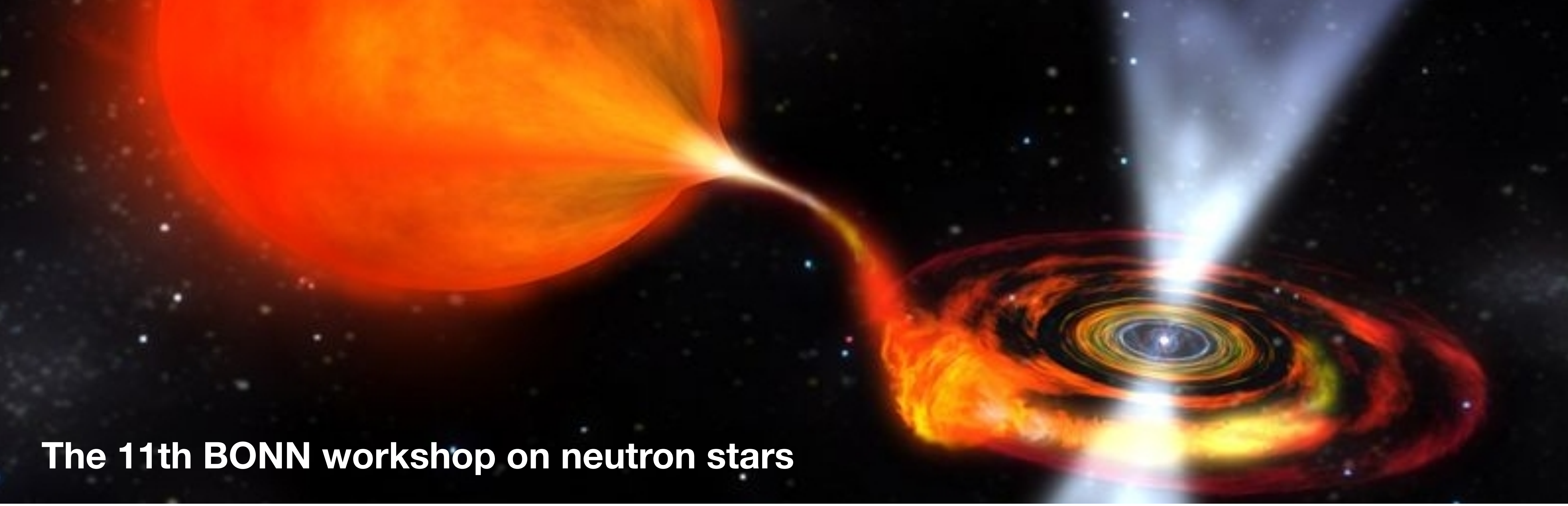

The 11th BONN workshop on neutron stars

# Testing Strong-Field Gravity with Pulsars and GWs

**Lijing Shao**

Max Planck Institute for Radio Astronomy, Bonn

MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut
für
Radioastronomie

BLACK HOLE CAM

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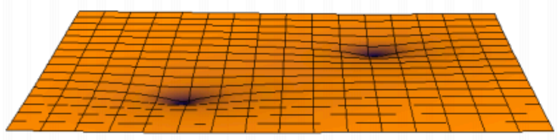
# Outline

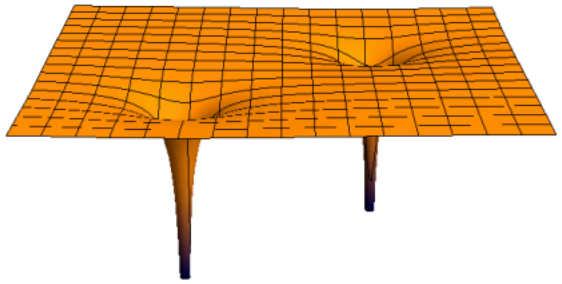
- ✦ Strong-field gravity (SFG)
- ✦ Testing SFG with pulsars
- ✦ Testing SFG with GW detectors
    - ✓ Binary black holes (BBHs): GW150914, GW151226, …
    - ✓ Binary neutron stars (BNSs): GW170817
- ✦ Complementarity in testing SFG with pulsars and GWs

