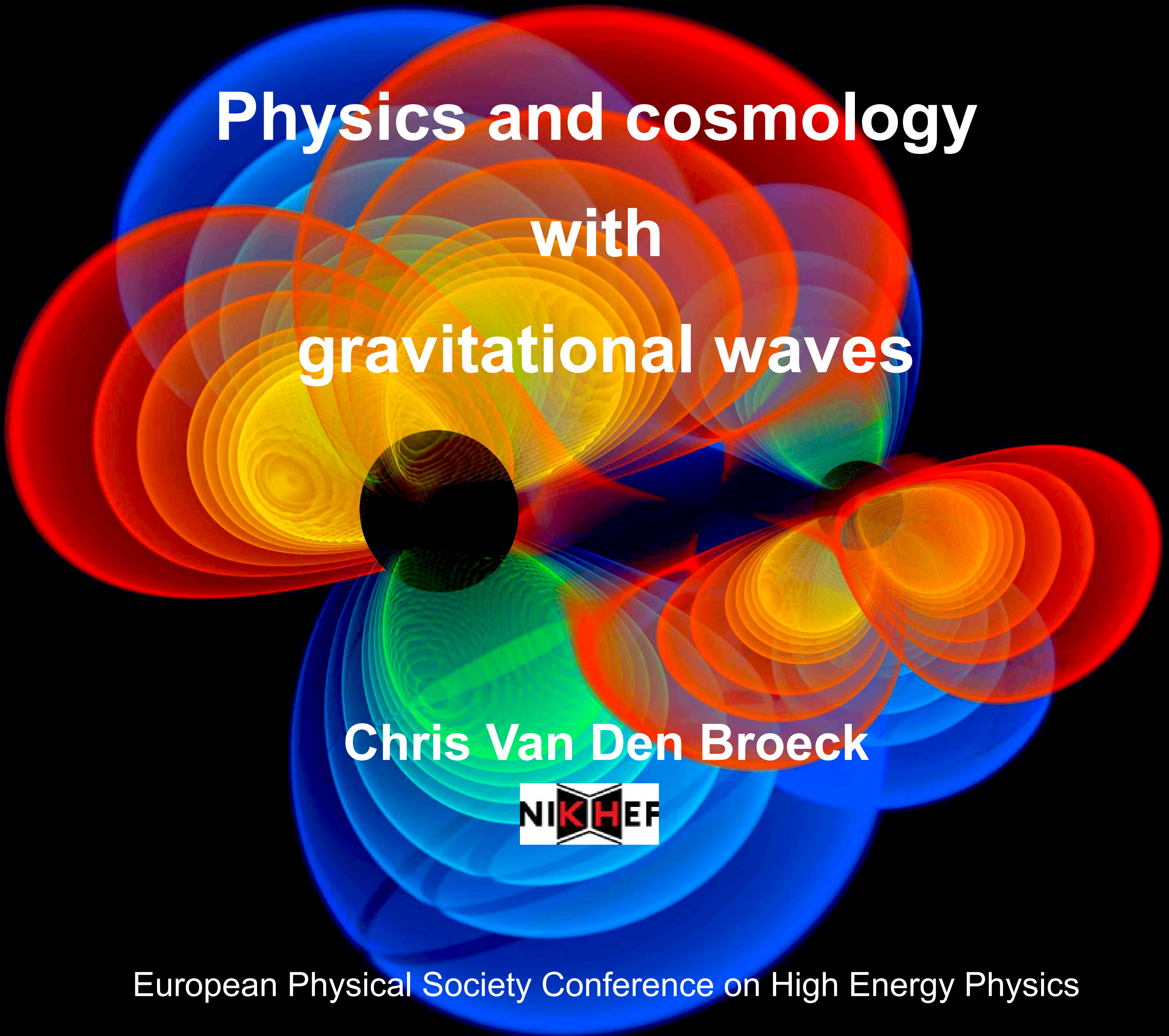

Physics and cosmology with gravitational waves

Chris Van Den Broeck

NIKHEF

European Physical Society Conference on High Energy Physics

Vienna, Austria, 2015

General relativity at its 100th birthday

- Gravitational physics encompasses important questions:
  - How to reconcile gravity and the quantum?
    - Unification of the four known forces?
  - What is the nature of black holes?
  - How did the Universe come into being and how did it evolve?
- General relativity in experiments and observations?
  - Solar system:
    Perihelium precession of Mercury, Shapiro time delay, bending of starlight by the Sun, frame dragging, equivalence principle, ...
  - Cosmology
  - Radio observations of binary neutron stars

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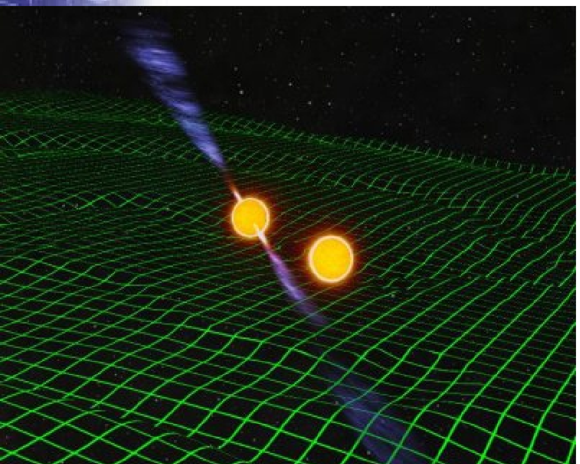
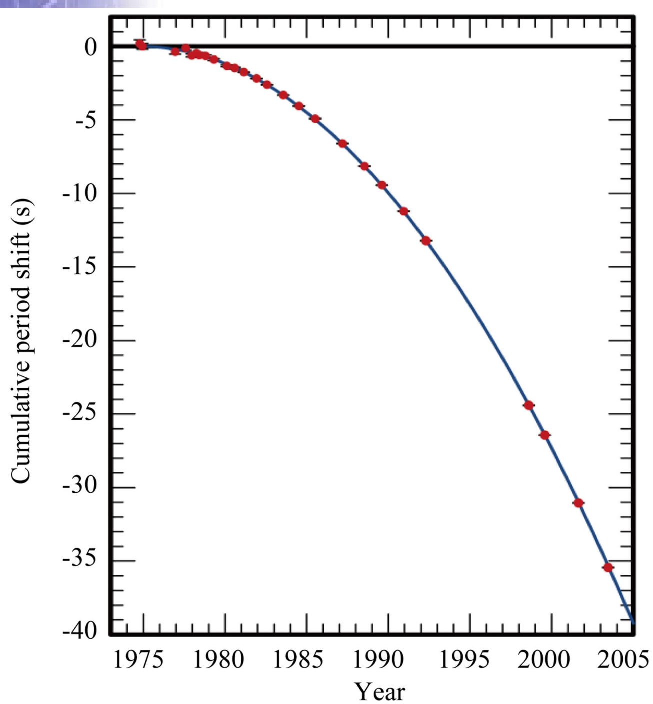
Existing tests only probe weak and/or stationary fields

No access to even the classical strong-field dynamics of spacetime

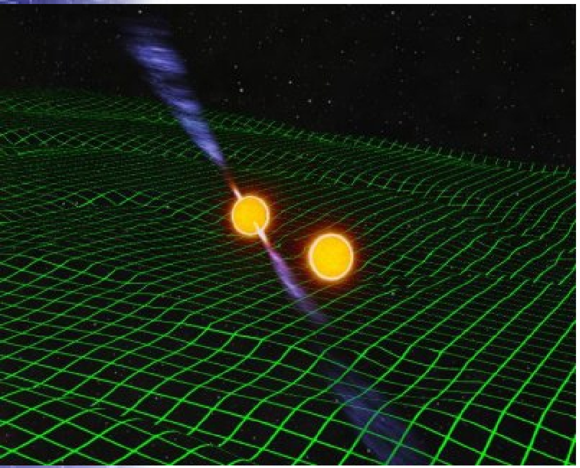
Gravitational waves





- Binary neutron stars in tight orbits lose orbital energy & angular momentum
  - Consistent with the emission of gravitational waves
  - Hulse & Taylor Nobel Prize 1993
- Still weak-field dynamics from perspective of full general relativity
  - Typical velocity $v/c \sim 10^{-3}$
  - Typical field strength $GM/c^2R \sim 10^{-6}$

Gravitational waves



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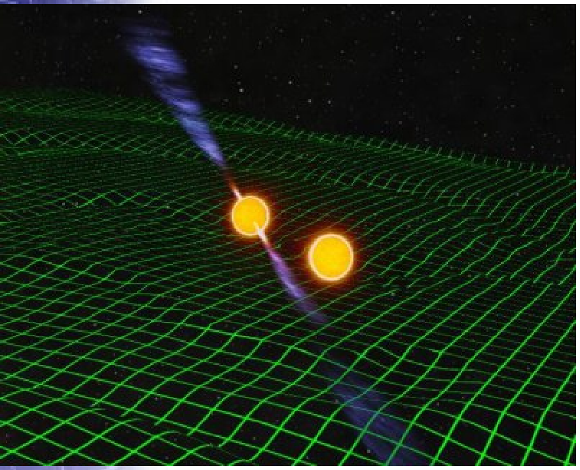
- Observe such objects as they merge?
  - Typical velocity $v/c > 0.5$
  - Typical field strength $GM/c^2R > 0.2$

Gravitational waves



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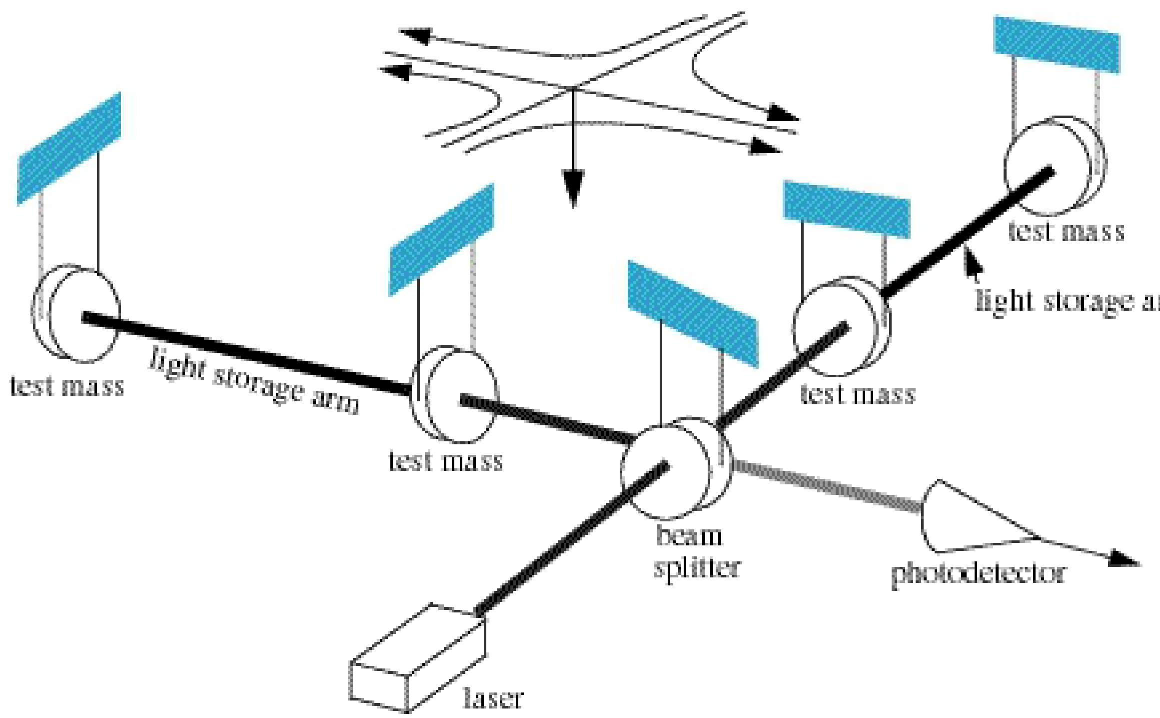
Need direct detection of gravitational waves

