Astronomy, Cosmology, and Fundamental Physics

with

Einstein Telescope

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NIKHEF

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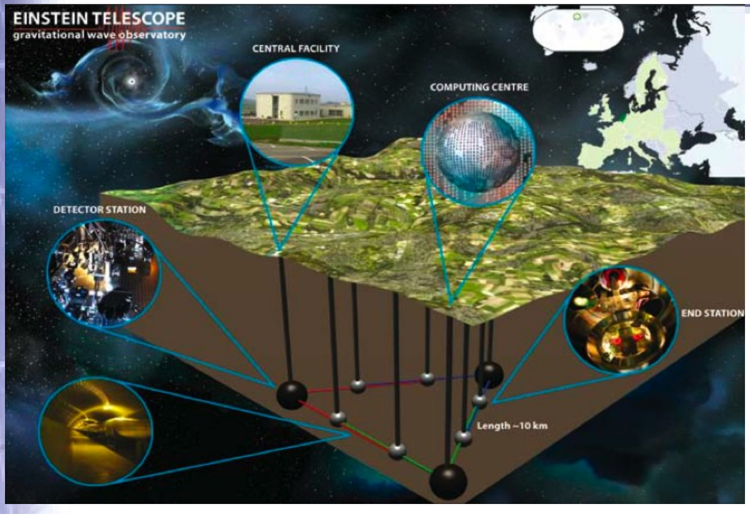
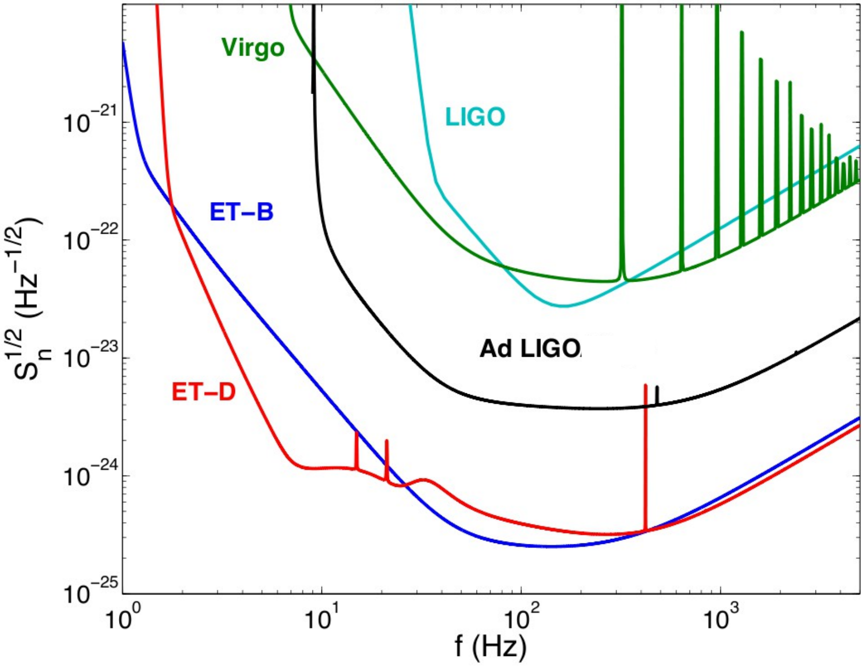
Overview

- What is Einstein Telescope?
- Astrophysics:
  - Reconstructing the evolution of inspiral rates
  - Making a census of neutron star and black hole masses
  - Neutron star equation of state
- Cosmology:
  - Inspiral events as "standard sirens"
  - Primordial gravitational waves
- Fundamental physics
  - Probing the genuinely strong-field dynamics of gravity