# Strong-field gravity



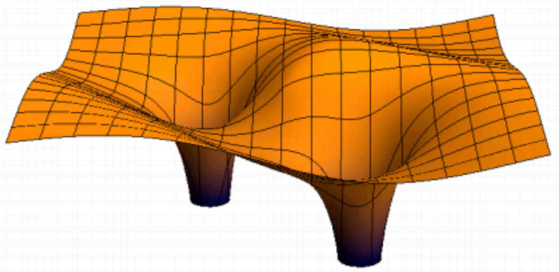
**Solar System**

G1



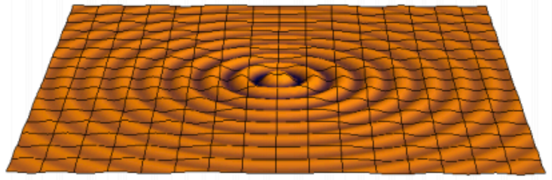
**Binary Pulsar**

G2



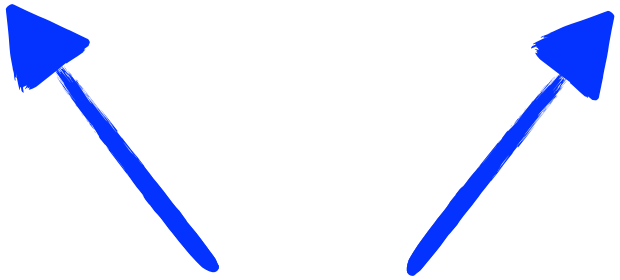
**BBH Merger**

G3



**LIGO/Virgo Sites**

GW



**Strong-field gravity (SFG)**

**G1 — Quasi-stationary weak-field regime**

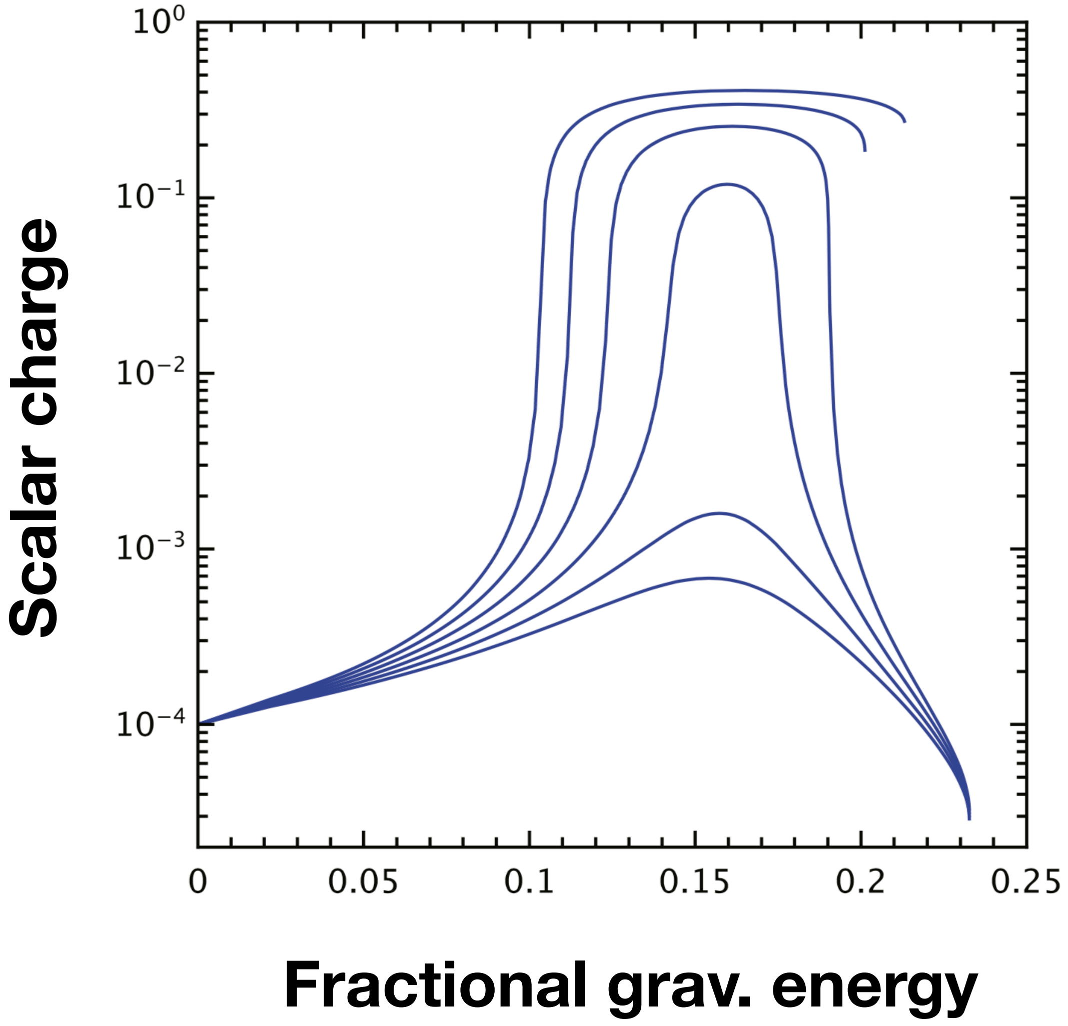
**G2 — Quasi-stationary strong-field regime**

