SCIENCE CASE FOR THE NEXT GENERATION OF GROUND-BASED GRAVITATIONAL WAVE DETECTORS

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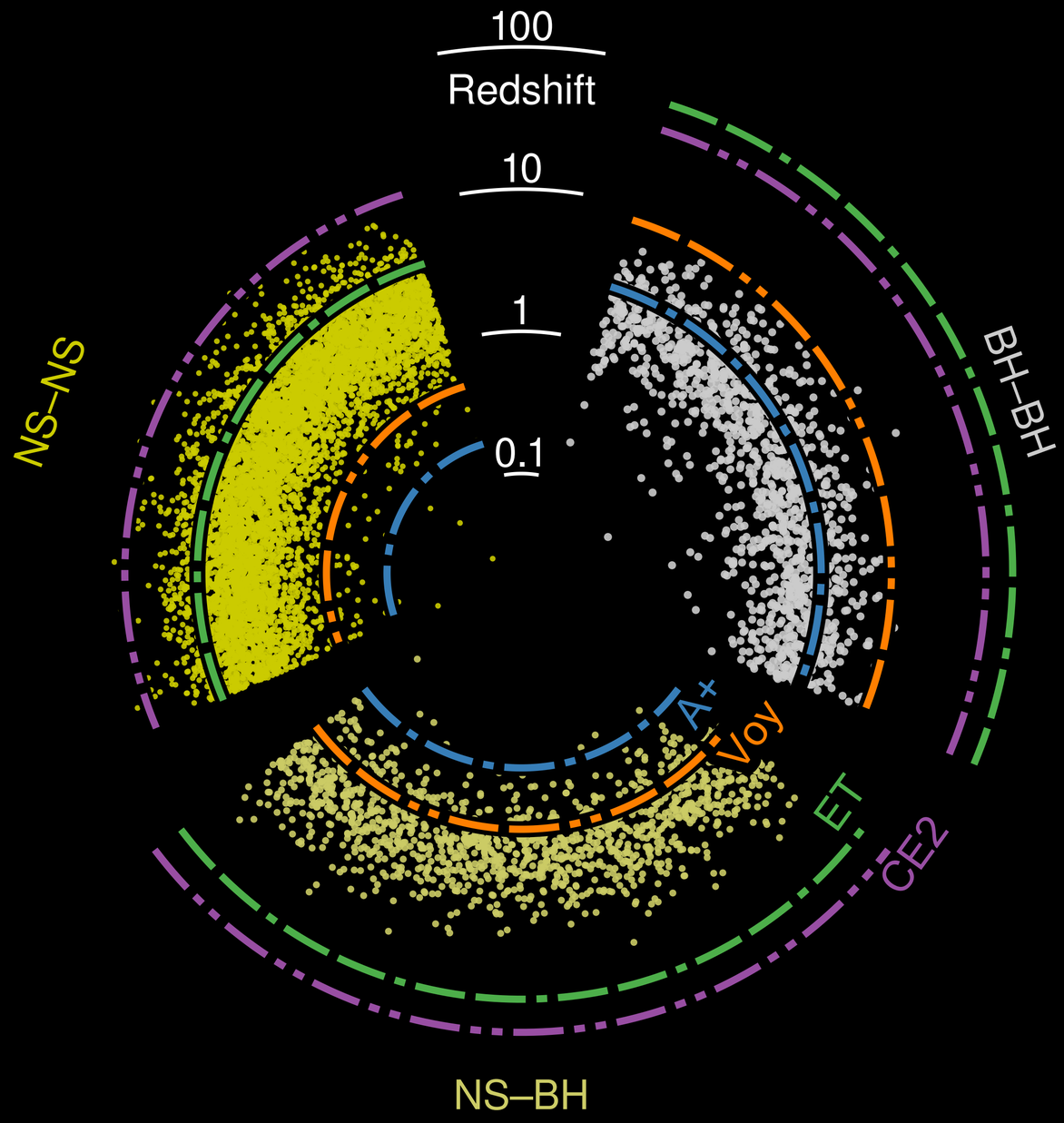
GWIC
Gravitational Wave International Committee

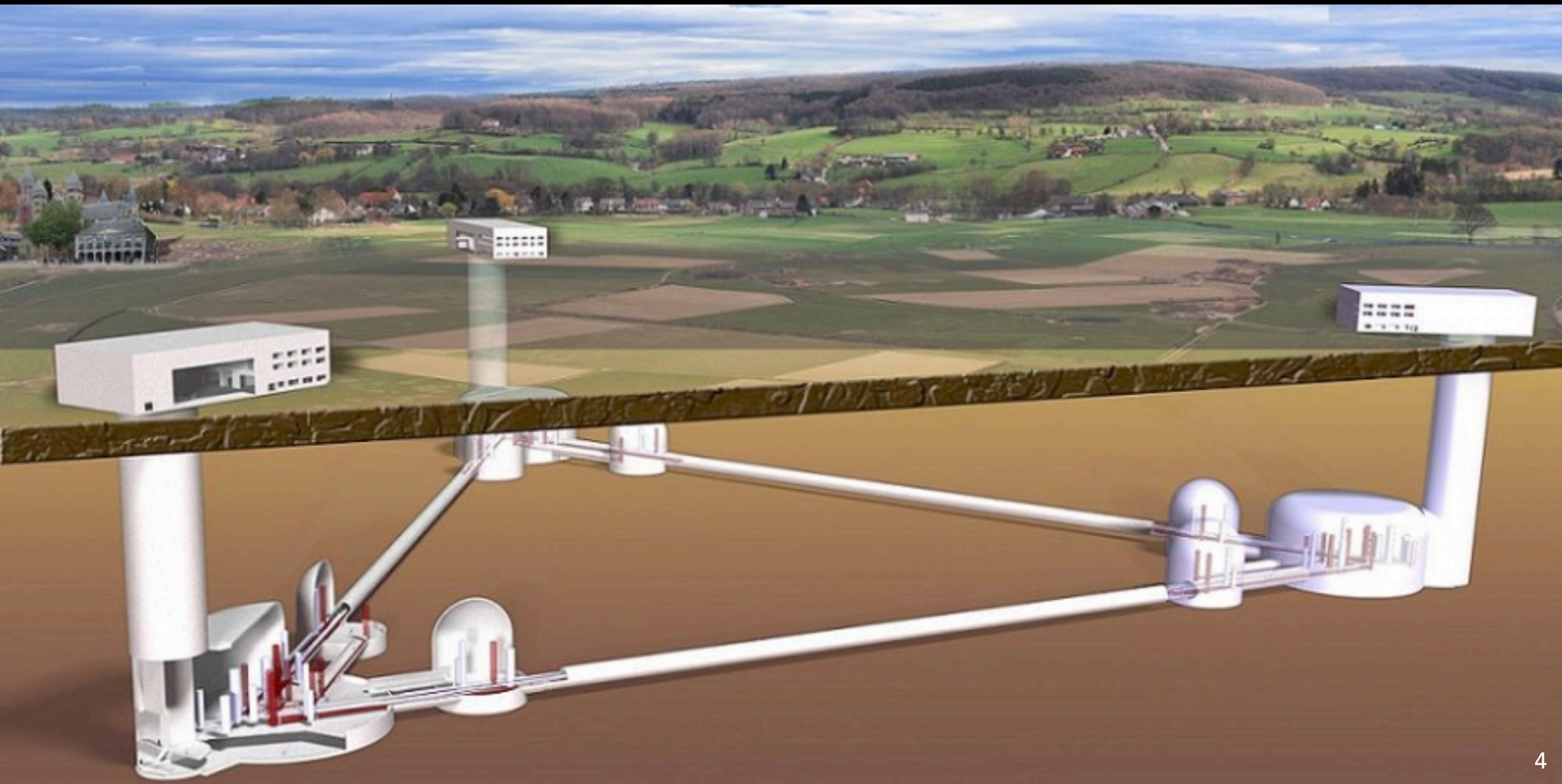
DISTANCE REACH OF ET, CE, VOYAGER, A+



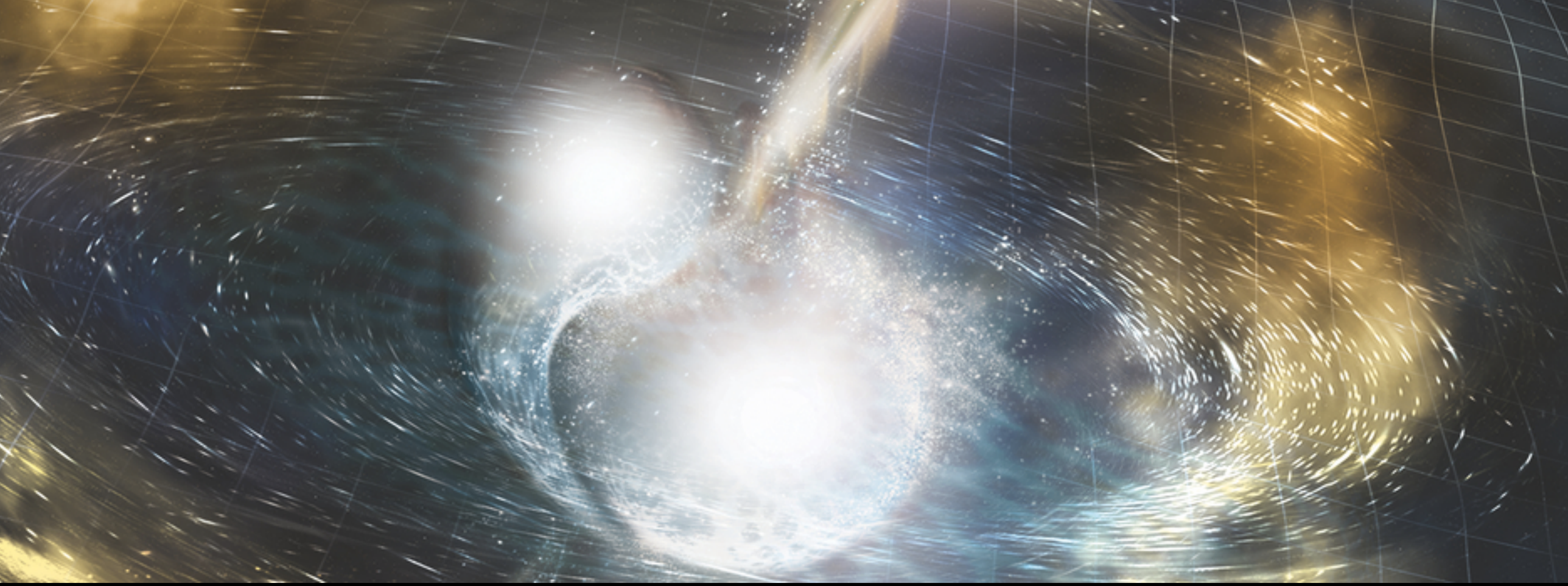
ET AND CE EFFORTS

- Einstein Telescope is a project studied in Europe
  - first efforts began in 2007
  - ET conceptual design study completed in 2011
  - currently huge effort to enter the ESFRI Roadmap–mandatory path to acquire funding
- Cosmic Explorer is envisaged to be a new facility in the US
  - NSF funded three-year horizon study (to be completed in 2021)
  - trade study (see talk by Ssohrab Borhanian) to assess capability of different networks
  - site selection, costing and sub-system design