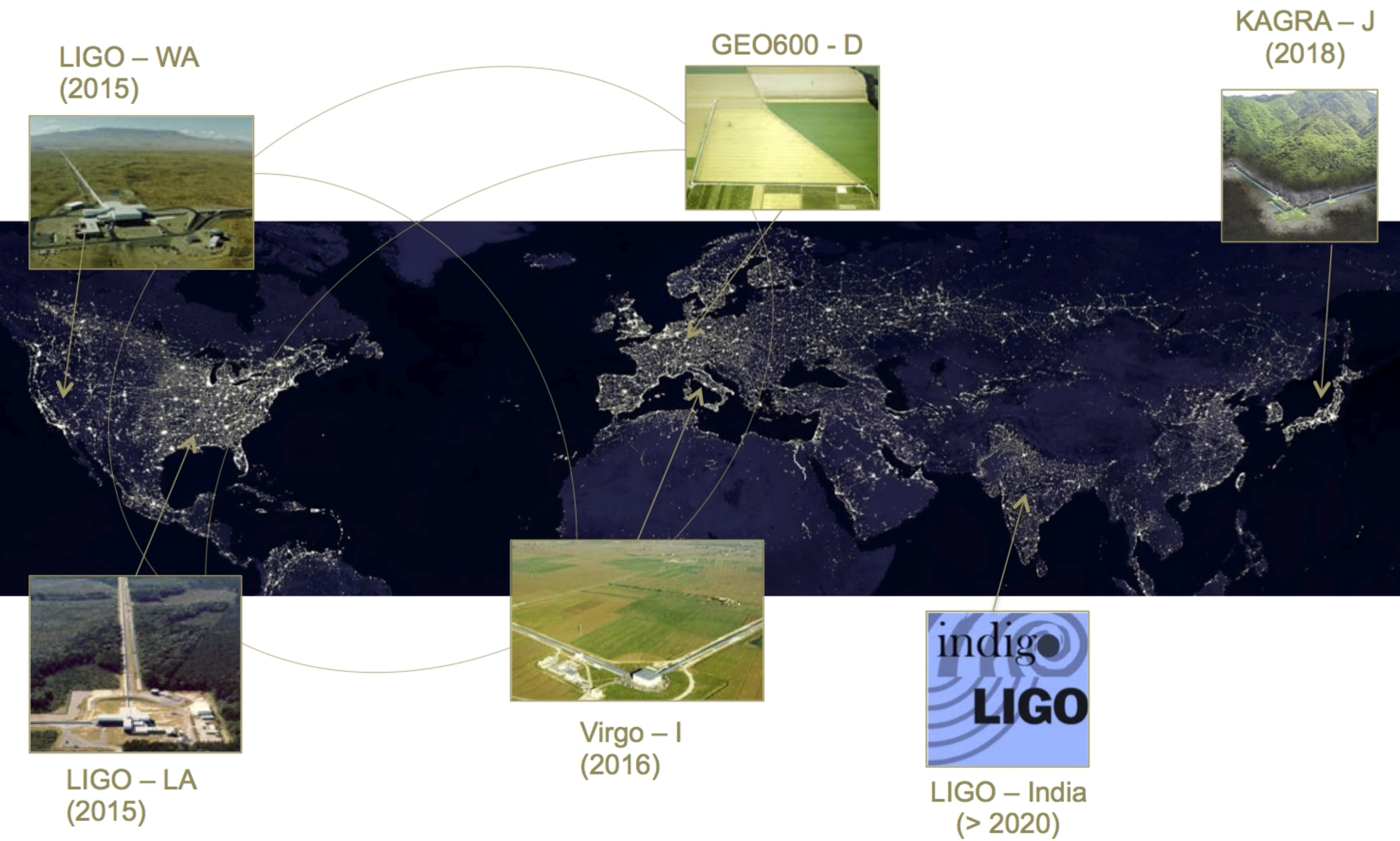
Gravitational wave detectors

- Interferometric gravitational wave detectors:



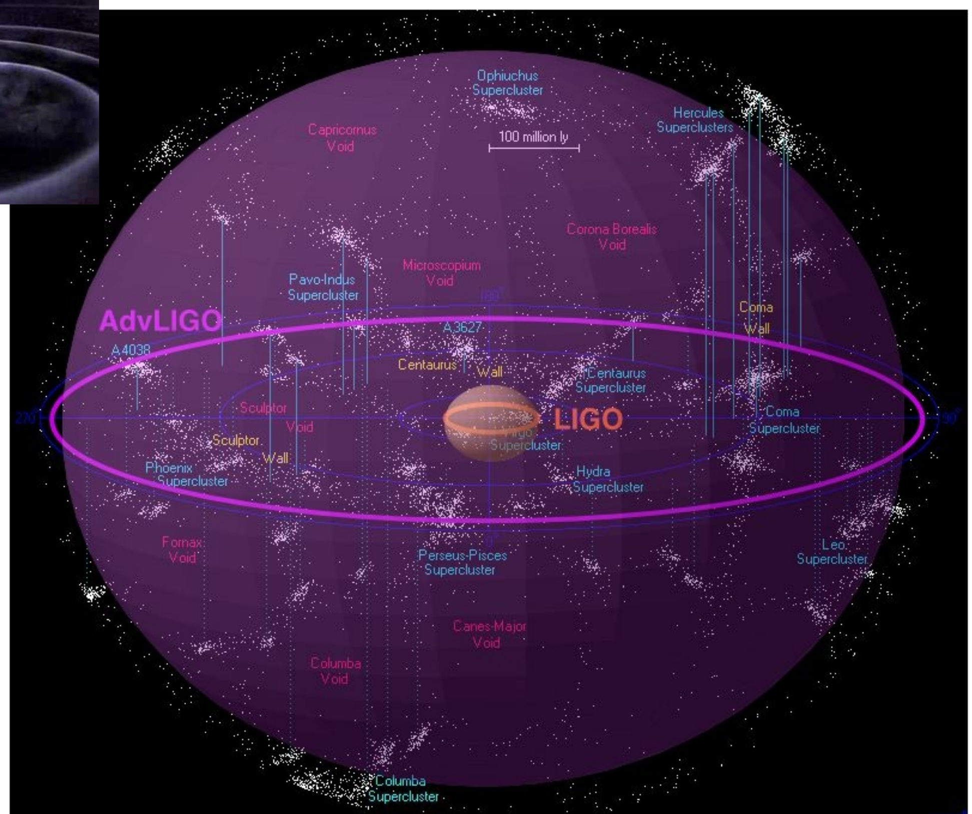
- Relative changes in arm length changes interference pattern at output
- Need the ability to reach $\Delta L/L < 10^{-23}$

A network of gravitational wave detectors



From initial to advanced detectors

- 1st generation network (2002-2011) reached design sensitivity
    - Proof of principle for large-scale interferometry as a way to directly detect gravitational waves
- Advanced detectors (starting 2015):



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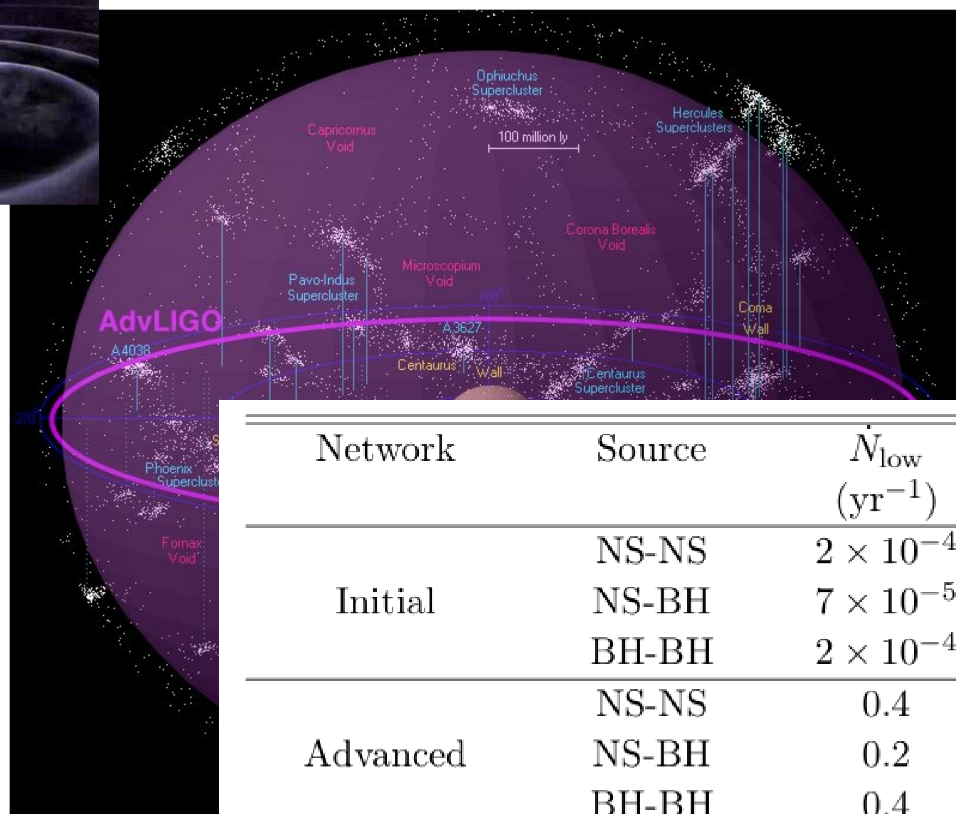
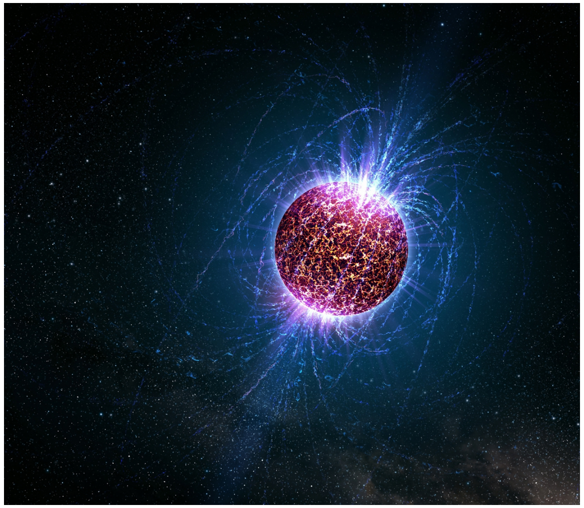


Network	Source	$\dot{N}_{\rm low}$ ($\rm yr^{-1}$)	$\dot{N}_{\rm re}$ ($\rm yr^{-1}$)	$\dot{N}_{\rm high}$ ($\rm yr^{-1}$)
Initial	NS-NS	2×10^{-4}	0.02	0.2
	NS-BH	7×10^{-5}	0.0004	0.1
	BH-BH	2×10^{-4}	0.007	0.5
Advanced	NS-NS	0.4	40	400
	NS-BH	0.2	10	300
	BH-BH	0.4	20	1000

