Intensive Course in Physics
Gravitational Waves

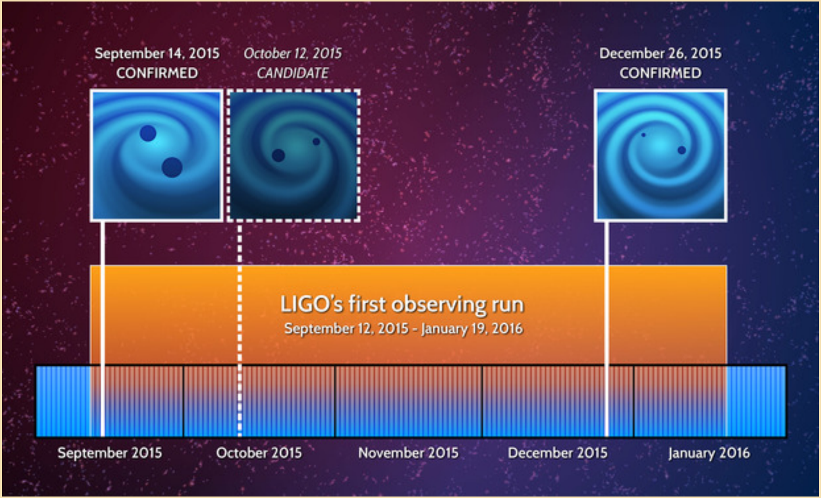
Tjonnie G. F. Li

Chapter 5: Science with Gravitational Waves

November 11, 2016

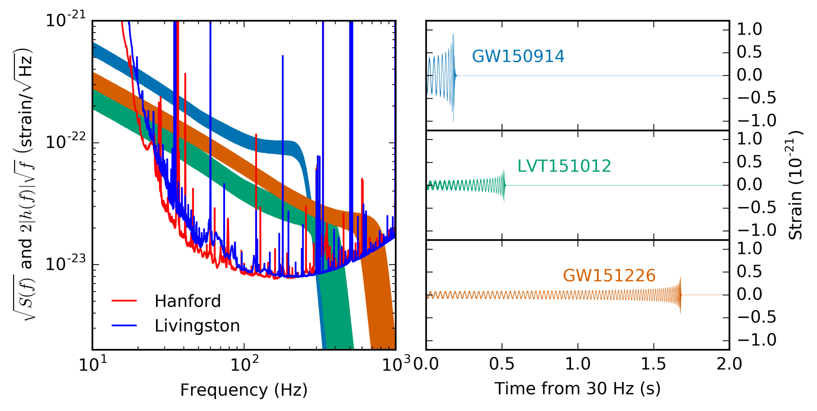
What do we know so far?

LIGO Detection Time Line



credit: LIGO

Detected Sources



B. P. Abbott et al. “Binary Black Hole Mergers in the First Advanced LIGO Observing Run”. In: *Physical Review X* 6.4, 041015 (Oct. 2016), p. 041015

Measuring properties of binaries

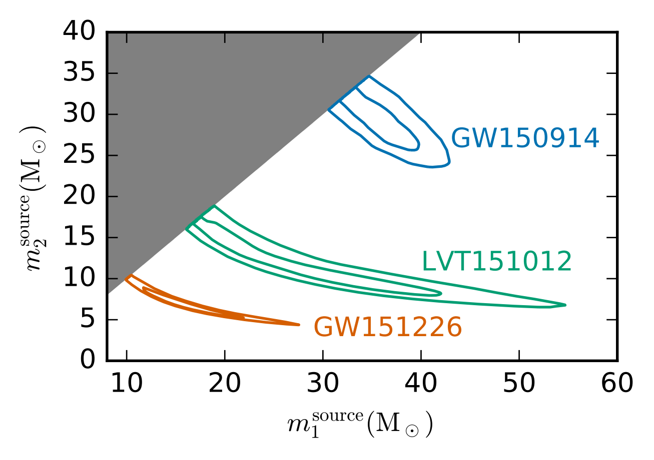
- Want to infer the properties of GW150914 from the data
- Bayesian inferenc

$$\Pr(\vec{\theta} \mid d) = \frac{\Pr(d \mid \vec{\theta}) \Pr(\vec{\theta})}{\Pr(d)} \tag{1}$$

  - $\vec{\theta} \in \{m_1, m_2, \mathbf{S_1}, \mathbf{S_2}, D_L, \ldots\}$
  - $\Pr(\vec{\theta} \mid d)$: Posterior
  - $\Pr(d \mid \vec{\theta})$: Likelihood
  - $\Pr(\vec{\theta})$: Prior
  - $\Pr(d)$: Evidence/Marginal likelihood

Use Markov-Chain-Monte-Carlo methods to sample the posterior

Component Masses



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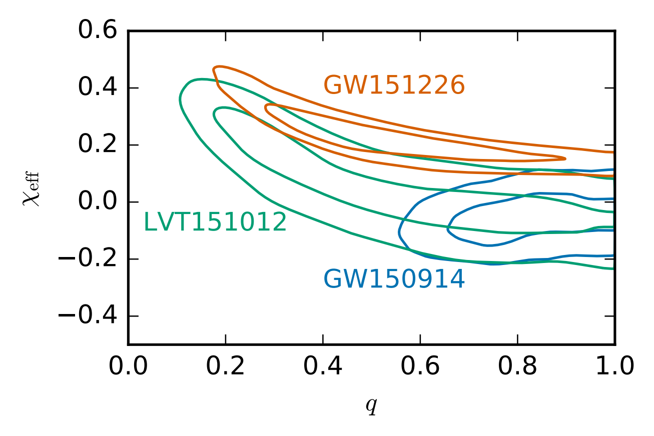
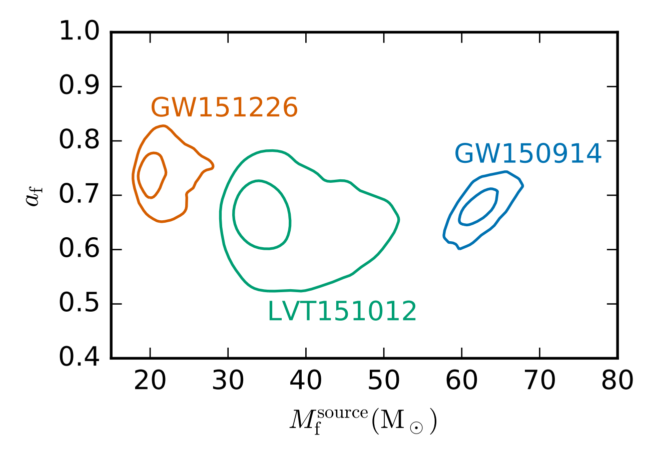
Mass Ratio and Spin