EINSTEIN TELESCOPE – A 10 KM TRIANGLE

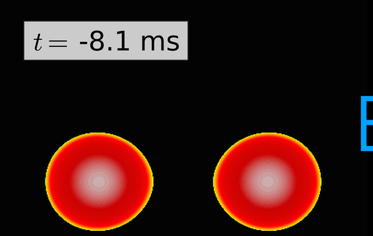


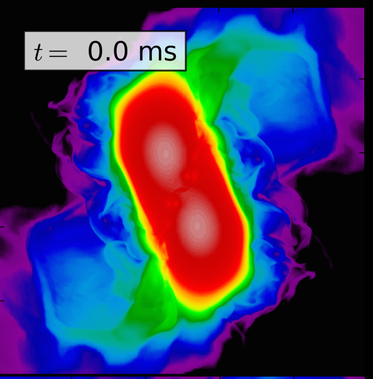
COSMIC EXPLORER

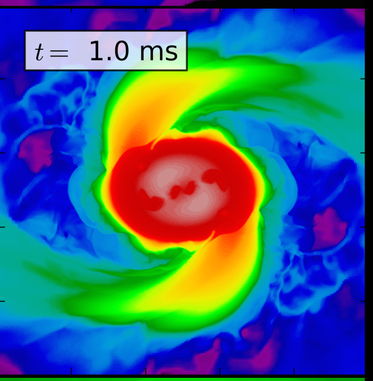


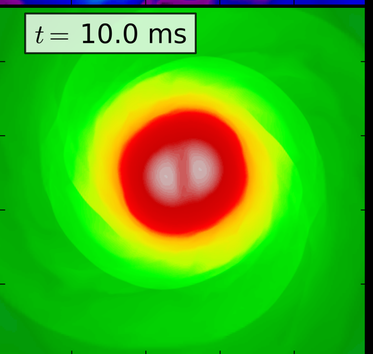
EXTREME MATTER IN EXTREME ENVIRONS

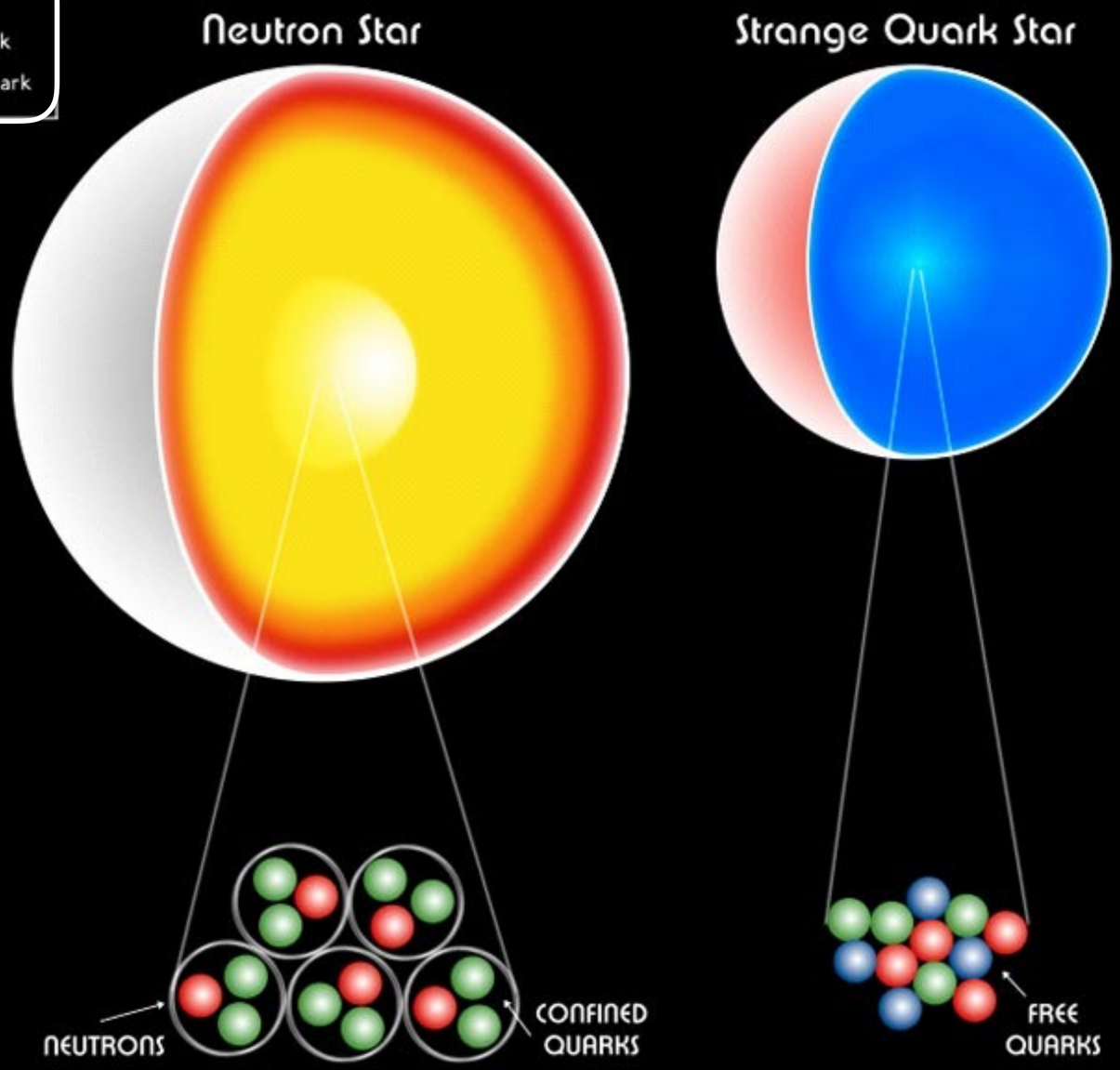
EQUATION OF STATE OF DENSEST MATTER







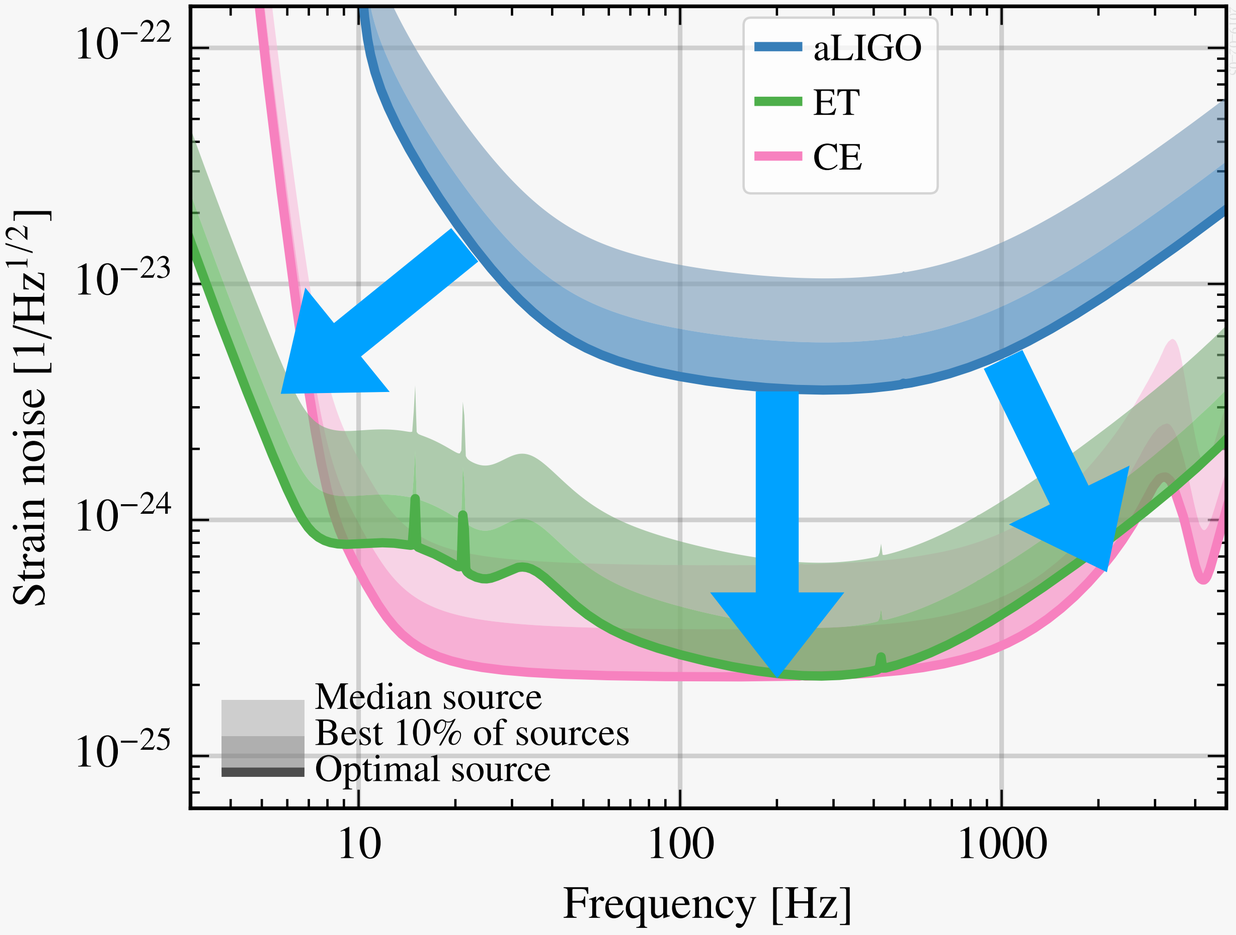


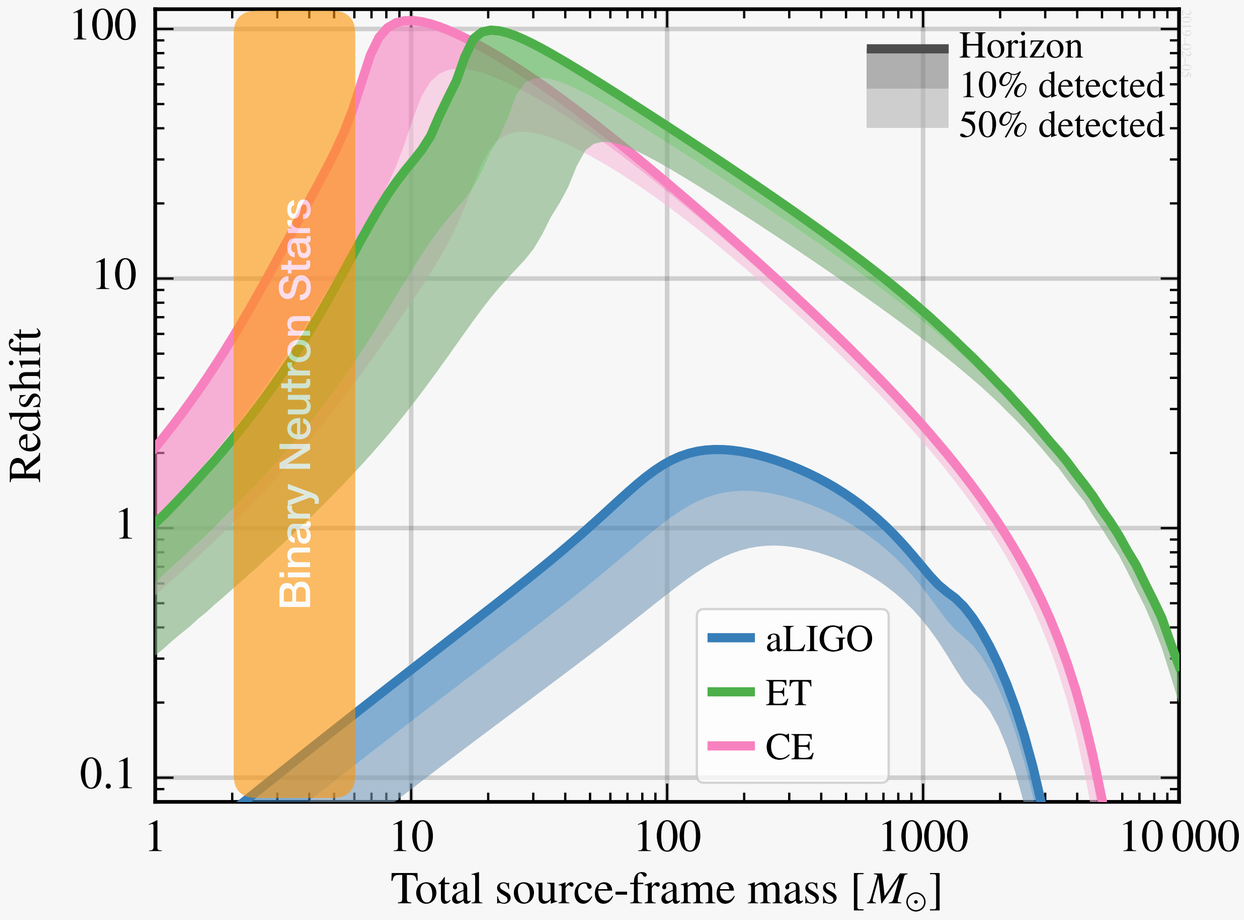