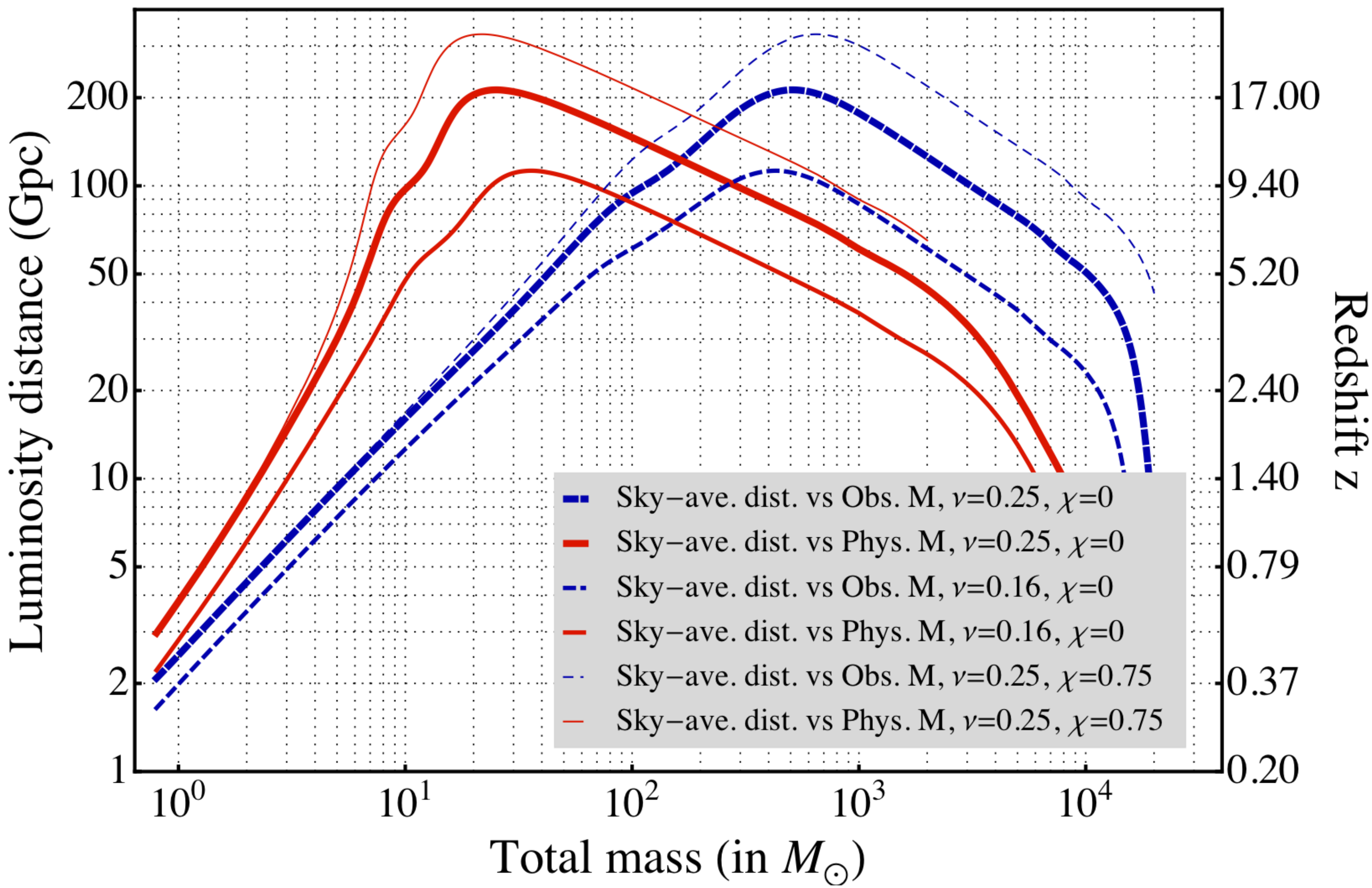
Einstein Telescope: Conceptual design



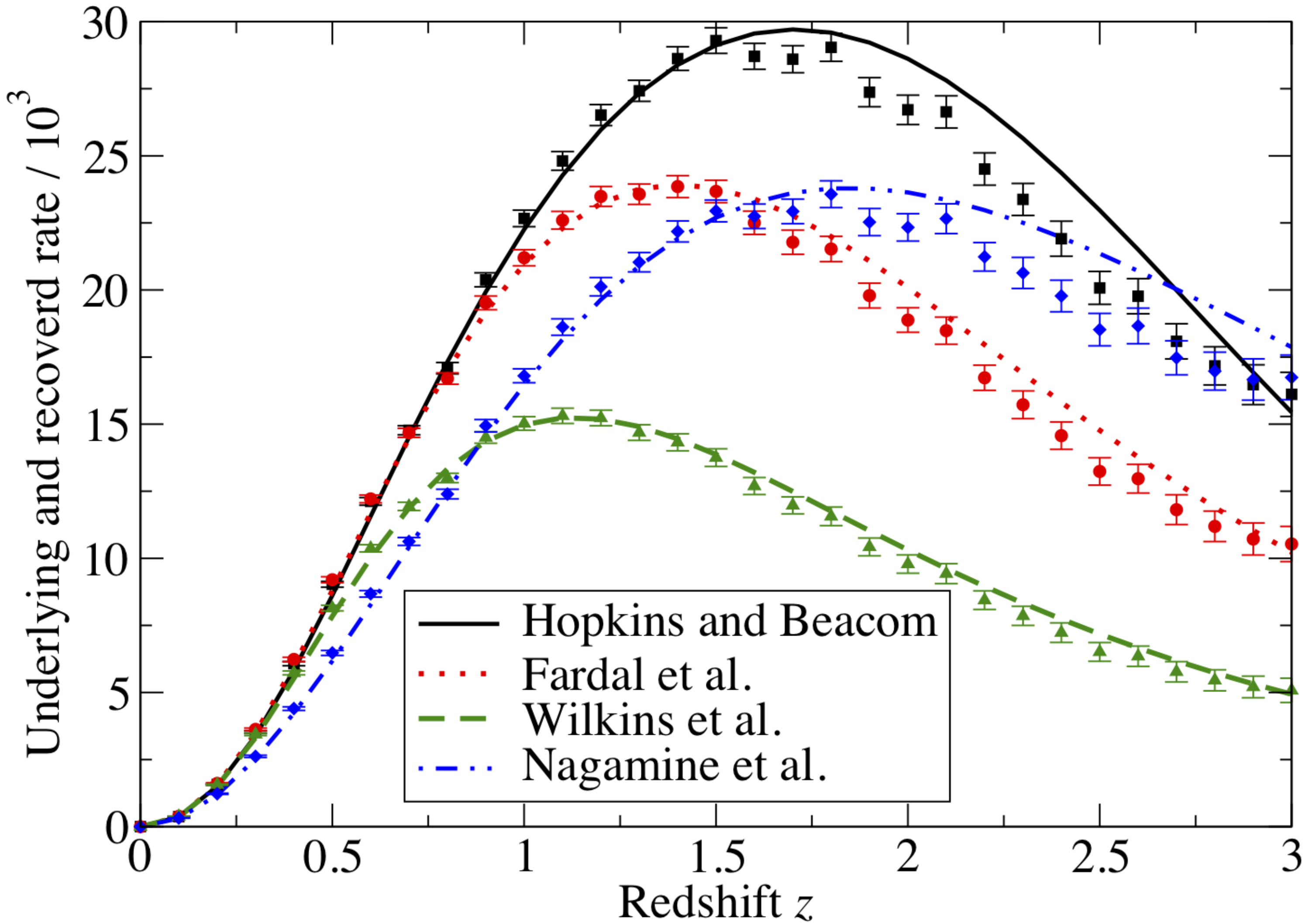


- Conceptual design study funded by EU, recently concluded
- 3rd generation observatory
  - Multiple interferometers, 10 km arm length, arranged in triangular configuration
  - Underground
  - Assuming technologies one should be able to achieve in 10-15 years
- 10^3-10^6 binary coalescence detections per year