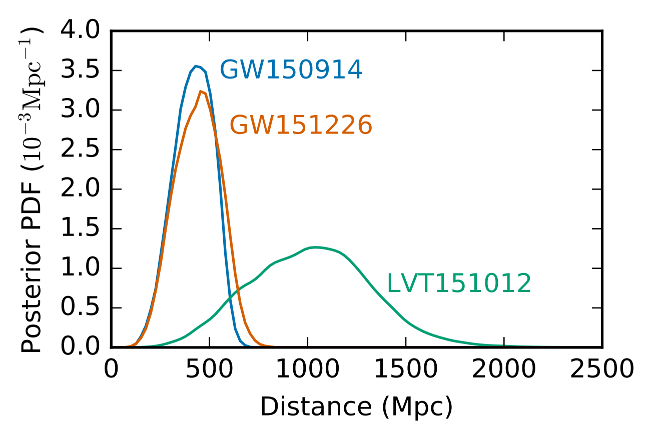
B. P. Abbott et al. "Binary Black Hole Mergers in the First Advanced LIGO Observing Run". In: *Physical Review X* 6.4, 041015 (Oct. 2016), p. 041015

Final Black Hole



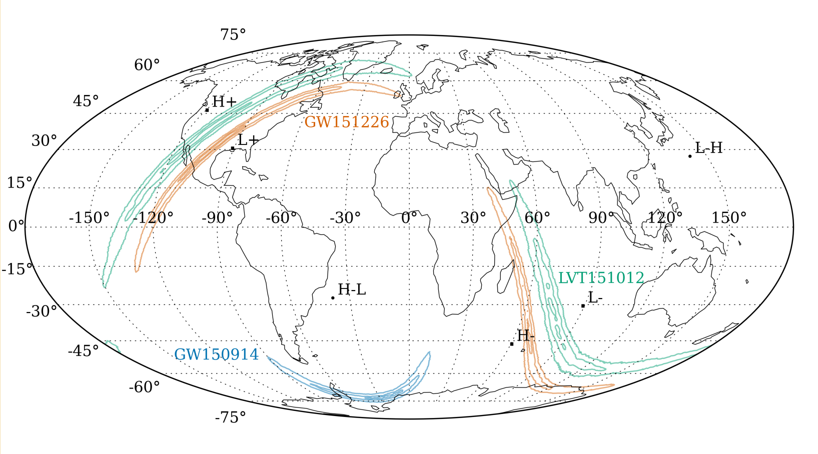
B. P. Abbott et al. "Binary Black Hole Mergers in the First Advanced LIGO Observing Run". In: *Physical Review X* 6.4, 041015 (Oct. 2016), p. 041015

Distance



B. P. Abbott et al. "Binary Black Hole Mergers in the First Advanced LIGO Observing Run". In: *Physical Review X* 6.4, 041015 (Oct. 2016), p. 041015

Sky Position I



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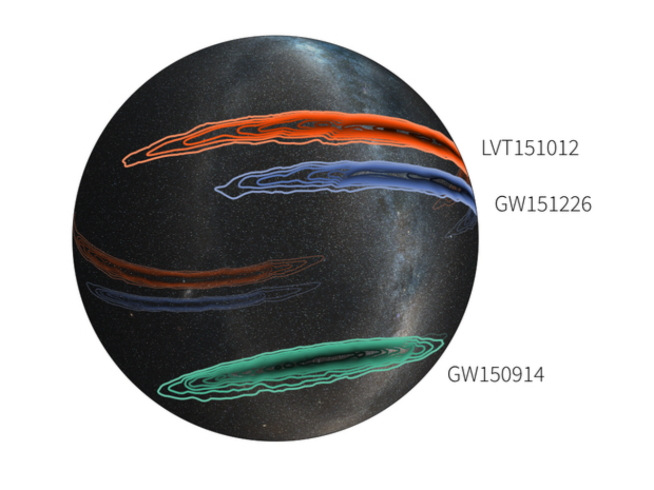
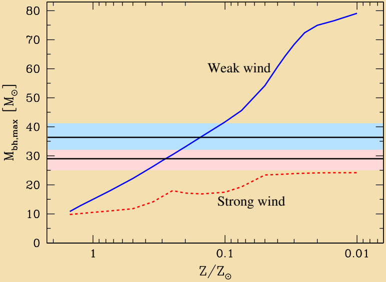
Sky Position II

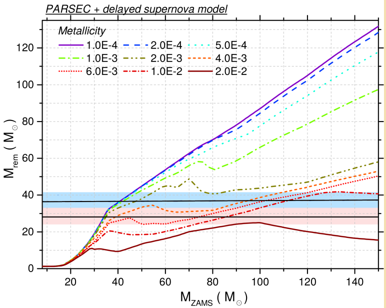


Credit: LIGO/Leo Singer (Milky Way image: Axel Mellinger)

Astrophysical implications

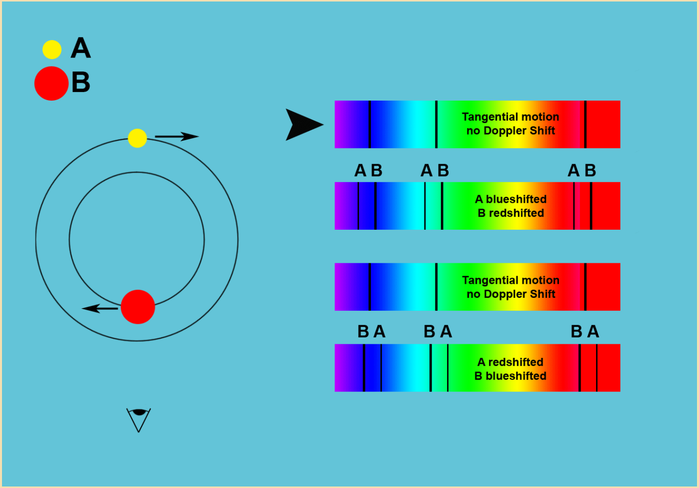


Abbott et al. [2]