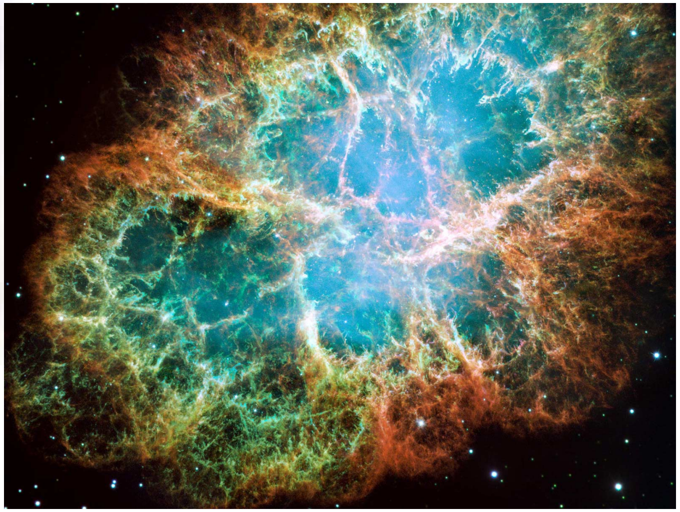
Sources of gravitational waves

Coalescing binary neutron stars and black holes

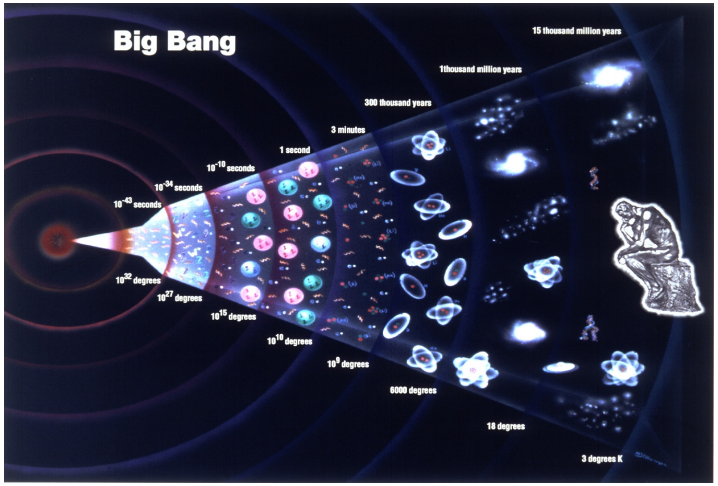
Fast-spinning neutron stars



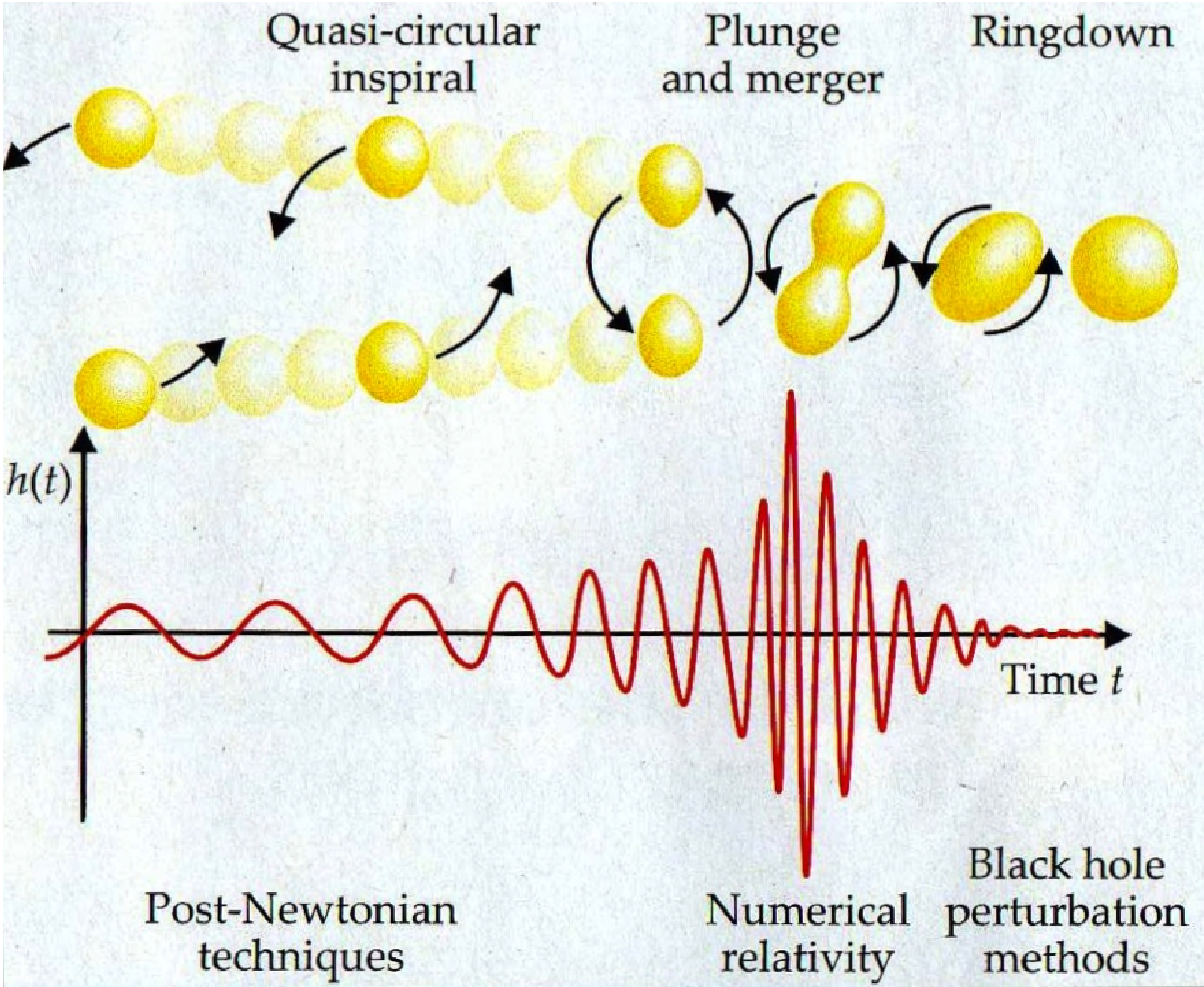
Bursts (e.g. supernovae)



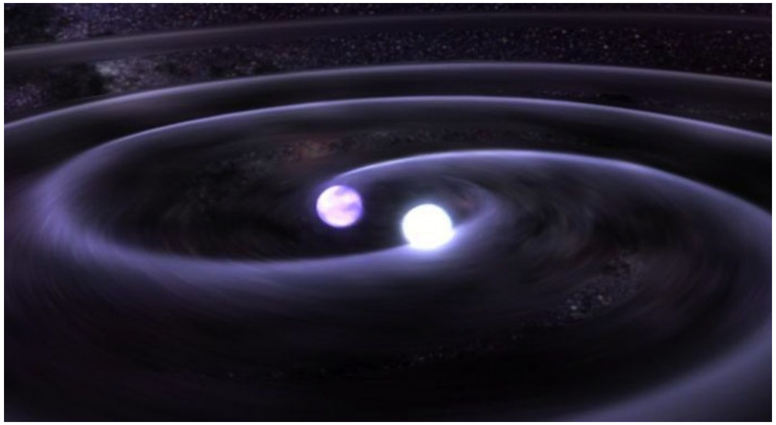
Primordial gravitational waves



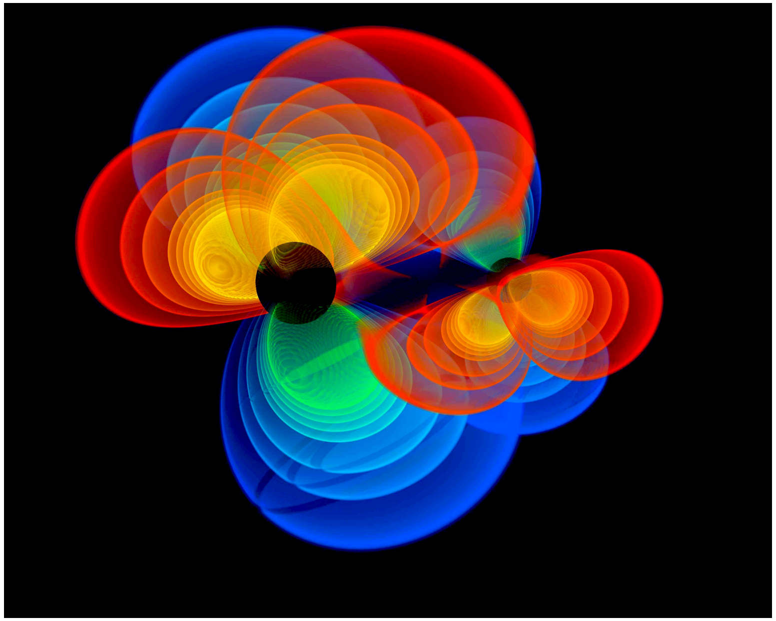
Coalescence of binary neutron stars and black holes



Probing the strong-field dynamics of spacetime



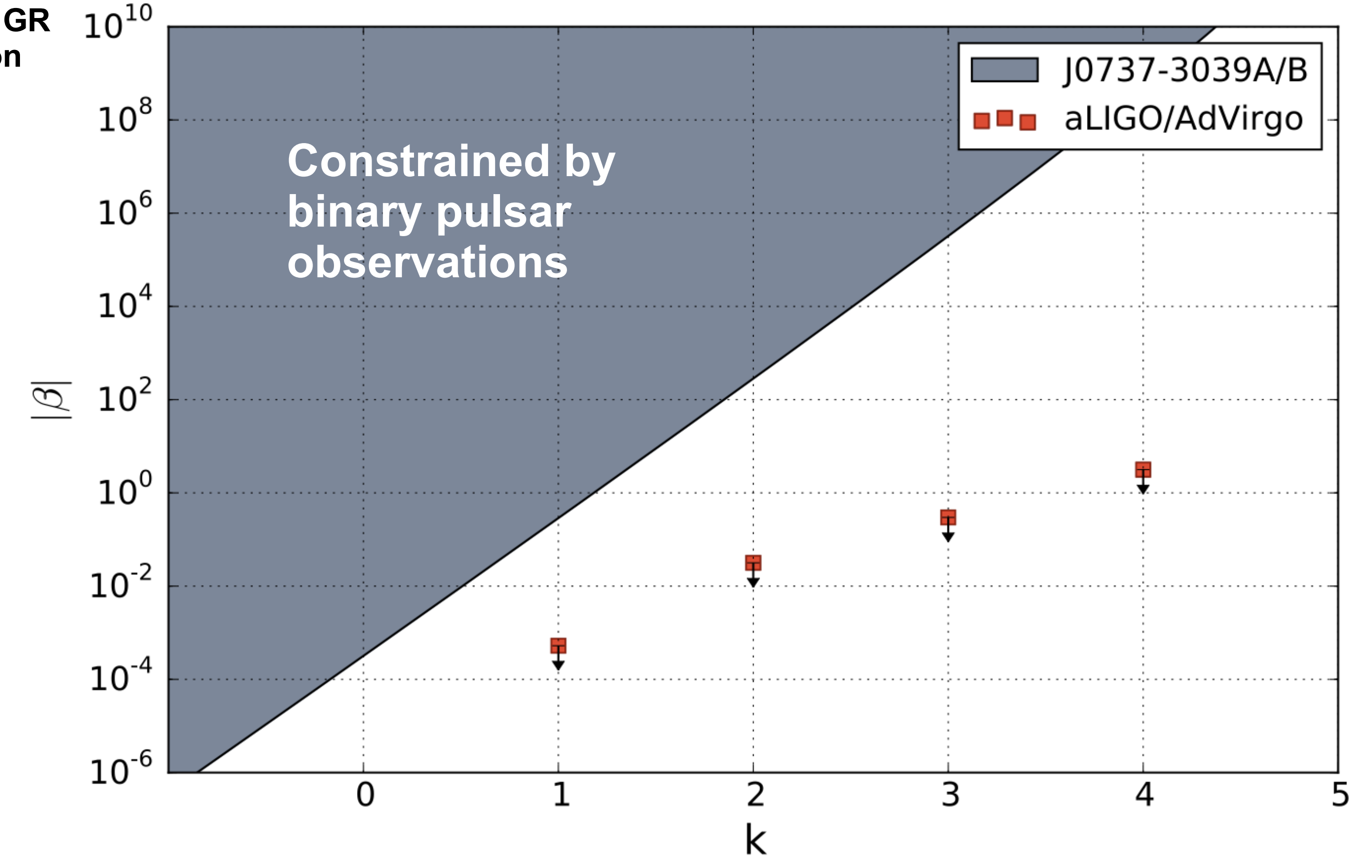
- Binary neutron star inspiral:
  - Clean empirical tests of analytically well-understood process
  - Will probe to $(v/c)^4$ beyond leading order
    - Current binary neutron star radio observations: zeroth order



- Binary black holes:
  - Inspiral, merger, ringdown in the detectors' sensitive band
  - More challenging from data analysis perspective, but great rewards

Probing the strong-field dynamics of spacetime

Size of GR violation



Order in (v/c) beyond leading order

Picture credit: M. Agathos

Yunes & Hughes, PRD **82**, 082002 (2010), Li et al., PRD **85**, 082003 (2012), Li et al., JPCS **363**, 012028 (2012), Agathos et al., PRD **89**, 082001 (2014)

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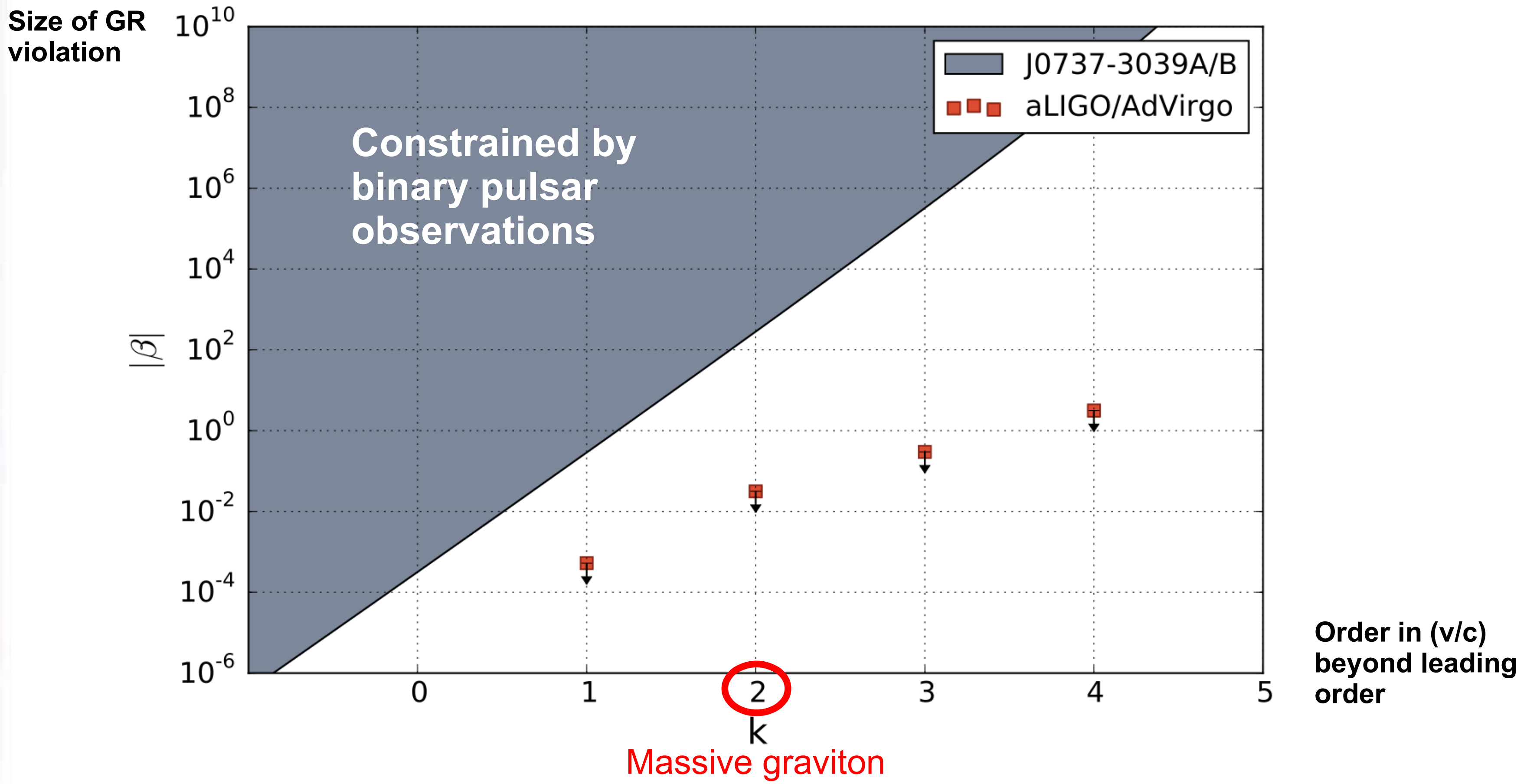

