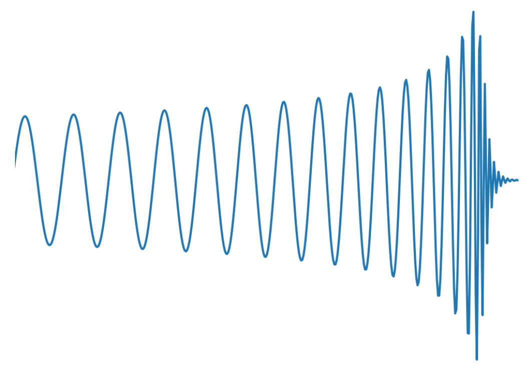
Testing Parity Symmetry of Gravity With Gravitational Wave



Max Planck Institute for Gravitationalphysics (Albert Einstein Institute)

Wang Yifan (王一帆)

2021.02.17

@IBS, Center for Theoretical Physics of the Universe

OUTLINE

1. A brief Overview of Gravitational Wave Astronomy
2. Testing General Relativity with Gravitational Waves
3. Testing the Parity Symmetry of Gravity by Gravitational Waves

Yi-Fan Wang *et al* 2021 *ApJ* **908** 58
https://arxiv.org/abs/2002.05668
Gravitational-Wave Implications for the Parity Symmetry of Gravity at GeV Scale

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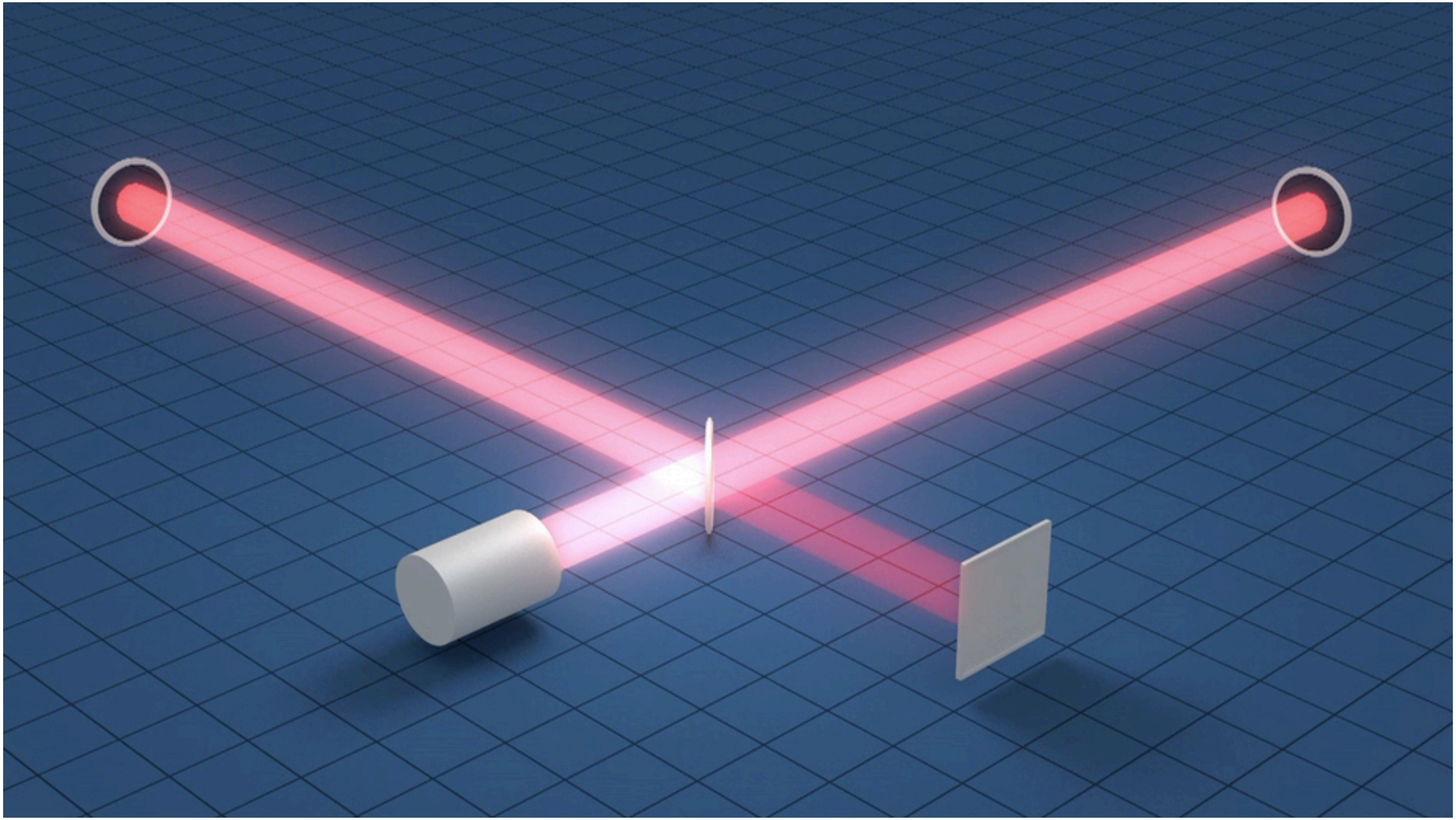
Gravitational Wave Astronomy



Laser Interferometer

ligo.caltech.edu

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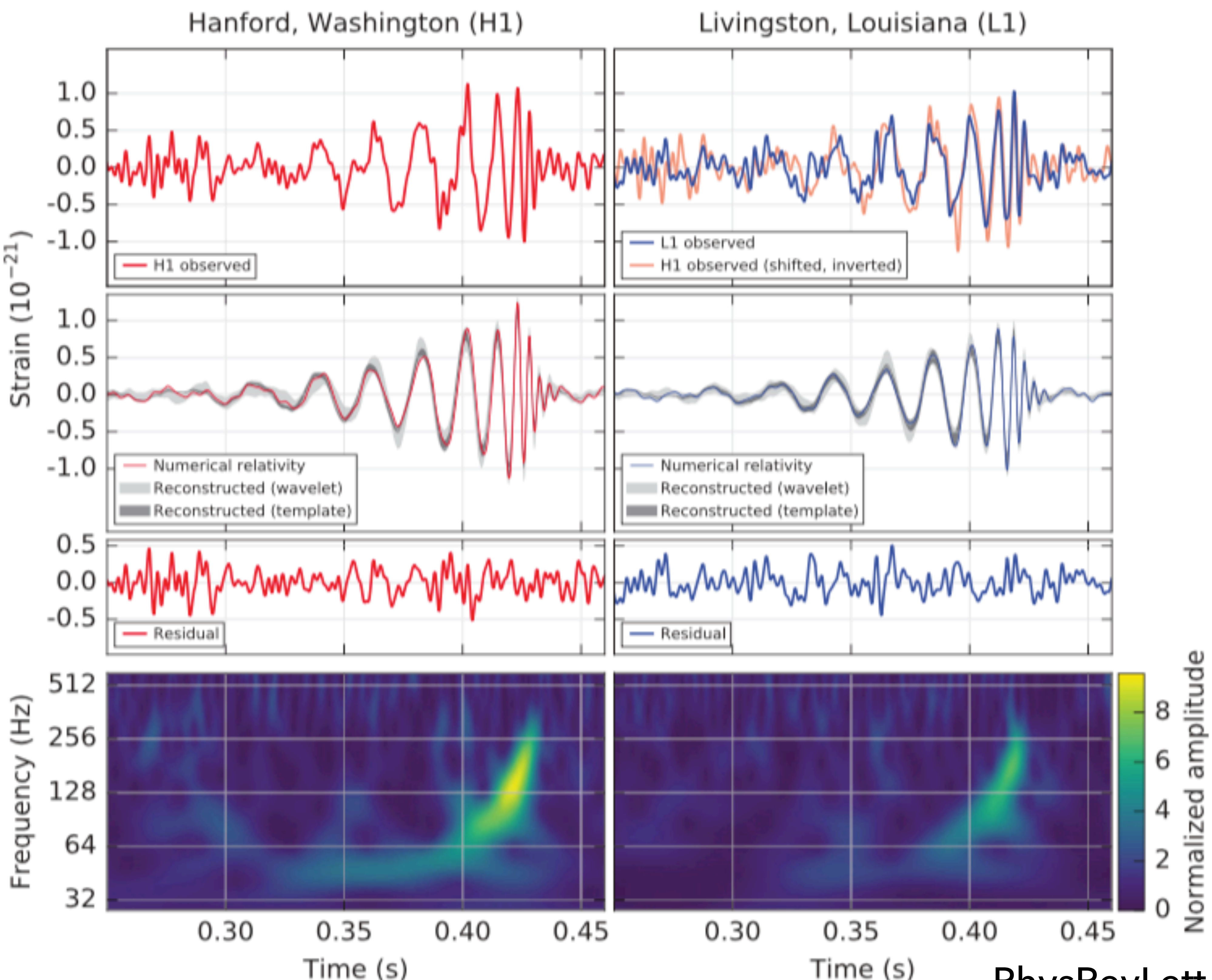
Gravitational Wave Astronomy



The first event GW150914

PhysRevLett. 116.061102

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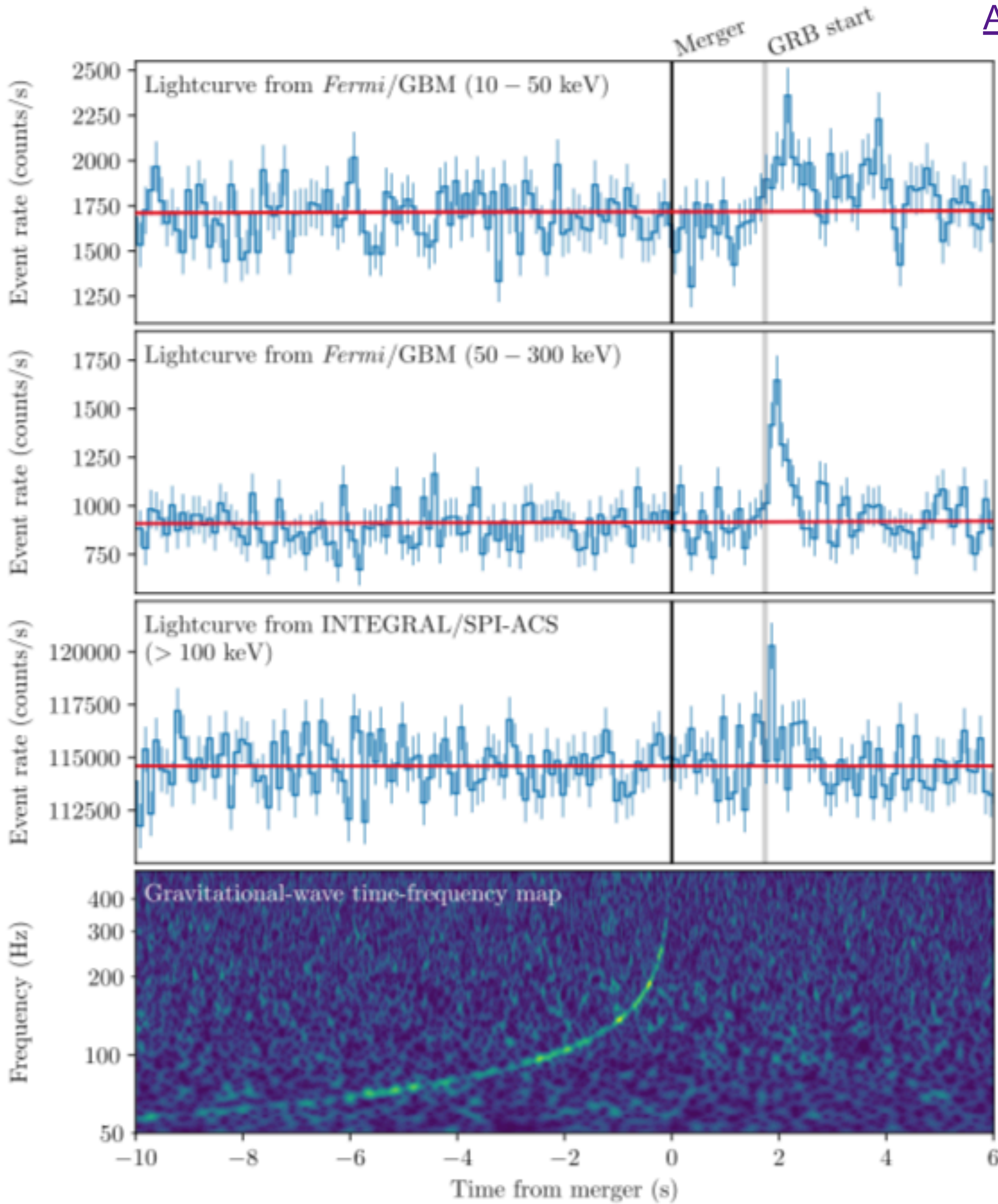
Gravitational Wave Astronomy