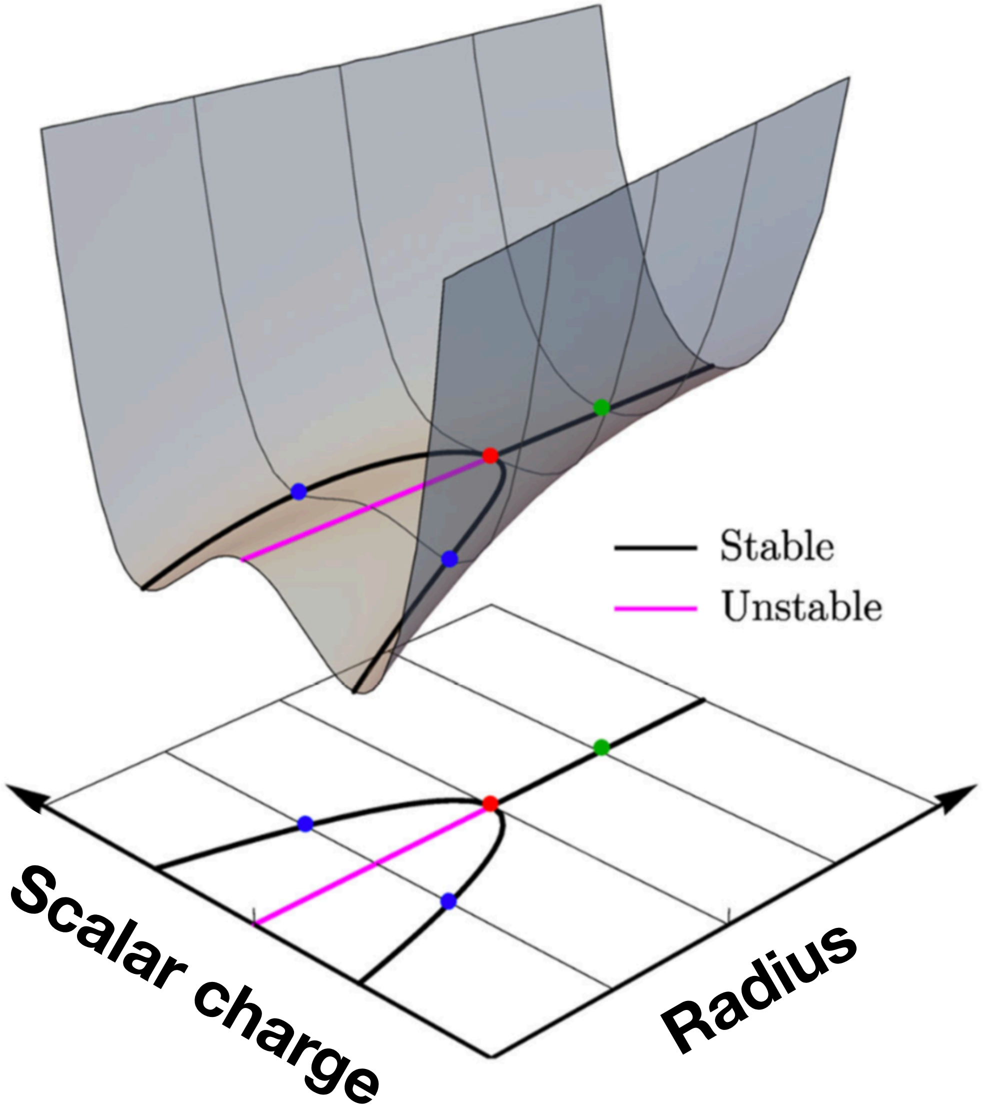
**G3 — Highly dynamical strong-field regime**

