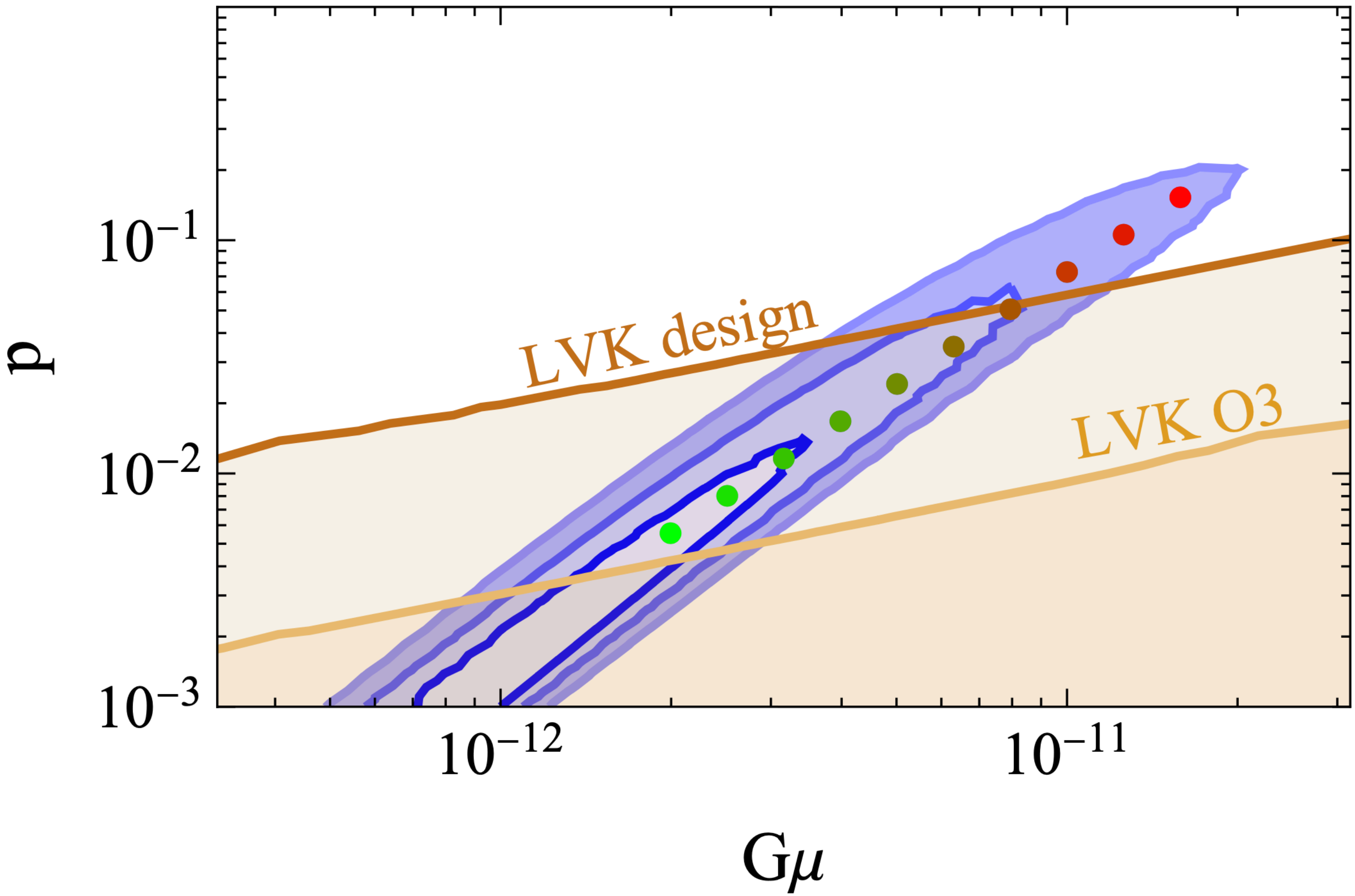
Simulation of cosmic string network – Cambridge cosmology group

String Intercommutation



U(1) bosonic strings intercommute with probability $p = 1$
Other strings (super, QCD-like, …) may have $p < 1$