Astrophys. J. Lett. **848**, L13 (2017)



Binary Neutron Star GW170817

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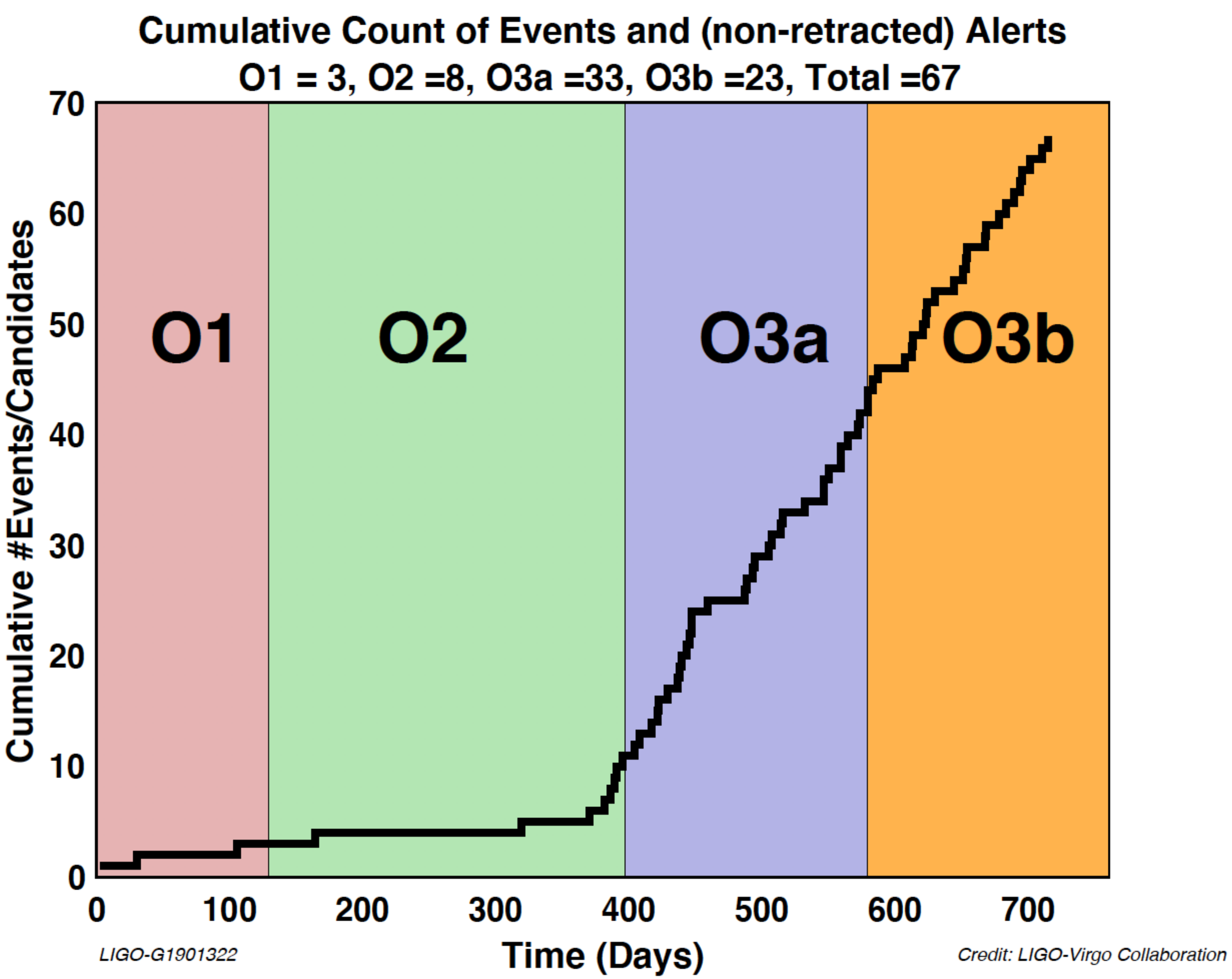
A very brief review of gravitational wave astronomy



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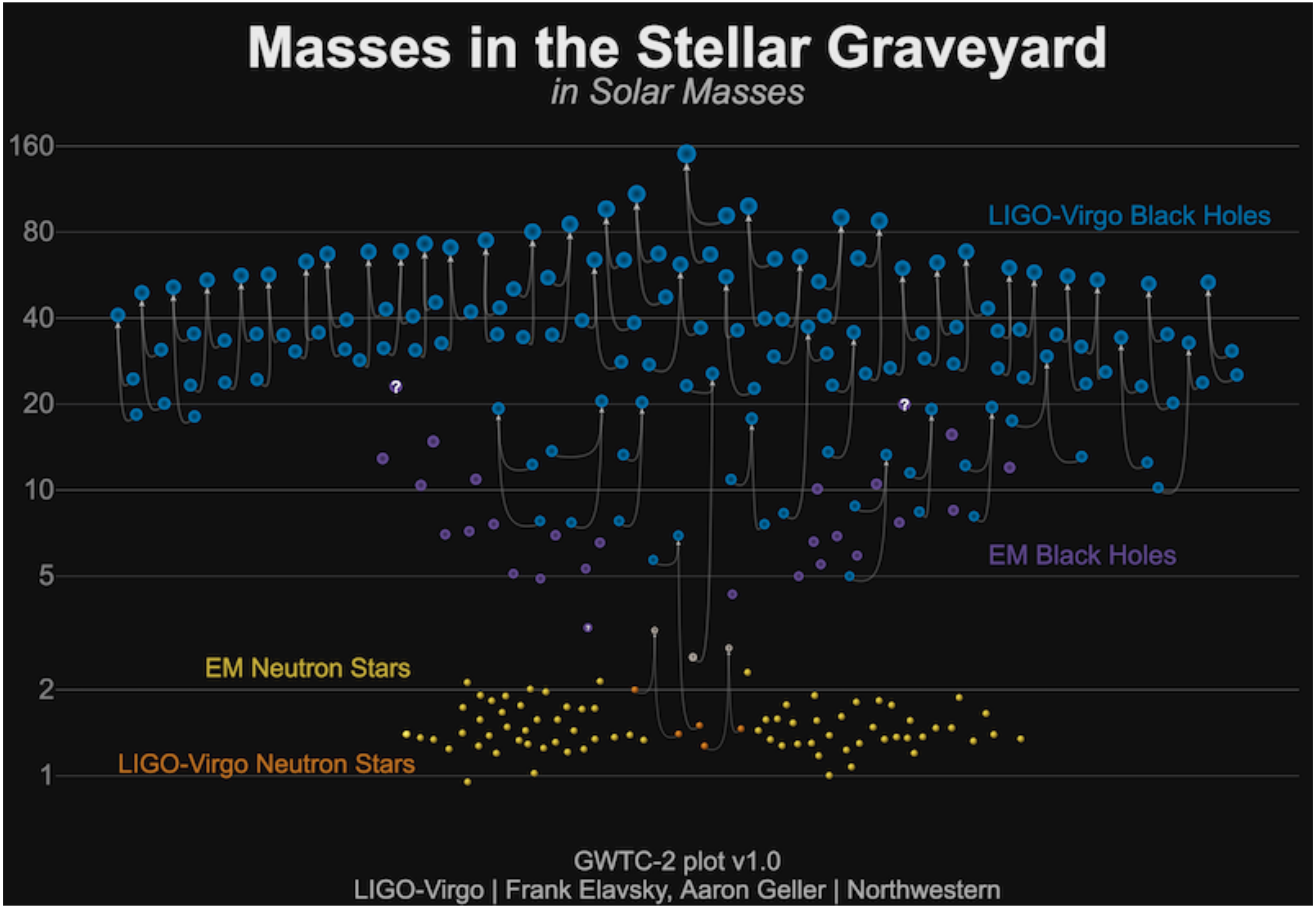
A very brief review of gravitational wave astronomy

- LIGO-Virgo-KAGRA Scientific Collaboration, The 1, 2, 3a Observation run —> 50 Compact Binary Coalescence events (Binary Black Hole, Binary Neutron Star, Black Hole-Neutron Star)



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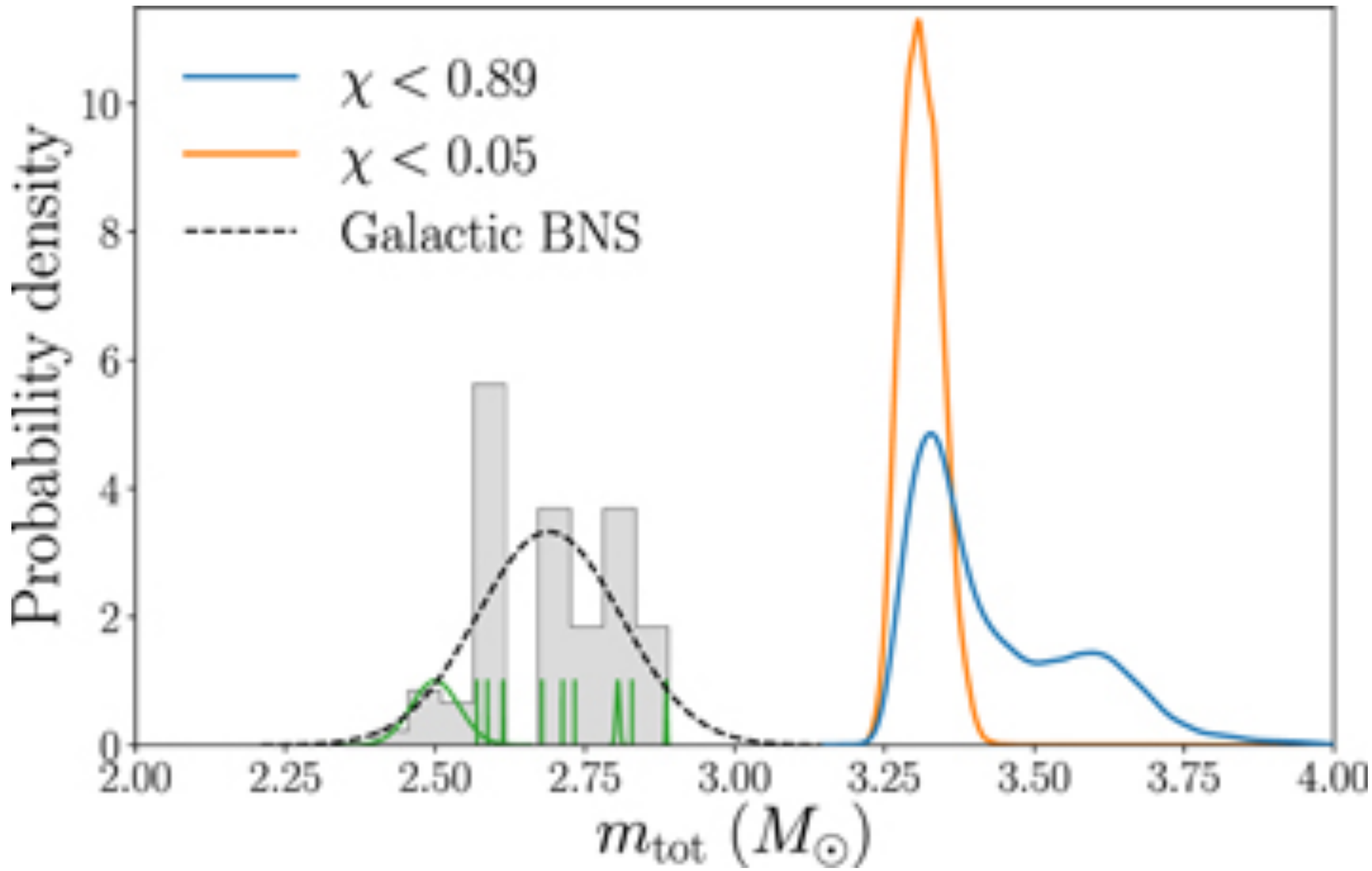
A very brief review of gravitational wave astronomy