**GW — Radiation regime**

Wex, arXiv:1402.5594

# An example of SFG





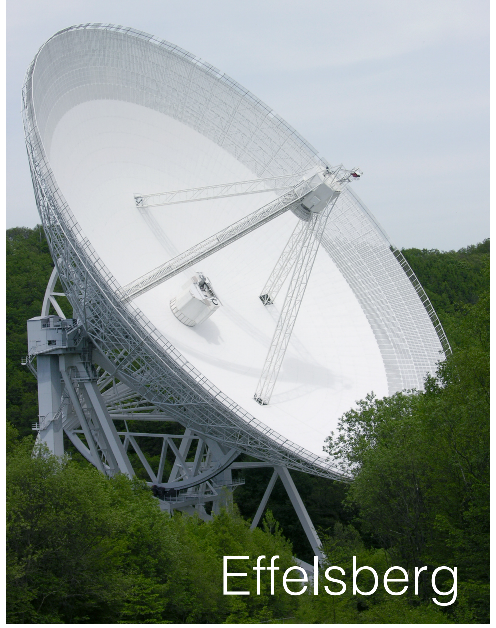
**Nonperturbative spontaneous scalarization could happen with NSs in a class of scalar-tensor theories**

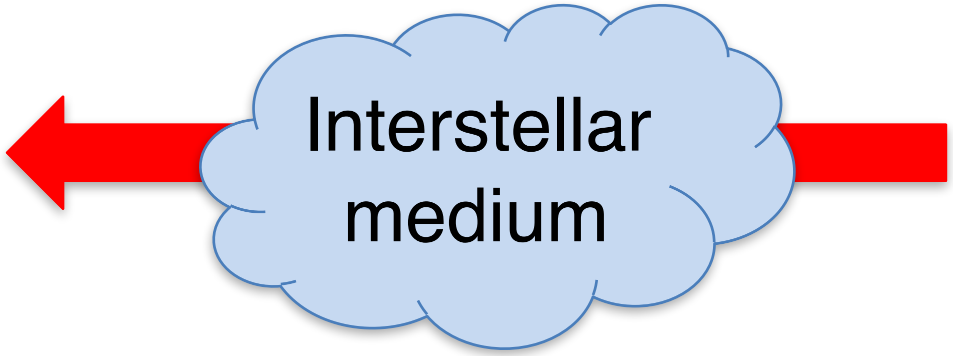
**Strong-field behaviour is analogous to Landau's *phase transition* after a critical point**

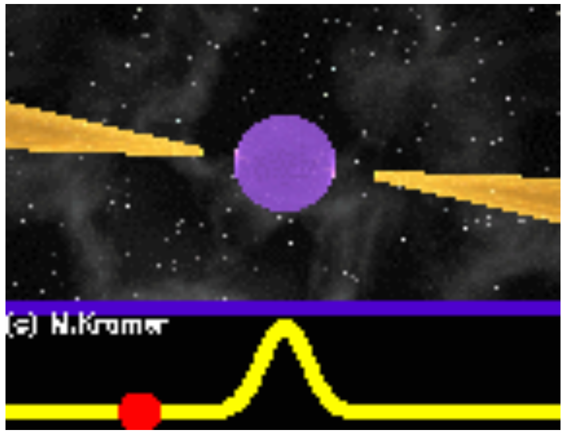
Damour & Esposito-Farèse 1993, PRL 70:2220
Damour & Esposito-Farèse 1996, PRD 54:1474
Shao & Wex 2016, SCPMA 59:699501