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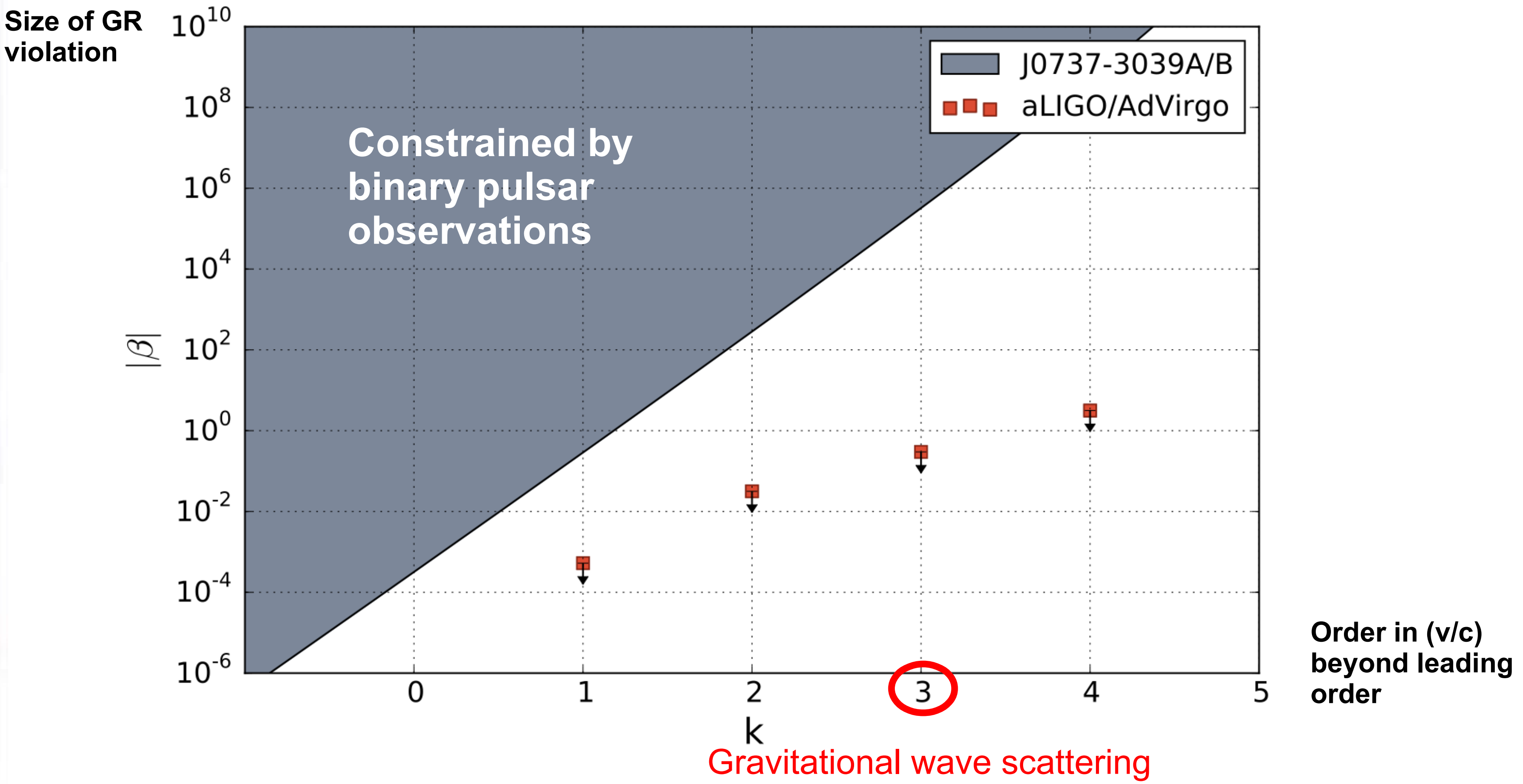

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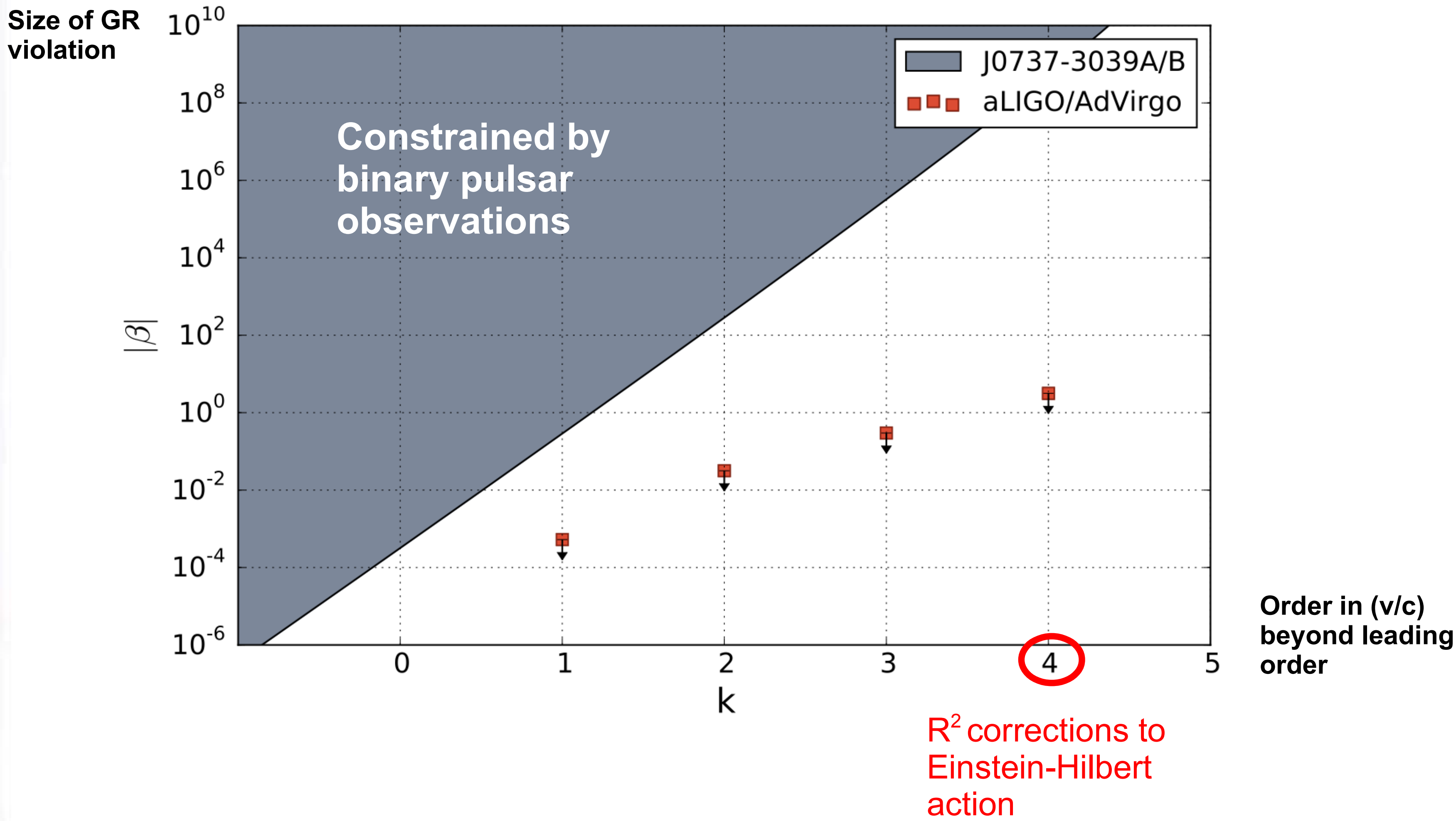

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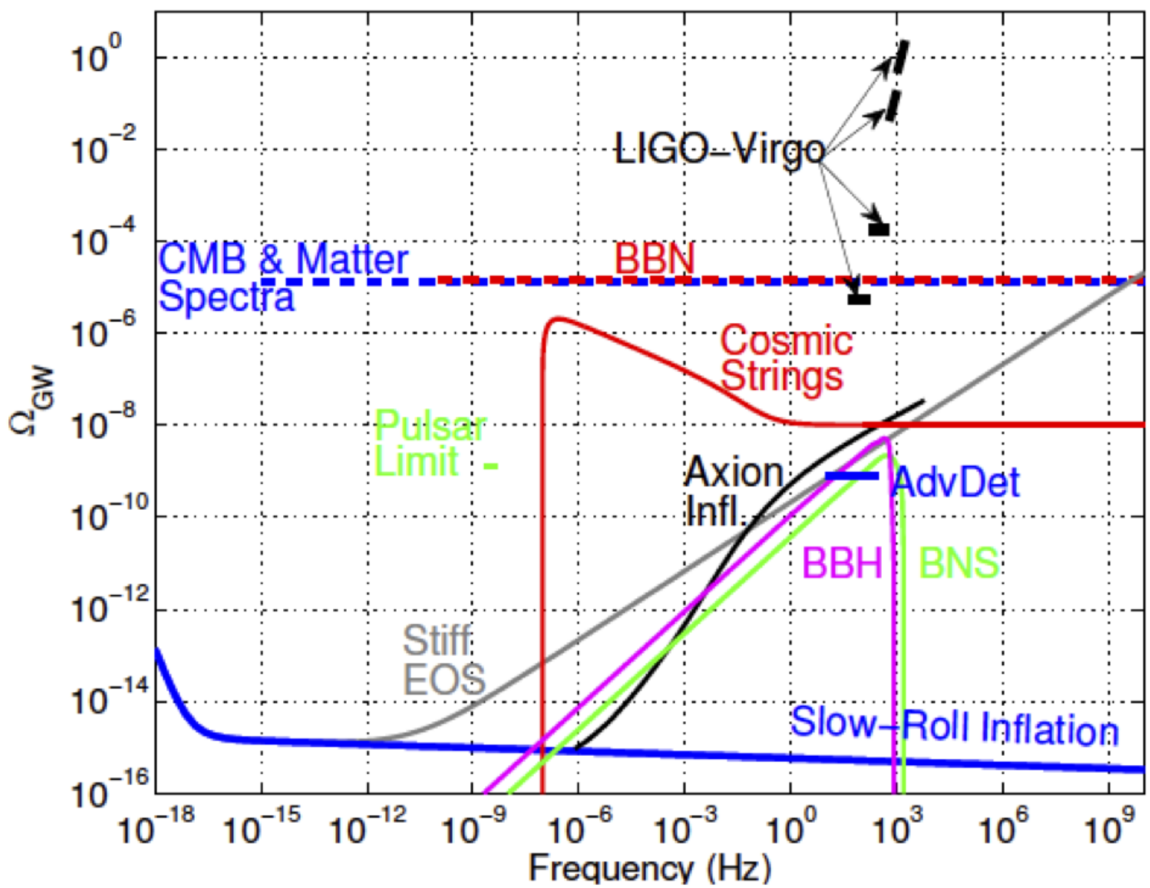
Early Universe cosmology

- Direct detection of primordial gravitational waves?

$$\Omega_{gw}(f) = \frac{d\rho_{gw}(f)}{\rho_c d(\ln f)}$$

Aasi et al., PRD **91**, 022003 (2015)



- From initial to advanced detectors: Sensitivity to gravitational wave backgrounds increases by $\sim 10^4$ in terms of GW energy density