- Milestone Events:
  - GW190425: The most massive binary neutron star event

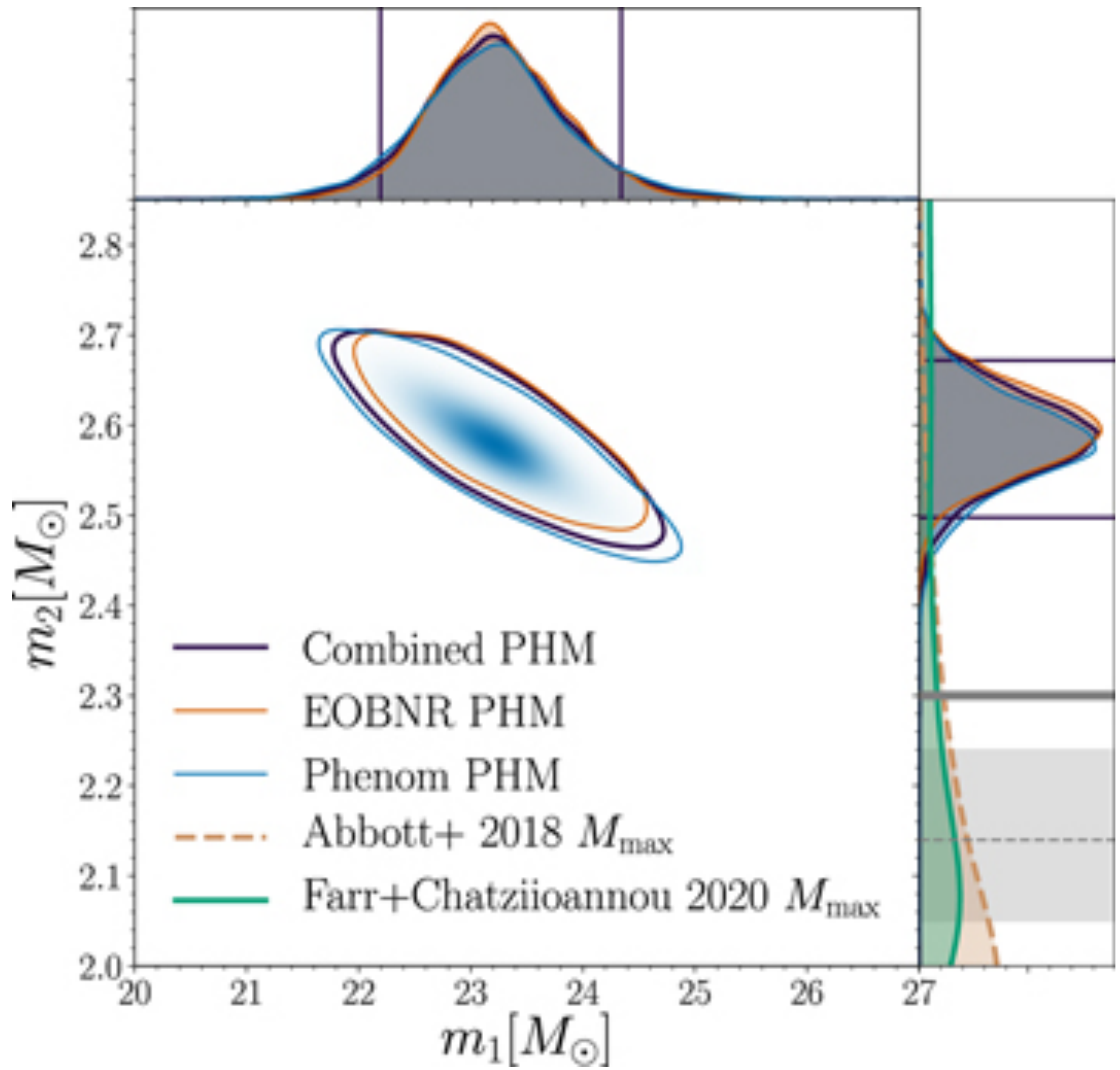


Astrophys. J. Lett. **892**, L3 (2020)

A very brief review of gravitational wave astronomy

- Milestone Events:

- GW190814: Non-symmetric mass+the lightest black hole/the heaviest neutron star



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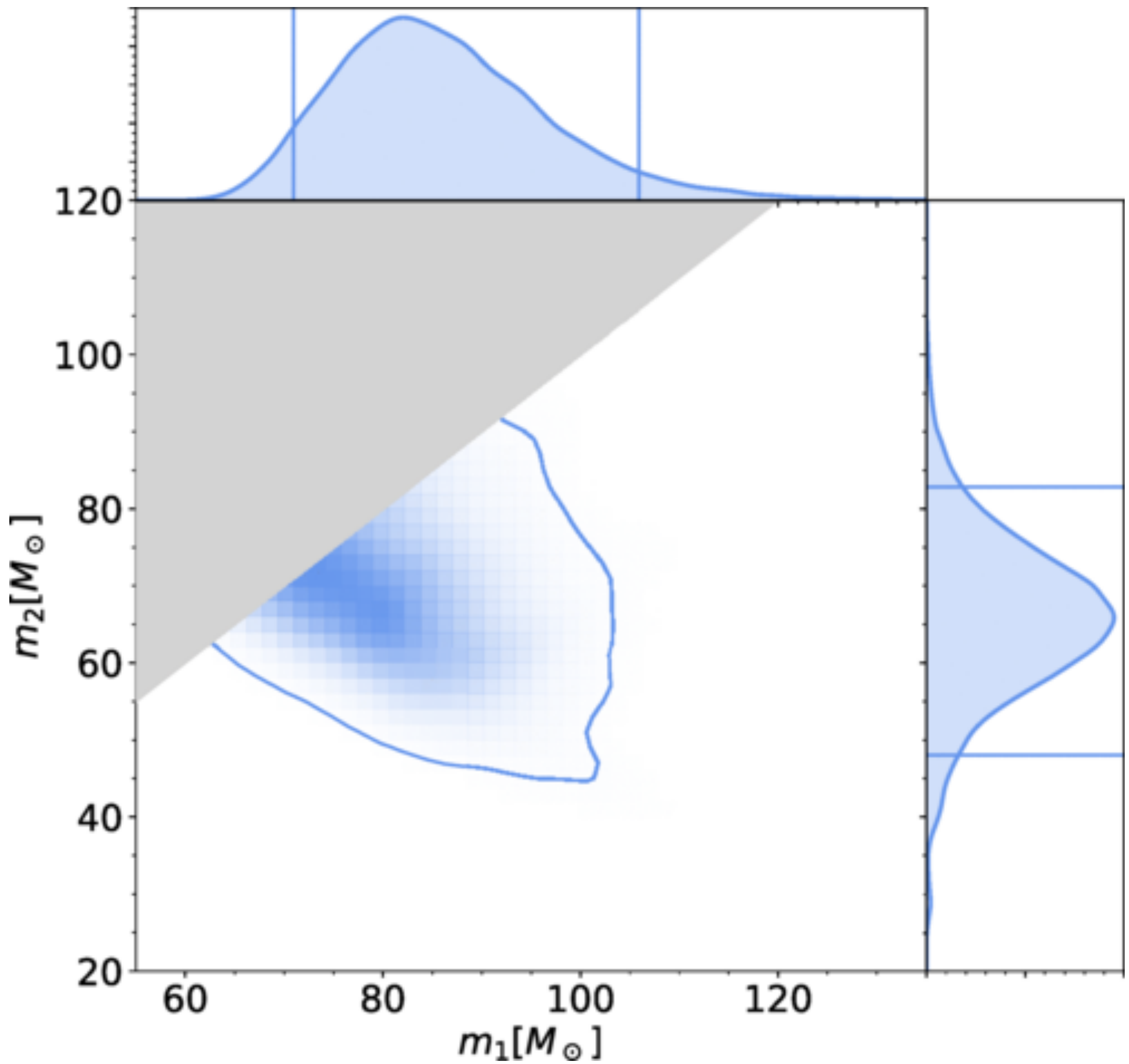
A very brief review of gravitational wave astronomy

- Milestone Events:
  - GW190521: The heaviest binary black hole —> 85 + 66 solar mass



A very brief review of gravitational wave astronomy

- Scientific Implications:

  - Testing the validity of General Relativity
  - Cosmology： measure H_0， exploring the nature of dark matter/dark energy
  - Nuclear physics： equation of state of neutron star
  - High energy astrophysics： the origin of short Gamma Ray Burst
  - Rate & Population for black holes and neutron stars —> stellar evolution
  - many more!

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A very brief review of gravitational wave astronomy

- More types of gravitational waves are yet to be discovered:
  - Burst (Supernova explosion)
  - Continuous Wave (Spinning neutron star)
  - Stochastic Gravitational-Wave Background (primordial GW)

- More gravitational waves from hypothetical sources are yet to be discovered:
  - Primordial Black Hole →
  - Cosmic String
  - More unknowns!

- Yi-Fan Wang, Alexander H. Nitz 2101.12269
- Alexander H. Nitz, Yi-Fan Wang 2102.00868
- *Alexander H. Nitz, Yi-Fan Wang Phys.Rev.Lett.* 126 (2021)
- Yi-Fan Wang et al, *Phys.Rev.D* 101 (2020) 6, 063019
- Sai Wang Yi-Fan Wang et al, *Phys.Rev.Lett.* 120 (2018) 19, 191102