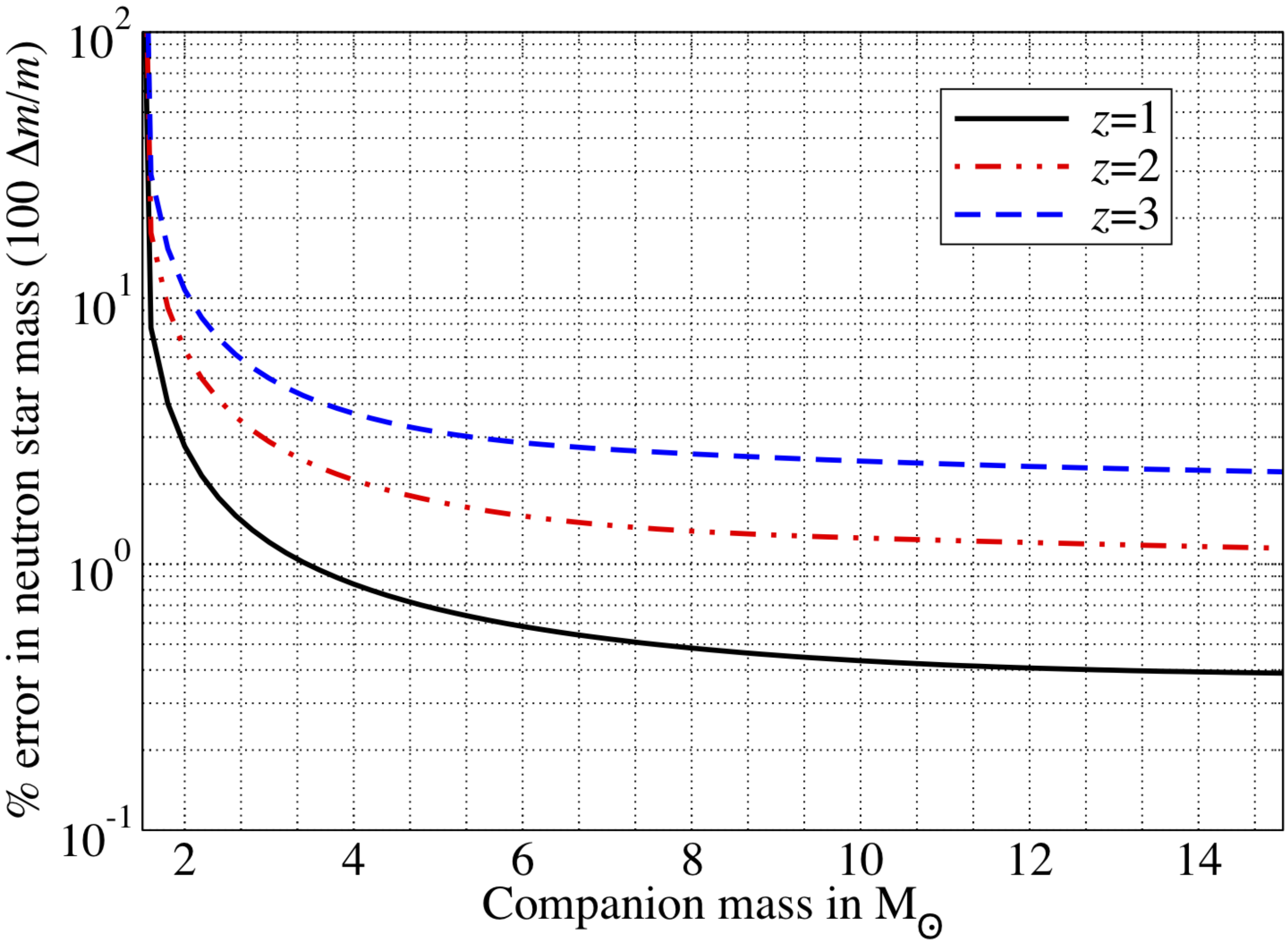
Einstein Telescope: Distance reach



Reconstructing the evolution of inspiral rates

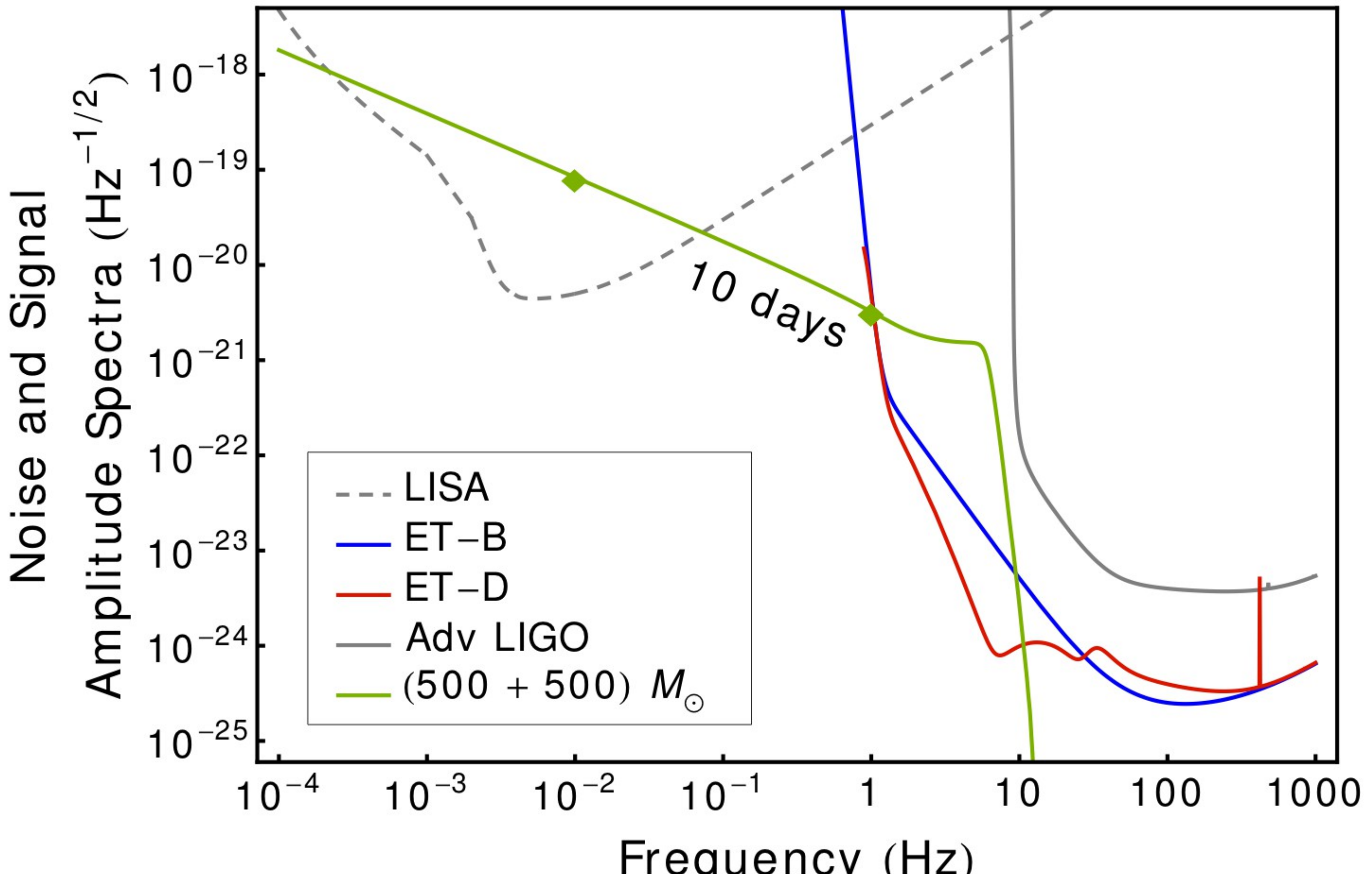


Making a census of neutron star and black hole masses

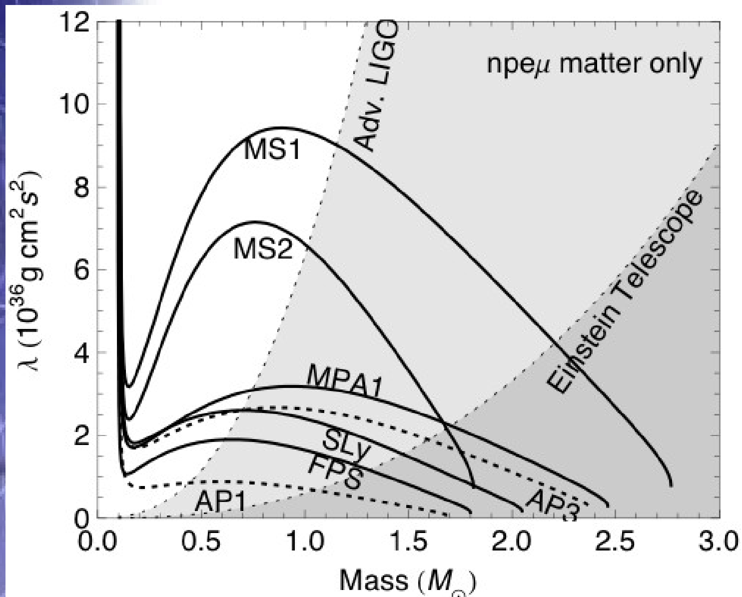


Do intermediate mass black holes exist?

- Stellar mass black holes: 3 - 30 M_{sun}
- Supermassive black holes: 10^6 - 10^{10} M_{sun}
- Intermediate? (Formed in globular clusters?)



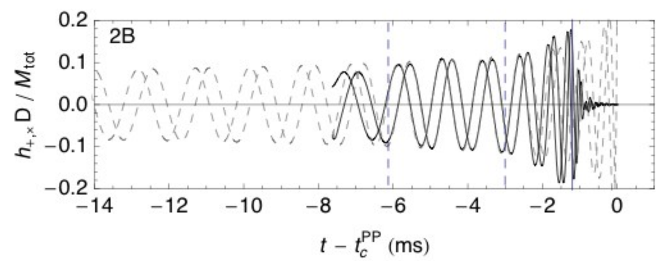
Neutron star equation of state

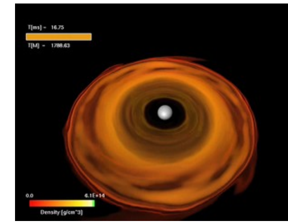


Many possible equations of state (EOS)

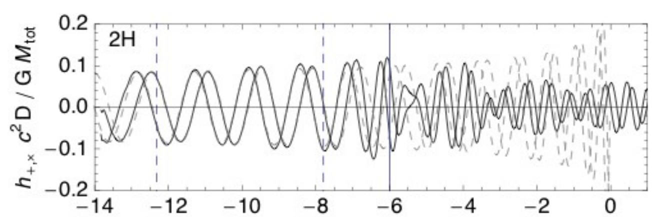
Extremes:

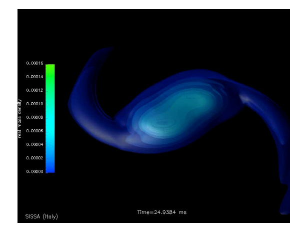
- "Soft" EOS: prompt collapse to a black hole





- "Hard" EOS: unstable bar mode, eventually BH





[Hinderer et al., arXiv:0911.3535]

- Advanced LIGO/Virgo, combining information from ~15 events: Will be able to tell difference between extremes
- ET: detailed measurement of the EOS

Cosmology with binary inspirals

- Standard candle in cosmology:
  Source for which intrinsic luminosity approximately known; can be used to measure distance

- If redshift also known, exploit distance-redshift relationship

  $d_L(z) = d_L(H_0, \Omega_M, \Omega_\Lambda, \Omega_k, w; z)$

  to probe dynamics and contents of the Universe, where

  - H_0 Hubble constant
  - Ω_M density of matter
  - Ω_Λ density of dark energy
  - Ω_k effect of spatial curvature
  - $w = p_{DE}/\rho_{DE}$ EOS of dark matter