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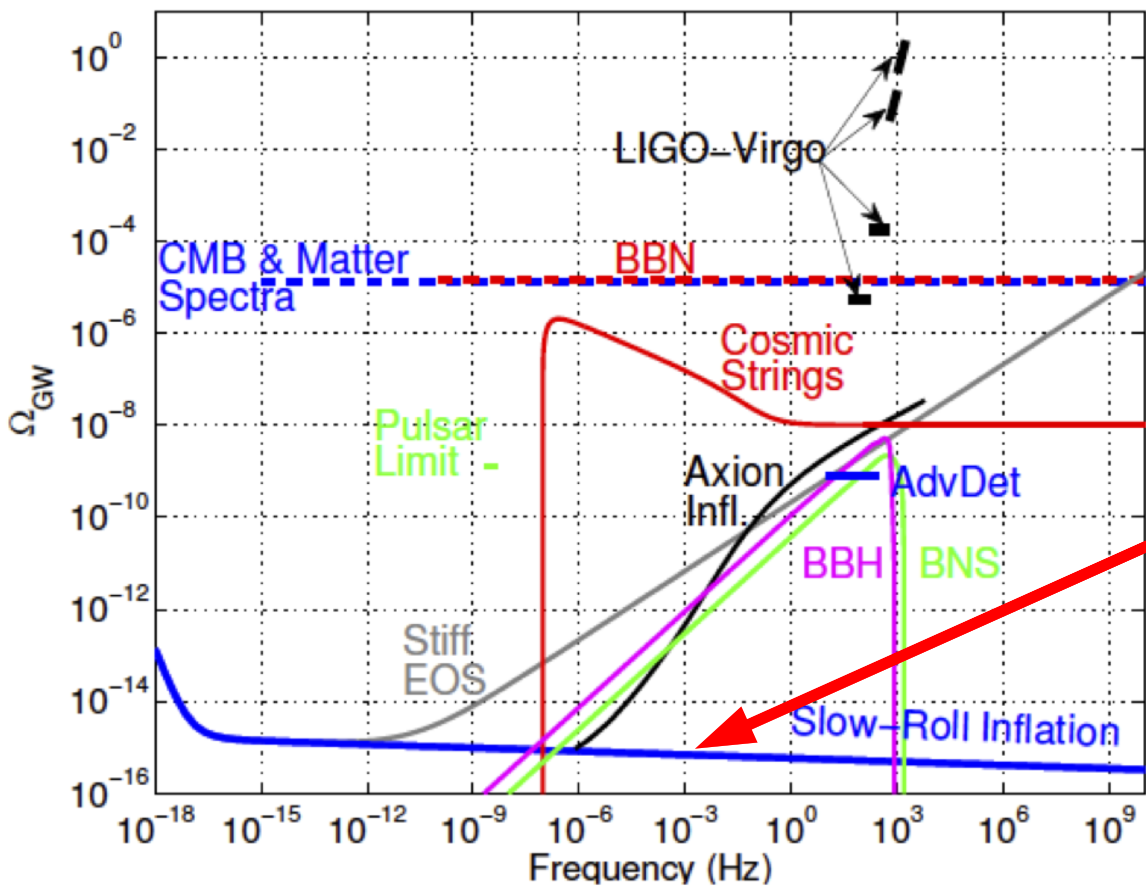

- From initial to advanced detectors: Sensitivity to gravitational wave backgrounds increases by ~10^4 in terms of GW energy density

Amplification of gravitational vacuum fluctuations during inflation

Early Universe cosmology

- Direct detection of primordial gravitational waves?

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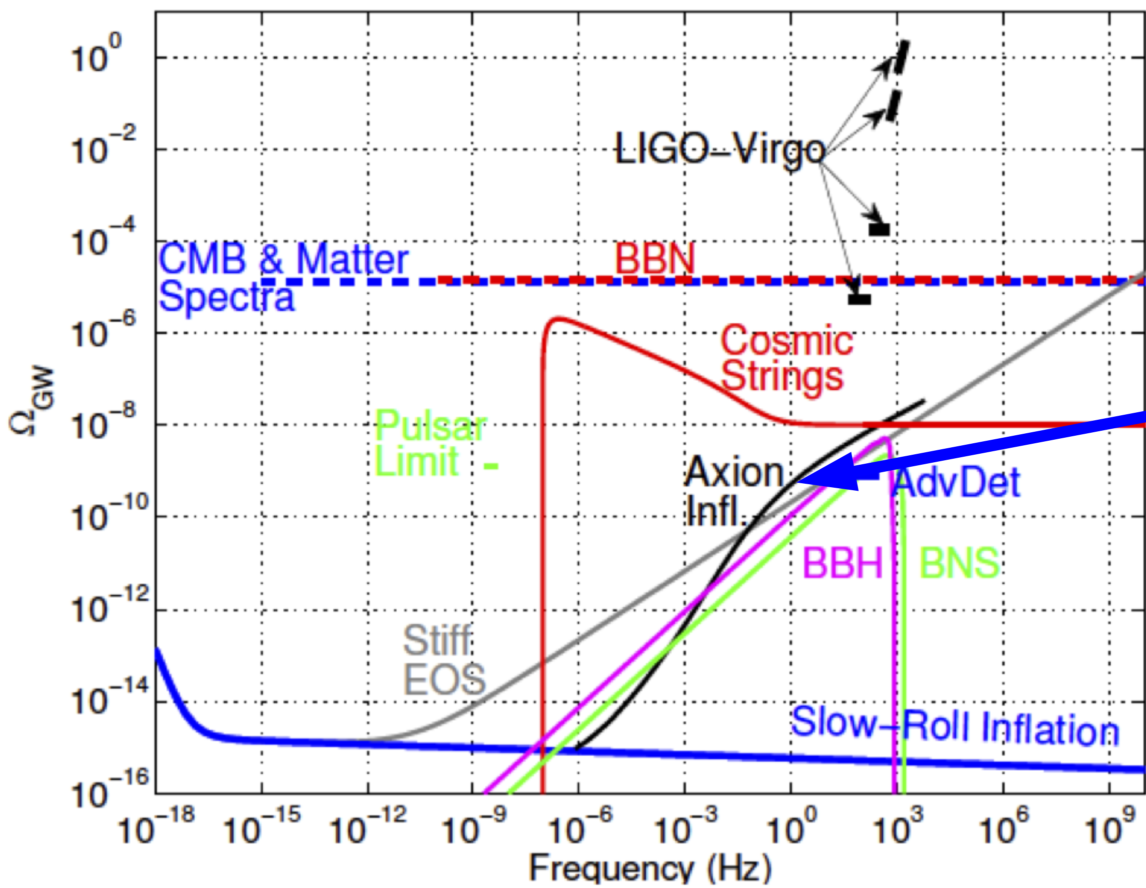
Aasi et al., PRD **91**, 022003 (2015)



- From initial to advanced detectors: Sensitivity to gravitational wave backgrounds increases by ~10^4 in terms of GW energy density

Axion-gauge coupling at the *termination* of inflation

Detection of gravitational waves in the next 20 years

- Advanced detectors (Advanced LIGO/Virgo, KAGRA, LIGO-India) 2015-...

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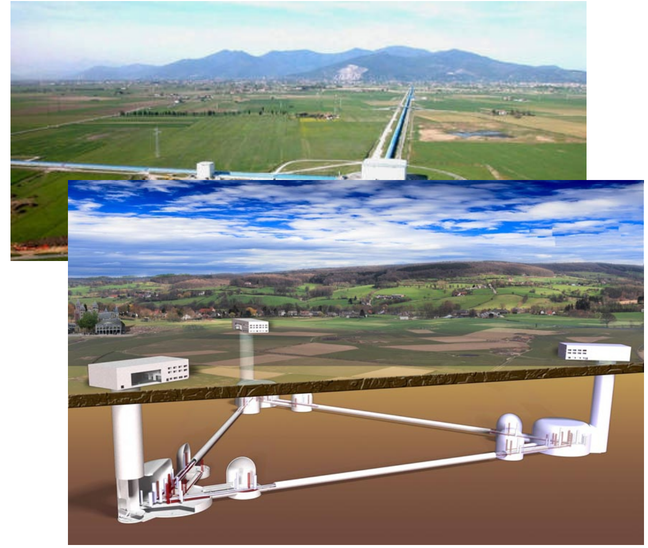

Detection of gravitational waves in the next 20 years

- Advanced detectors (Advanced LIGO/Virgo, KAGRA, LIGO-India) 2015-...
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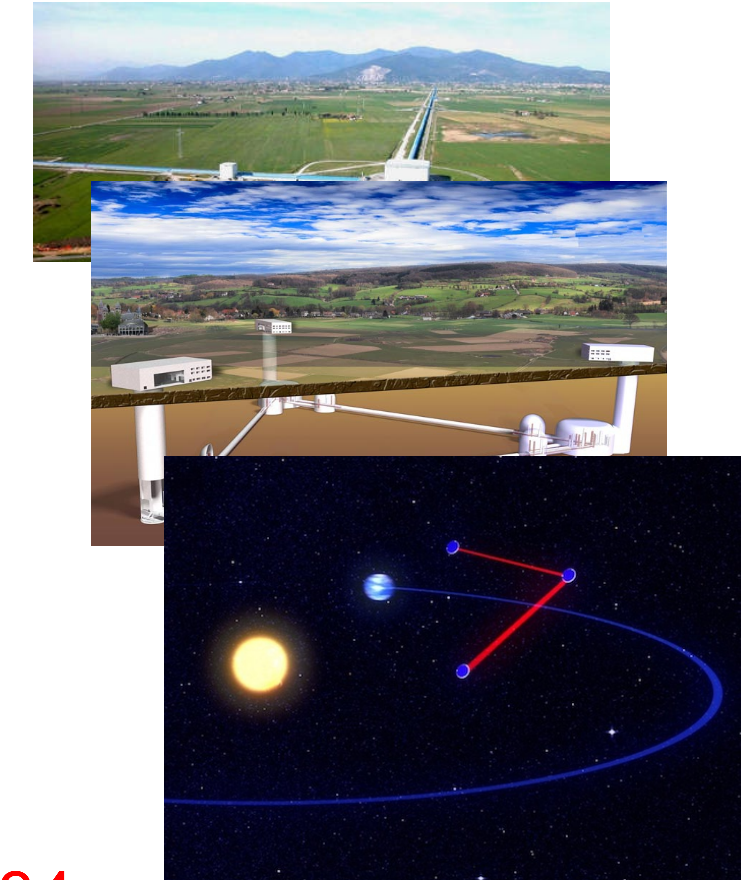
- Space-based (eLISA) Approved, launch in 2034