Densities ~ 4 x10^{17} kg/m^3


DEEPER, WIDER,
SHARPER

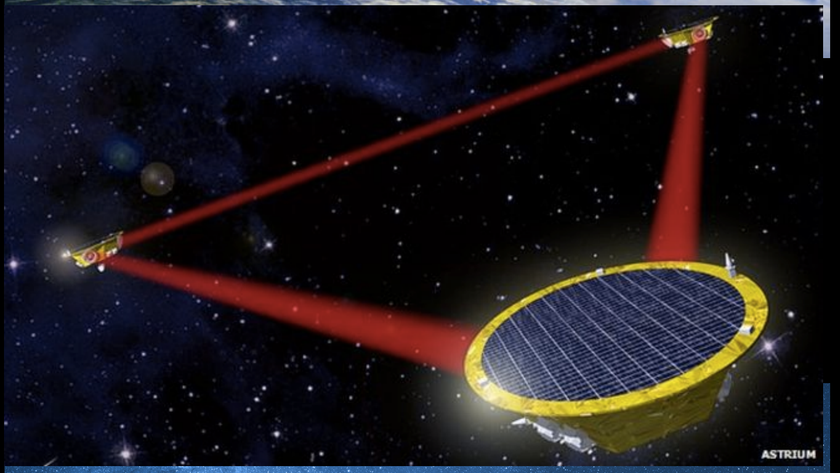
EINSTEIN TELESCOPE AND COSMIC EXPLORER

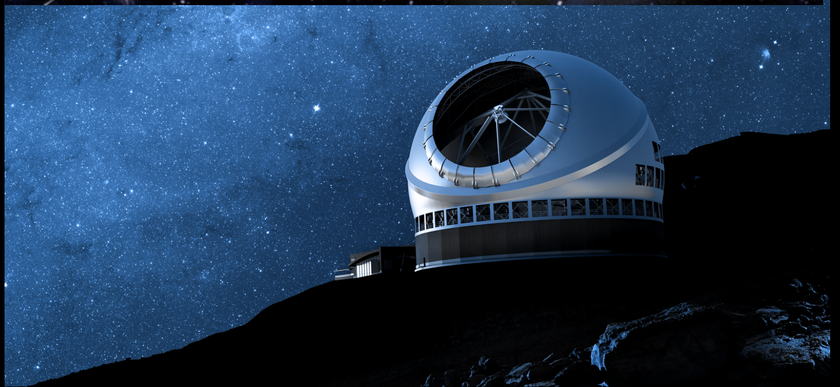


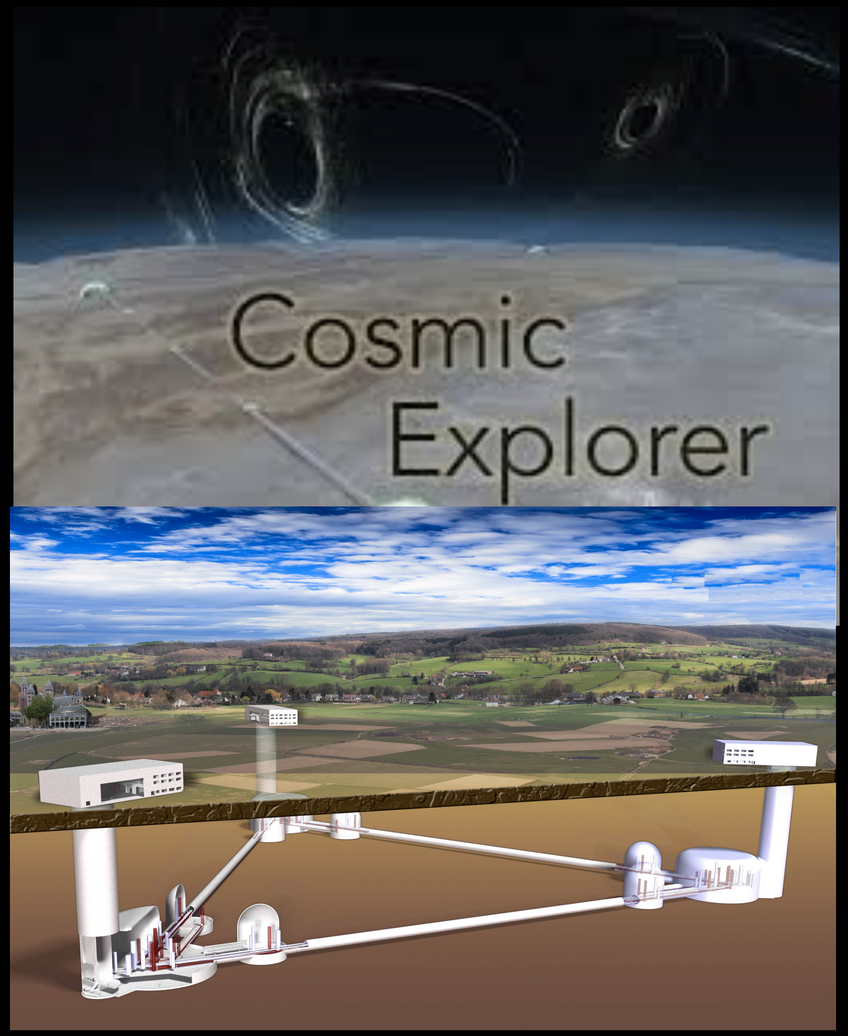


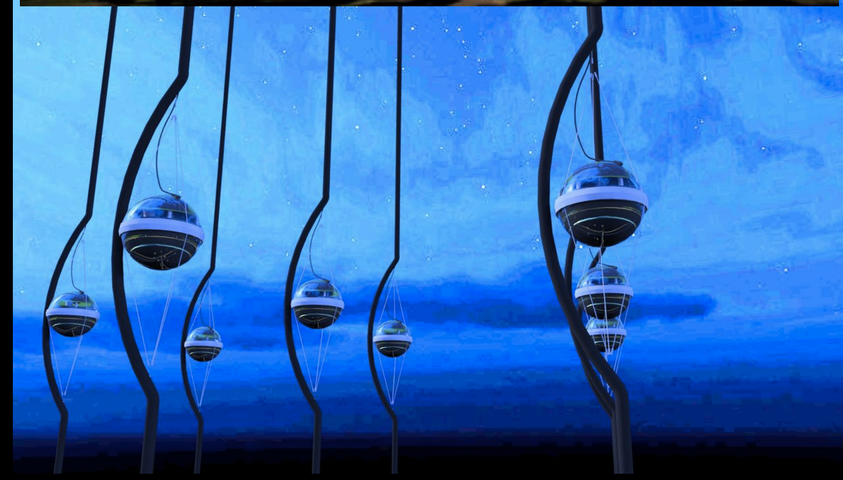
Credit: Evan Hall

MULTIMESSENGER SCIENCE

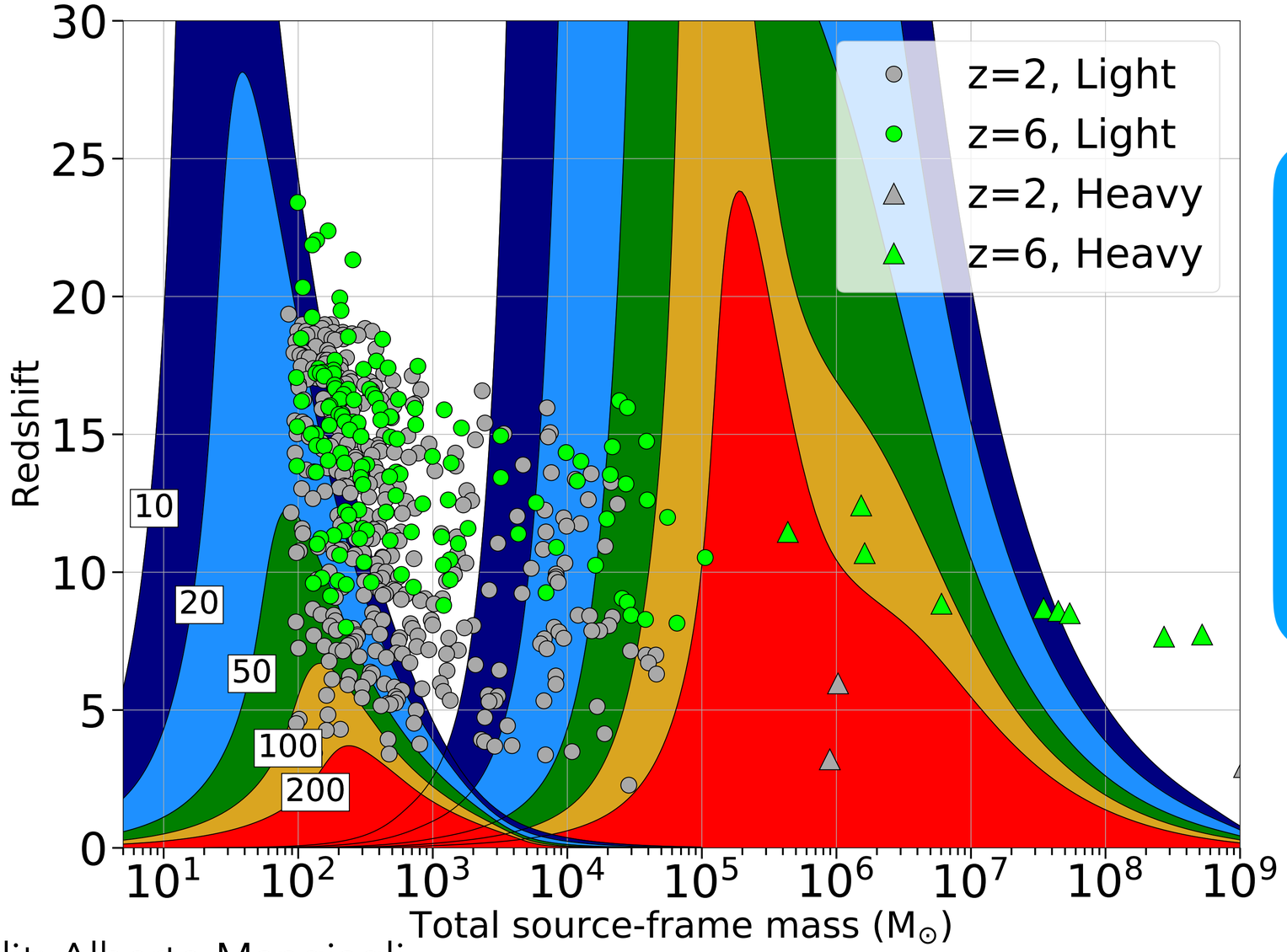








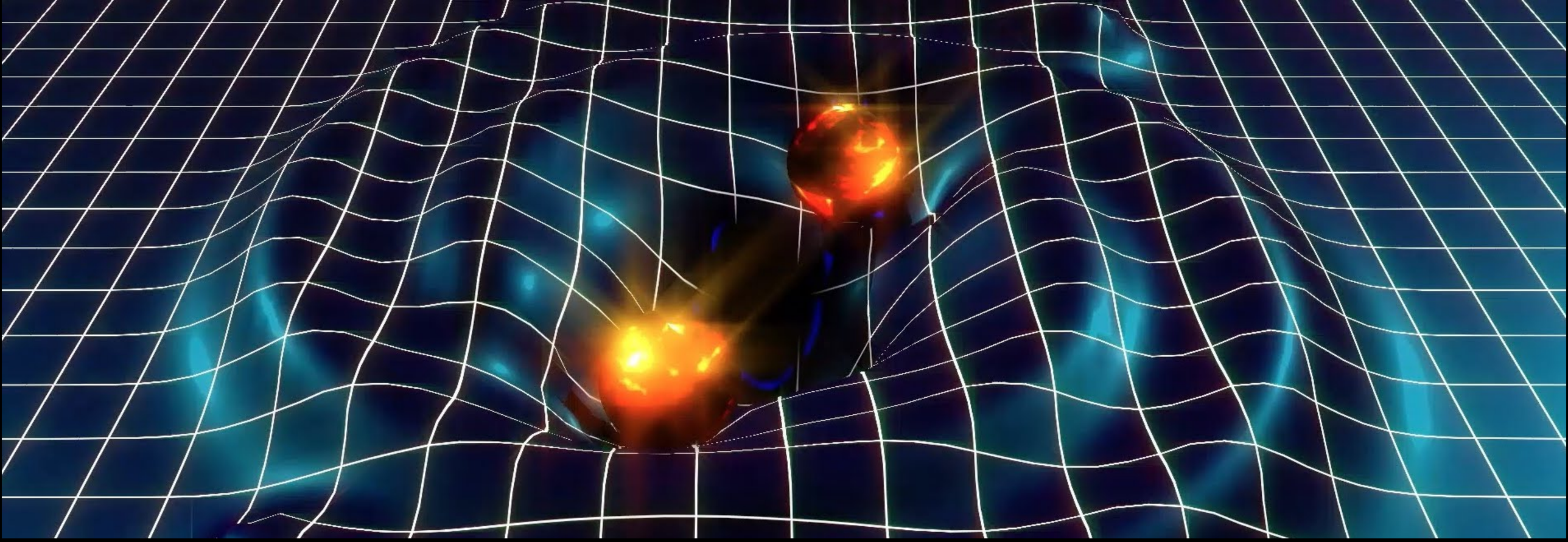
ORIGIN AND EVOLUTION OF SEED BLACK HOLES