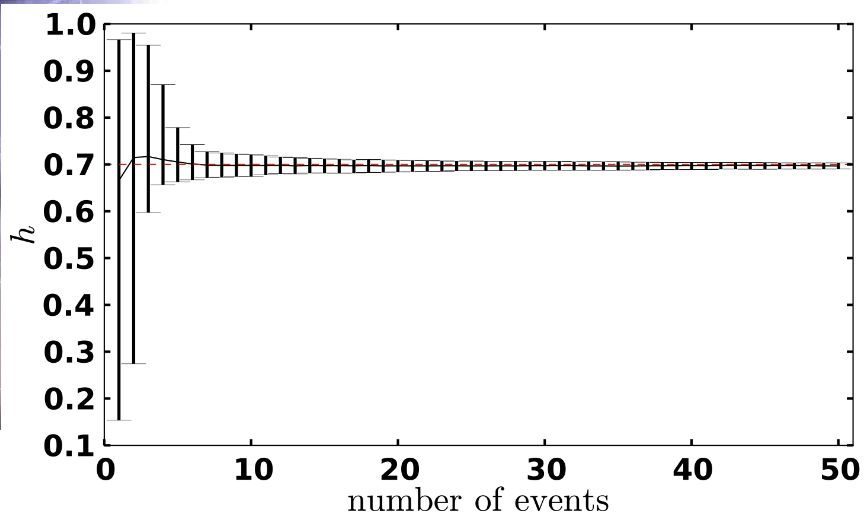
- Currently: mainly Type Ia supernovae

- Problem: need for calibration using closer-by sources

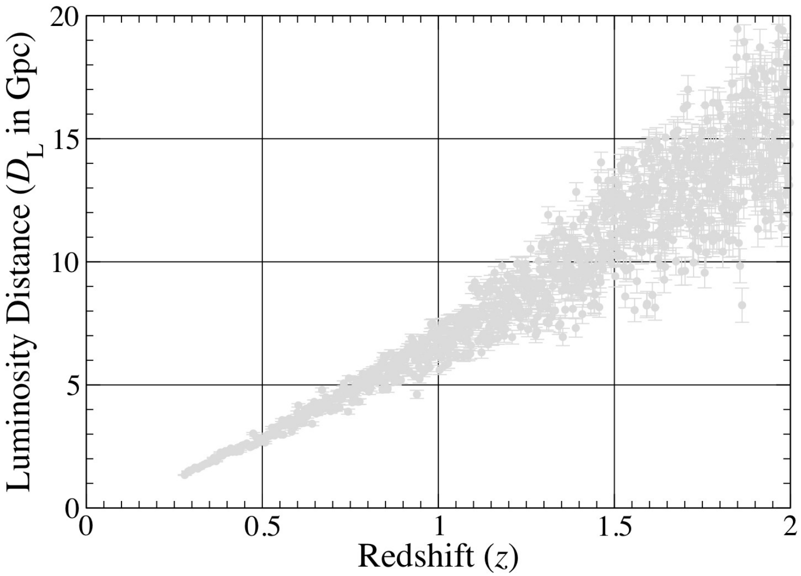
→ *"Cosmic distance ladder"*

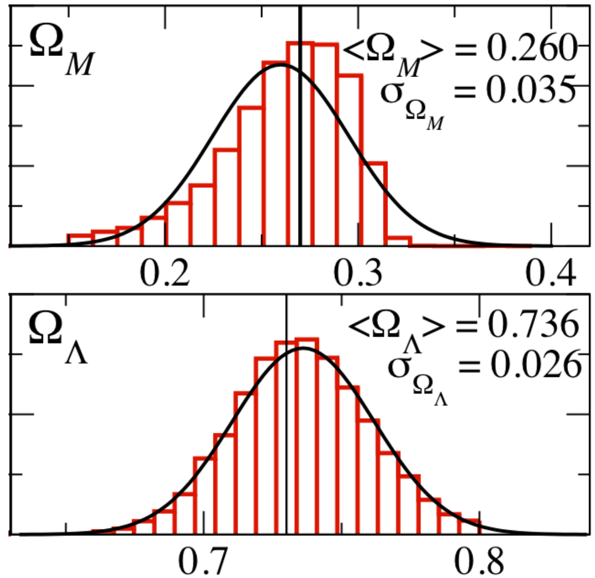
Cosmology with binary inspirals

- Binary neutron stars and black holes are standard sirens (Schutz '86):
  - Distance can be inferred from the gravitational wave signal itself, if (some) information about sky position, orientation
  - No need for a cosmic distance ladder!
  - Systematics will be known
- Need to extract redshift:
  - Use electromagnetic counterparts, e.g. gamma ray bursts
    [Nissanke et al., arXiv:0904.1017]
  - Assuming a mass distribution
    [Taylor, Gair, Mandel, arXiv:1108.5161]
  - Use galaxy clustering: no need for counterparts!
    [Del Pozzo, arXiv:1108.1317]
  - If EOS already determined, get redshift from the GW waveform through effect of tidal deformations on orbital motion
    [Messenger & Read, arXiv:1107.5725]

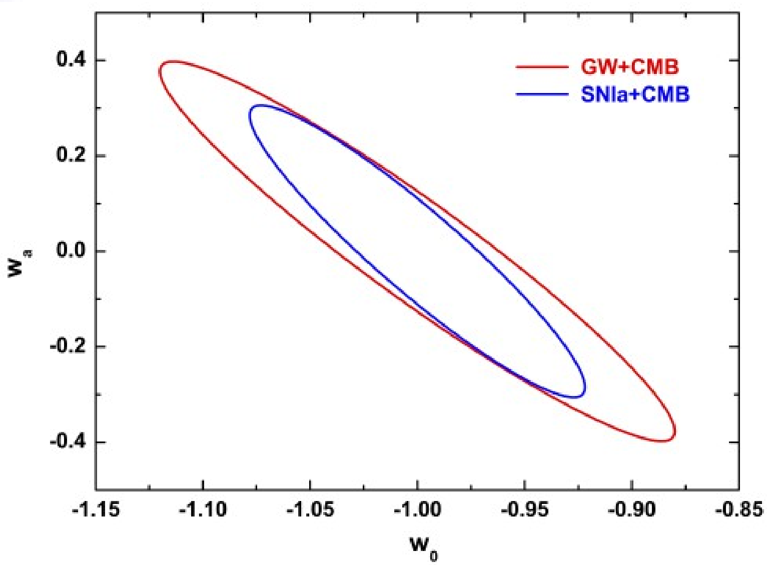


Cosmology with binary inspirals





[Sathyaprakash, Schutz, CVDB, arXiv:0904.4151]



$w = p_{DE}/\rho_{DE}$ EOS of dark matter

Could be time dependent:

$w(a) \simeq w_0 + w_a (1 - a) + ...$

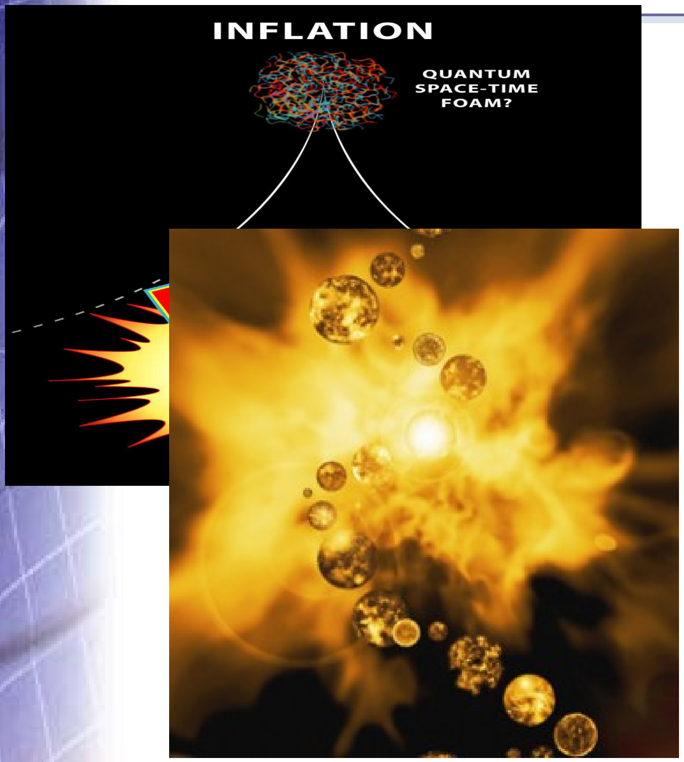
Comparable accuracies to conventional measurements, but completely independent systematics (no cosmic distance ladder!)