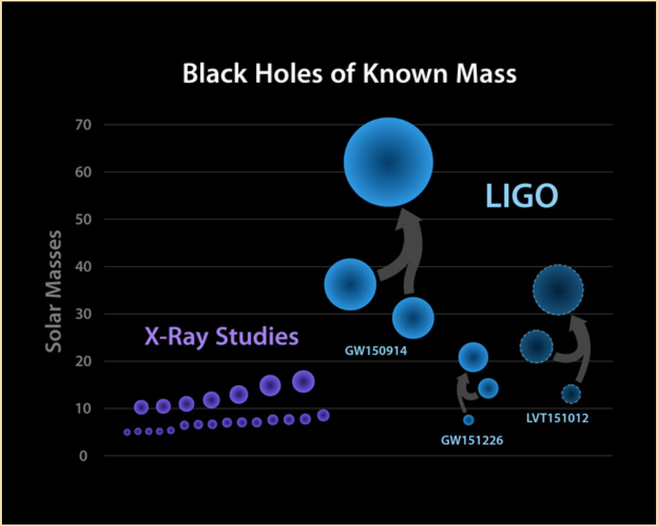
- Relatively weak massive-star winds
- Metallicity < 1/2 of the solar value
- Formed in low-mass galaxy in the local Universe
- Formed at high redshift with time delay until merger

Masses from Binaries



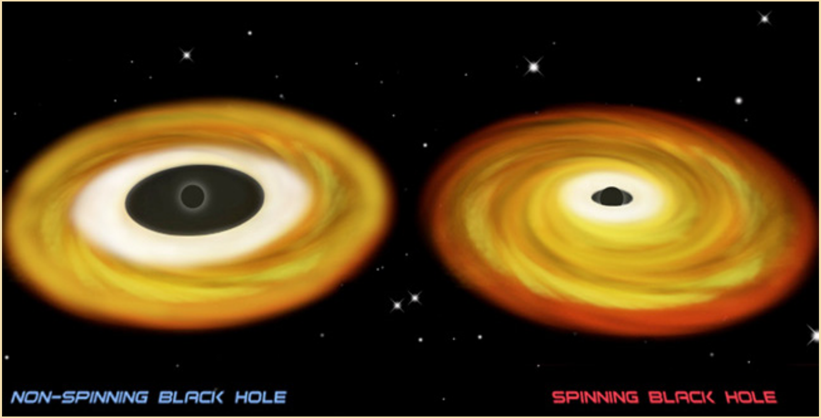
Credit: Wikipedia

Black Hole Census I

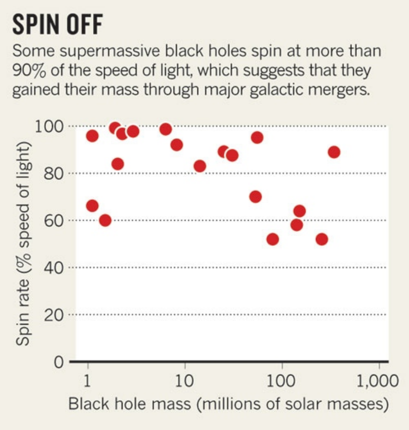


Credit: LIGO

How to measure spin?

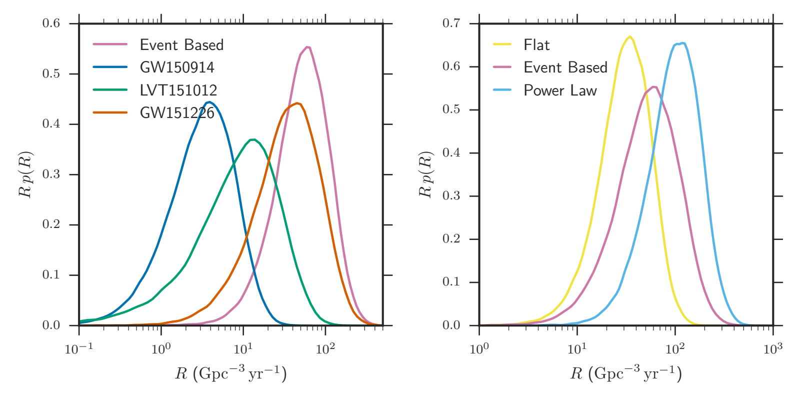


Black Hole Census II



Credit: Christopher Reynolds, Univ. Maryland

Merger Rates



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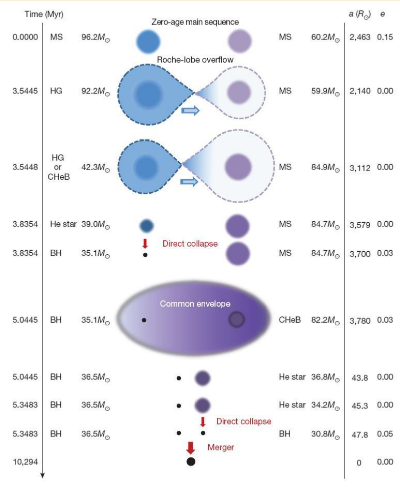
Binary Black Hole Formation Scenarios



Left: Belczynski et al. [3]. Right: Marta Volonteri (Univ. of Michigan)

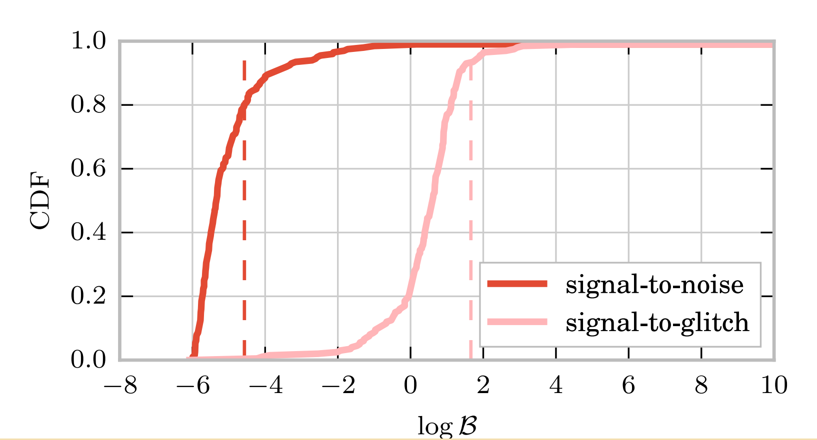
Testing GR with binary mergers

Is it useful to test Einstein's gravity using binary mergers?