Damour & Esposito-Farèse 1996, PRD 54:1474
Esposito-Farèse 2004, AIP Conf. Proc. 736:35
Sennett, Shao, Steinhoff 2017, PRD 96:084019

# Pulsar timing



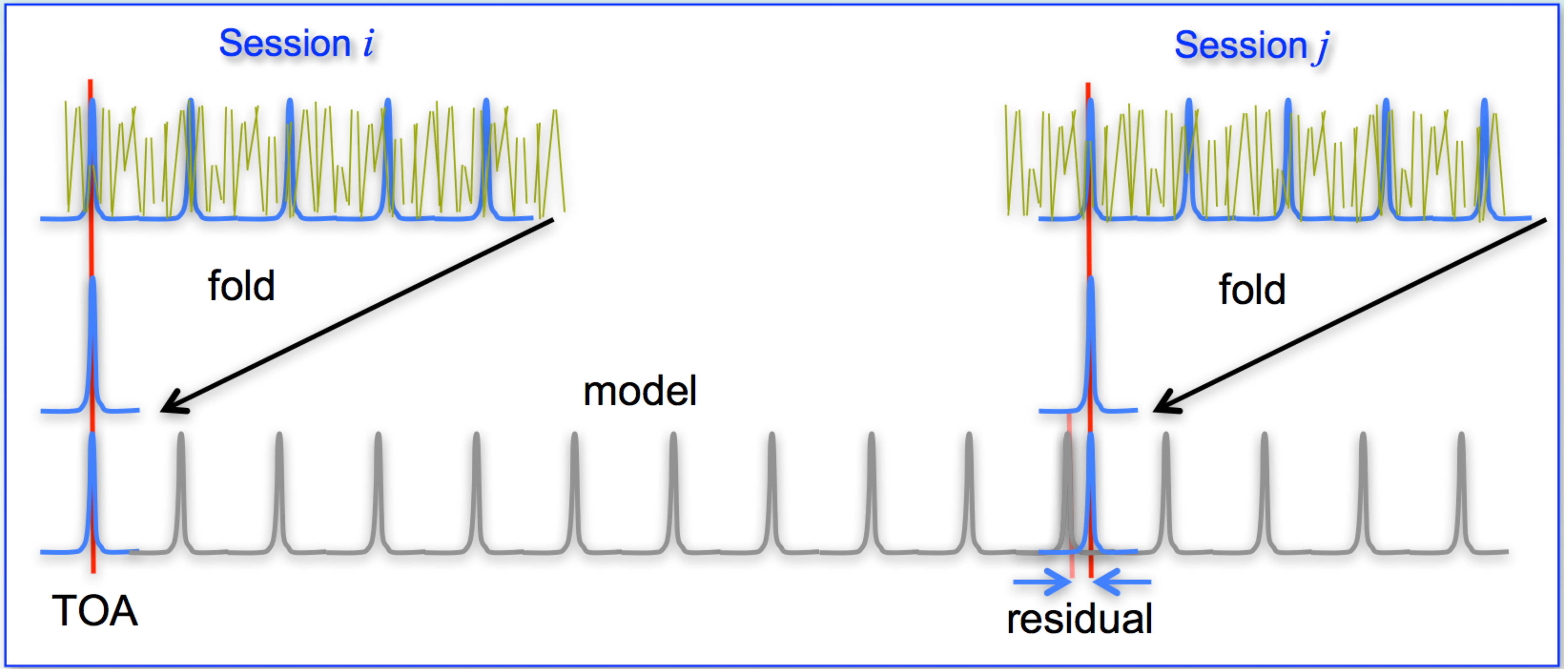

Interstellar medium



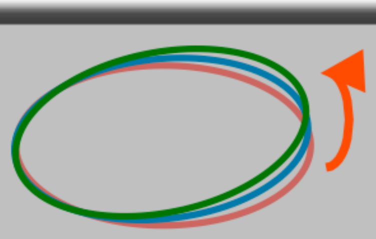
© M. Kramer

**Phase-connected timing solution:**

© N. Wex

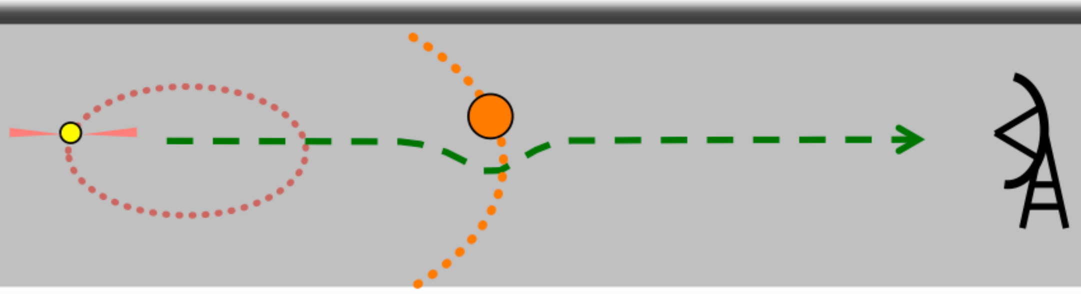


# Timing of relativistic binary pulsars



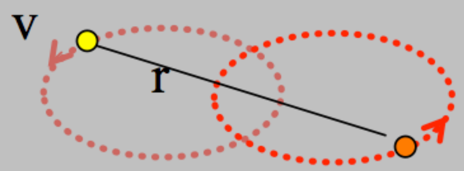
## Precession

$$\dot{\omega} = 3\frac{G^{2/3}}{c^2}\left(\frac{P_b}{2\pi}\right)^{-5/3}\frac{1}{1-e^2}\left[(m_1+m_2)\right]^{2/3}$$