[Zhao, CVDB, Baskaran, Li, arXiv:1009.0206]

Primordial gravitational waves

- Inflation:
  Period of exponential growth of Universe (first ~10^{-32} secs)

Primordial gravitational waves



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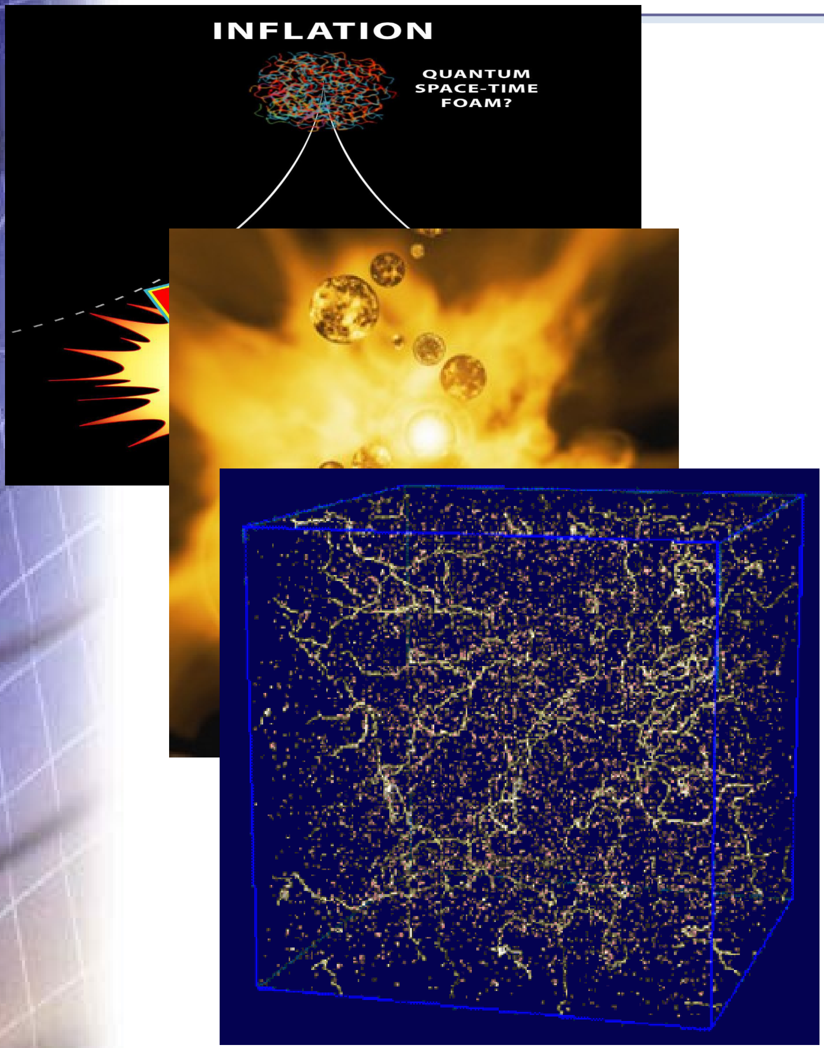
Primordial gravitational waves



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- Cosmic strings:
  Topological defects, or fundamental (super)strings

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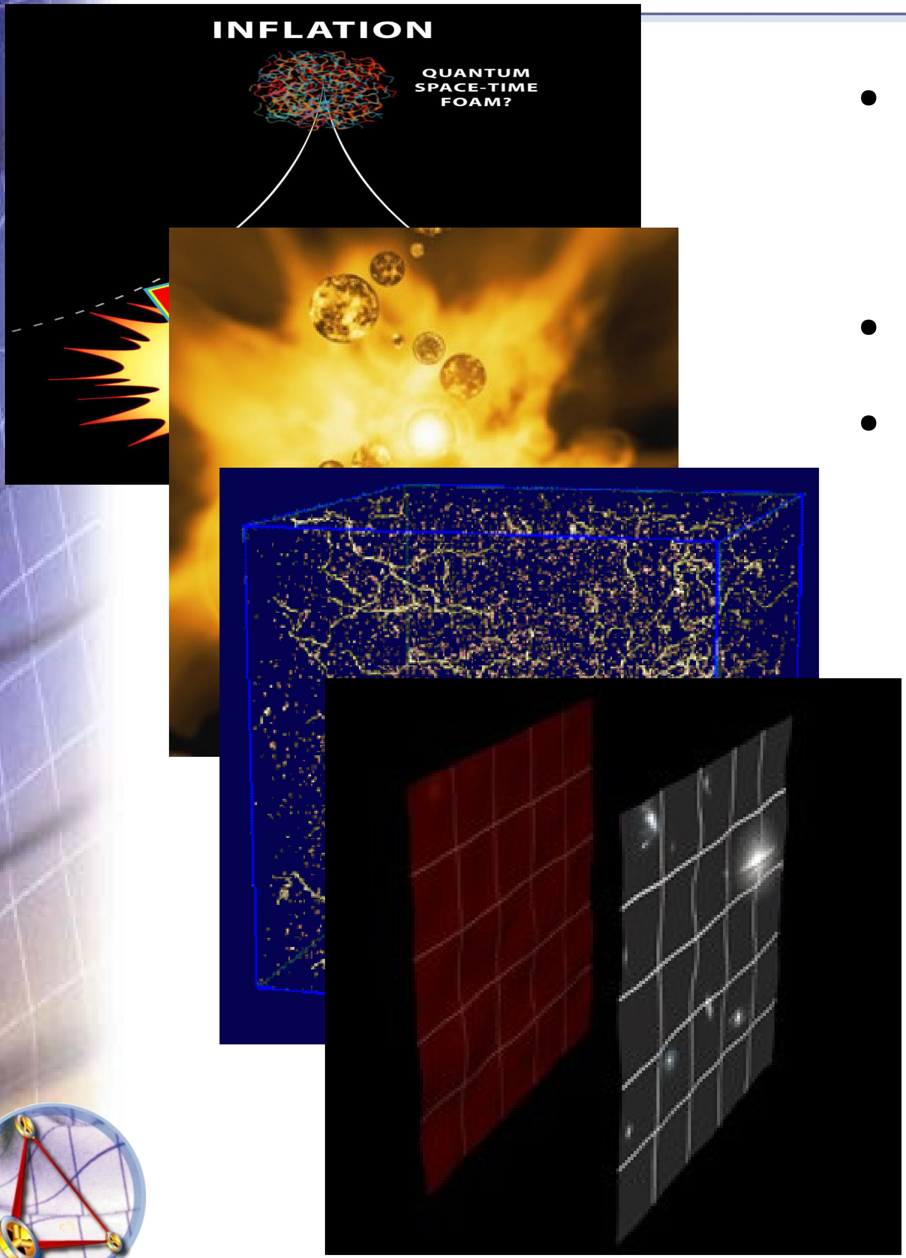