Credit: Alberto Mangiagli

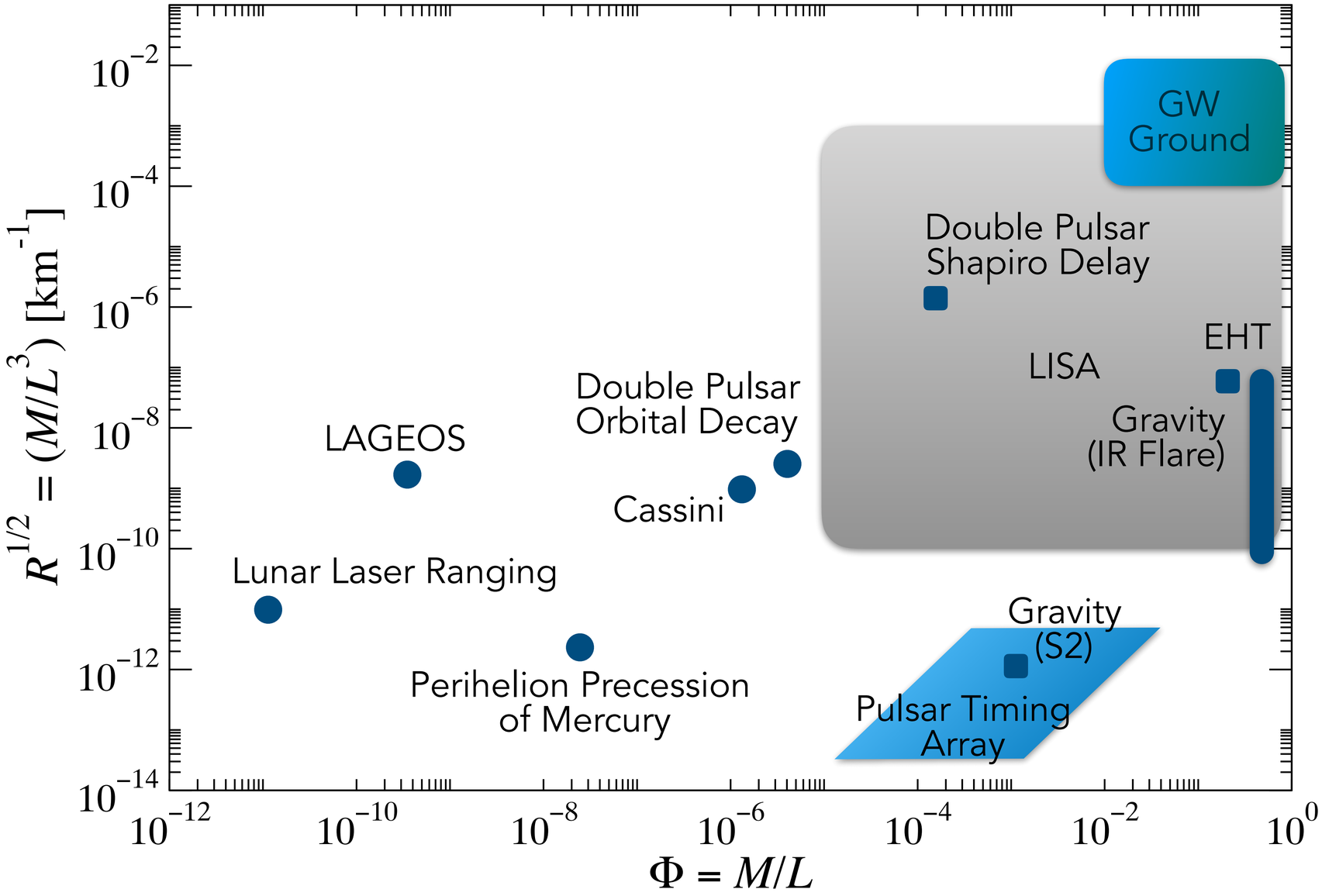
3G + LISA, will characterize every binary black hole merger in the universe, and explore demographics of seed black holes and their growth

R Valiante+ in preparation



EXTREME GRAVITY AND THE NATURE OF SPACETIME

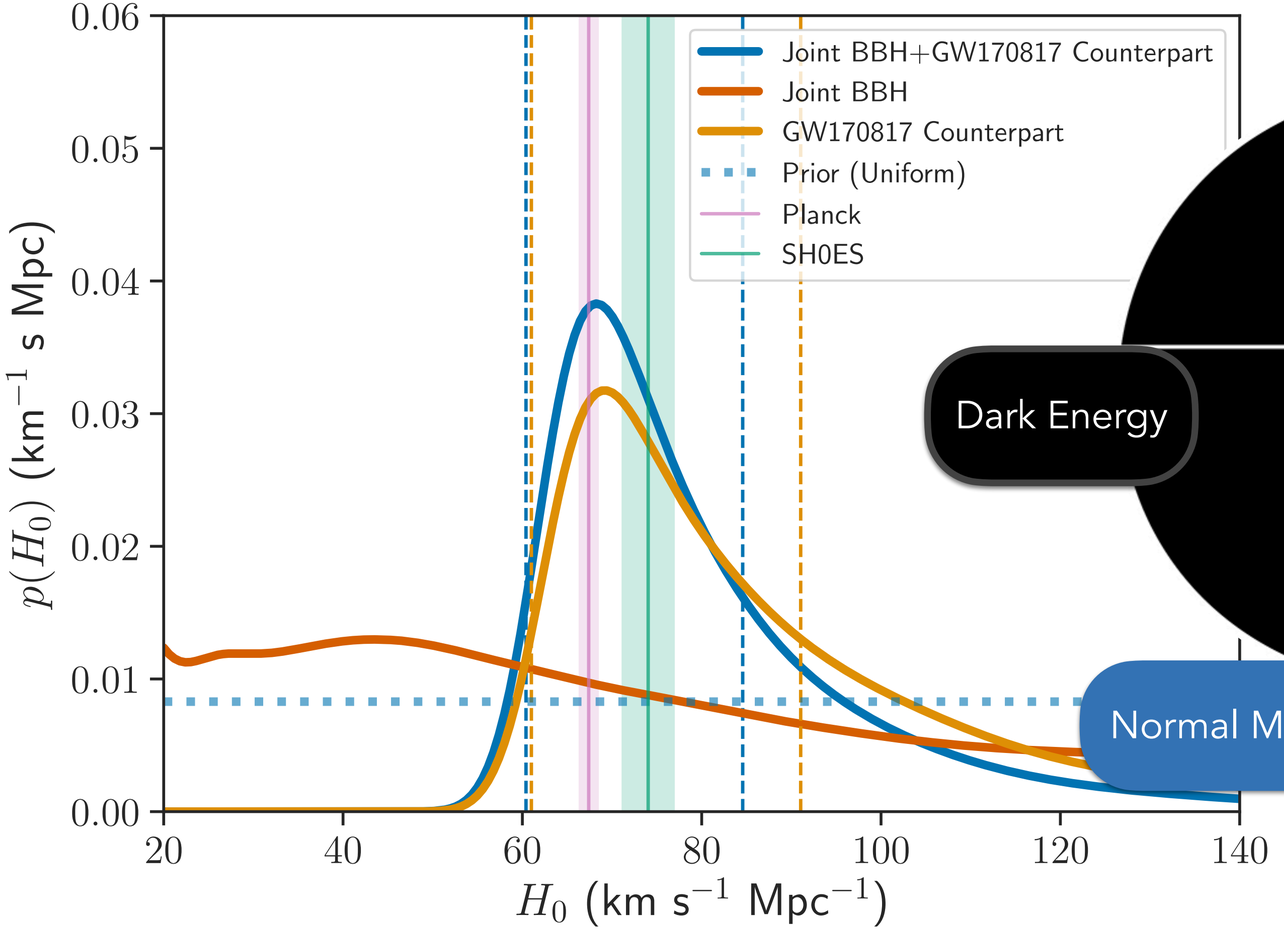
TESTS OF GENERAL RELATIVITY AND MODIFIED THEORIES OF GRAVITY

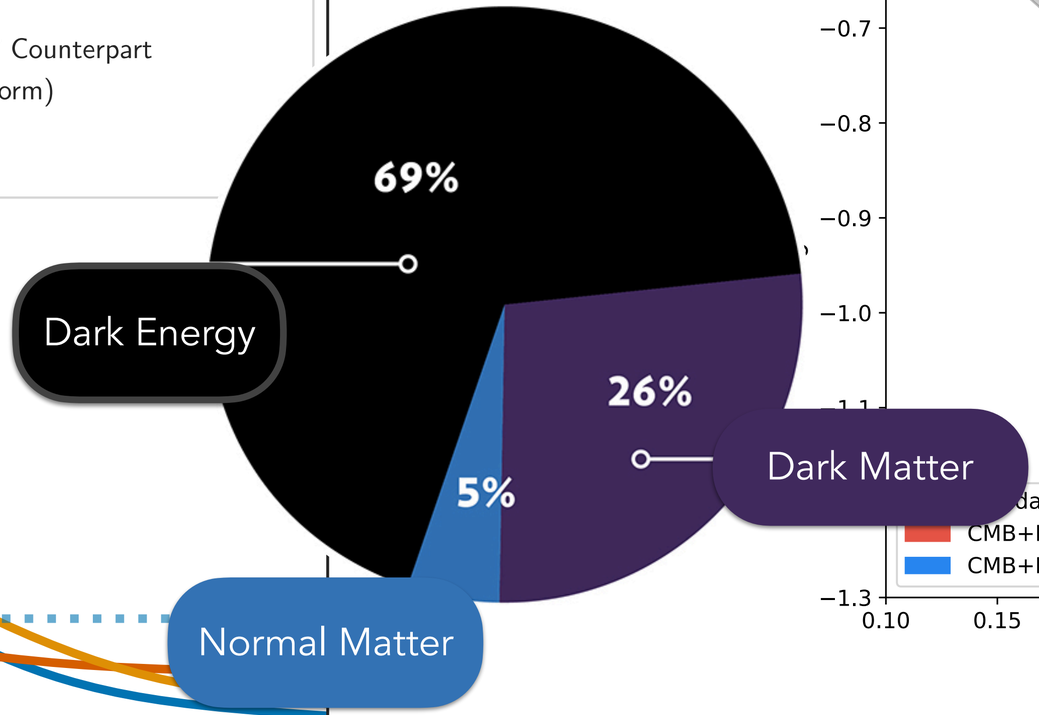


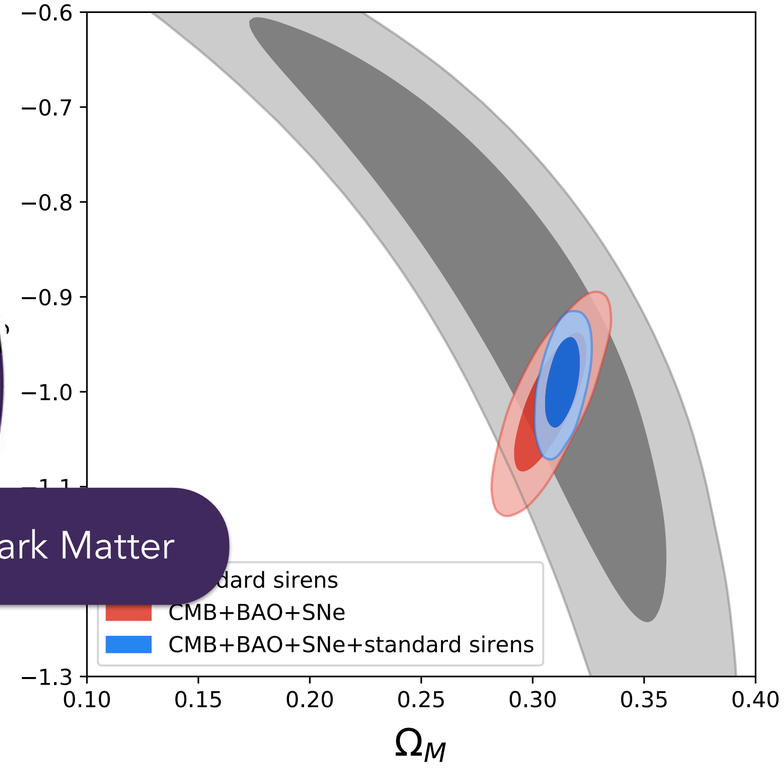
3G network will test general relativity in regions of greatest curvature and surface gravity of any experiment