	Solar system	Binary pulsars	Binary merger
$GM/(c^2R)$	$\sim 10^{-8}$	$\sim 10^{-6}$	~ 0.2
v/c	$\sim 10^{-5}$	$\sim 10^{-3}$	~ 0.4

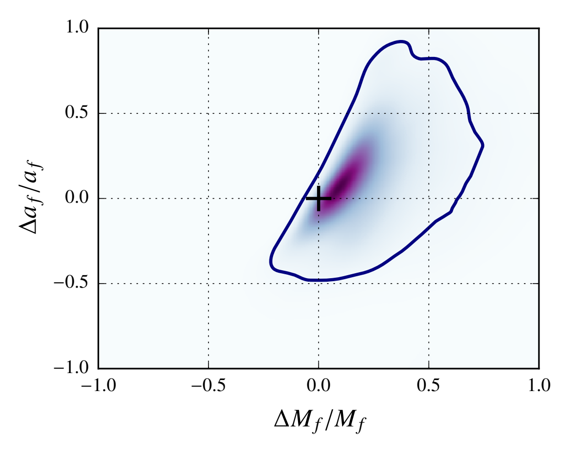
Empirical access to genuinely strong-field dynamics of spacetime

Scrutinise various aspects of GR



B. Abbott et al. "Tests of General Relativity with GW150914". In: *Phys. Rev. Lett.* 116.22 (2016)

Scrutinise various aspects of GR



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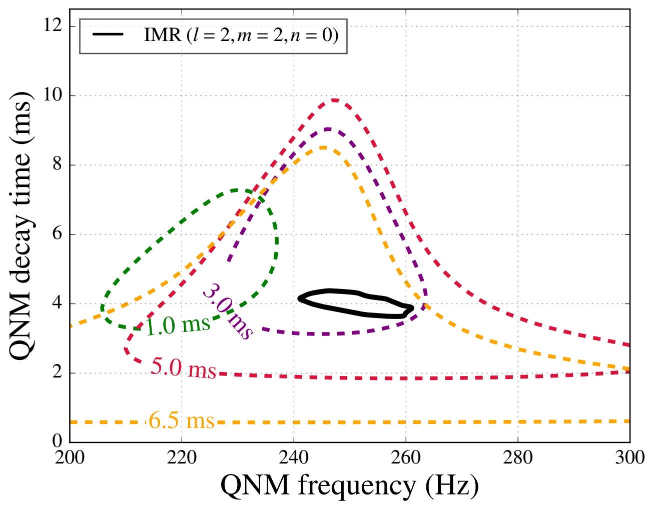

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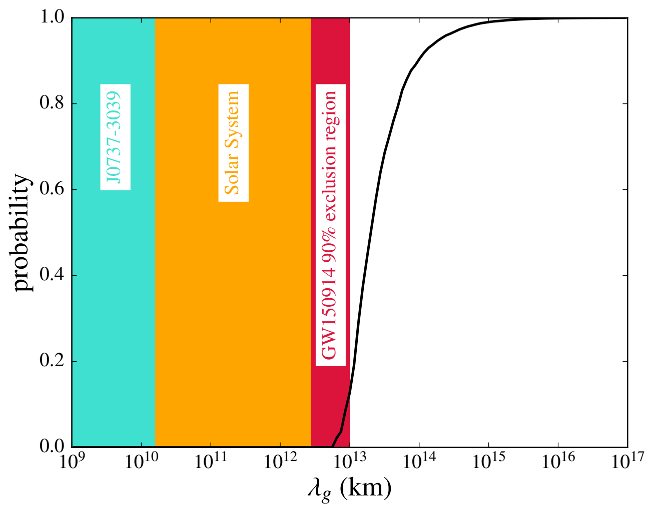

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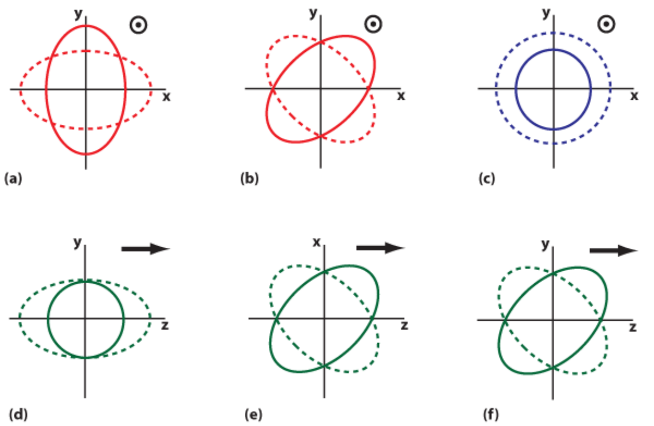
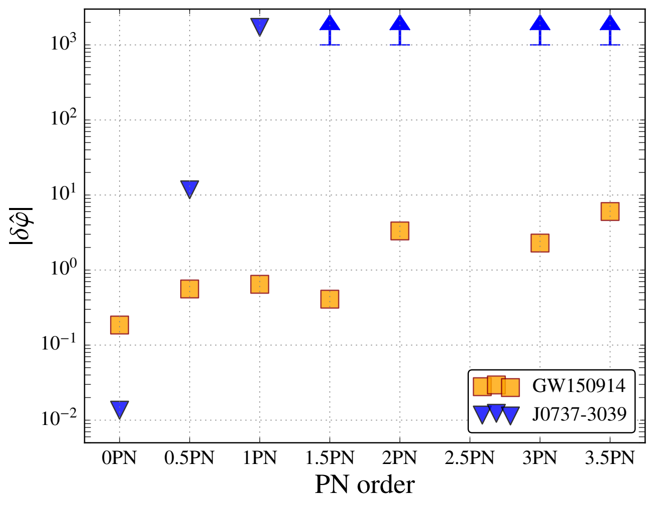