- Inflation:
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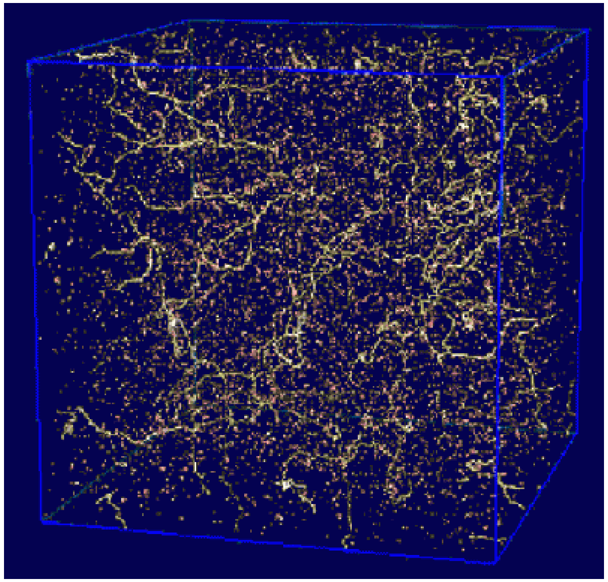
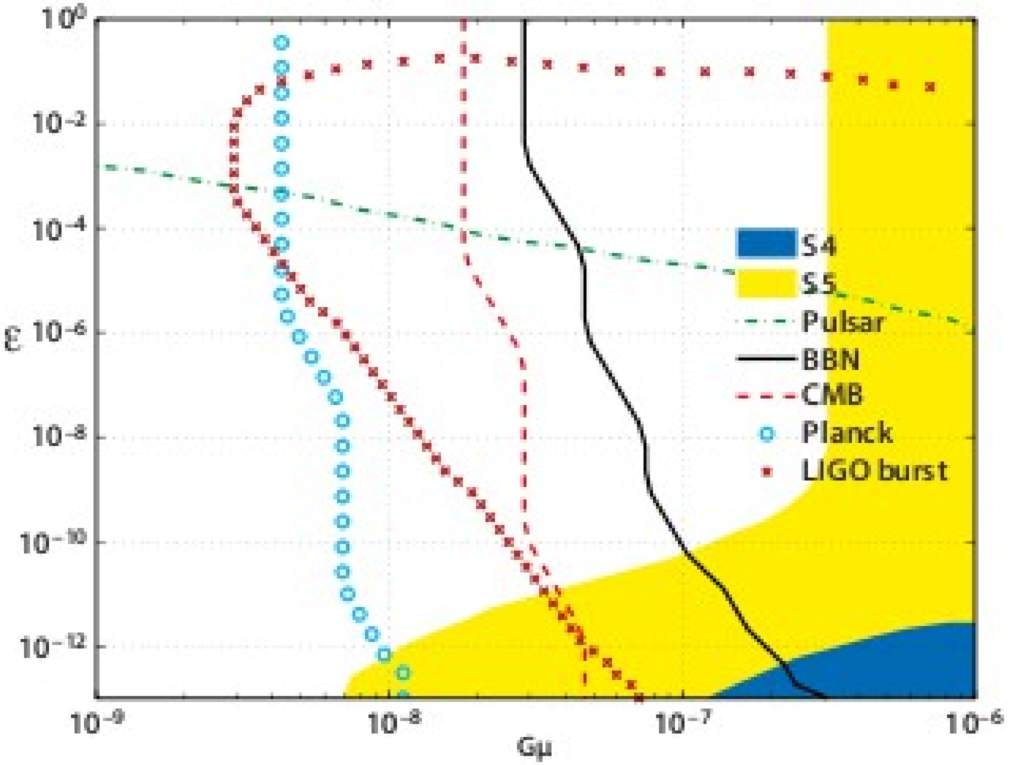
- Predictions from quantum gravity theories:
  - Pre-Big-Bang cosmology
  - Brane world scenarios
  - "Bounce" cosmologies
  - ....

Cosmic strings

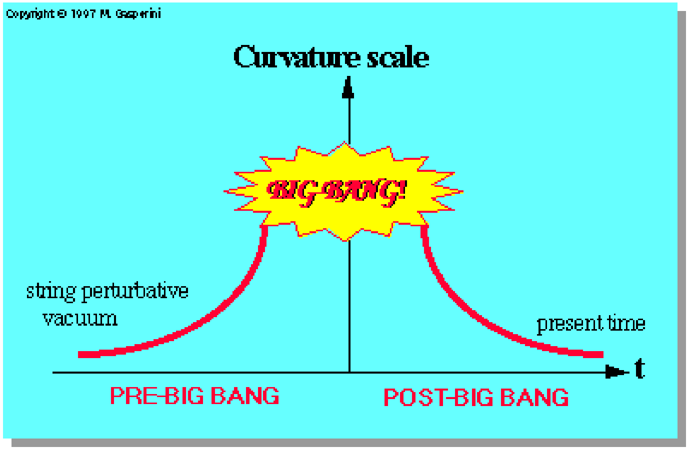


- Existing LIGO data already give best upper limits on properties of cosmic string networks!

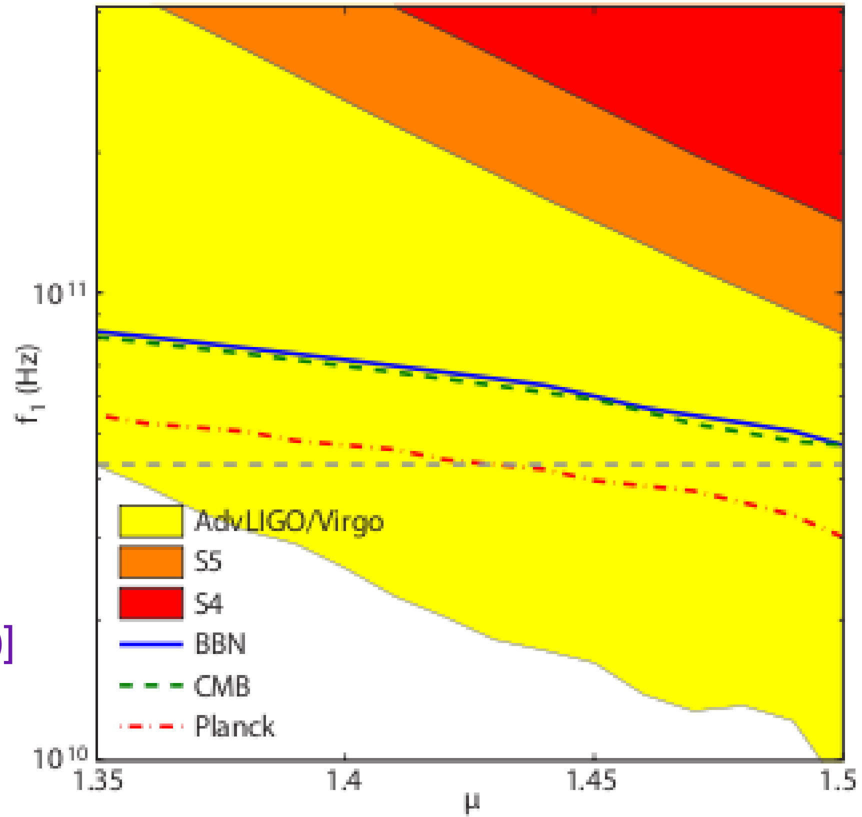
[Abbot et al., Nature **460**, 990 (2009)]



Pre-Big-Bang cosmology



- "Pre-Big-Bang scenario" inspired by string theory:
  Advanced LIGO/Virgo will put stronger bounds than any other method
  ... or find primordial gravitational GW!