COSMOGRAPHY–MEASURING THE UNIVERSE

Abbott+, arXiv:1908.06060







advanced detectors and their upgrades could resolve the tension after ~50-100 binary neutron star observations with EM counterparts; 3G detectors will provide decisive sky localization required for EM follow-up

GWIC-3G SCT AND CONSORTIUM

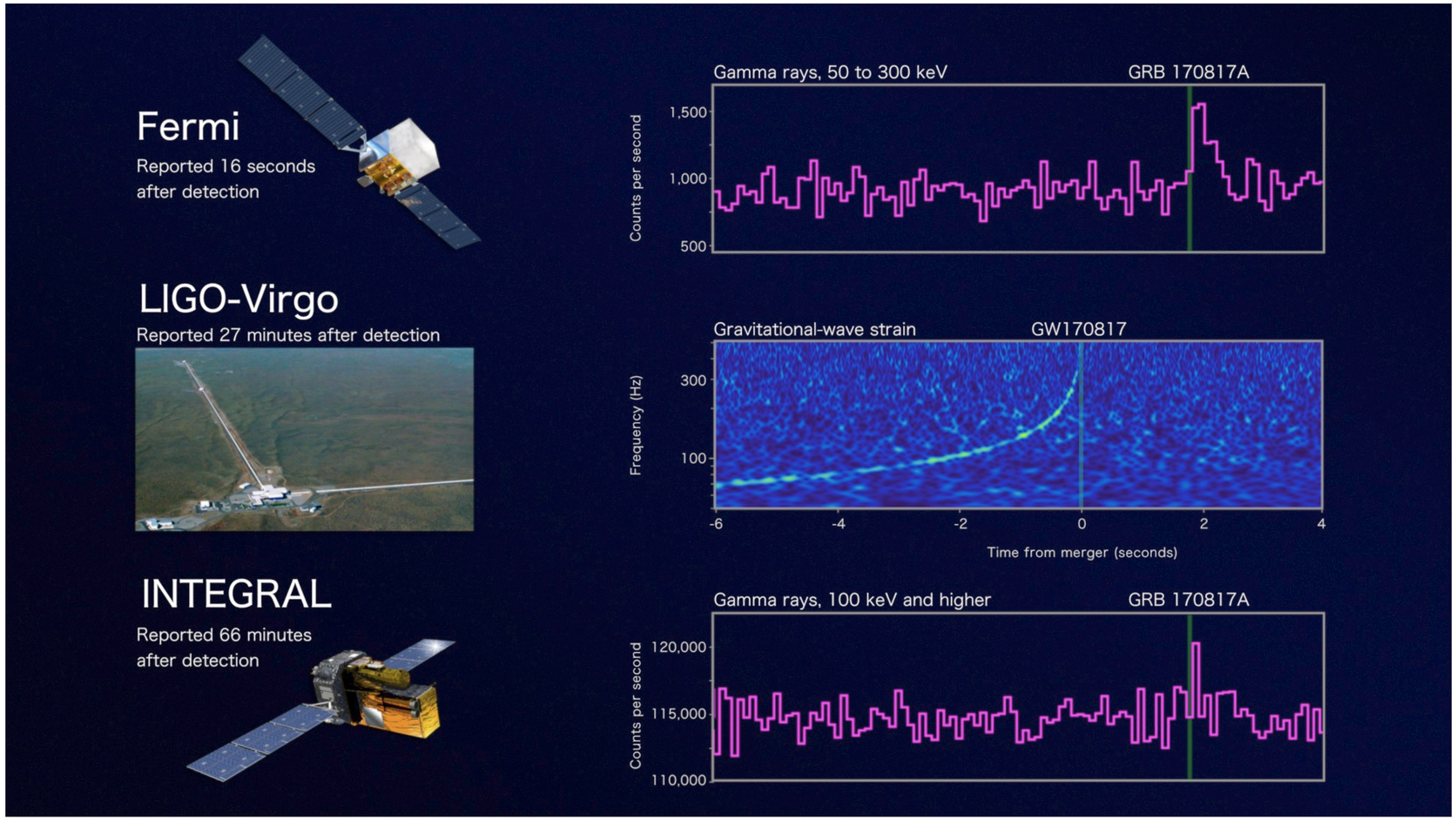
- science case team
  - Bailes, Bizourd, Buonanno, Burrows, Colpi, Evans, Fairhurst, Hild, Kalogera, Kasliwal, Lehner, Mandel, Mandic, Nissanke, Papa, Reddy, Rosswog, Sathyaprakash, Van Den Broeck
- science case consortium
  - 220 scientists around the world and growing
- broad scientific community
  - general relativity, numerical relativity, quantum gravity
  - transient astronomy, high-energy astrophysics
  - cosmology, dark energy and dark matter
  - nuclear physics and higher energy particle physics

OPPORTUNITY FOR NEW DISCOVERIES

- gravitational window is a completely different observational tool compared to em window
  - experience tells us that each observational window had led to discoveries never imagined before
    - x-ray, radio, infra-red, gamma-ray, cosmic rays, …
- gravitational wave detectors, especially at good sensitivities, should be expected to make new discoveries
  - could lead to new physics that help us understand missing links in fundamental physics and astrophysics

SPEED OF GRAVITATIONAL WAVES FROM GW170817 AND GRB170817A

Abbott+ ApJ Letters, 848, L12 (2017)



3G network would improve this limit by three orders of magnitude

$$-3 \times 10^{-15} \leq \frac{v_{\rm GW} - v_{\rm EM}}{v_{\rm EM}} \leq 7 \times 10^{-16}$$

TESTS OF WAVE PROPAGATION

$$E^2 = p^2c^2 + Ap^\alpha c^\alpha, \quad \alpha \geq 0$$

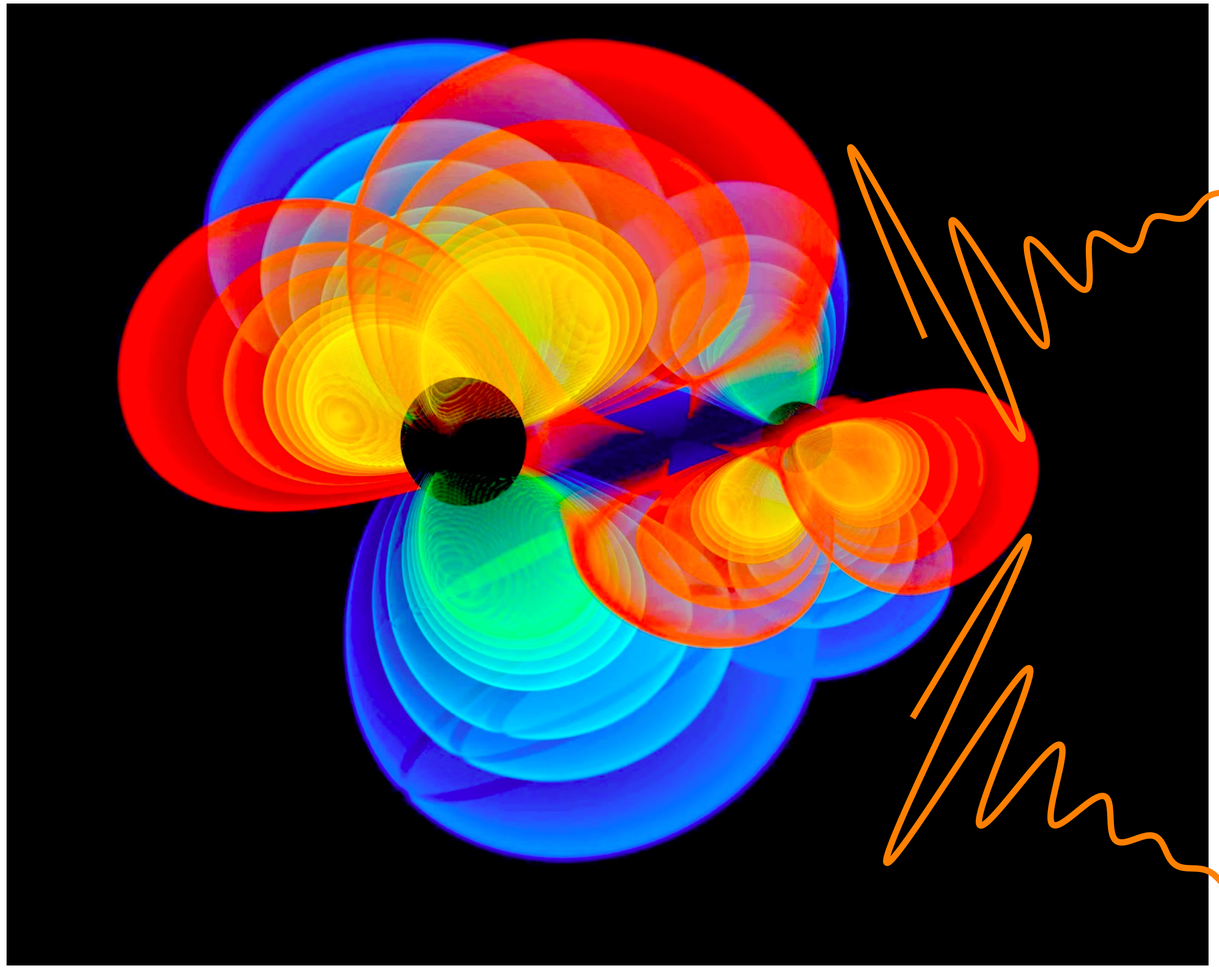
- modified theories of gravity predict dispersion
- dispersion modifies the phase and frequency
- best constraints in the gravity sector for superluminal gravitational waves

Abbott+ PRL, 118, 221101 (2017)

- GW170104 bound on graviton mass: $m_g < 7.7 \times 10^{-23}$ eV

3G network will observe sources @ z~20 and improve limit on graviton mass by an order of magnitude

QUASI-NORMAL MODES AND NO-HAIR TESTS



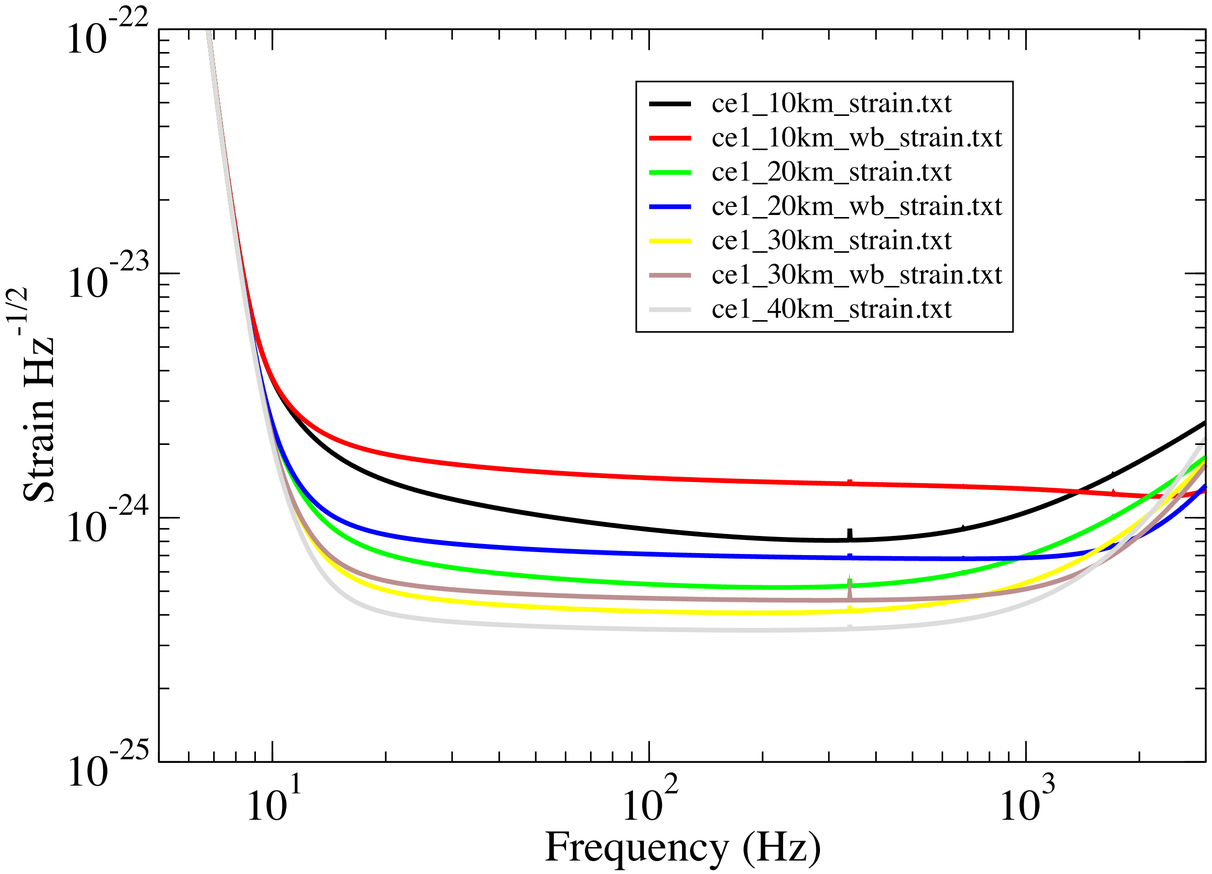
- Deformed black holes emit quasi-normal modes
  - complex frequencies depend only on the mass and spin
- Measuring two or more modes would provide a smoking gun evidence of Kerr black holes
  - If modes depend on other parameters, consistency between different mode frequencies would fail