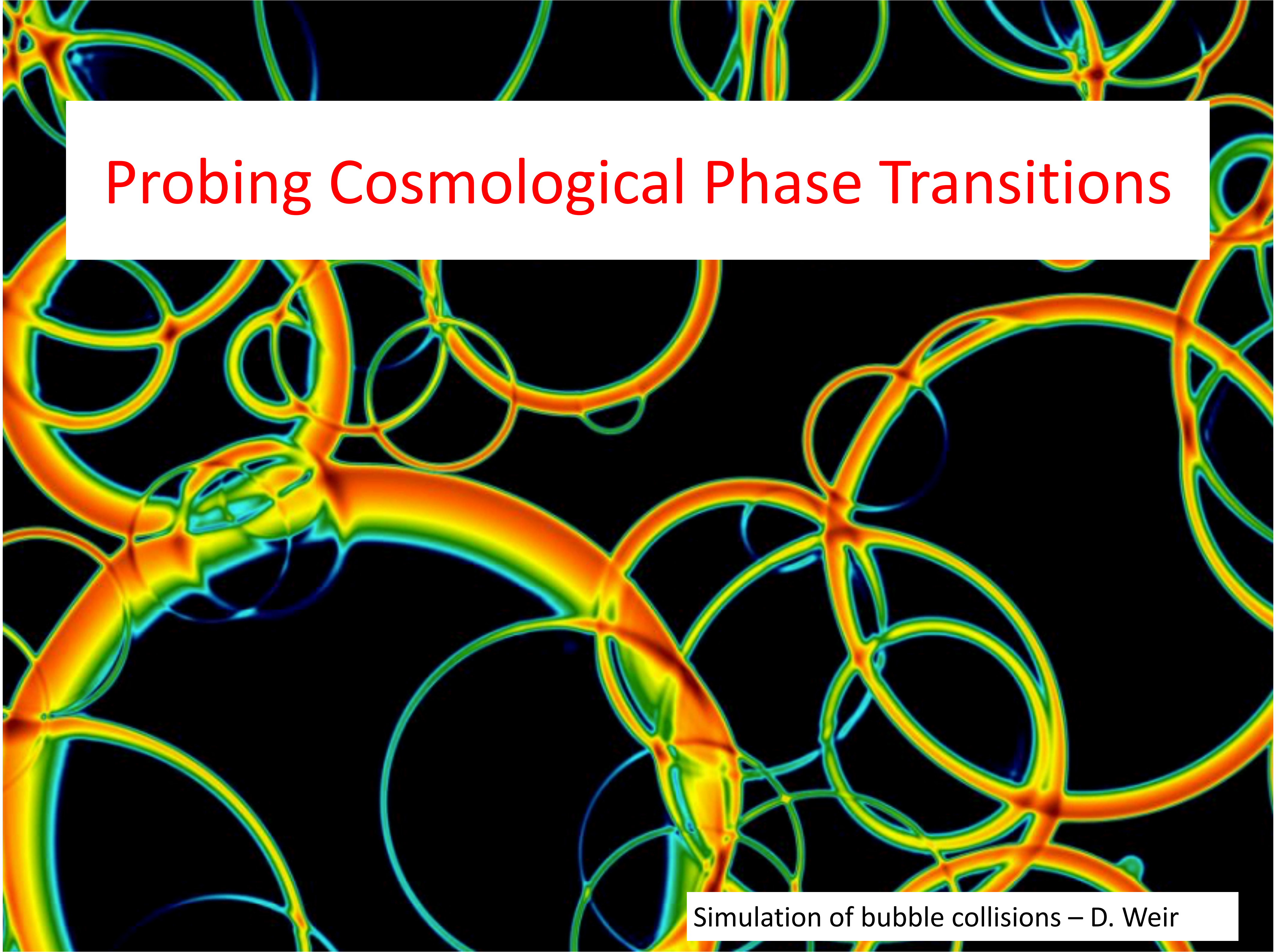
Superstrings vs LVK



(Super)string model compatible with LVK for $p \sim 0.001 - 0.1$

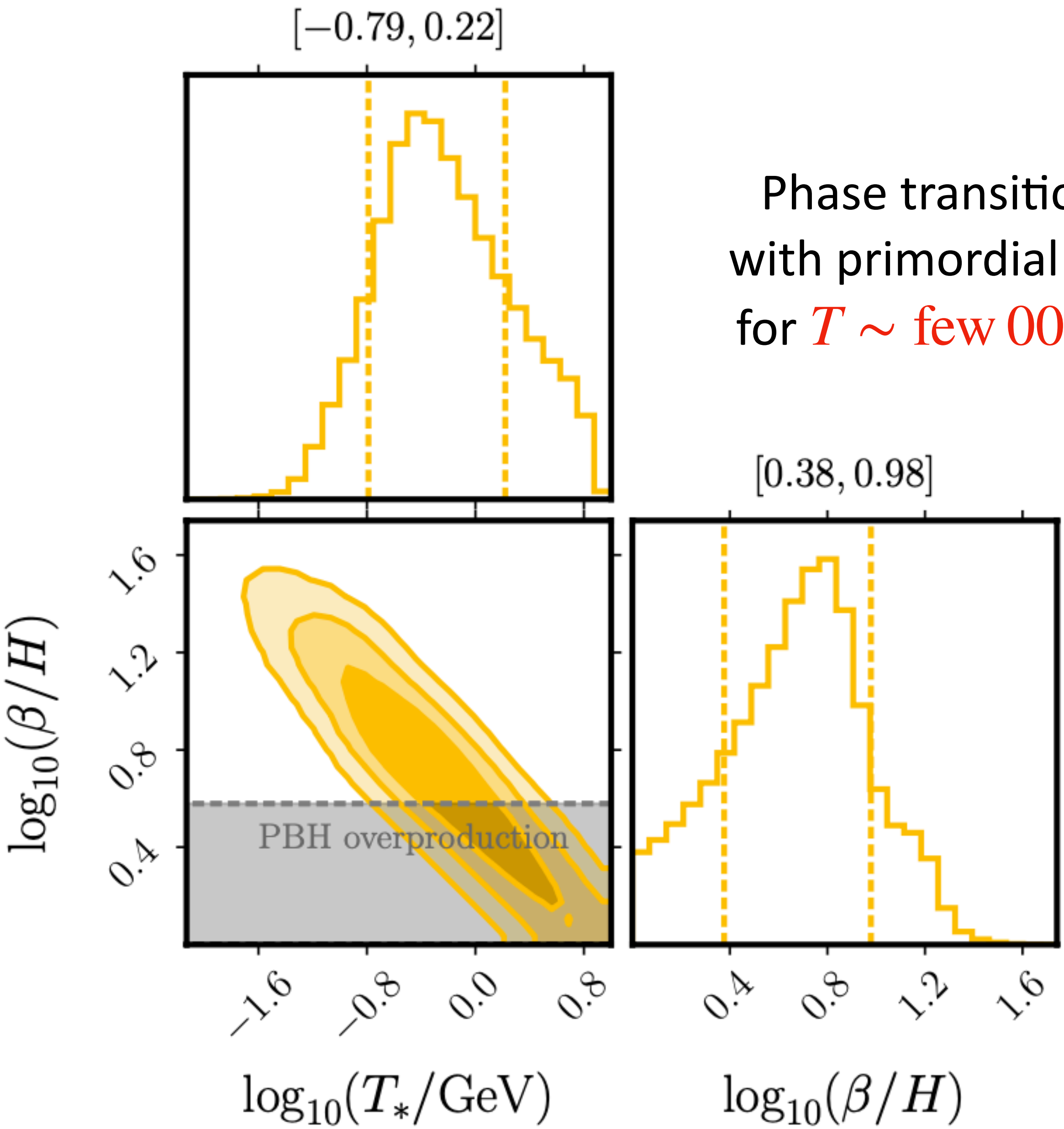
JE, Lewicki, Lin, & Vaskonen: arXiv:2306.17147