$$\log B^{\rm GR}_{\rm scalar} = -0.2 \pm 0.5$$

B. Abbott et al. "Tests of General Relativity with GW150914". In: *Phys. Rev. Lett.* 116.22 (2016)

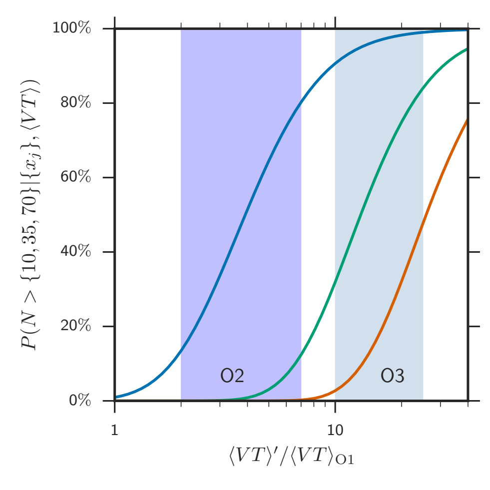
Scrutinise various aspects of GR



B. Abbott et al. "Tests of General Relativity with GW150914". In: *Phys. Rev. Lett.* 116.22 (2016)

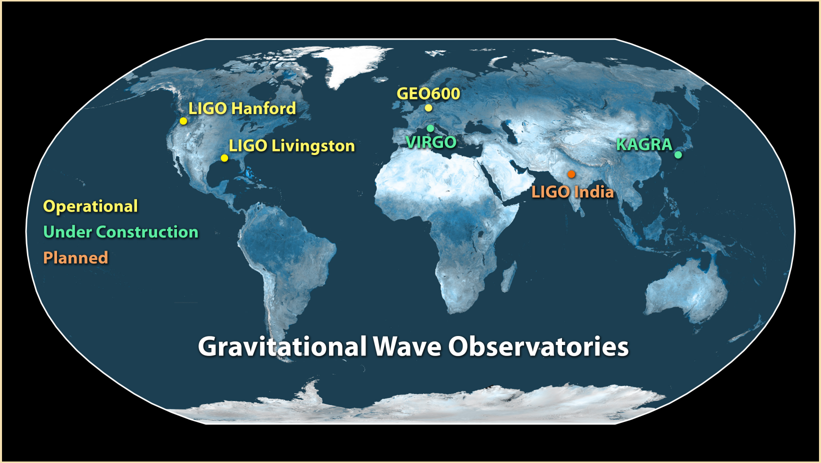
What can we expect in the future?

More Events



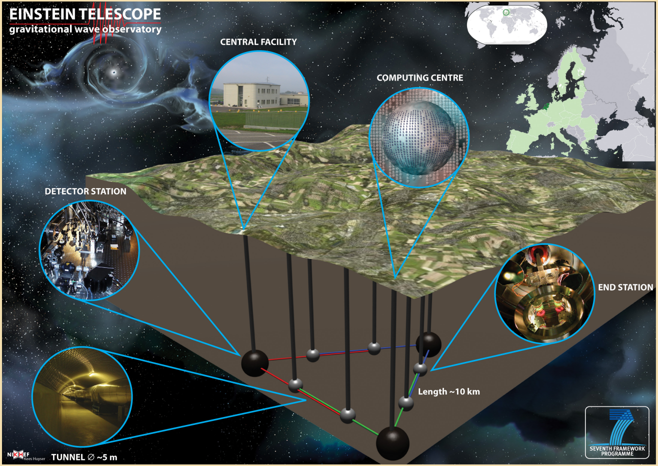
B. P. Abbott et al. "Binary Black Hole Mergers in the First Advanced LIGO Observing Run". In: *Physical Review X* 6.4, 041015 (Oct. 2016), p. 041015

More Detectors



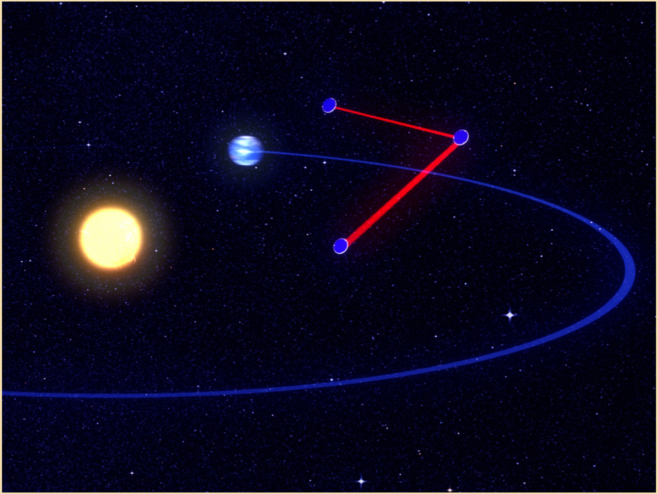
Credit: LIGO

Better Detectors



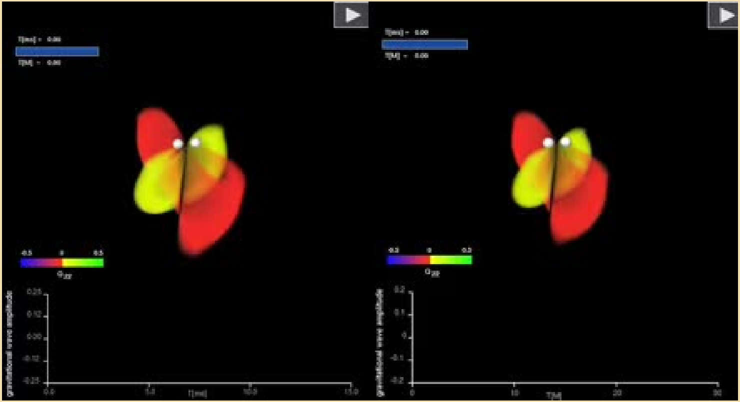
Einstein Telescope Science Team. *Einstein gravitational wave Telescope conceptual design study.* Tech. rep. ET-0106C-10. 2011