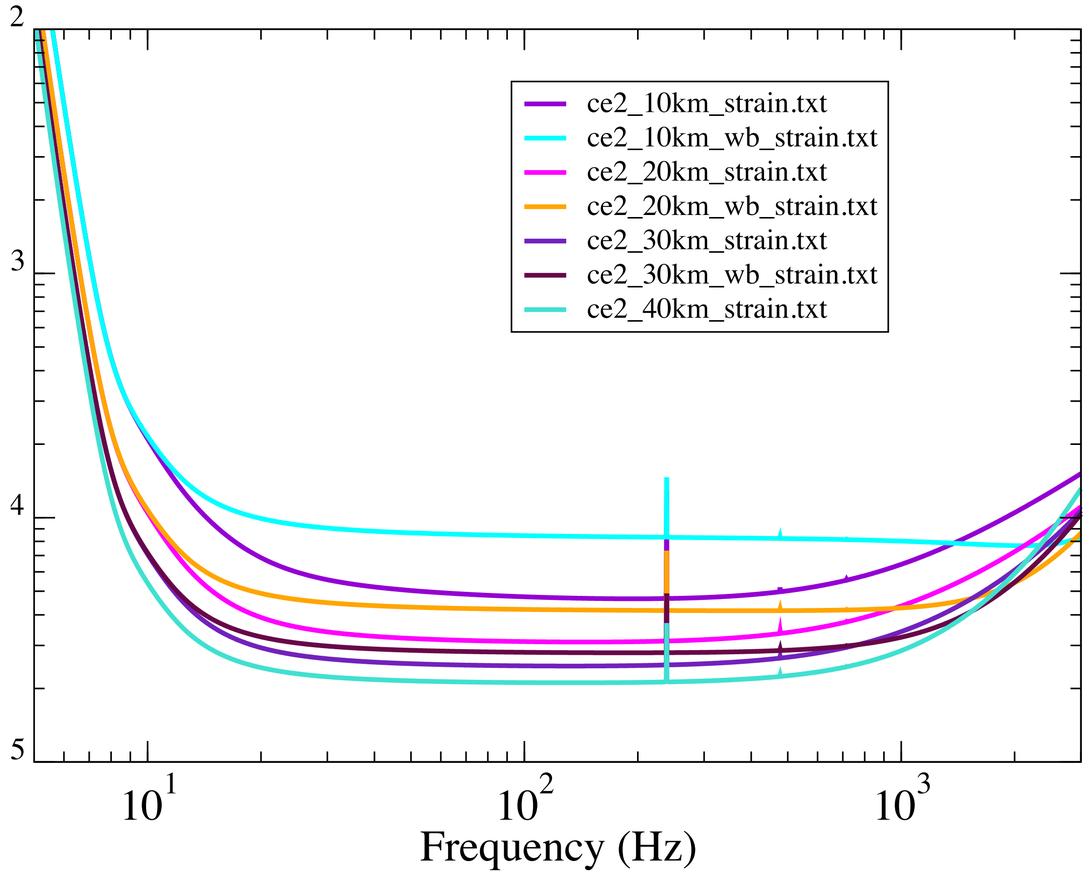
Dreyer+ 2004, Berti+ 2006, Berti+ 2007, Kamaretsos+ 2012, Gossan+2012, Bhagwat+ 2017, Brito+ 2018

WHY TEST GENERAL RELATIVITY

- so far GR has passed all experimental and observational tests
  - solar system tests, binary pulsars, black hole orbital dynamics, …
- but theoretical and observational problems exist
  - generic prediction of singularity, black hole information loss, accelerated expansion of the Universe, non-detection of dark matter, …
- GR is violated in quantum gravity theories
  - birefringence of gravitational waves in Chern-Simons theory
  - violation of Lorentz invariance in Loop quantum gravity
  - Planck-scale structure of black hole horizons

TRADE STUDIES

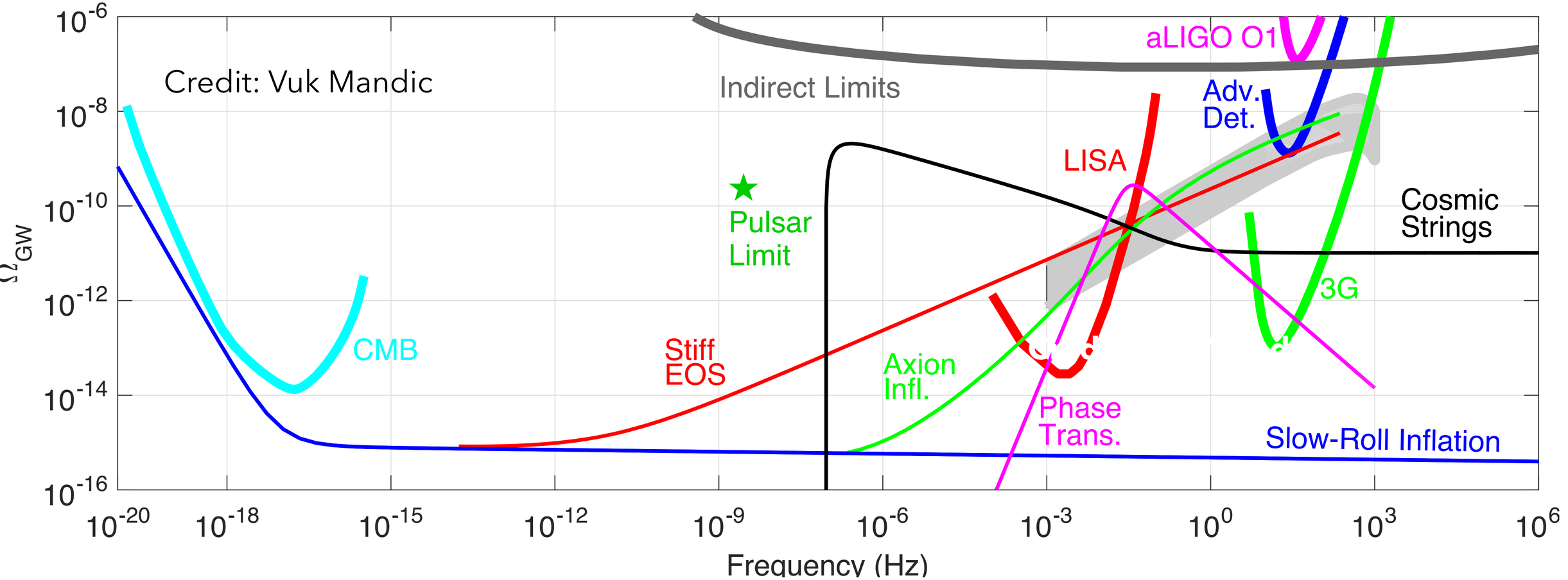




IN SUMMARY ...

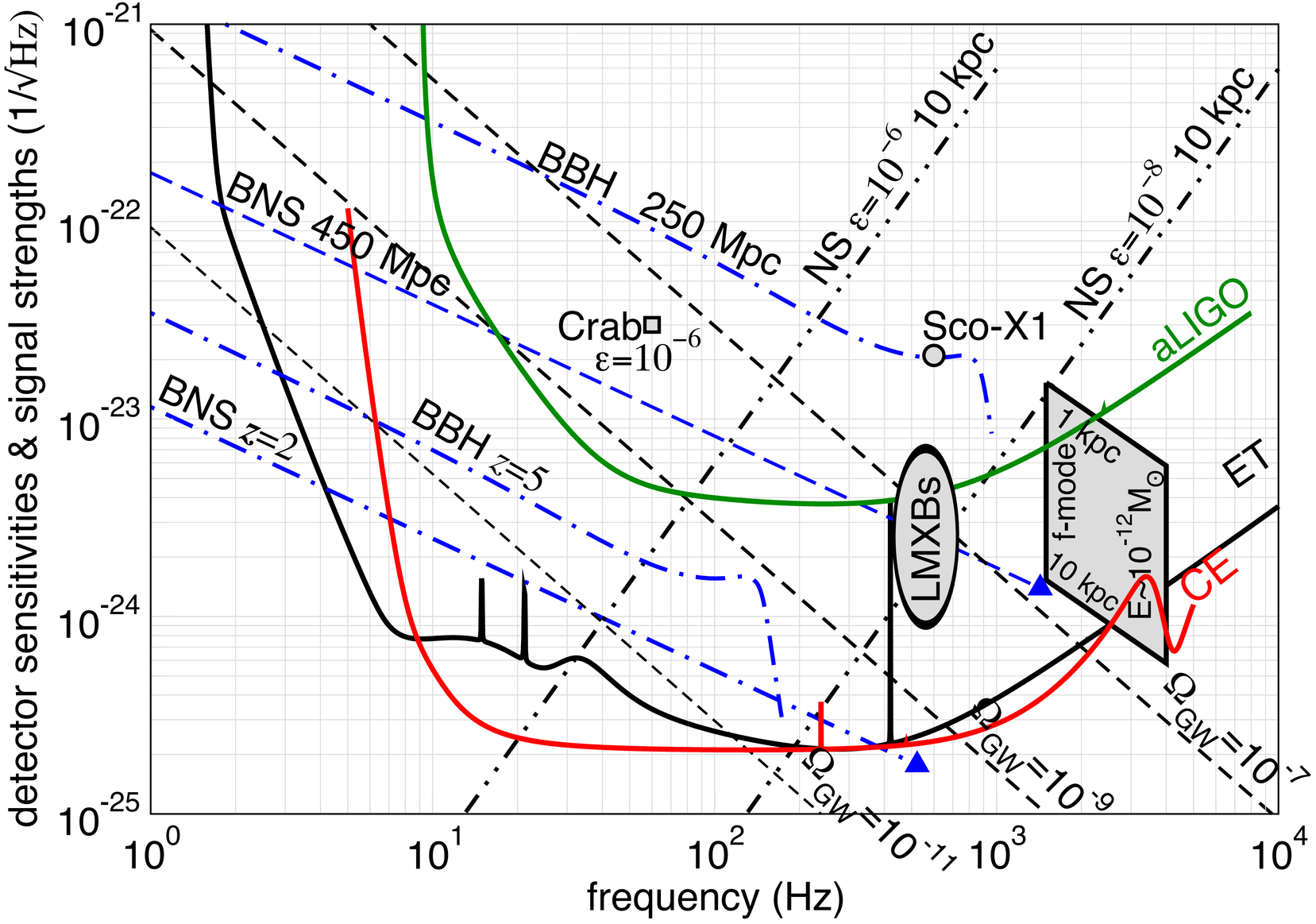
- explore the state of ultra dense nucleons and the origin of heavy elements
- reveal phase transition from nucleons to free quarks and insight into the QCD phase diagram
- determine H_0 and the nature of dark energy equation of state and its variation with redshift
- study the nature of black holes, test the no-hair theorem and gravity in ultra strong fields
- detect gravitational waves from supernova and determine the physics of core-collapse supernova
- provide a new tool for measuring distances to cosmological sources