Probing Cosmological Phase Transitions



Simulation of bubble collisions – D. Weir

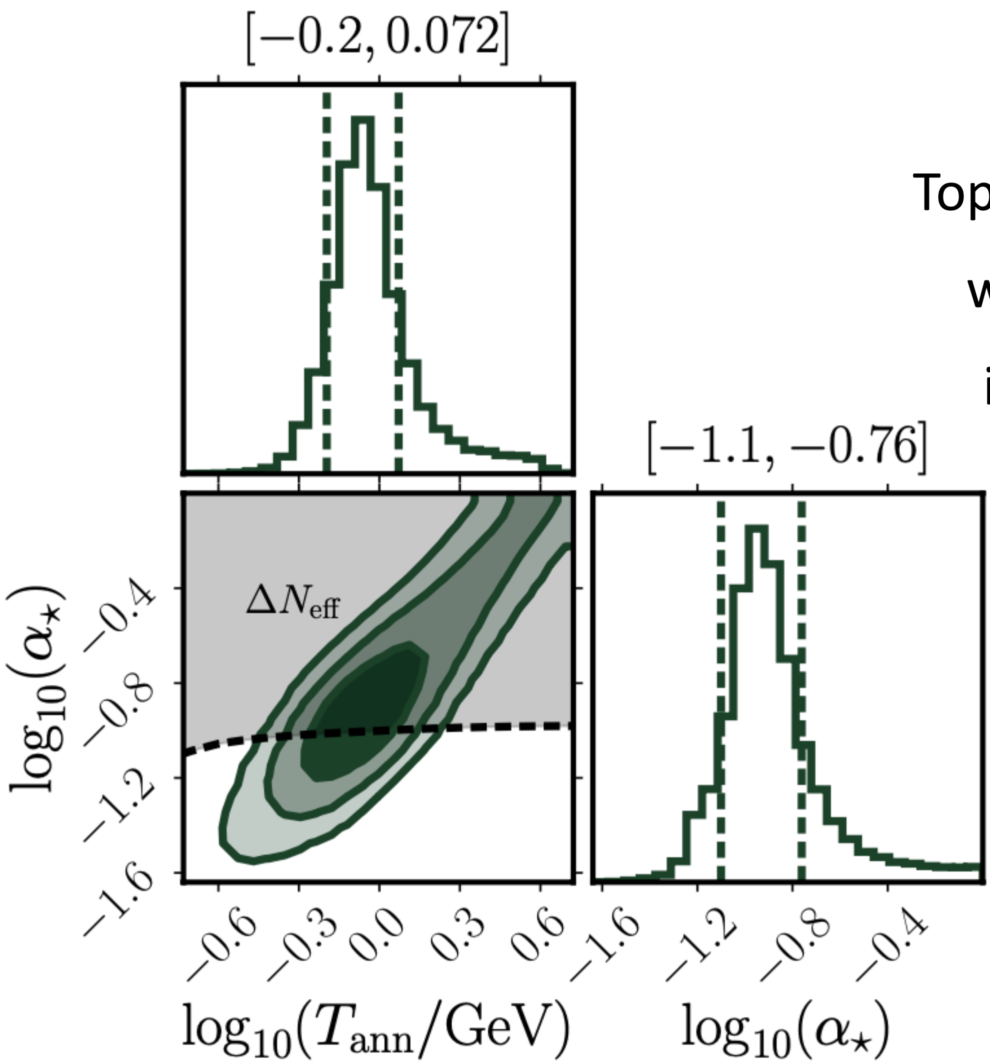
Phase Transition Fit to NANOGrav AION



Phase transition model compatible with primordial black hole abundance for $T \sim \text{few } 00\,\text{MeV}$ (hidden sector)

JE, Fairbairn, Franciolini, Hütsi, Iovino, Lewicki, Raidal, Urrutia, Vaskonen & Veermäe, arXiv:2308.08546