Going to Space

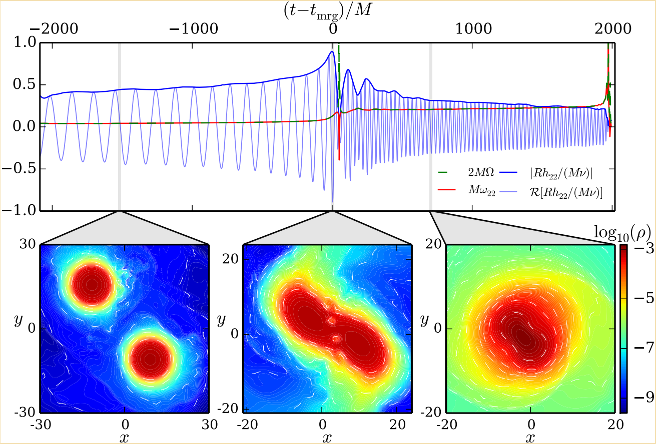


Credit: ESA

Nuclear Equation of State

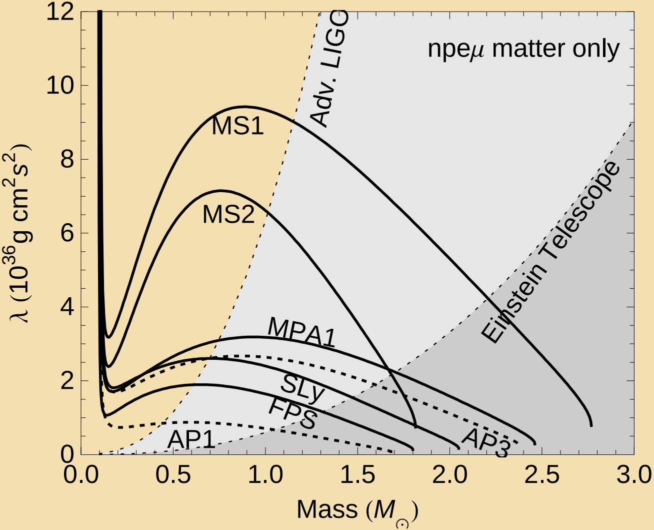


BNS Schematic



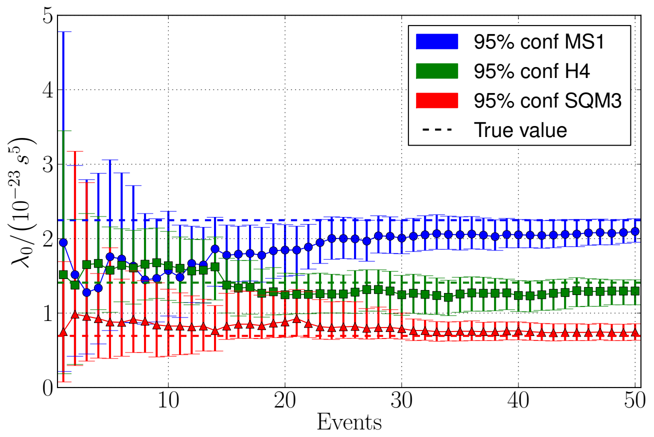
S. Bernuzzi et al. "Modeling the Complete Gravitational Wave Spectrum of Neutron Star Mergers". In: *Physical Review Letters* 115.9, 091101 (Aug. 2015), p. 091101. arXiv: 1504.01764 [gr-qc]

Tidal Deformability



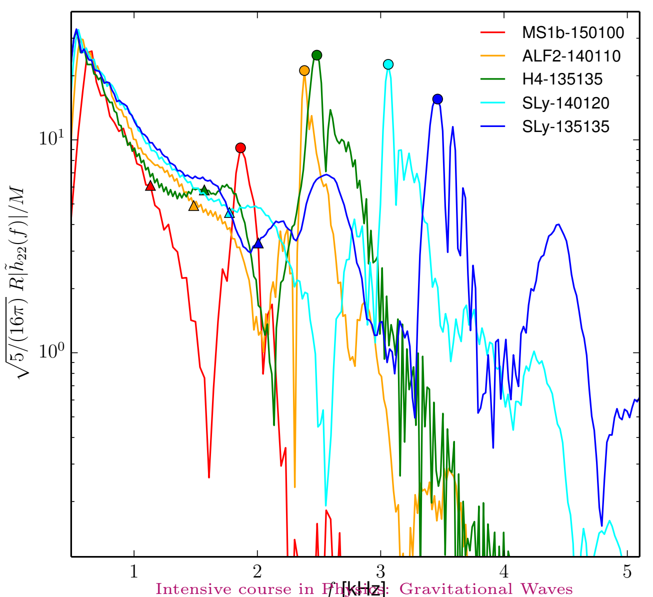
T. Hinderer et al. "Tidal deformability of neutron stars with realistic equations of state and their gravitational wave signatures in binary inspiral". In: *Phys. Rev. D*

Measuring Tidal Deformability

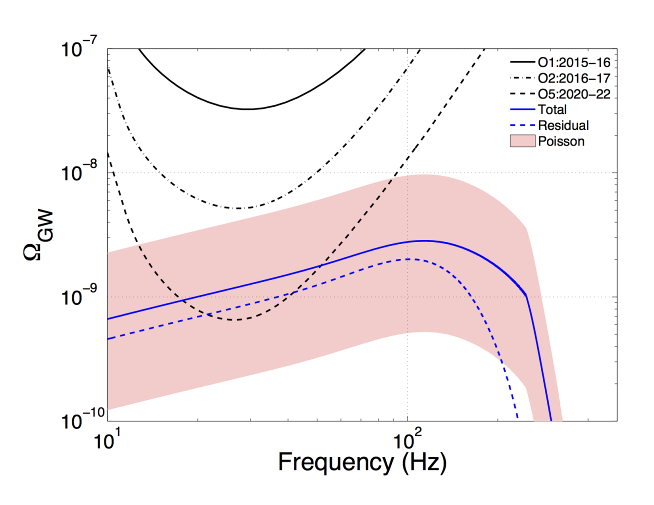


W. Del Pozzo et al. "Demonstrating the Feasibility of Probing the Neutron-Star Equation of State with Second-Generation Gravitational-Wave Detectors". In: *Physical Review Letters* 111.7, 071101 (Aug. 2013), p. 071101. arXiv: 1307.8338 [gr-qc]