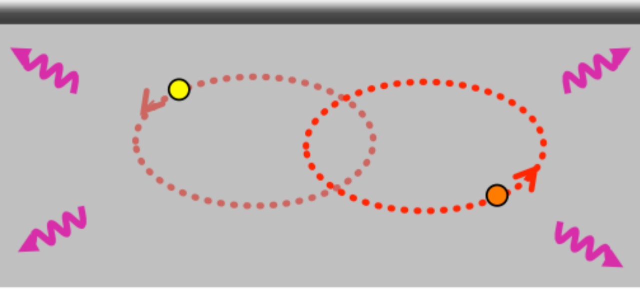
## Shapiro Delay

$$\Delta t = 2\frac{G}{c^3}m_2 \ln\left[\frac{1+e\cos\varphi}{1-\sin i \sin(\varphi-\varphi_0)}\right]$$



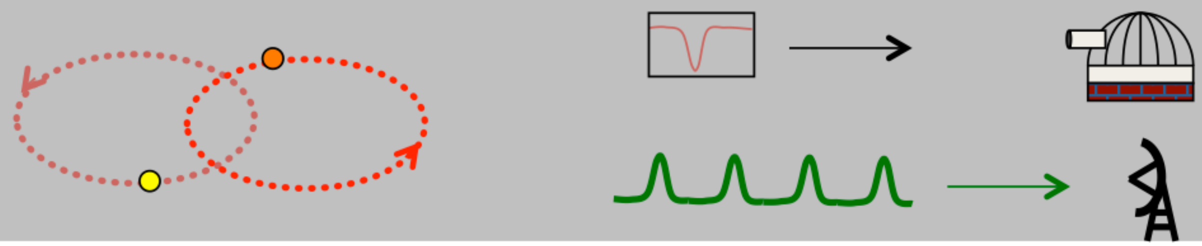
## Grav Redshift/Time Dilation

$$\gamma = \frac{G^{2/3}}{c^2}\left(\frac{P_b}{2\pi}\right)^{1/3} e\,\frac{m_2(m_1+2m_2)}{(m_1+m_2)^{4/3}}$$



## Gravitational Radiation

$$\dot{P}_b = -\left(\frac{192\pi}{5}\right)\frac{G^{5/3}}{c^5}\left(\frac{P_b}{2\pi}\right)^{-5/3}\left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right)\frac{1}{(1-e^2)^{7/2}}\frac{m_1 m_2}{(m_1+m_2)^{1/3}}$$