STOCHASTIC BACKGROUND LANDSCAPE

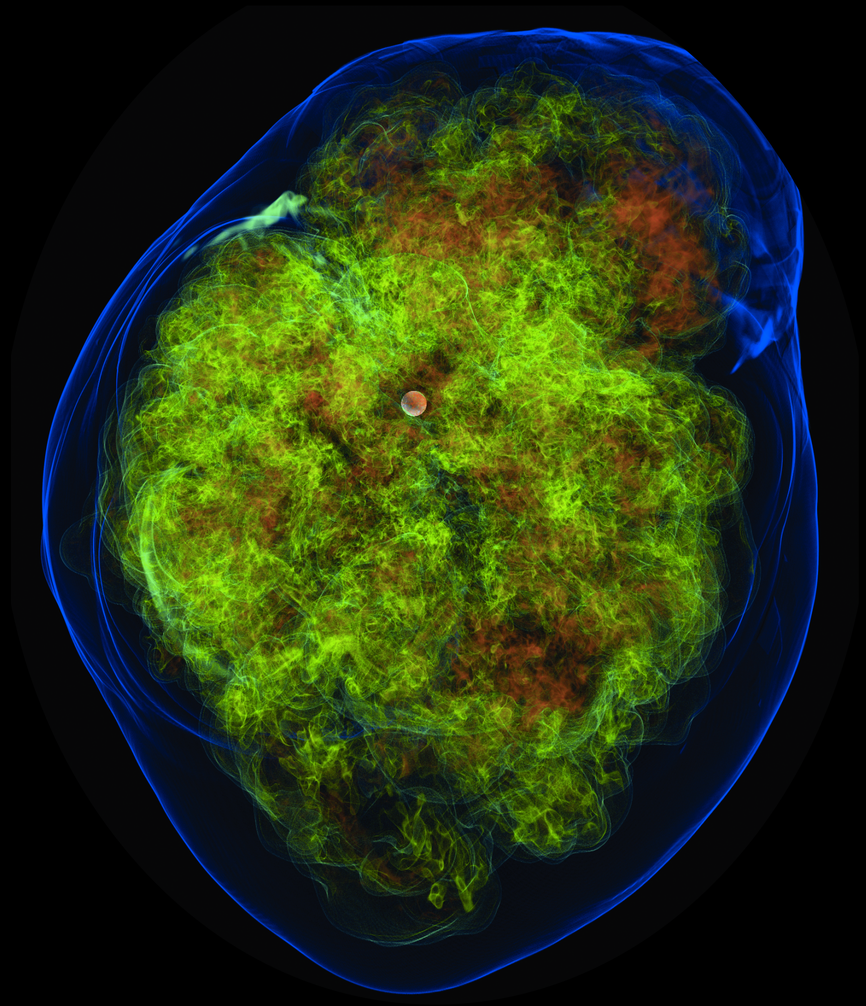


- slow-roll inflation
- stiff equation of state
- axion inflation
- early universe phase transitions
- cosmic strings

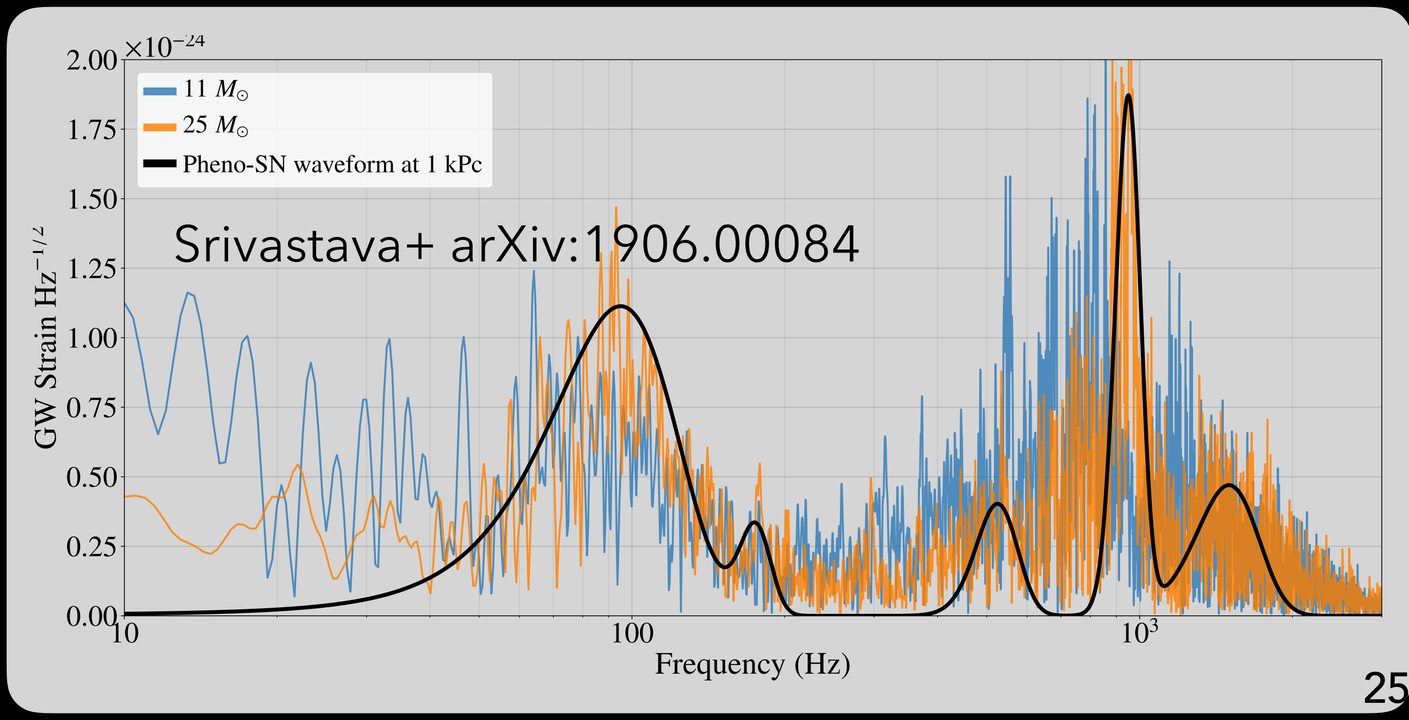
LANDSCAPE OF 3G SOURCES



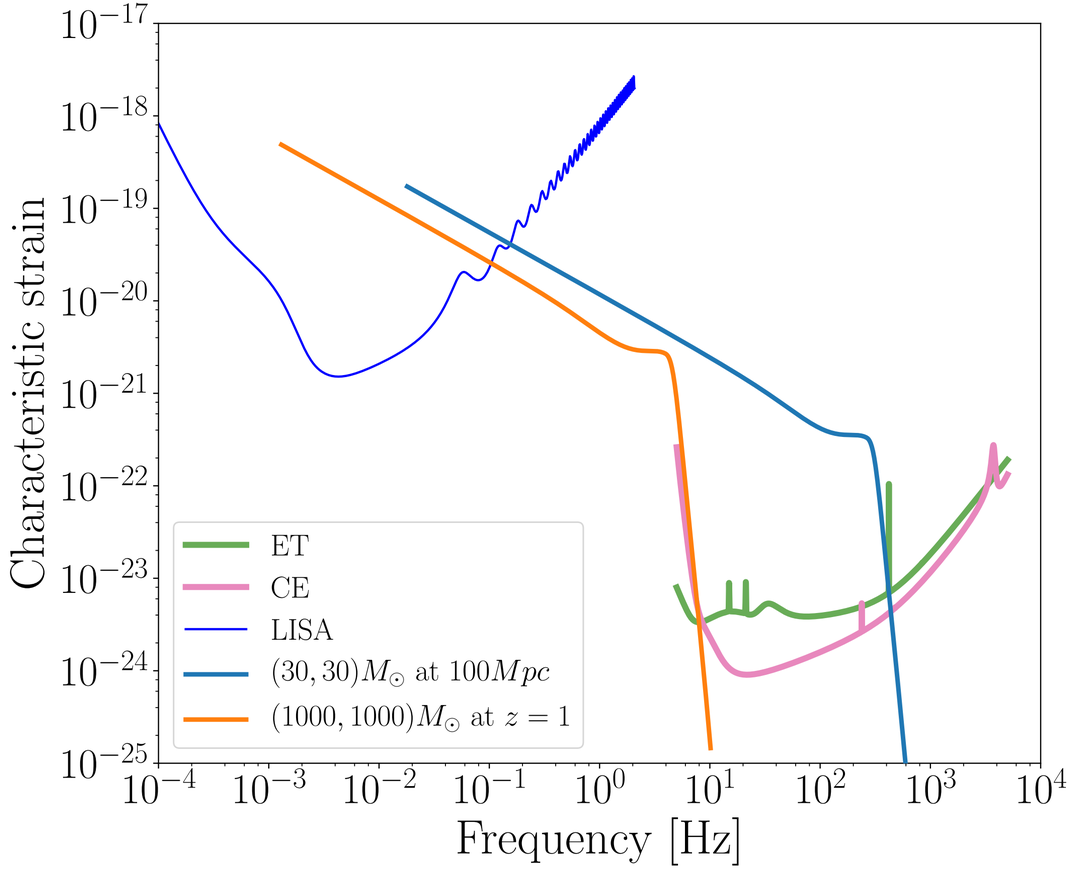
SUPERNOVAE IS THIS THE FINAL WORD?



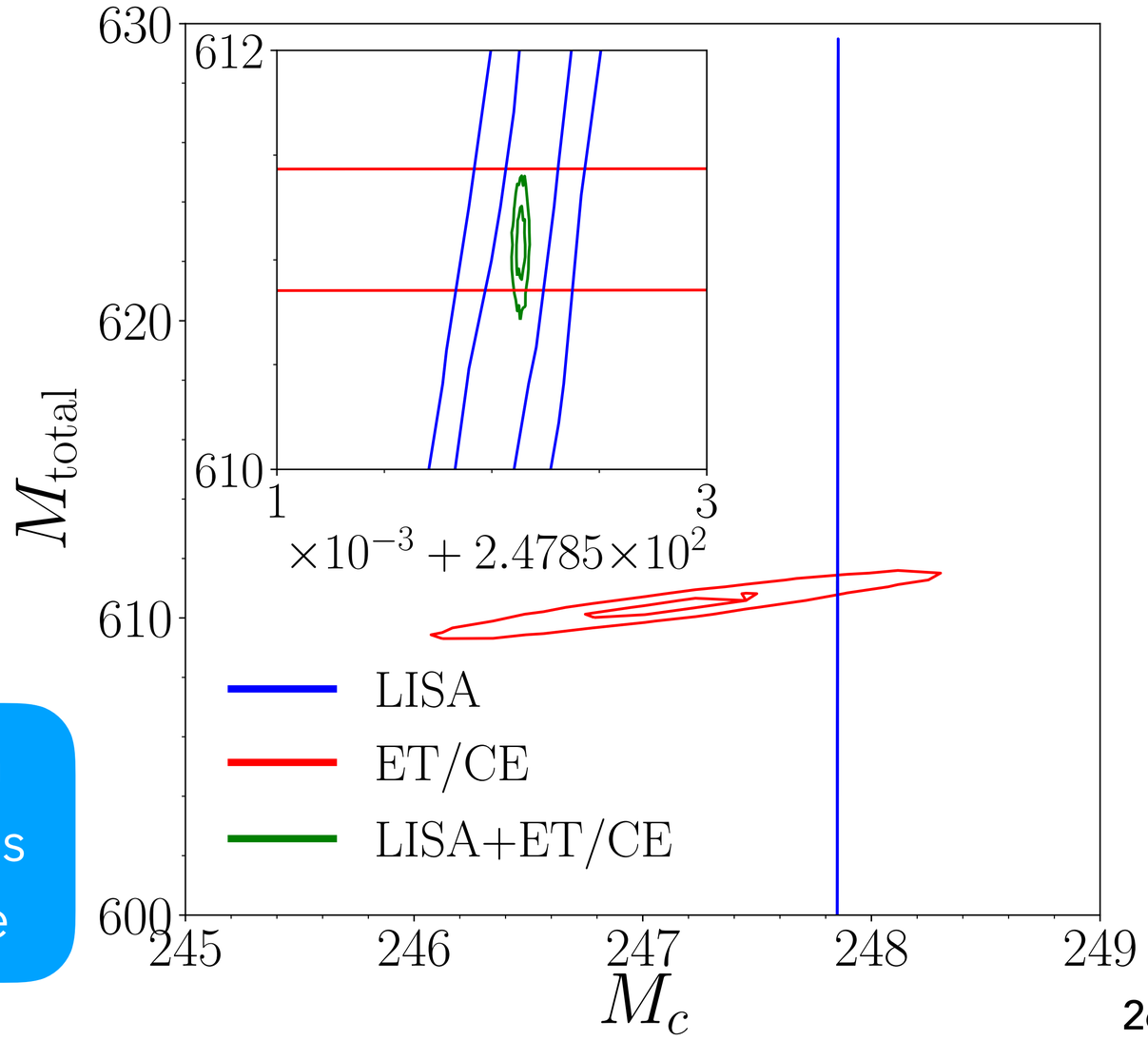
- signature of physics of supernova
  - progenitor mass
  - proto-NS core oscillation modes
  - core rotation rate
  - mass accretion rate from shock
  - geometry of collapse
- NS equation of state
  - spectrum of GW signal
  - following the phase evolution
- fate of collapse
  - neutron star vs black hole formation
- 3G sensitive to CCSN in the Milky Way, rates 1-2 per century