Post-Merger Spectrum

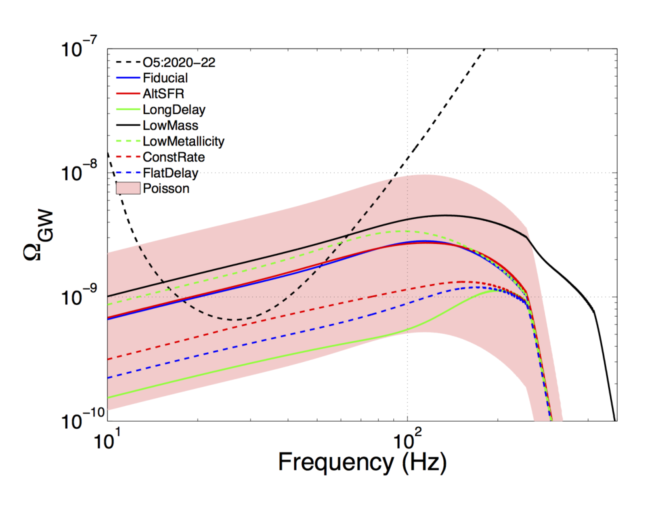


Stochastic Gravitational-Wave Background



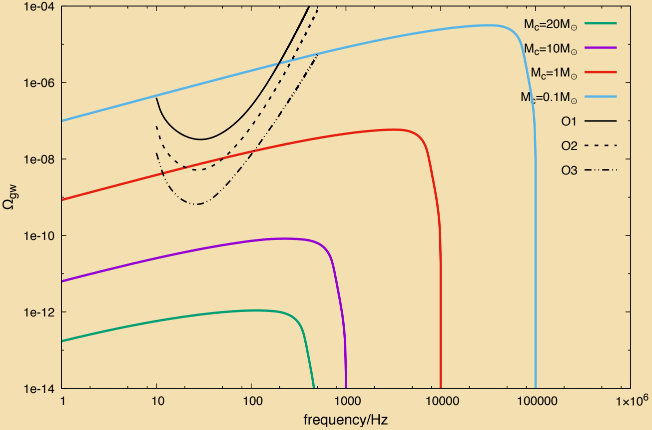
B. P. Abbott et al. "GW150914: Implications for the Stochastic Gravitational-Wave Background from Binary Black Holes". In: *Physical Review Letters* 116.13, 131102 (Apr. 2016), p. 131102. arXiv: 1602.03847 [gr-qc]

Probing Star Formation



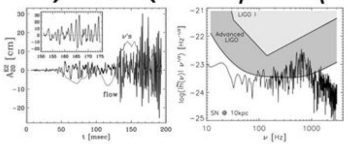
B. P. Abbott et al. "GW150914: Implications for the Stochastic Gravitational-Wave Background from Binary Black Holes". In: *Physical Review Letters* 116.13, 131102 (Apr. 2016), p. 131102. arXiv: 1602.03847 [gr-qc]

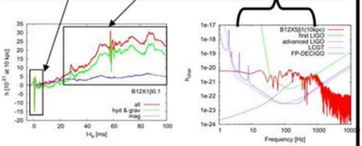
Stochastic Background from Primordial Black Holes

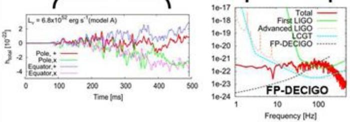


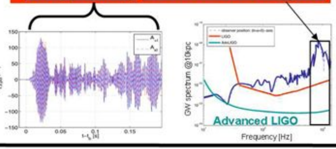
Supernova Models

Model Dim.	Candidate Explosion Mechanism: Neutrino-driven mechanism (slow/no rotation)	Candidate Explosion Mechanism: MHD mechanism (rapid rotation/large B fields)
2D	SASI & Convection "stochastic" and broad-band signal	Bounce & MHD Outflows "Bounce with "tail" broad-band signal
3D	SASI & Convection "stochastic" and broad-band signal	Non-axisymmetric Instabilities "Long-lasting" narrow-band signal