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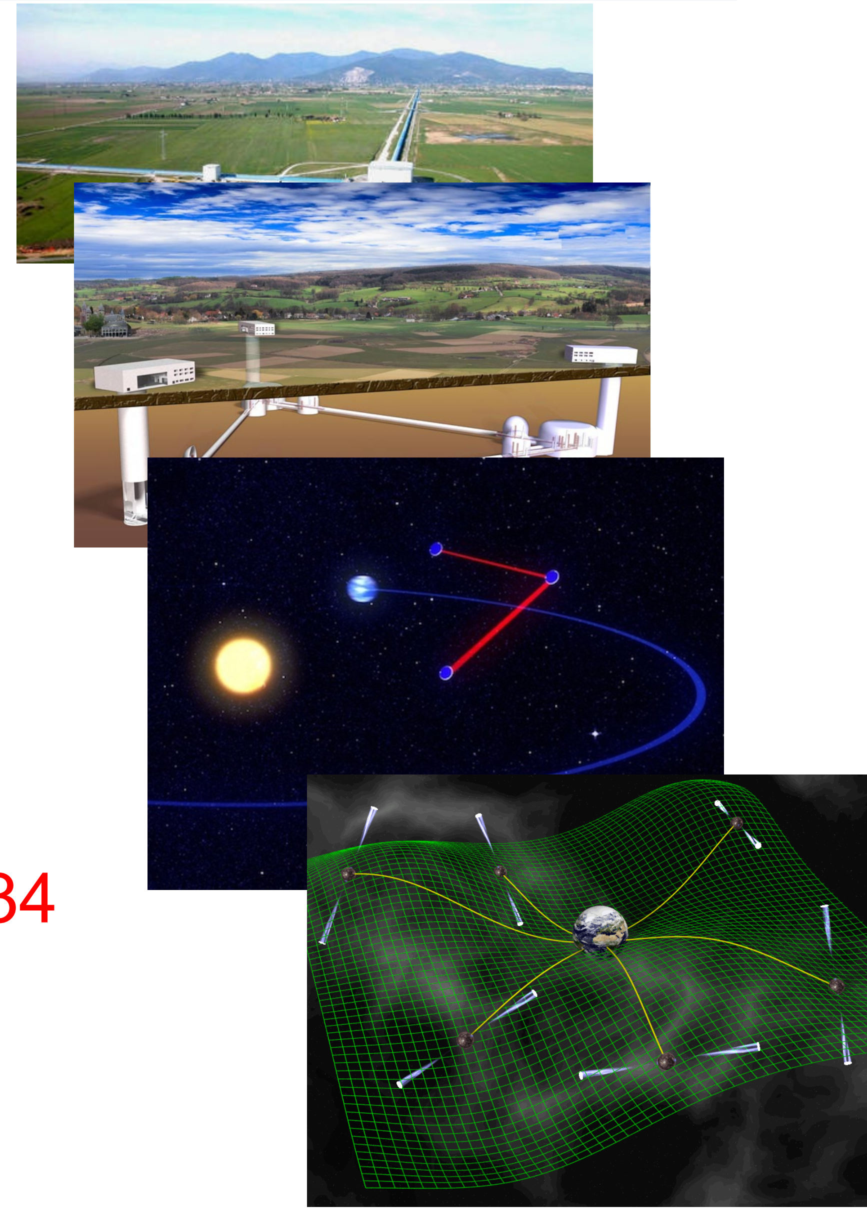
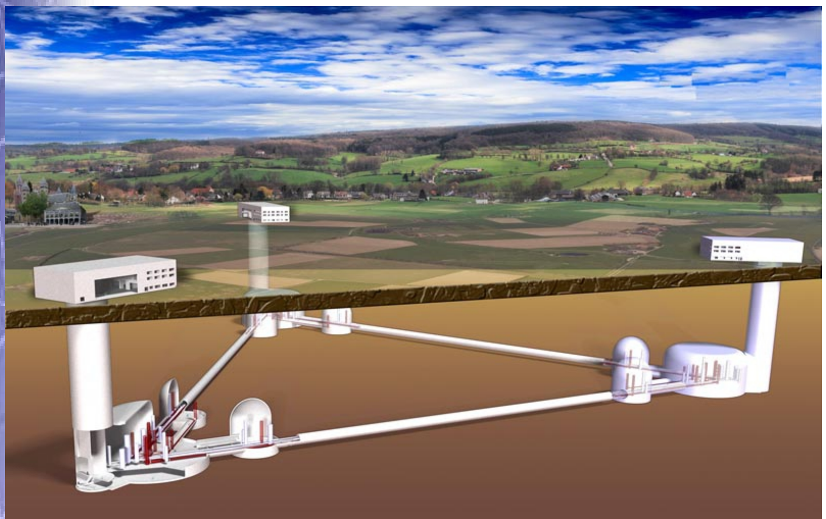
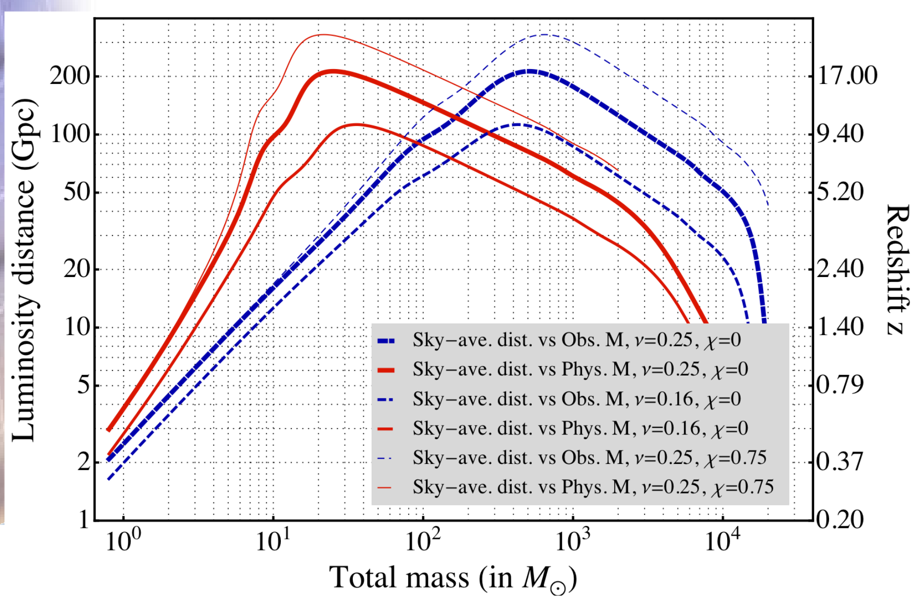
  2015-...
- Einstein Telescope
  ~2030?
- Space-based (eLISA)
  Approved, launch in 2034
- Pulsar timing
  Detection ~2025?



Science with Einstein Telescope

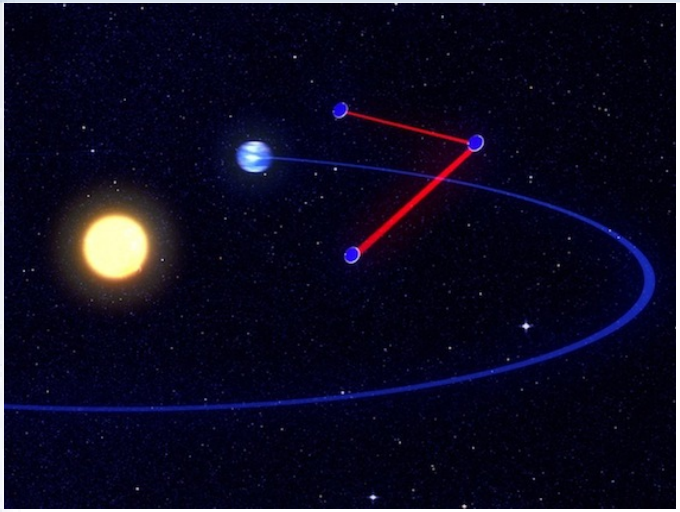




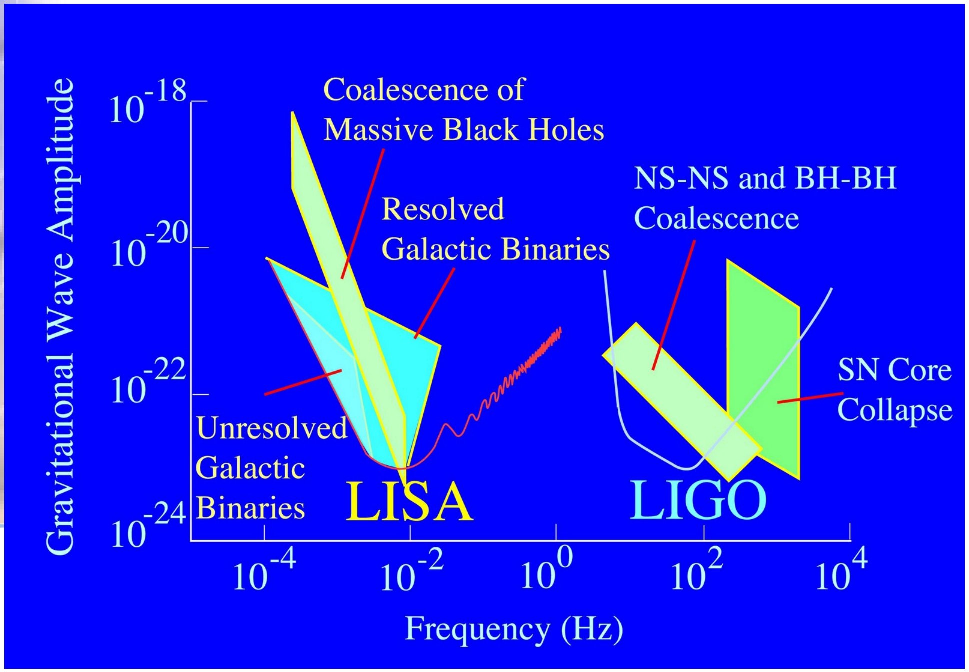
Sathyaprakash et al., CQG **29**, 124013 (2012)

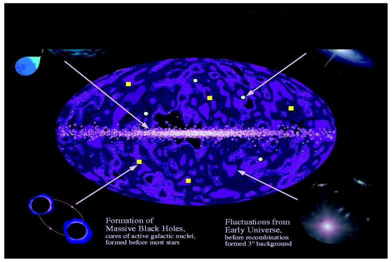
- EU-funded conceptual design study (2011)
- Will see ~10^5 binary mergers per year
  - Compare Advanced LIGO/Virgo: tens per year
- Binary black hole and neutron star mergers seen throughout much of observable Universe
  - Detailed census of black holes in binaries
  - High-precision tests of GR
  - Use coalescing binaries as cosmic distance markers
    - Independent probe of late-time evolution of the Universe

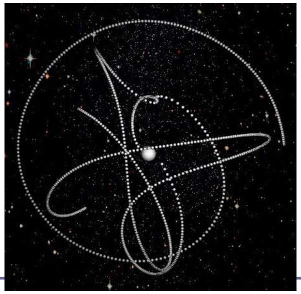
Science with space-based detectors: eLISA

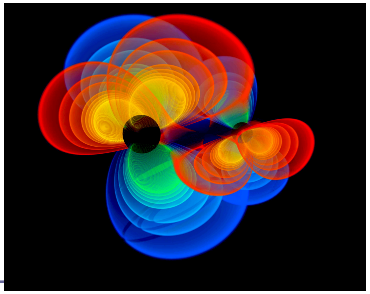


- Funded by ESA
  - Approved for launch in 2034
- Low-frequency regime ($10^{-5} – 10^{-1}$ Hz)
  - Complementary to ground-based detectors
  - Different sources:
    - Galactic white dwarf binaries
    - Capture orbits: test of no hair theorem
    - Supermassive binary black holes