Domain Wall Fit to NANOGrav AION



Topological defects produced

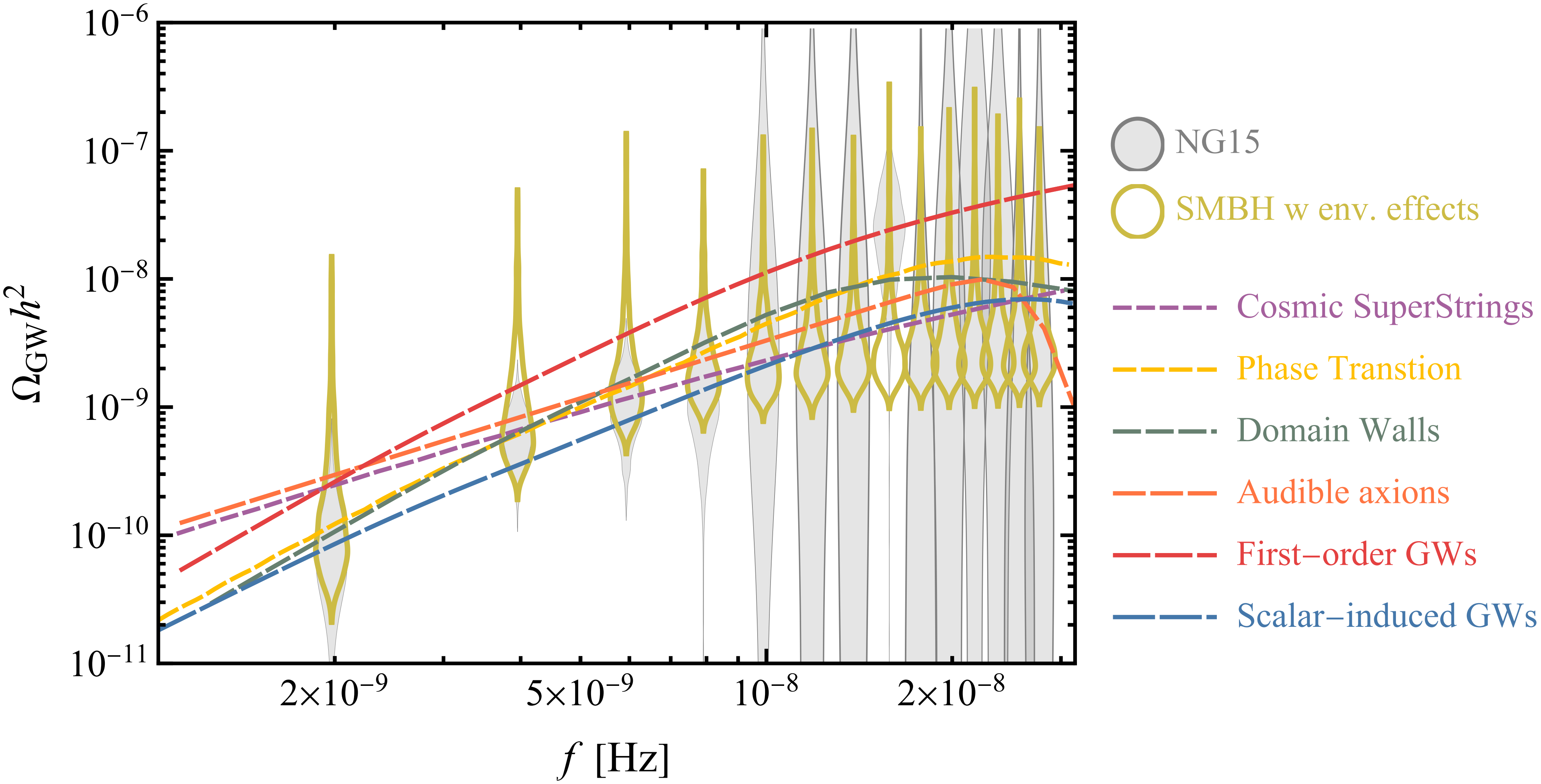
when discrete symmetry

is broken after inflation

Domain wall model compatible with cosmology for annihilation temperature $T_{\rm ann} \sim \mathrm{GeV}$ (hidden sector)

JE, Fairbairn, Franciolini, Hütsi, Iovino, Lewicki, Urrutia, Vaskonen & Veermäe, arXiv:2308.08546