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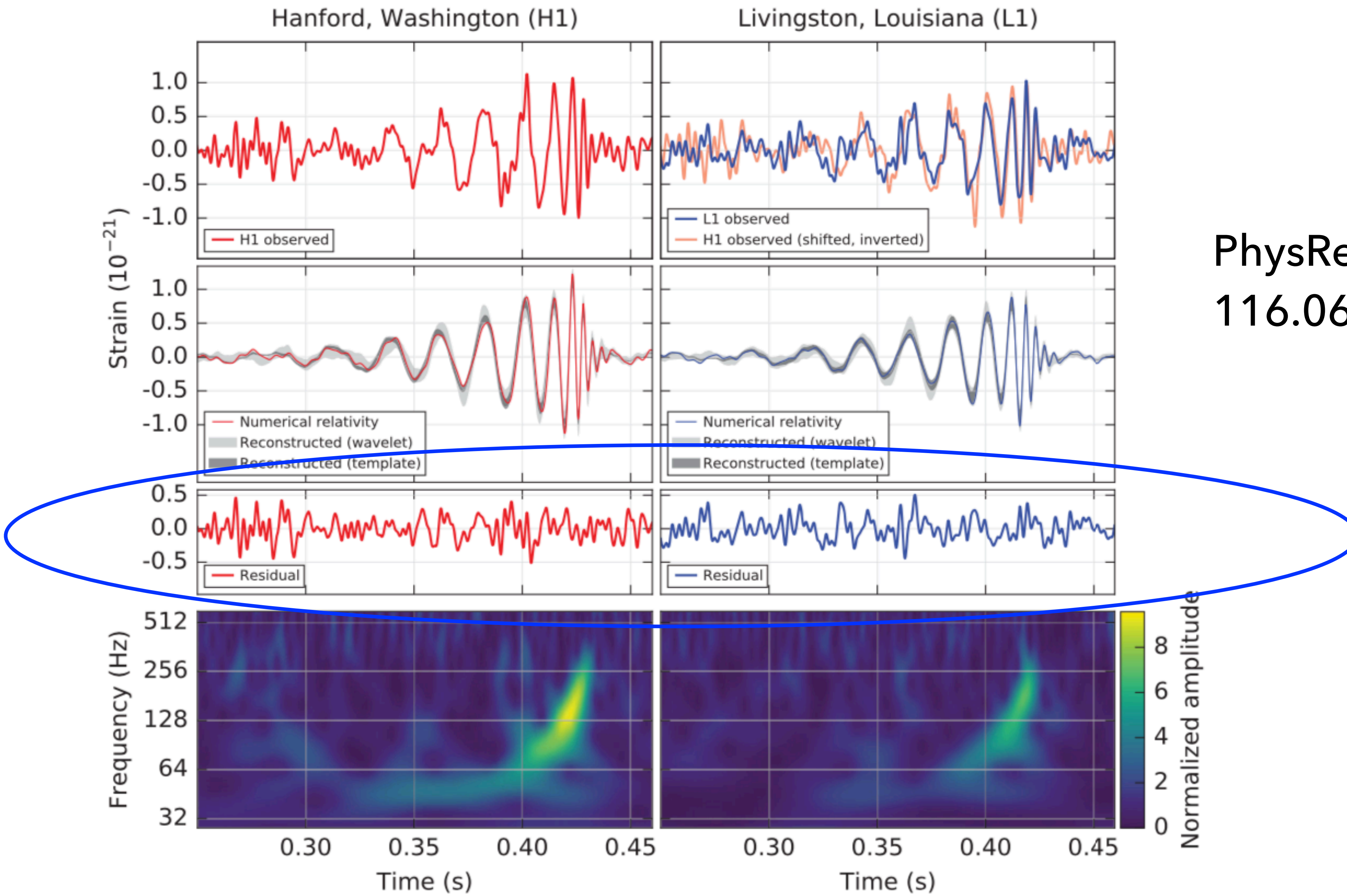
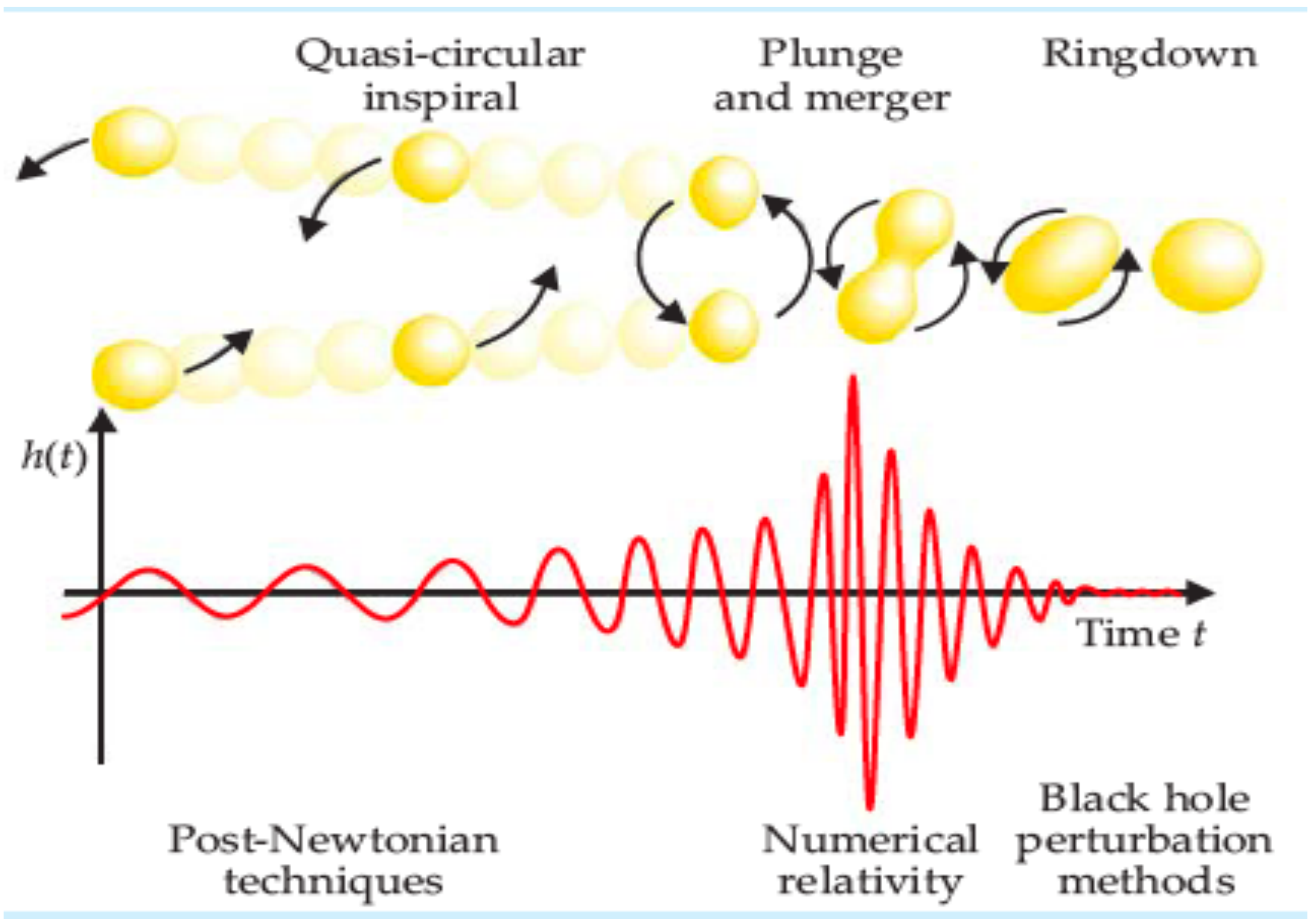
Review: Testing GR with GW

- 1. Residual Analysis:
  - Subtracting the best-fit template from the data and testing whether the residuals are consistent with pure noise
  - a non-parametrization method



PhysRevLett. 116.061102

- 2. Parametrized tests:

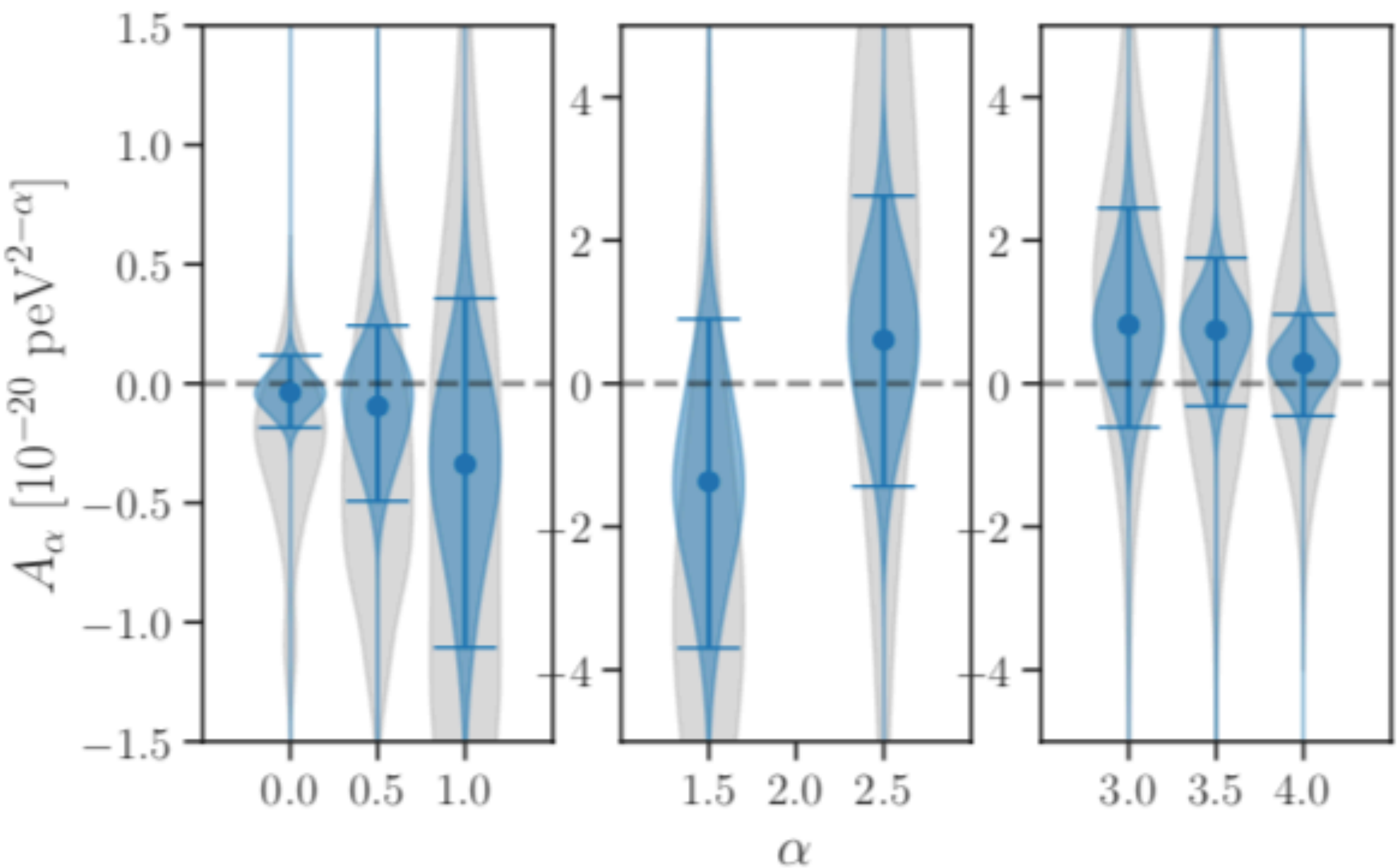


$$h = h_{\rm GR} + \delta h_{nonGR}$$

REVIEW: TESTING GR WITH GW

- 3. Possible propagation modification effects on GR:
  - Modifying dispersion relation: $E^2 = p^2c^2 + Ap^\alpha c^\alpha$
  - Massive Graviton: $\alpha = 0 \rightarrow A = m_g^2 c^4$

2010.14529



- $m_g \leq 1.76 \times 10^{-23} eV/c^2$ —> Compton wavelength: $7 \times 10^{13} km$