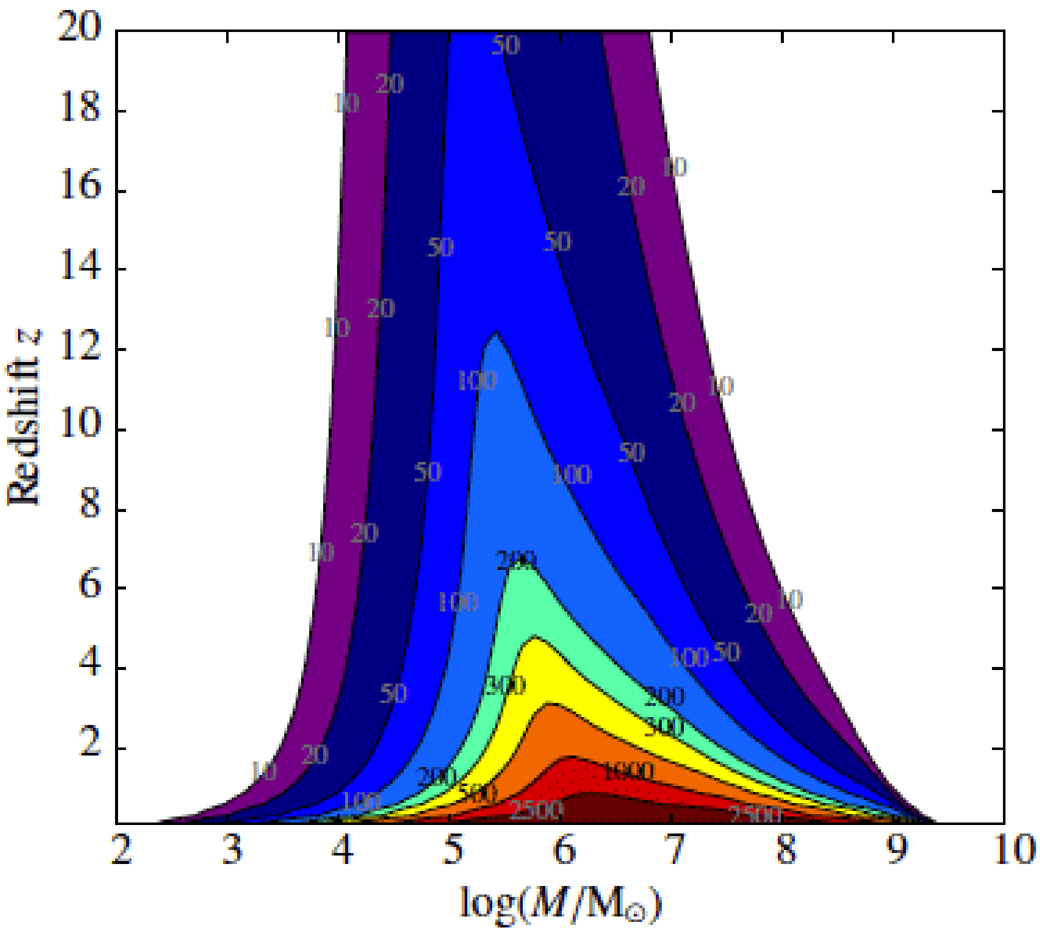






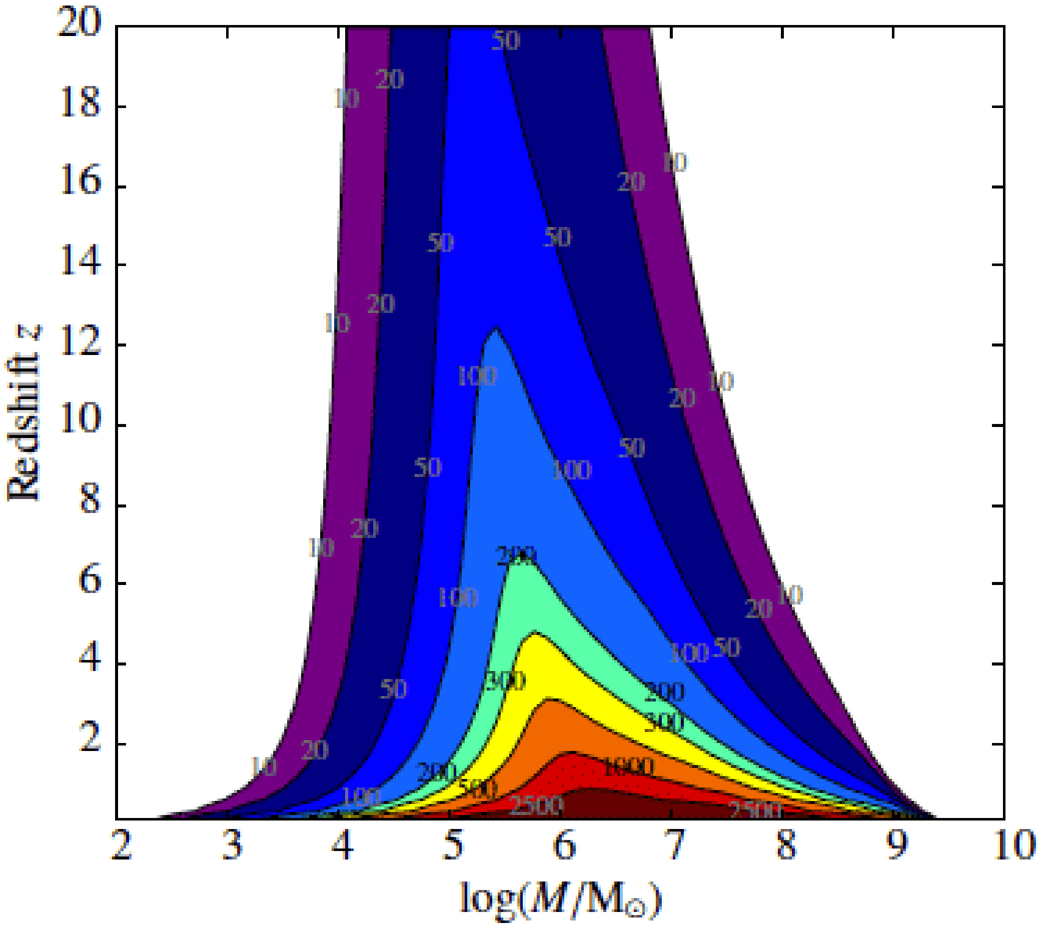


Science with space-based detectors: eLISA



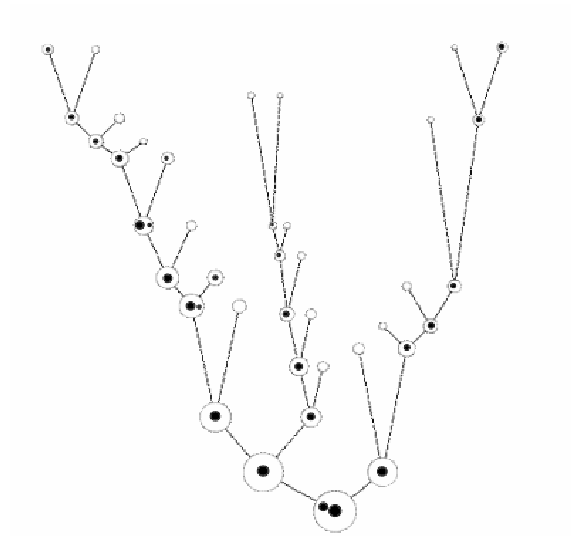
Gair et al., Living Rev. Relativity **16**, 7 (2013)

Science with space-based detectors: eLISA



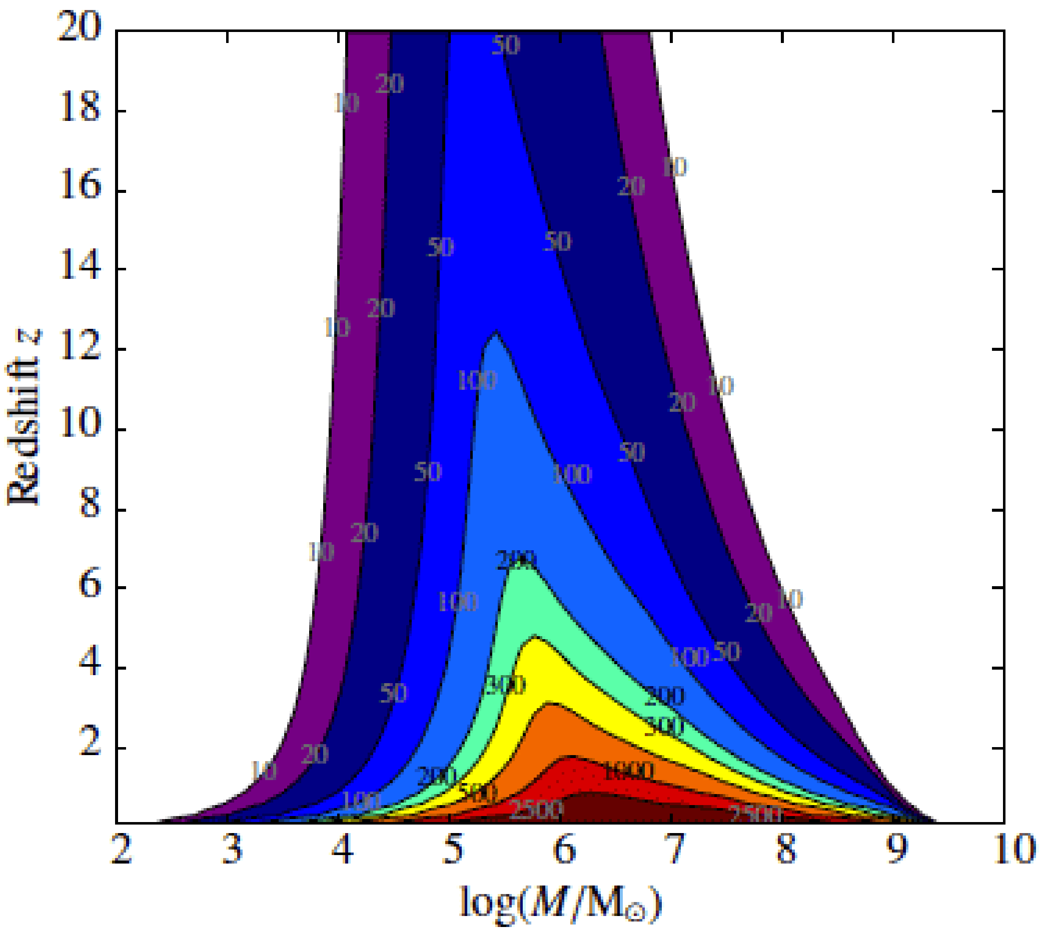
Gair et al., Living Rev. Relativity **16**, 7 (2013)

- Directly view the merger history of massive black holes



Credit: M. Volonteri

Science with space-based detectors: eLISA



Gair et al., Living Rev. Relativity **16**, 7 (2013)

Pathfinder mission to be launched in 2015!

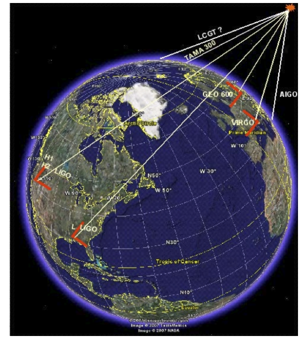
Scientific promise of direct gravitational wave detection

- Empirical access to genuinely strong-field dynamics of spacetime
- Making a census of black holes in all mass ranges, all distances
- Studying the large-scale structure of spacetime
- Direct detection of primordial gravitational waves?

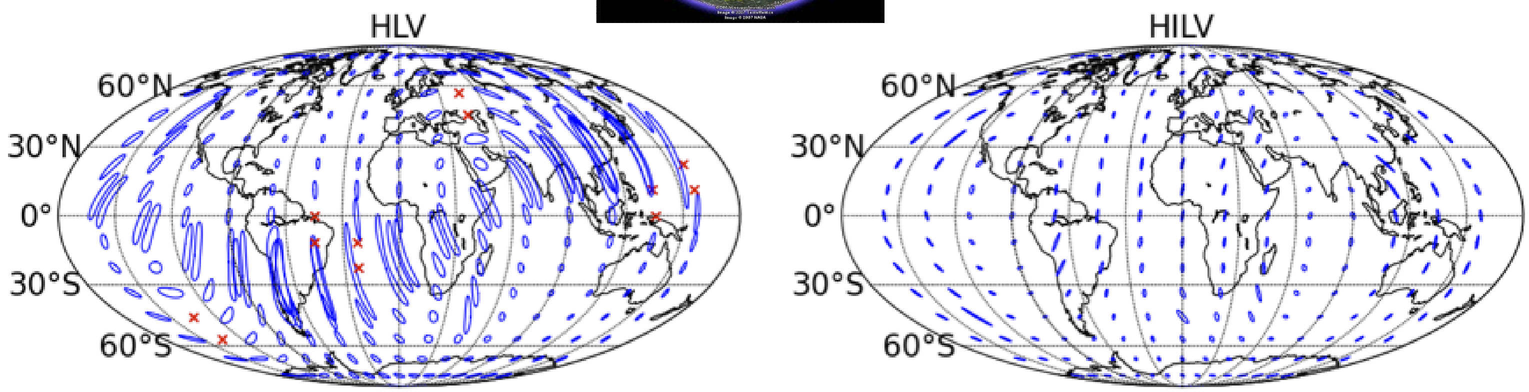
Stay tuned!

Backup slides

A network of gravitational wave detectors

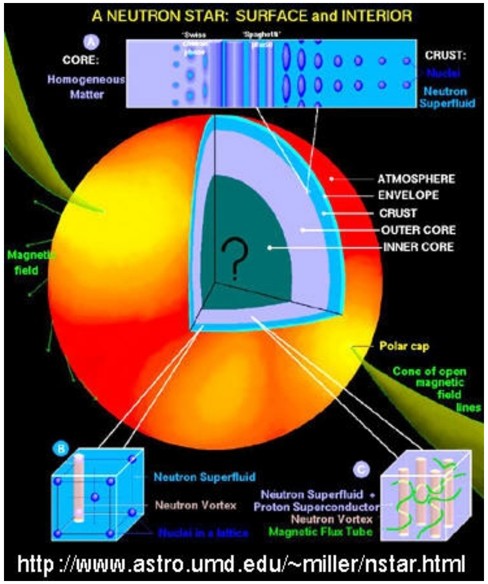


arXiv:1304.0670

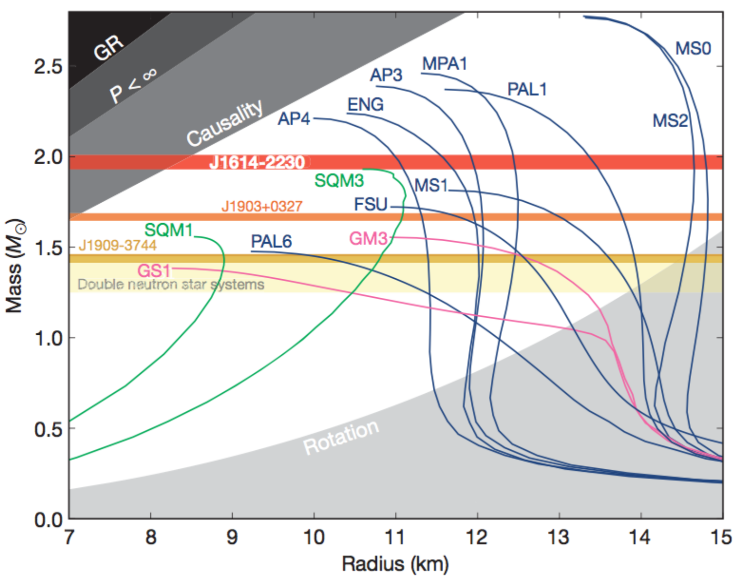


- Network of detectors allows for rapid sky localization
  - Possibility of electromagnetic counterparts
    - E.g. short, hard gamma ray bursts believed to be mergers of binary neutron stars, or neutron star-black hole
  - 60+ astronomy groups (radio to γ rays) have signed up to receive alerts
    - LOFAR, Pan-STARRS, HESS, HAWC, VERITAS, XMM-Newton, Fermi, Swift, ...

Astrophysics with binary neutron star coalescence



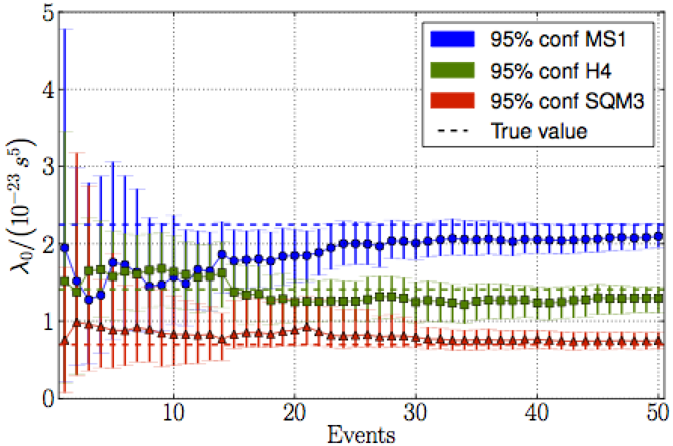
- Interior of neutron stars poorly understood:
  - Superfluid and superconducting interior
    - "Pinning" of fluid vortices to the crust?
  - Origin of magnetic field?
  - More exotic objects (e.g. strange quark stars)?