Fits to NANOGrav



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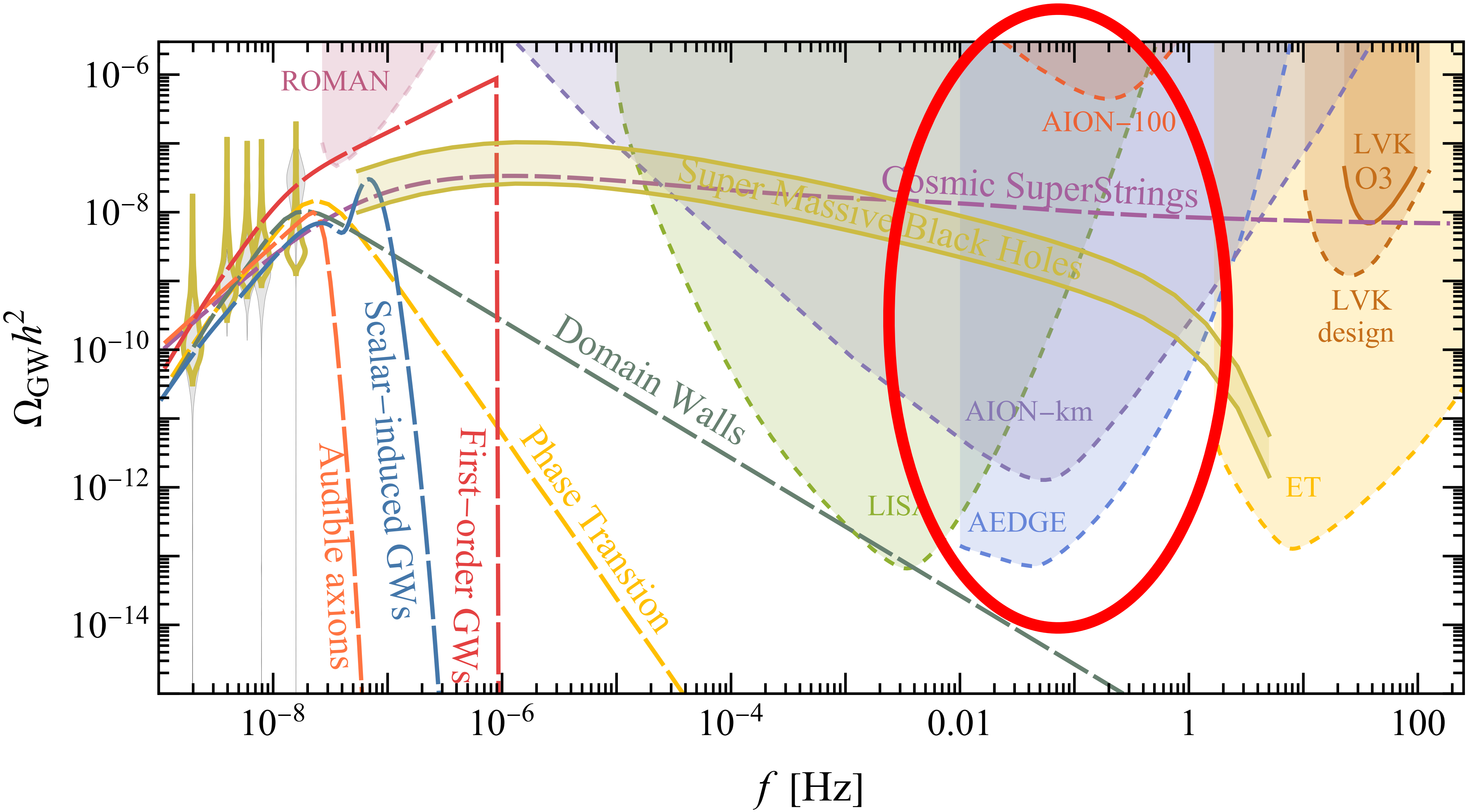
Extension of Fits to Higher Frequencies



JE, Fairbairn, Franciolini, Hütsi, Iovino, Lewicki, Raidal, Urrutia, Vaskonen & Veermäe, arXiv:2308.08546

Quo Vadis NANOGrav?

- **Astrophysics or fundamental physics?**
- Biggest bangs since the Big Bang, or physics beyond the SM?
- SMBH binaries driven by GWs alone disfavoured
- SMBH binaries driven by GWs and environmental effects fit better
- **Better fits with cosmological BSM models**
- Discrimination possible with future measurements: fluctuations, anisotropies, polarization, experiments at higher frequencies - including atom interferometers AION
- **Time and more data will tell!**

JE, Fairbairn, Franciolini, Hütsi, Iovino, Lewicki, Raidal, Urrutia, Vaskonen & Veermäe, arXiv:2308.08546