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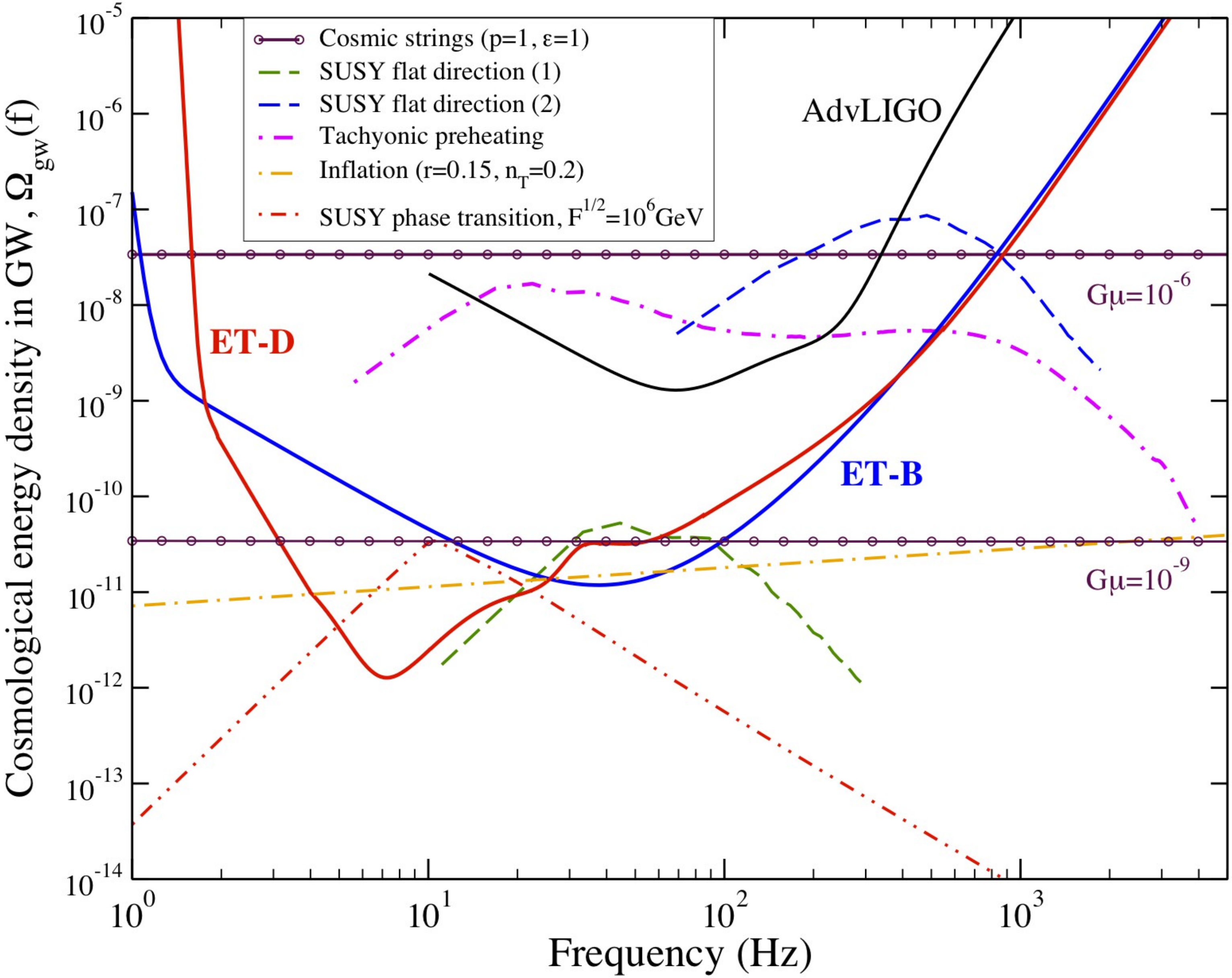
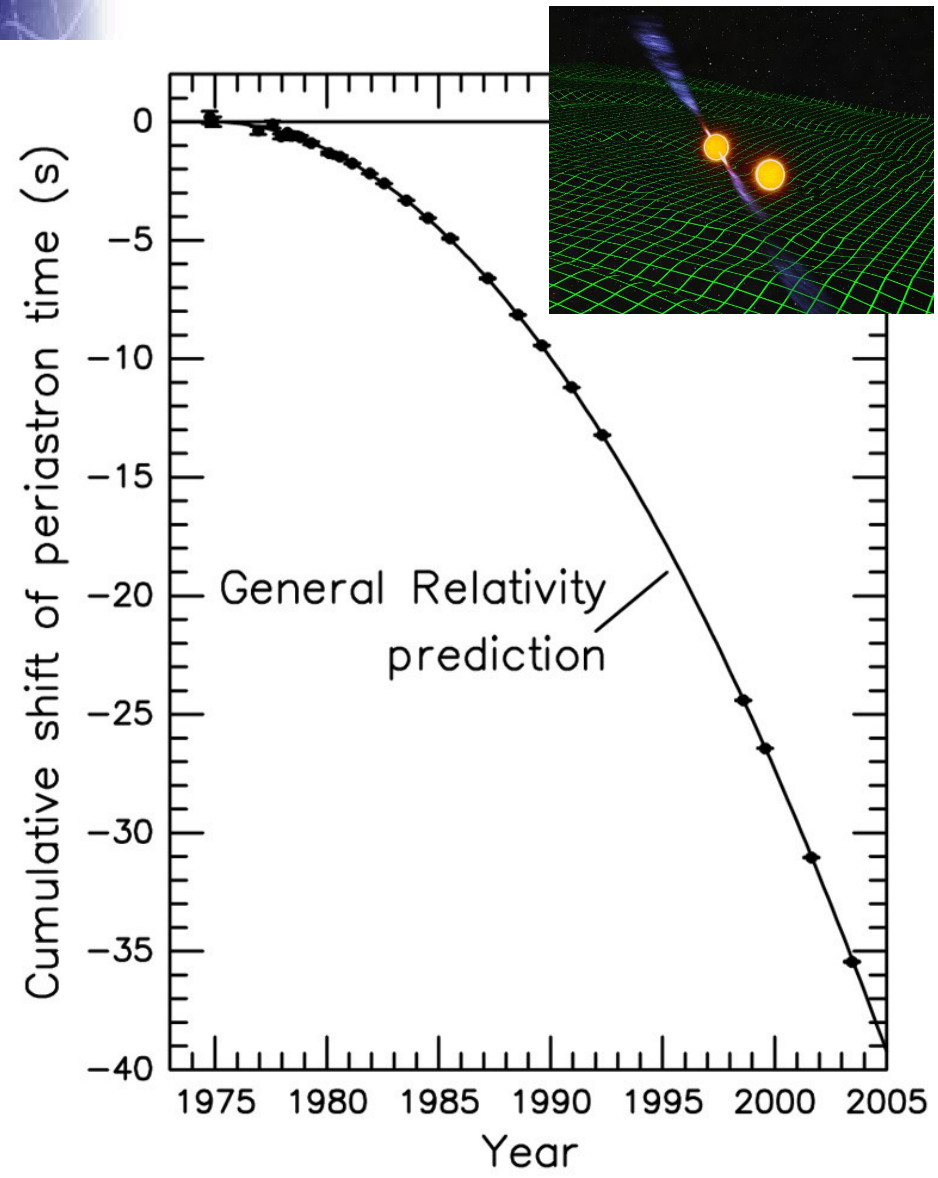
Early Universe cosmology



Testing the strong-field dynamics of gravity



- Hulse-Taylor and similar binary pulsars only constrain dissipation at quadrupole level
- Most interesting dynamical effects occur starting at $(v/c)^3$ beyond leading order!
  - "Tail effects"
  - Spin-orbit interaction
  - ...