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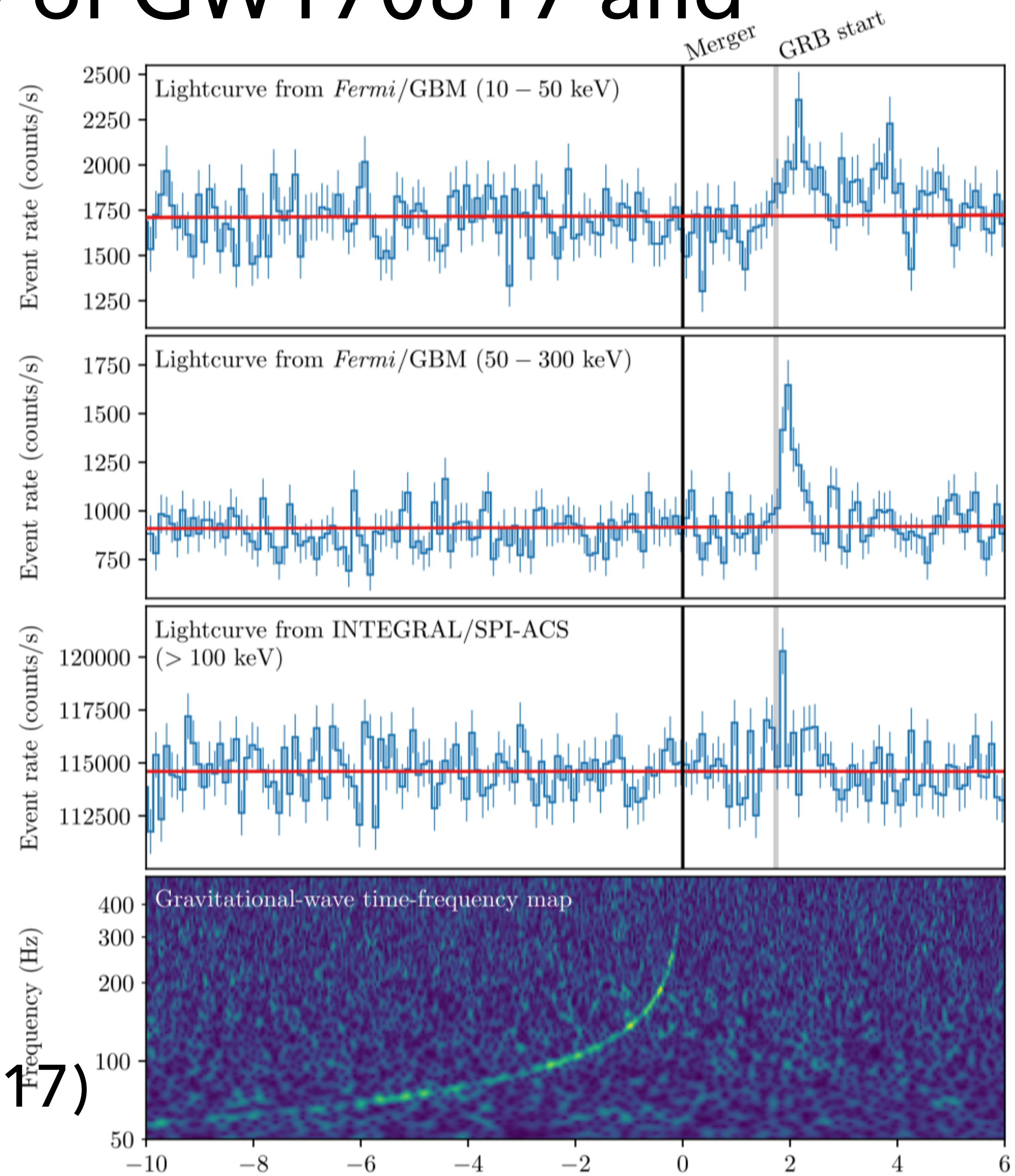
- 4: Speed –> with the time delay of GW170817 and GRB170817A

$$-3 \times 10^{-15} < \frac{v_g}{v_c} - 1 < 7 \times 10^{-16}$$



Astrophys. J. Lett. 848, L13 (2017)

- Constraining models of dark energy and dark matter from modified gravity

SUMMARY: TESTING GR WITH GW

- Model independent tests

  e.g. previous slides

- Model specific tests:
  - e.g. Einstein-dilaton-Gauss-Bonnet
  - dynamical Chern-Simons gravity.

- Effective Field Theory
  - Adding higher derivative terms into the action

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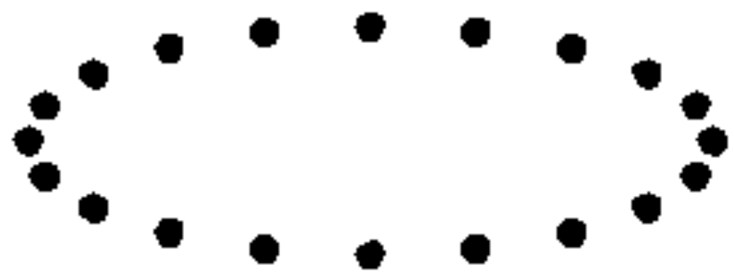
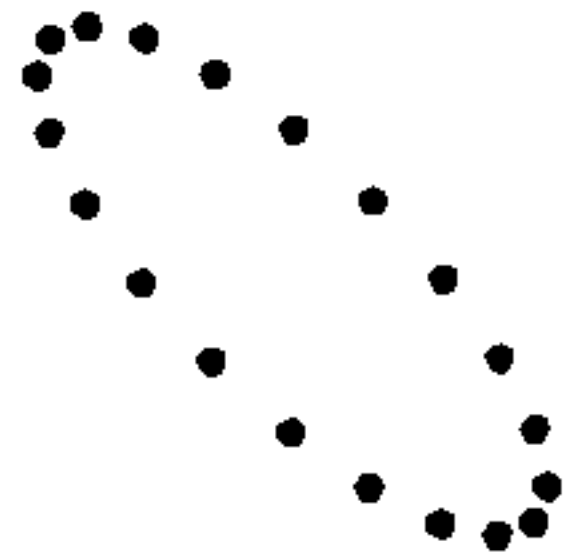
Testing Parity Symmetry of Gravity

- Polarization of GW:



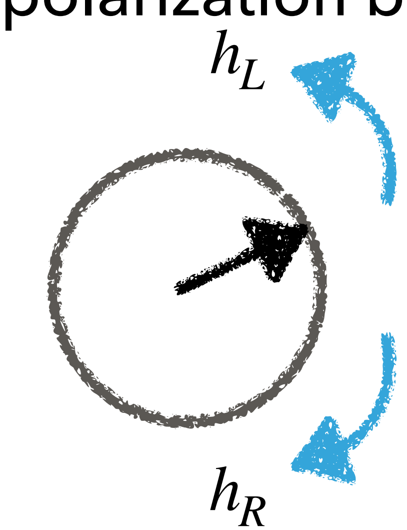
h_+



$h_\times$

- Changing the linear polarization basis to circular polarization basis:

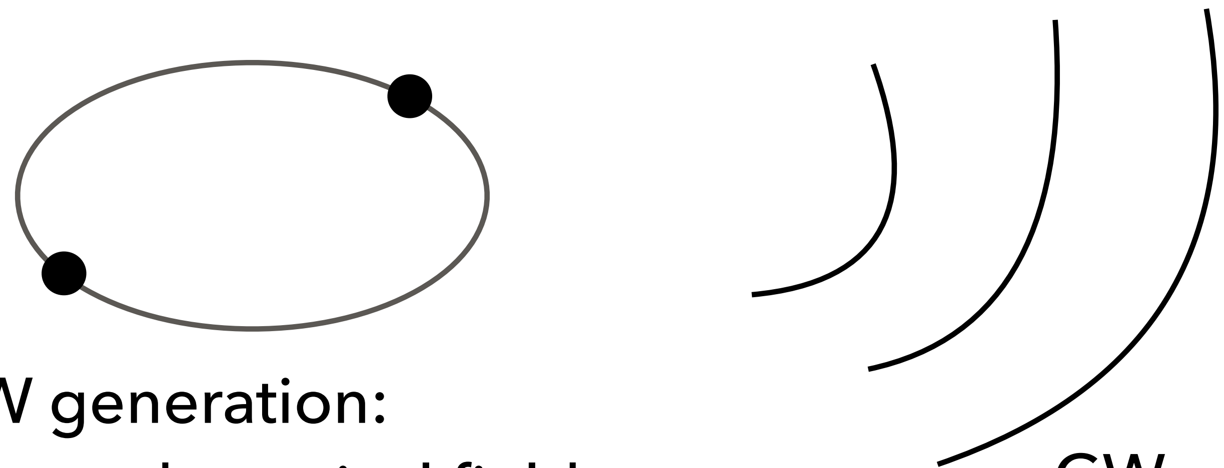
$$h_L = \frac{h_+ + ih_\times}{\sqrt{2}}, h_R = \frac{h_+ - ih_\times}{\sqrt{2}}$$



Parity of GW: invariance under transformation between L and R!

Testing Parity Symmetry of Gravity

- Focusing on the propagation modification due to parity broken (symmetry between the left- and right-handed GW states)



1. Action from <u>effective field theory</u> –> 2. Equation of Motion –> 3. GW waveform –> 4. Comparing with data –> 5. (un)luckily no violation, put constraints

Testing Parity Symmetry of Gravity

- 1. Linearized action for GW propagation in a FRW Universe in General Relativity (GR)

$$S = \frac{1}{16\pi G}\int dt d^3x a^3 \left[\frac{1}{4}\dot{h}_{ij}^2 - \frac{1}{4a^2}(\partial_k h_{ij})^2\right],$$

a: scale factor, can be set to 1 in this work

- 2. Equation of motion:

η: conformal time

$$h_{ij} = \sum_{A=R,L}\int \frac{d^3k}{(2\pi)^3} h_A(k,\eta) e^{i\vec{k}\cdot\vec{x}} p_{ij}^A(\hat{k}),\quad p_{ij}^L = \frac{e_{ij}^+ + ie_{ij}^\times}{\sqrt{2}}, p_{ij}^R = \frac{e_{ij}^+ - ie_{ij}^\times}{\sqrt{2}}$$

$$h_A'' + 2\mathscr{H} h_A' + k^2 h_A = 0\ ,$$

$\mathscr{H}$: Hubble parameter k: wave number

- A=Left/ Right circular polarized state, following the same equation of motion

$$h_L = \frac{h_+ + ih_\times}{\sqrt{2}}, h_R = \frac{h_+ - ih_\times}{\sqrt{2}}$$

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Testing Parity Symmetry of Gravity

- 1. Linearized action for GW propagation in a FRW Universe in Effective Field Theory (to the leading order, three derivatives)

$$S = \frac{1}{16\pi G}\int dt d^3x \left[\frac{1}{4}\dot{h}_{ij}^2 - \frac{1}{4}(\partial_k h_{ij})^2 + \frac{1}{4}\left(\frac{c_1}{M_{\rm PV}}\epsilon^{ijk}\dot{h}_{il}\partial_j\dot{h}_{kl} + \frac{c_2}{M_{\rm PV}}\epsilon^{ijk}\partial^2 h_{il}\partial_j h_{kl}\right)\right],$$

c_1, c_2: free parameters to be determined by a specific theory, can be set to 1

M_{PV}: energy threshold in EFT

ϵ^{ijk}: anti-symmetric symbol

- For a detailed derivation for the total derivatives, c.f. PRL 113, 231301 (2014)
- An example for the above action: Horava Lifschitz gravity

- T. Takahashi and J. Soda, Phys. Rev. Lett. 102, 231301 (2009).
- A. Wang, Q. Wu, W. Zhao, and T. Zhu, Phys. Rev. D 87, 103512 (2013).