MULTIBAND - LISA AND 3G



Cutler+ arXiv:1903.04069

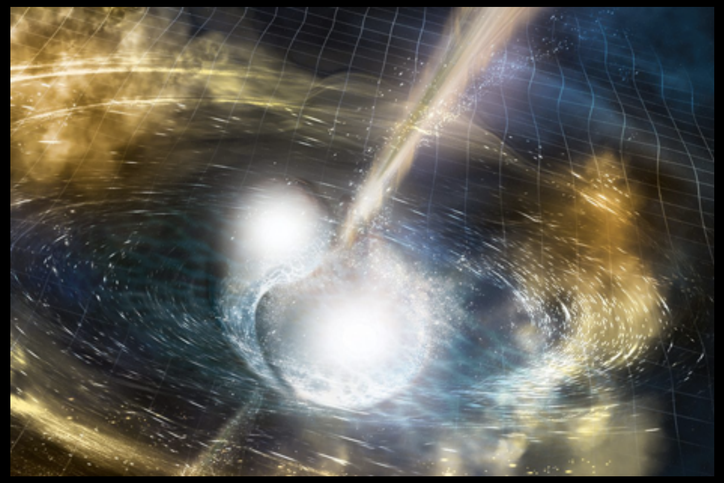


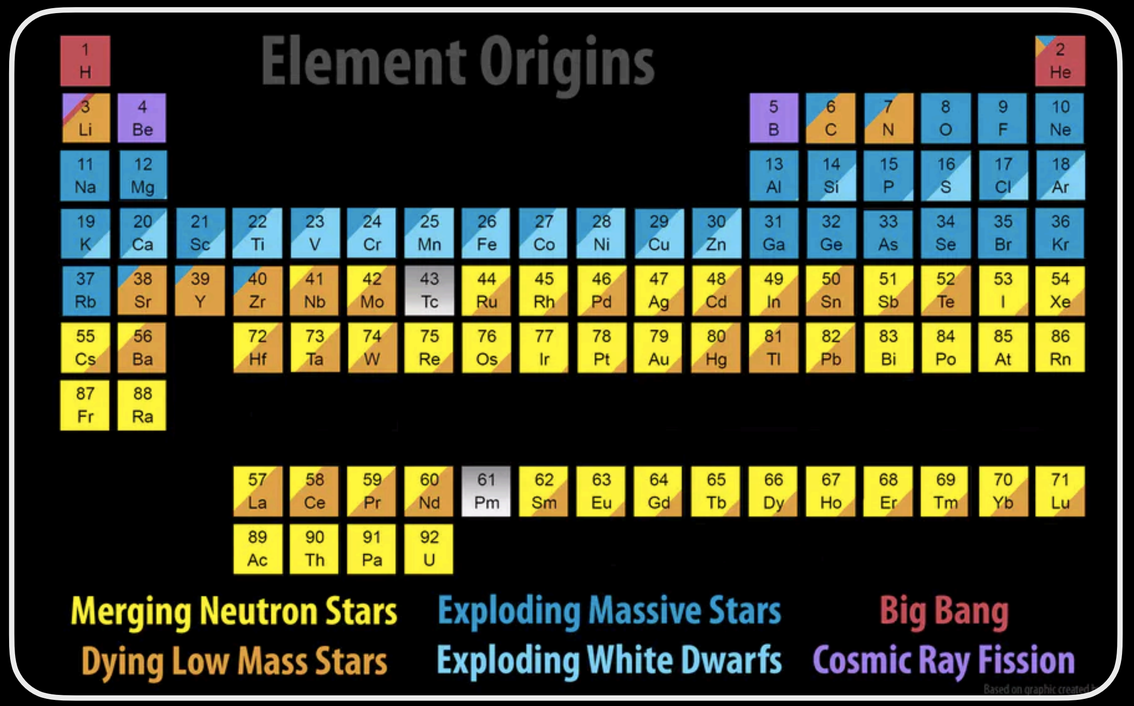
Multi-band observations with LISA will help 3G detectors to improve characterization of sources and tests of GR by several orders of magnitude

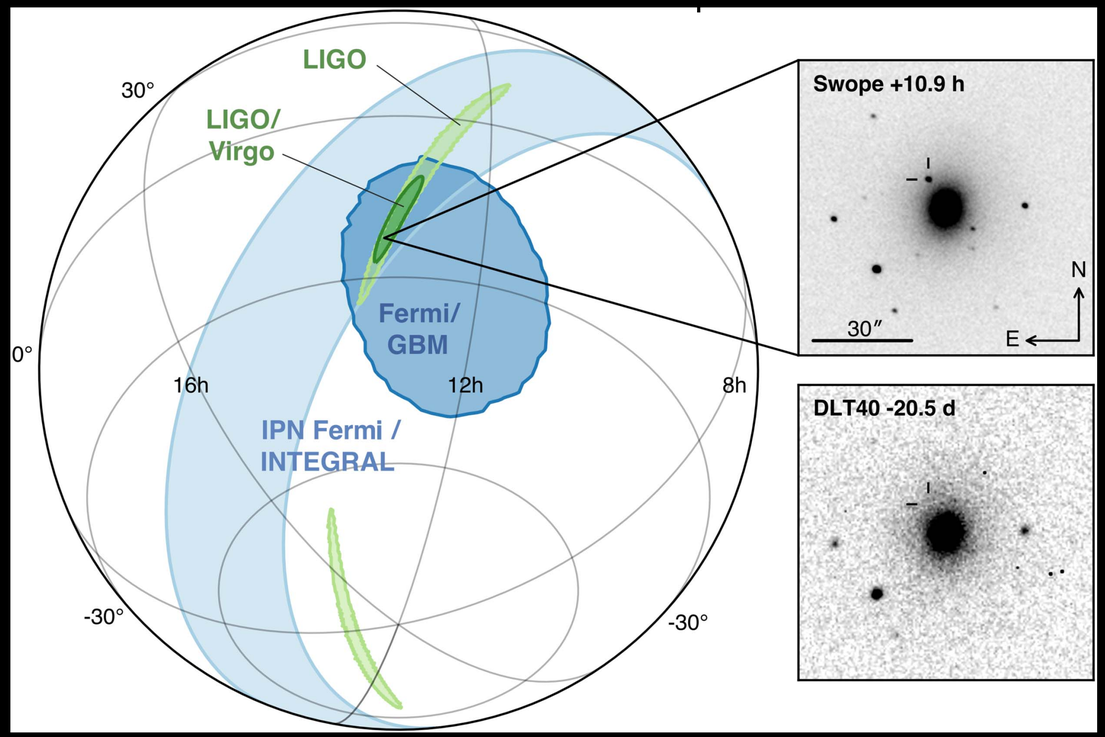
3G NETWORK WILL EXPLORE FUNDAMENTAL PROPERTIES OF SPACETIME AND MATTER

- equation of state of dense nuclear matter
  - mass-radius relationship, phase transitions to quark-gluon plasma
- multimessenger astronomy
  - GRBs, heavy elements, Hubble parameter, dark energy EoS
- strong field tests in general relativity and modified theories of gravity
  - beyond the quadrupole formula, spin precession, higher modes, Lorentz Invariance violation, massive gravity, scalar modes, additional polarization modes, black hole no-hair theorem
- new fields and novel compact objects
- primordial stochastic backgrounds

WHAT OBSERVATORIES AND INSTRUMENTS MIGHT STILL BE THERE WHEN 3G IS OPERATING?

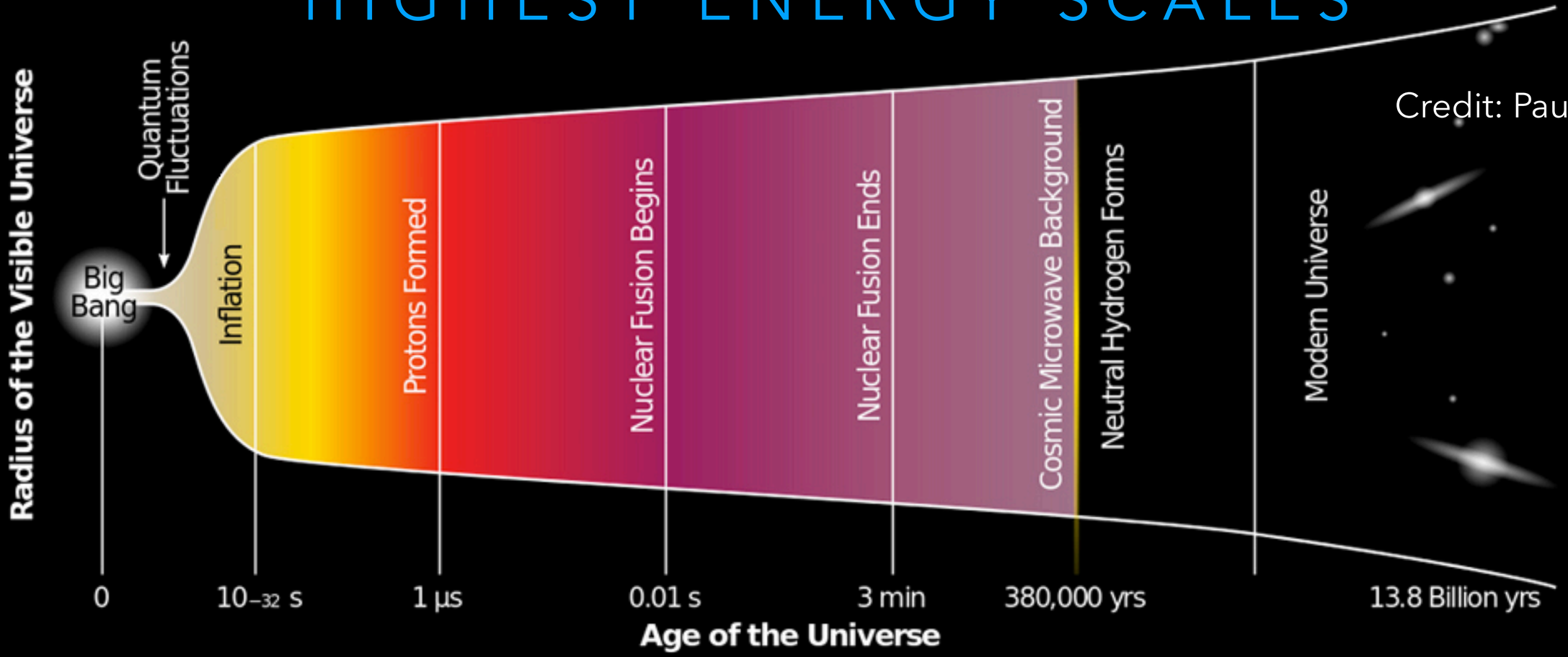






3G network will help identify thousands of kilonova and trace the origin of heavy elements

EXPLORE FUNDAMENTAL PHYSICS AT HIGHEST ENERGY SCALES



Credit: Paul Shellard

3G network will explore laws of physics at energy scales inaccessible to particle accelerators and potentially discover remnants of phase transitions and new physics