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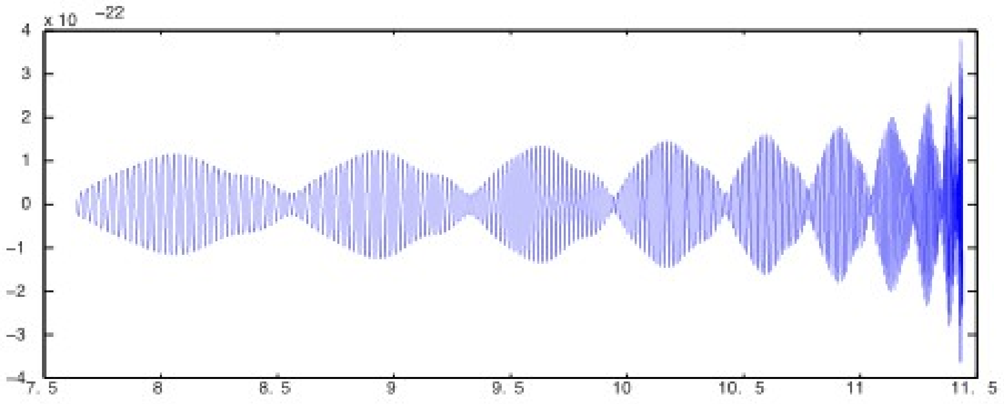
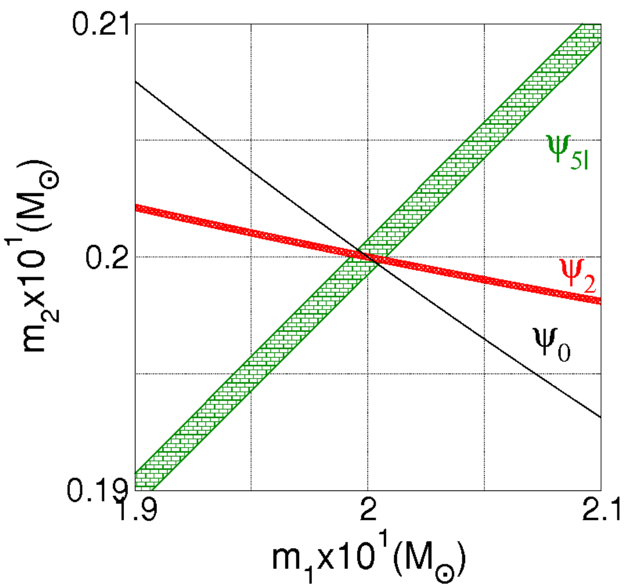
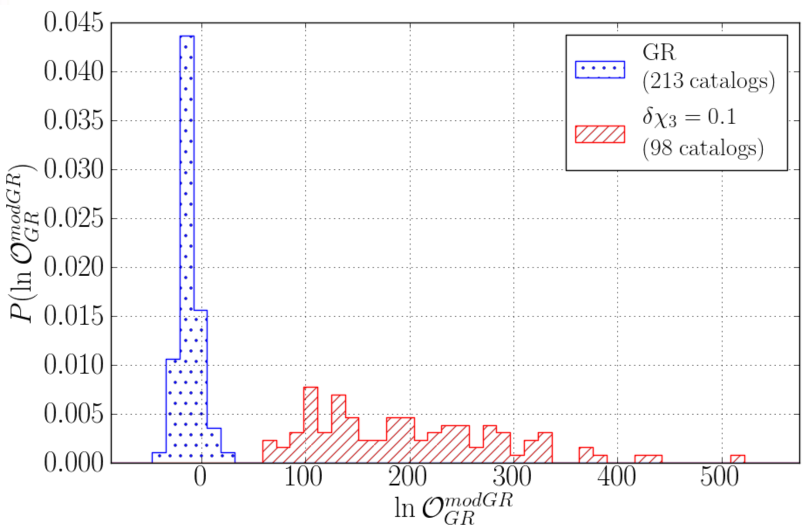


- Hulse-Taylor and similar binary pulsars only constrain dissipation at quadrupole level
- Most interesting dynamical effects occur starting at $(v/c)^3$ beyond leading order!
  - "Tail effects"
  - Spin-orbit interaction
  - ...
- Exploit rich dynamics at late stages of inspiral, and merger/ringdown
- Can only be done with direct detection of gravitational waves

Testing the strong-field dynamics of gravity

$$\Phi(v(t)) = \left(\frac{v}{c}\right)^{-5} \sum_{n=0}^{7} \left[\psi_n + \psi_n^{(l)} \ln\left(\frac{v}{c}\right)\right] \left(\frac{v}{c}\right)^n$$





- Generic test of strong-field dynamics by checking consistency of coefficients in the phase with GR prediction
  [Mishra et al., arXiv:1005.0304]
- Similar tests using ringdown
  [Karametsos et al., arXiv:1107.0854]
  [Gossan et al., arXiv:1111.5819]
- Bayesian model selection framework has been developed to perform such tests in a systematic way
  [Li et al., arXiv:1110.0530, 1111.5274]
  - Construct odds ratio for violation of GR versus GR
  - Combine information from all observed sources
  - 2nd generation, 15 sources: Few % resolution in low order coefficients
    [See talk by Tjonnie Li]

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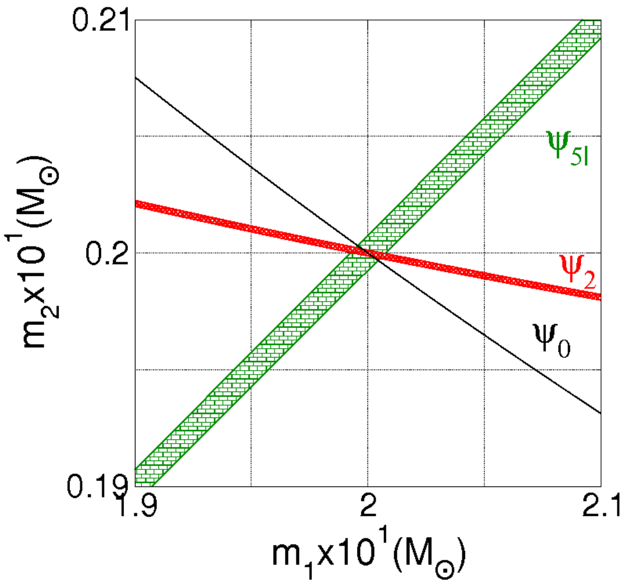

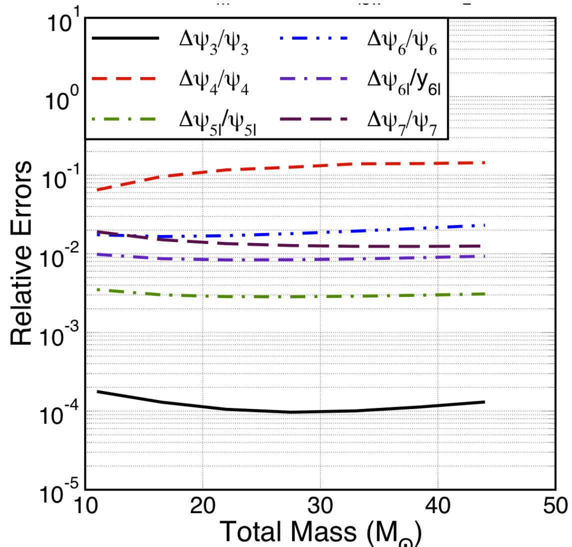

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  - Combine information from all observed sources
  - 2nd generation, 15 sources: Few % resolution in low order coefficients
    [See talk by Tjonnie Li]
  - ET: $\gg 10^3$ sources/yr!

Summary

- Astrophysics:
  - Reconstructing almost the entire evolution of inspiral rates
  - Making a complete census of neutron star and black hole masses
  - In-depth access to neutron star equation of state
- Cosmology:
  - Inspiral events as "standard sirens" for independent cosmography
    - Contents of the Universe
    - Nature of dark energy?
  - Primordial gravitational waves
    - Inflation (10^{-32} secs after Big Bang)
    - Phase transitions: new physics?
    - Cosmic (super)strings
    - Direct access to quantum gravity effects?
- Probing the strong-field dynamics of classical gravity through BBH