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Testing Parity Symmetry of Gravity

- 2. Equation of motion (EoM):

$$h_A'' + (2 + \nu_A)\mathscr{H} h_A' + (1 + \mu_A)k^2 h_A = 0 \ ,$$

velocity/phase birefringence

Amplitude birefringence

- For different polarized states, ν_A, μ_A takes different sign —> birefringence

$$\mu_A = \frac{\rho_A(c_1 - c_2)k}{M_{pv}} \qquad \nu_A = -\frac{\rho_A c_1 k}{M_{pv}\mathscr{H}}$$

$\rho_A = \pm 1$ for L and R

c_1 = c_2 –> amplitude birefringence

- 3. GW waveform / solution of the EoM:

$$h_A^{PV} = \frac{1}{\sqrt{\tilde{c}}} \exp\left(-\int (1 + \frac{\nu_A}{2})\mathscr{H} d\tau\right) \exp\left(ik\int \tilde{c} dk\right) \cdot h_A^{GR}$$

- speed of GW: $\tilde{c} = \sqrt{1 + \mu_A}$ $\sim k^2$
- dispersion relation $E^2 = p^2 \pm Ap^3$

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TESTING PARITY SYMMETRY OF GRAVITY

- 3. Solving the equation of motion, the GW waveform is:

$$h_A^{\mathrm{PV}}(f) = h_A^{\mathrm{GR}}(f)\left(1 + \rho_A \delta h\right) e^{i\rho_A \delta\Psi}$$

velocity/phase birefringence

Amplitude birefringence

$\rho_A = \pm 1$ for left and right, respectively

$$h_L = \frac{h_+ + ih_\times}{\sqrt{2}}, h_R = \frac{h_+ - ih_\times}{\sqrt{2}}$$

$$h = \frac{\delta L}{L} = F_+ h_+ + F_\times h_\times$$

h: Strain

F+,Fx: antenna pattern function

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Testing Parity Symmetry of Gravity

- 3. GW waveform:

δh is negligibly small

$$h_+^{\rm PV}(f) = h_+^{\rm GR}(f) - h_\times^{\rm GR}(f)(i\delta h - \delta\Psi),$$

$$h_\times^{\rm PV}(f) = h_\times^{\rm GR}(f) + h_+^{\rm GR}(f)(i\delta h - \delta\Psi)\,.$$

$$\delta\Psi(f) = A_\mu(\pi f)^2/H_0, \qquad A_\mu = M_{\rm PV}^{-1}\int_0^z \frac{(1+z')dz'}{\sqrt{\Omega_M(1+z')^3+\Omega_\Lambda}},$$

f: frequency of GW

- 4. With the waveform and data, we can perform GW parameter inference and estimate A_μ

1. Action from effective field theory –> 2. Equation of Motion –> 3. GW waveform –> 4. Comparing with data –> 5. (un)luckily no violation, put constraints

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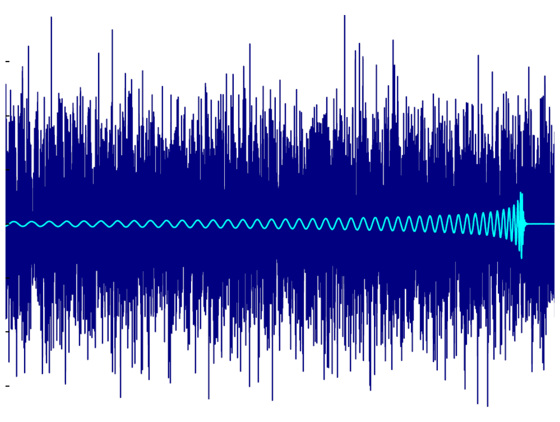
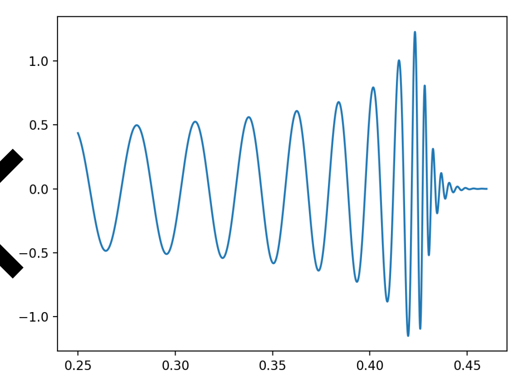
- 5. How to perform parameter estimation? By match filtering

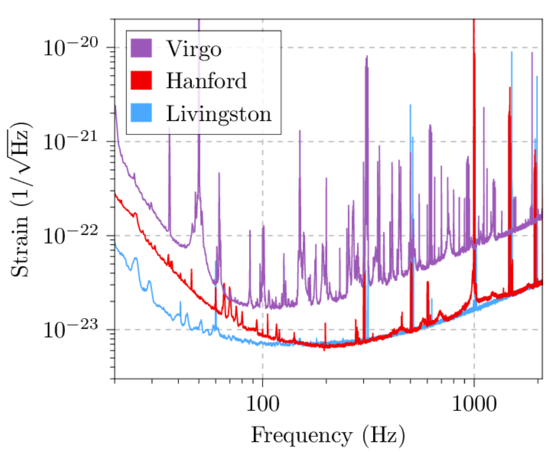
Signal   Template

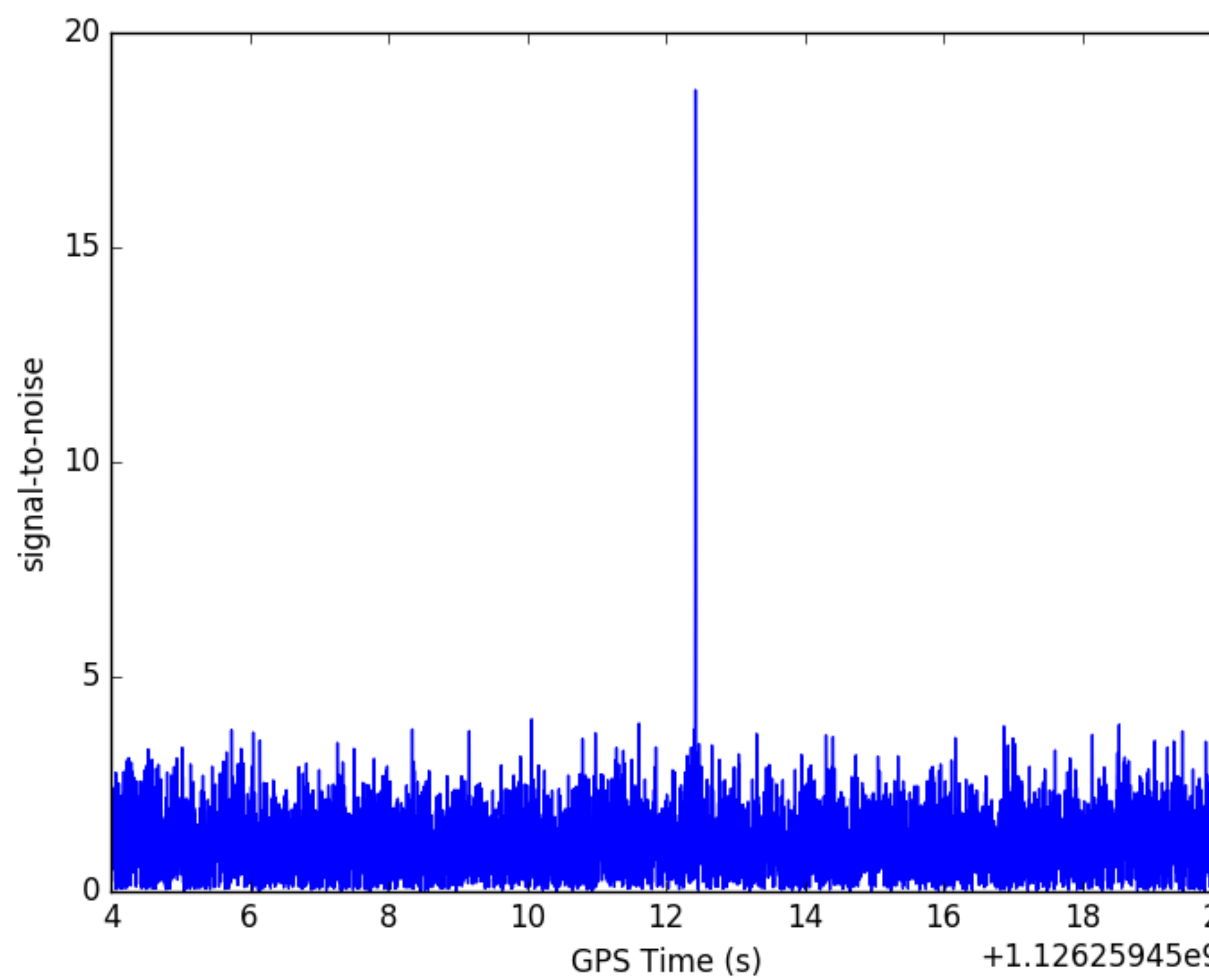
$$\frac{S}{N}(t) = 4\Re \int_0^\infty \frac{\tilde{s}(f)\tilde{h}^*(f)}{S_n(f)} \exp^{2\pi i f t}\, df$$

Noise power spectrum









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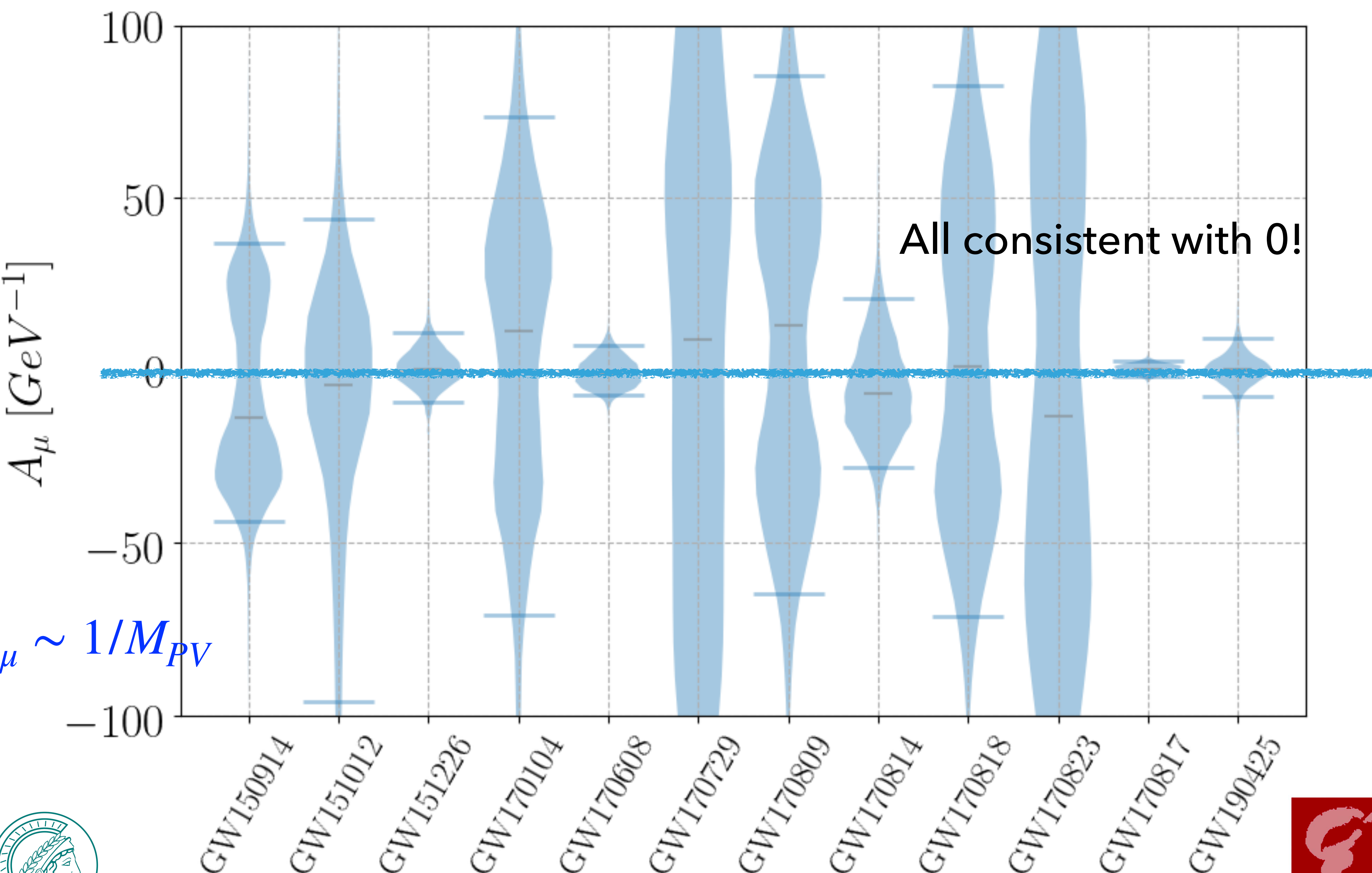
Results:



$A_\mu \sim 1/M_{PV}$

10 Binary Black Hole + 2 Binary Neutron Star

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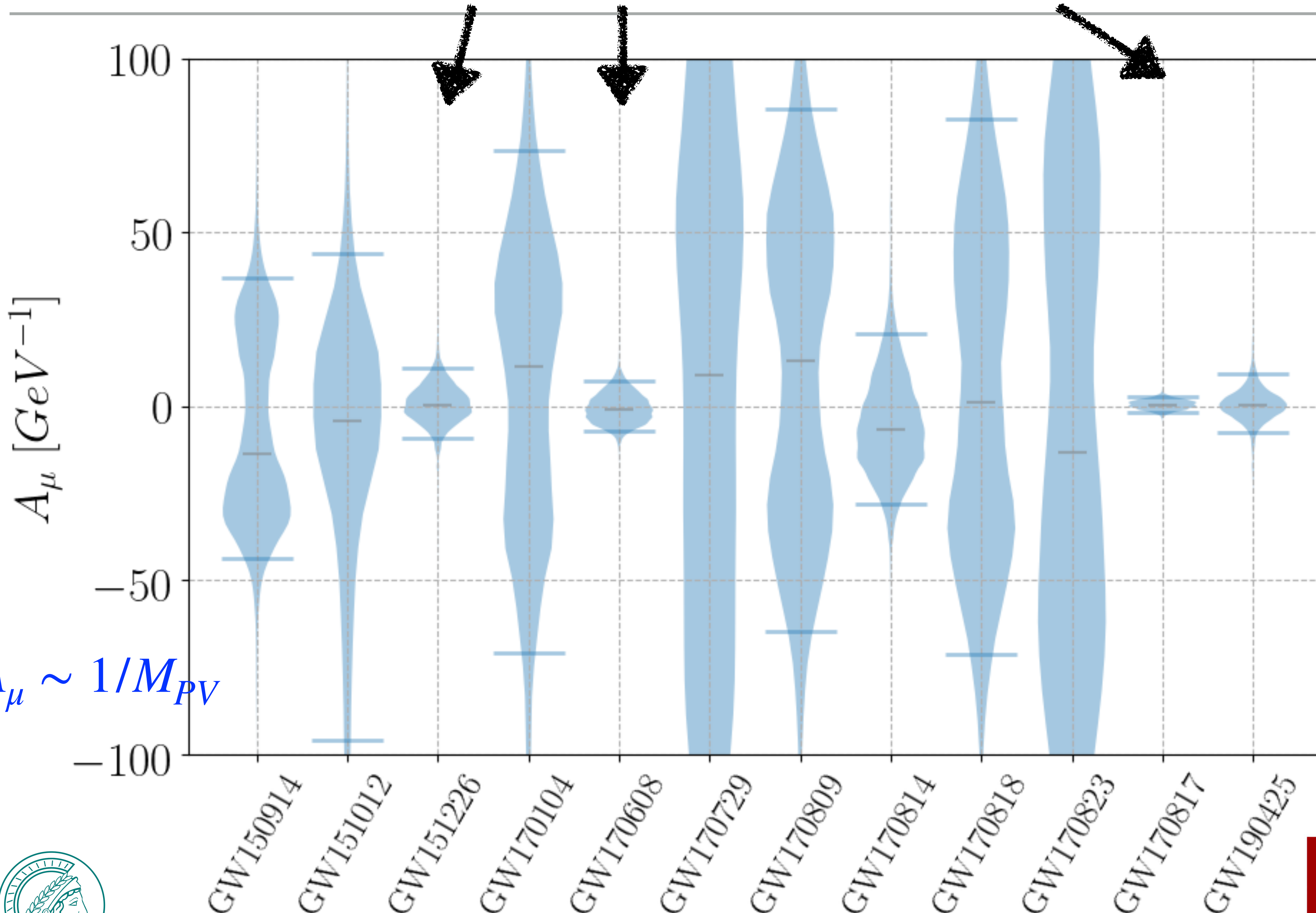
Results:

Low mass events yield better constraints



$A_\mu \sim 1/M_{PV}$

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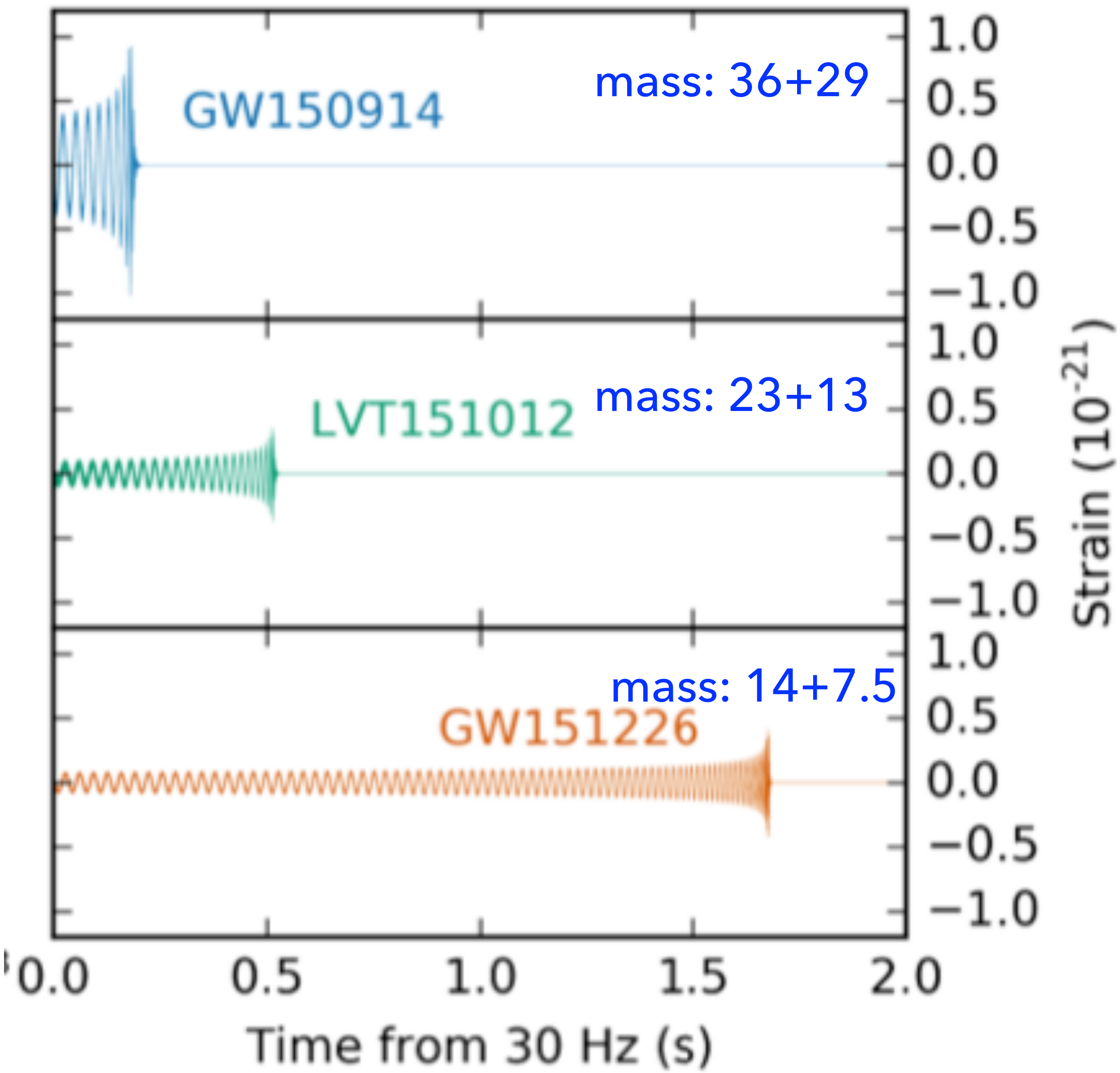
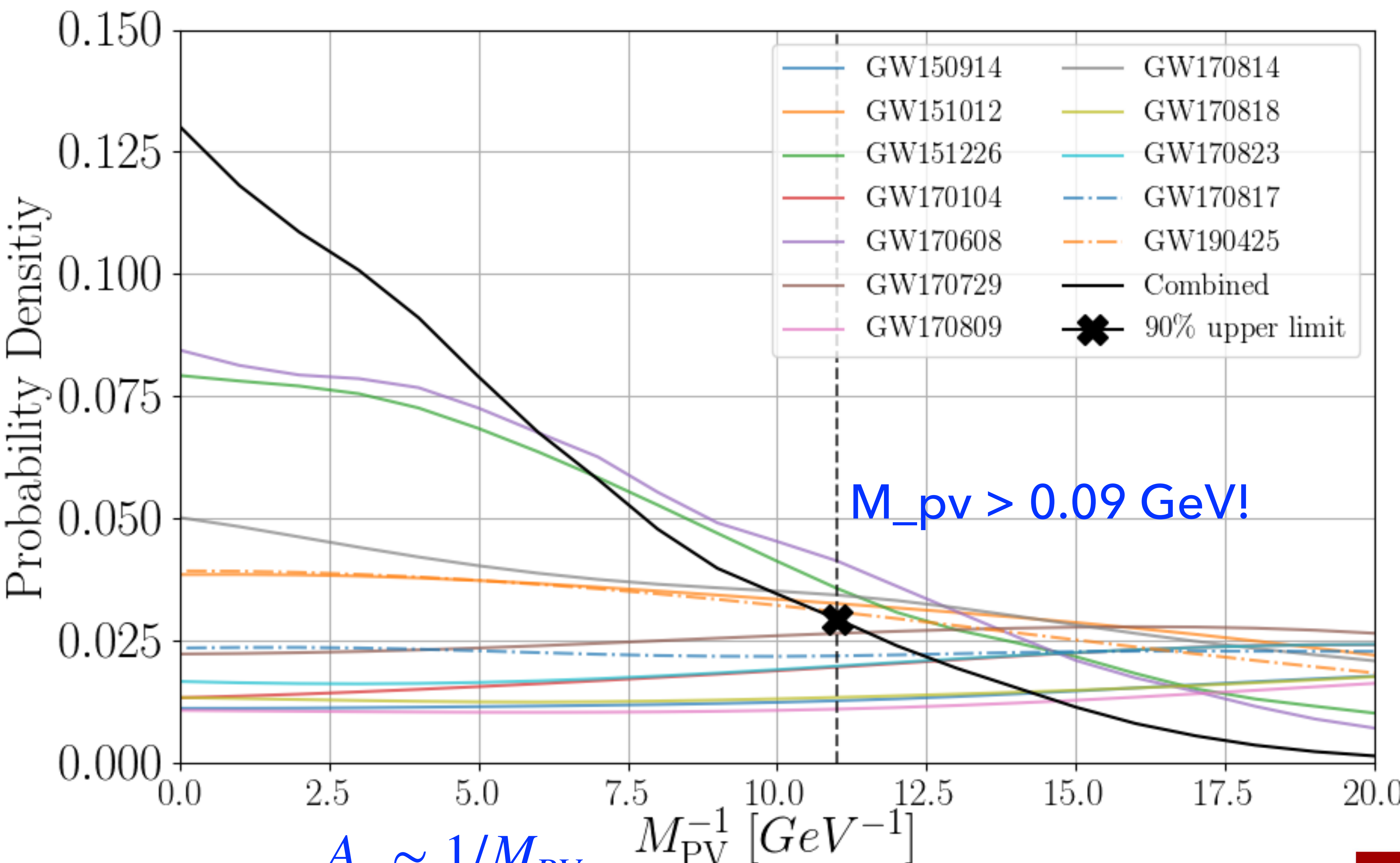
RESULTS:

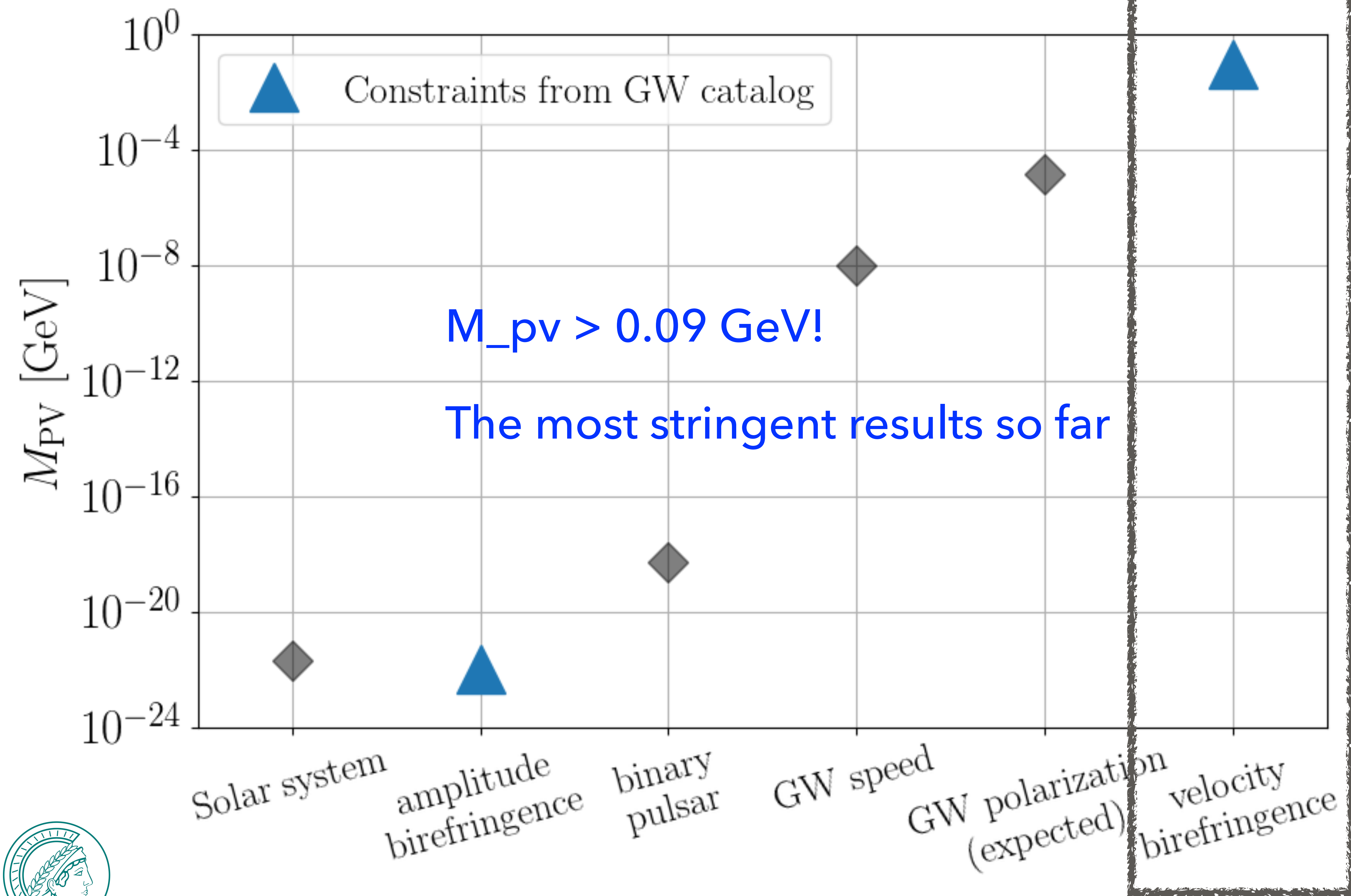

GW150914
mass: 36+29
LVT151012
mass: 23+13
mass: 14+7.5
GW151226
1.0
0.5
0.0
−0.5
−1.0
Strain (10^{-21})
0.0
0.5
1.0
1.5
2.0
Time from 30 Hz (s)

RESULTS:



$A_\mu \sim 1/M_{PV}$

Comparison with Existing Results:



M_pv > 0.09 GeV!

The most stringent results so far

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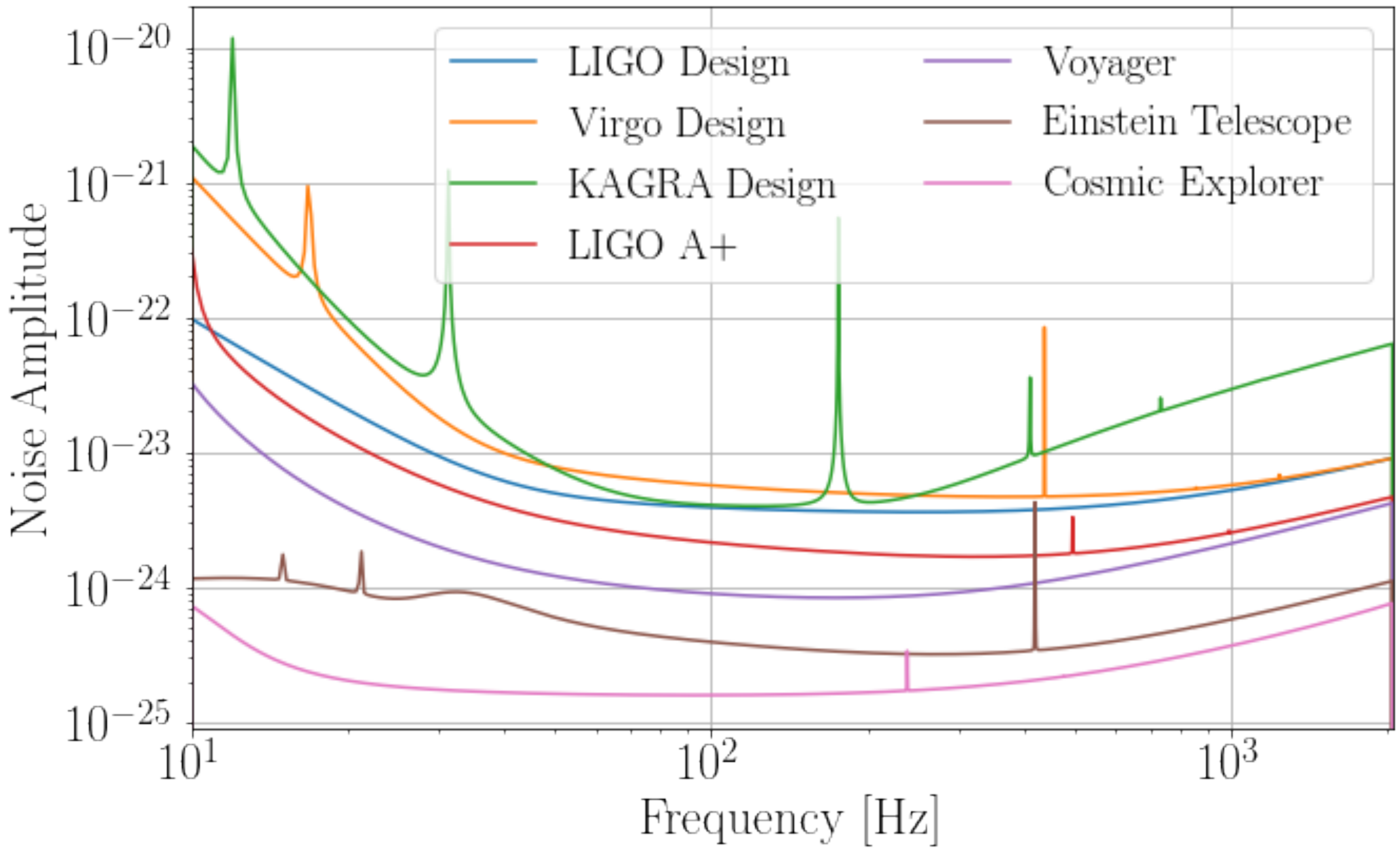
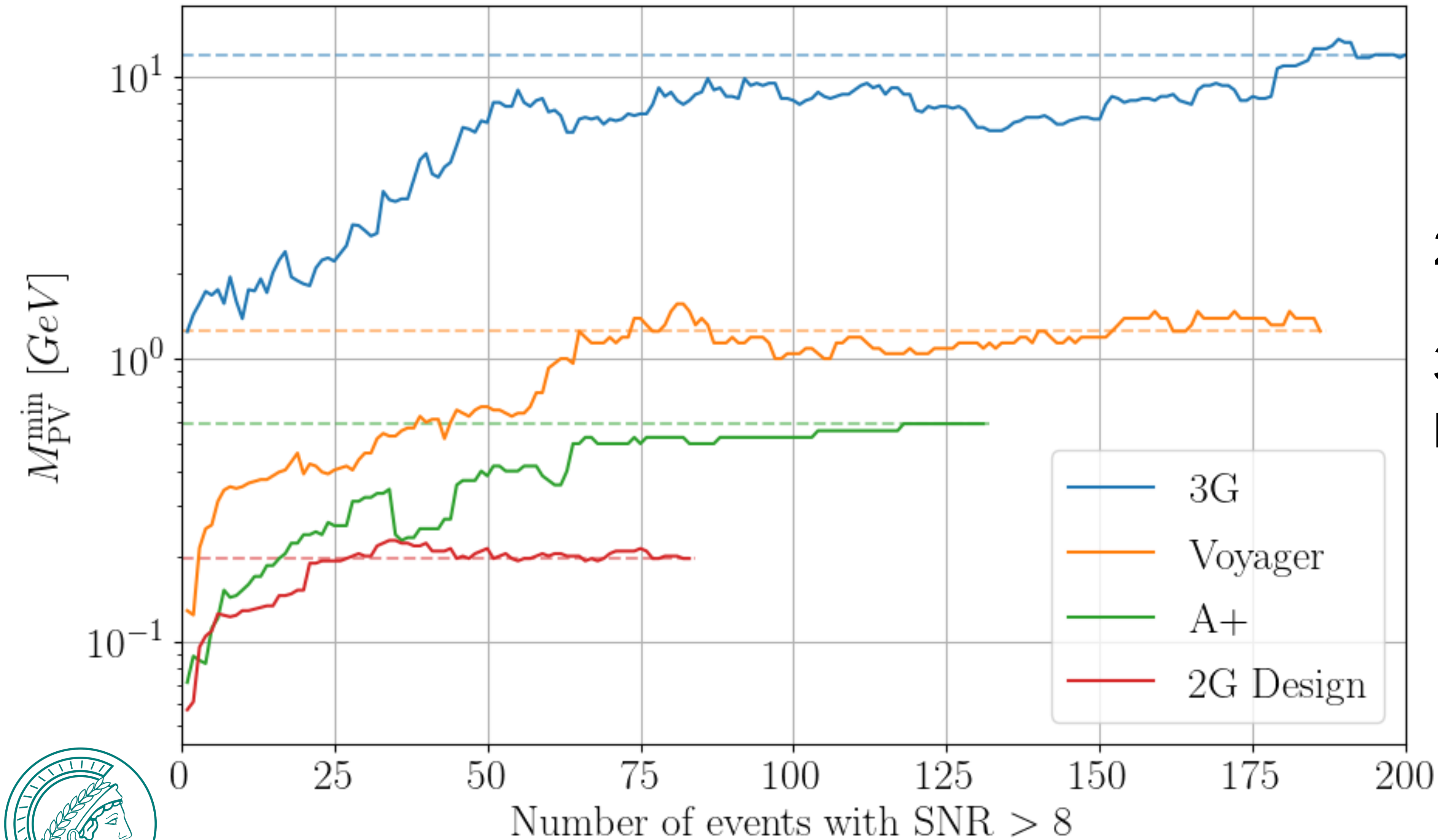
Future GW Detectors:

- LIGO and Virgo are constantly upgrading towards design sensitivity
- KAGRA joined
- 2.5 generation design: LIGO A+, Voyager
- 3rd generation design: Cosmic Explorer, Einstein Telescope



FUTURE GW DETECTORS:

- Inject 200 sources uniformly located within 2Gpc (5Gpc for the third generation detector network), mass uniformly $[5,50]M_{\odot}$
- Choose Signal to Noise Ratio (SNR) > 8 to be detection threshold



2G = LIGO+Virgo+KAGRA

3G = Cosmic Explorer + Einstein Telescope

TO SUMMARIZE:

- GW can put interesting constraints on the parity-violating energy scale at GeV scale —> high energy regime!

- Testing GR with effective field theory has clear physical meaning

- All posterior results are released in https://github.com/yi-fan-wang/ParitywithGW to facilitate open data GW science

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