- Range of qualitatively different predictions for neutron star equation of state

Demorest et al., Nature **467**, 1081 (2010)

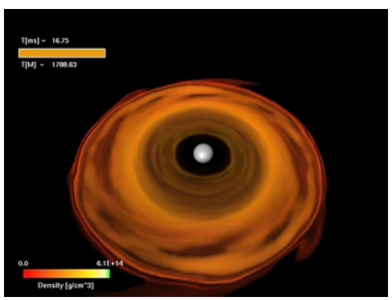
Astrophysics with binary neutron star coalescence

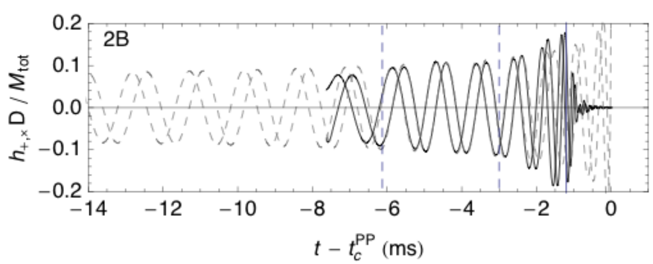


- Tidal deformation during inspiral already distinguishes between hard, moderate, and soft equations of state

Del Pozzo et al., PRL **111**, 071101 (2013)

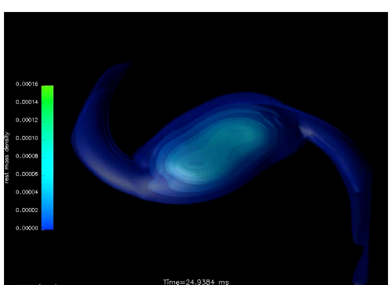
- Merger will provide further information:

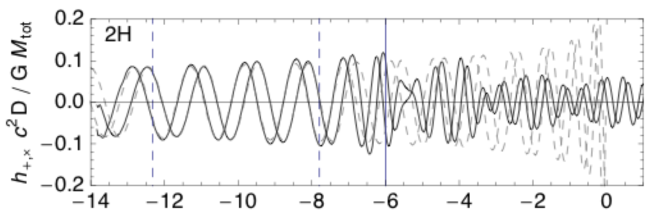




- Soft EOS:

  Prompt collapse to black hole



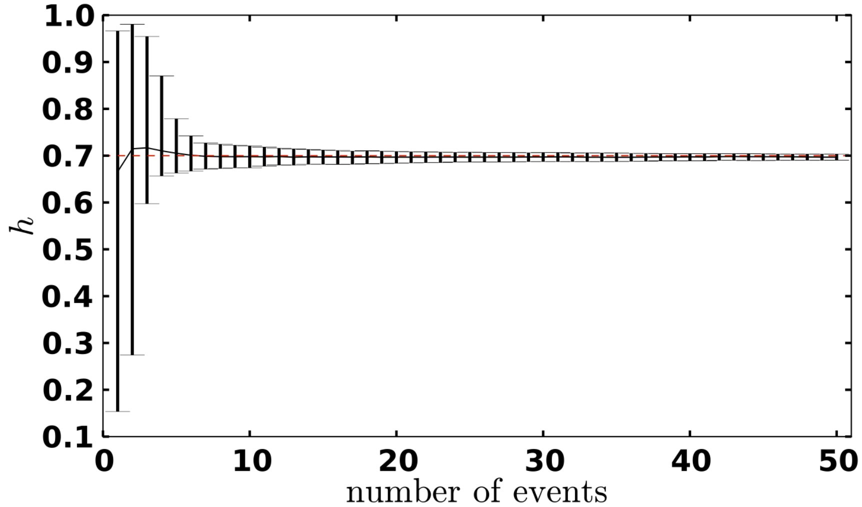


- Hard EOS:

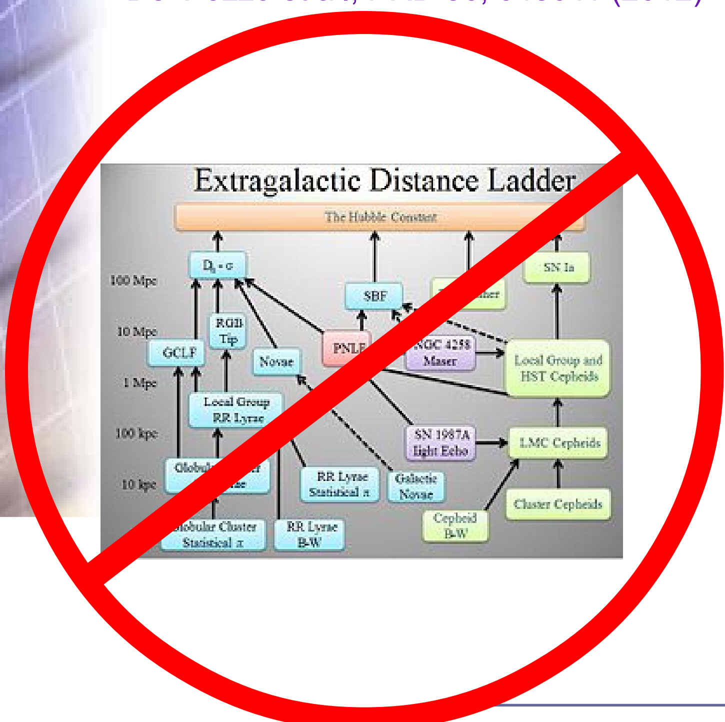
  Unstable bar mode, eventually black hole

Read et al.., PRD **79**, 124033 (2009)

Cosmology without a cosmic distance ladder



Del Pozzo et al., PRD **86**, 043011 (2012)



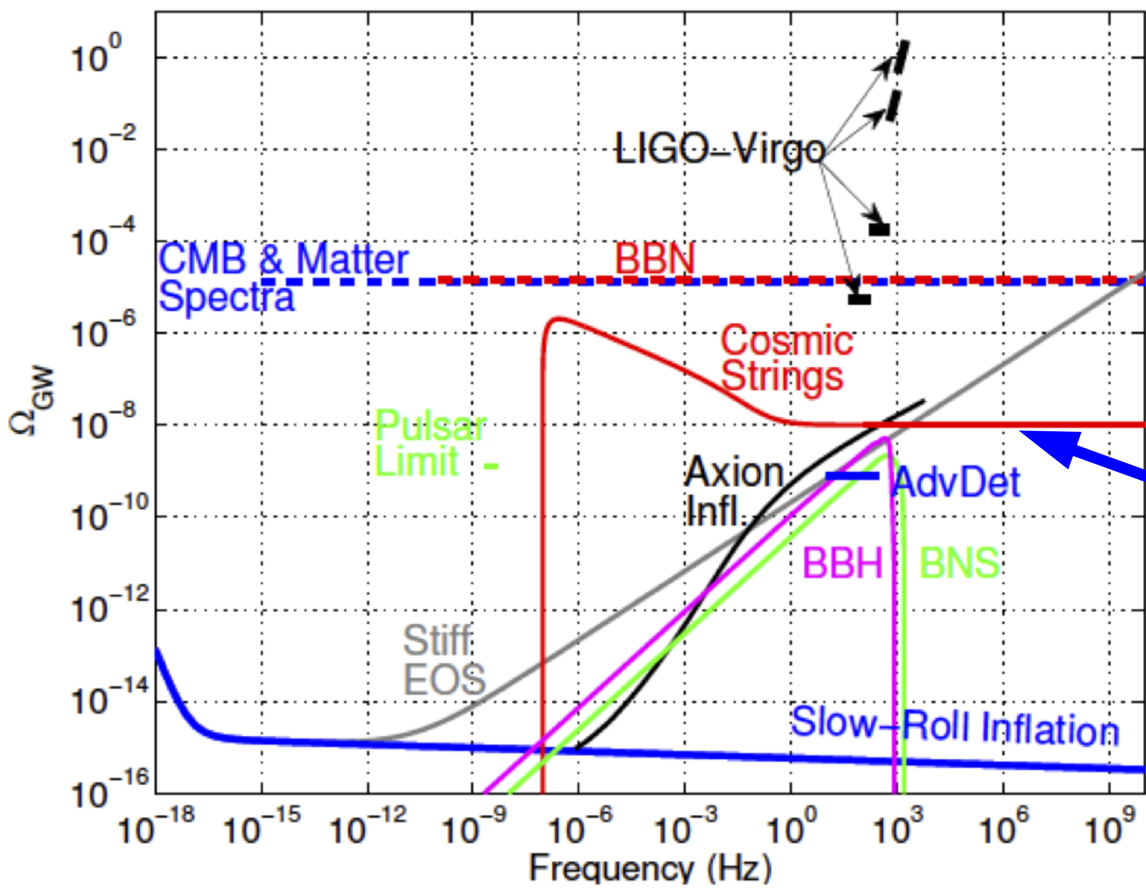
- Coalescences of binary neutron stars are cosmic distance markers
    - Phasing gives masses, spins
      ⇒ Expected amplitude *up to distance*
    - Compare with measured amplitude
      ⇒ Infer distance
    - Independently obtain redshift using e.g. electromagnetic counterparts
- Precision measurements of late-time evolution of the Universe
- Self-calibrating "standard sirens"!
    - No "cosmic distance ladder"

Early Universe cosmology

- Direct detection of primordial gravitational waves?

$$\Omega_{gw}(f) = \frac{d\rho_{gw}(f)}{\rho_c d(\ln f)}$$

Aasi et al., PRD **91**, 022003 (2015)



- From initial to advanced detectors:
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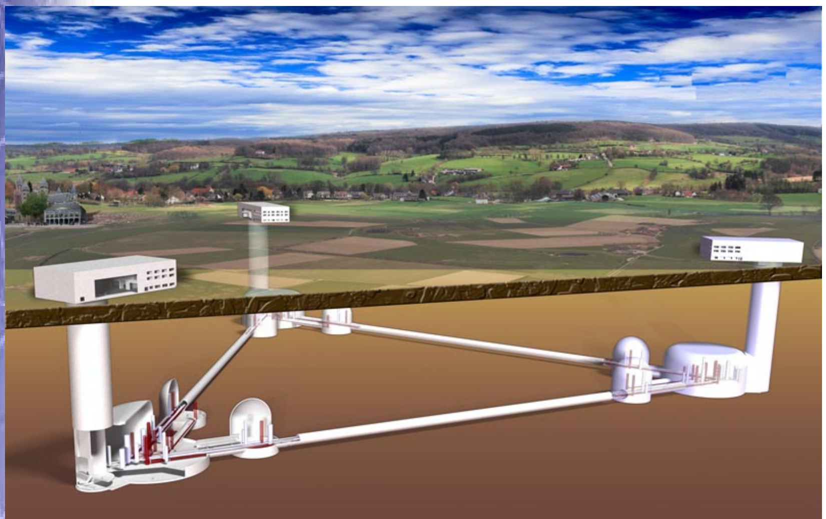
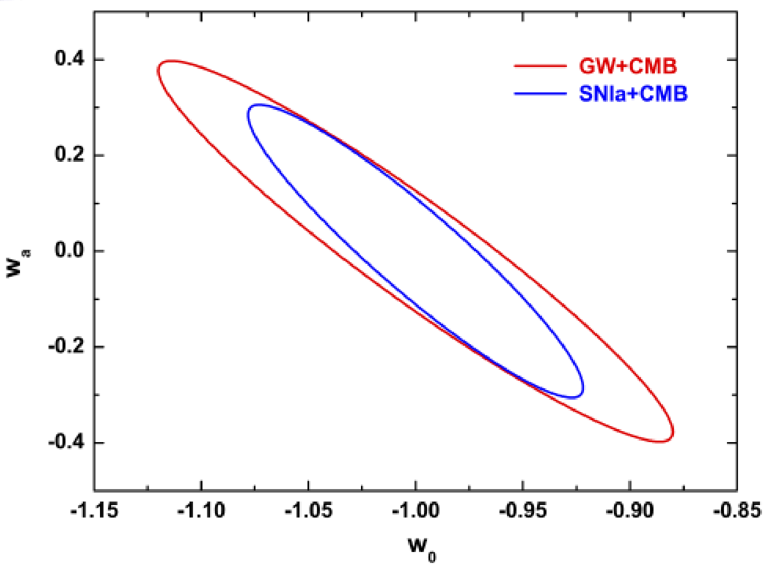
Cosmic string cusps and kinks

Science with Einstein Telescope





Zhao et al., PRD **83**, 023005 (2011)

- EU-funded conceptual design study (2011)
- Will see ~10^5 binary mergers per year
  - Compare Advanced LIGO/Virgo: tens per year
- Stellar mass binary black hole and neutron star mergers seen throughout much of observable Universe
  - Detailed census of black holes in binaries
  - High-precision tests of GR
  - Use coalescing binaries as cosmic distance markers
    - Probe equation of state of dark energy

      $w = P/\rho$