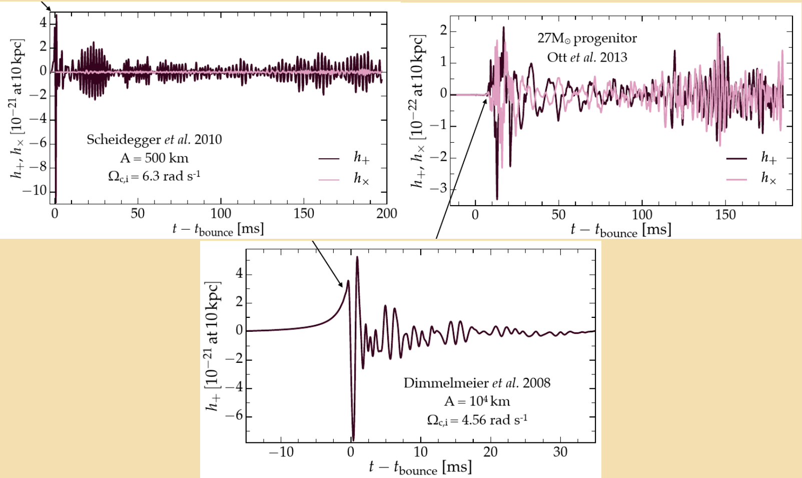




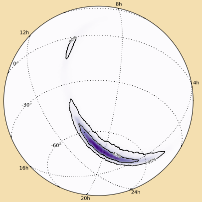


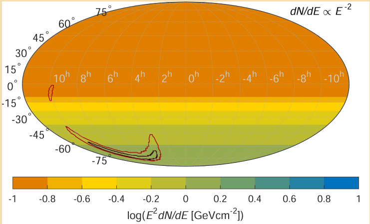


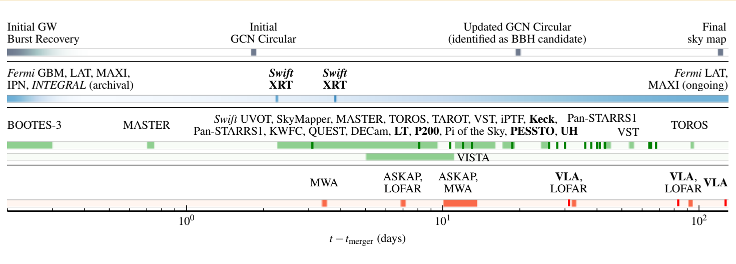
Supernova Waveforms



Multi-messenger astronomy

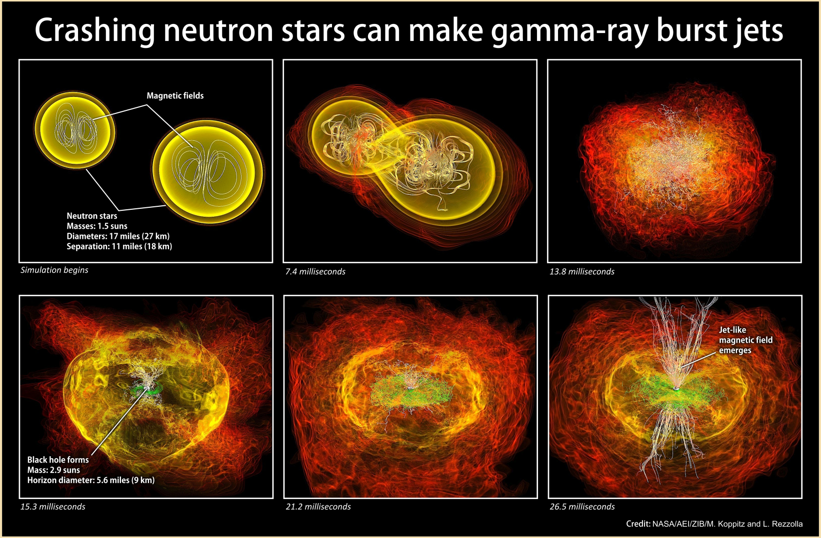




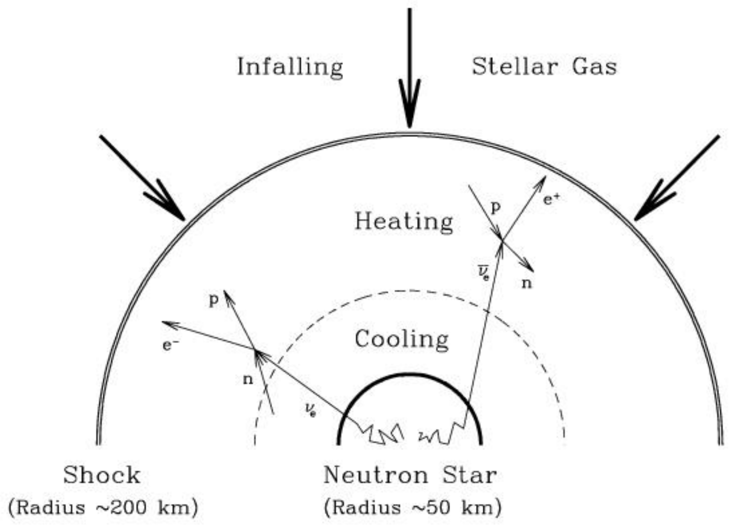


Abbott et al. [10] and ANTARES Collaboration et al. [11]

Gamma Ray Bursts



Supernova Process



Appendix

References I

[1] B. P. Abbott et al. "Binary Black Hole Mergers in the First Advanced LIGO Observing Run". In: *Physical Review X* 6.4, 041015 (Oct. 2016), p. 041015.

[2] B. P. Abbott et al. "Astrophysical Implications of the Binary Black Hole Merger GW150914". In: *ApJ* 818, L22 (Feb. 2016), p. L22. arXiv: 1602.03846 [astro-ph.HE].

[3] K. Belczynski et al. "The first gravitational-wave source from the isolated evolution of two stars in the 40-100 solar mass range". In: *Nature* 534 (June 2016), pp. 512–515. arXiv: 1602.04531 [astro-ph.HE].

[4] B. Abbott et al. "Tests of General Relativity with GW150914". In: *Phys. Rev. Lett.* 116.22 (2016).

References II

[5] Einstein Telescope Science Team. *Einstein gravitational wave Telescope conceptual design study.* Tech. rep. ET-0106C-10. 2011.

[6] S. Bernuzzi et al. “Modeling the Complete Gravitational Wave Spectrum of Neutron Star Mergers”. In: *Physical Review Letters* 115.9, 091101 (Aug. 2015), p. 091101. arXiv: 1504.01764 [gr-qc].

[7] T. Hinderer et al. “Tidal deformability of neutron stars with realistic equations of state and their gravitational wave signatures in binary inspiral”. In: *Phys. Rev. D* 81.12, 123016 (June 2010), p. 123016. arXiv: 0911.3535 [astro-ph.HE].

References III

[8] W. Del Pozzo et al. "Demonstrating the Feasibility of Probing the Neutron-Star Equation of State with Second-Generation Gravitational-Wave Detectors". In: *Physical Review Letters* 111.7, 071101 (Aug. 2013), p. 071101. arXiv: 1307.8338 [gr-qc].

[9] B. P. Abbott et al. "GW150914: Implications for the Stochastic Gravitational-Wave Background from Binary Black Holes". In: *Physical Review Letters* 116.13, 131102 (Apr. 2016), p. 131102. arXiv: 1602.03847 [gr-qc].

[10] B. P. Abbott et al. "Localization and broadband follow-up of the gravitational-wave transient GW150914". In: *ArXiv e-prints* (Feb. 2016). arXiv: 1602.08492 [astro-ph.HE].

References IV

[11] ANTARES Collaboration et al. "High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with ANTARES and IceCube". In: *ArXiv e-prints* (Feb. 2016). arXiv: 1602.05411 [astro-ph.HE].