## Second Orbit

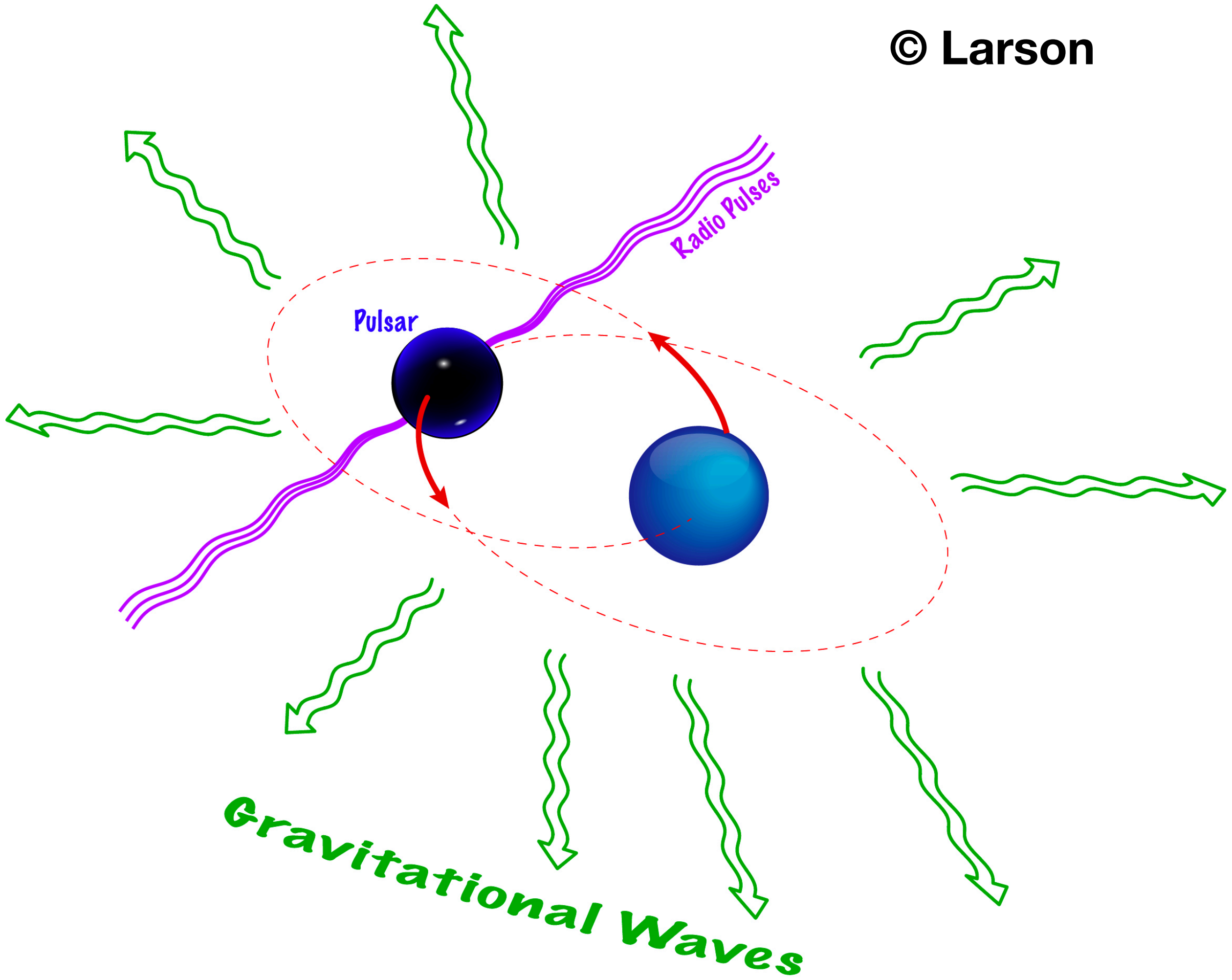
$$\frac{m_1}{m_2} = \frac{a_2\sin i}{a_1\sin i}$$

**Physics 1993**

© David Nice

# The Hulse-Taylor pulsar

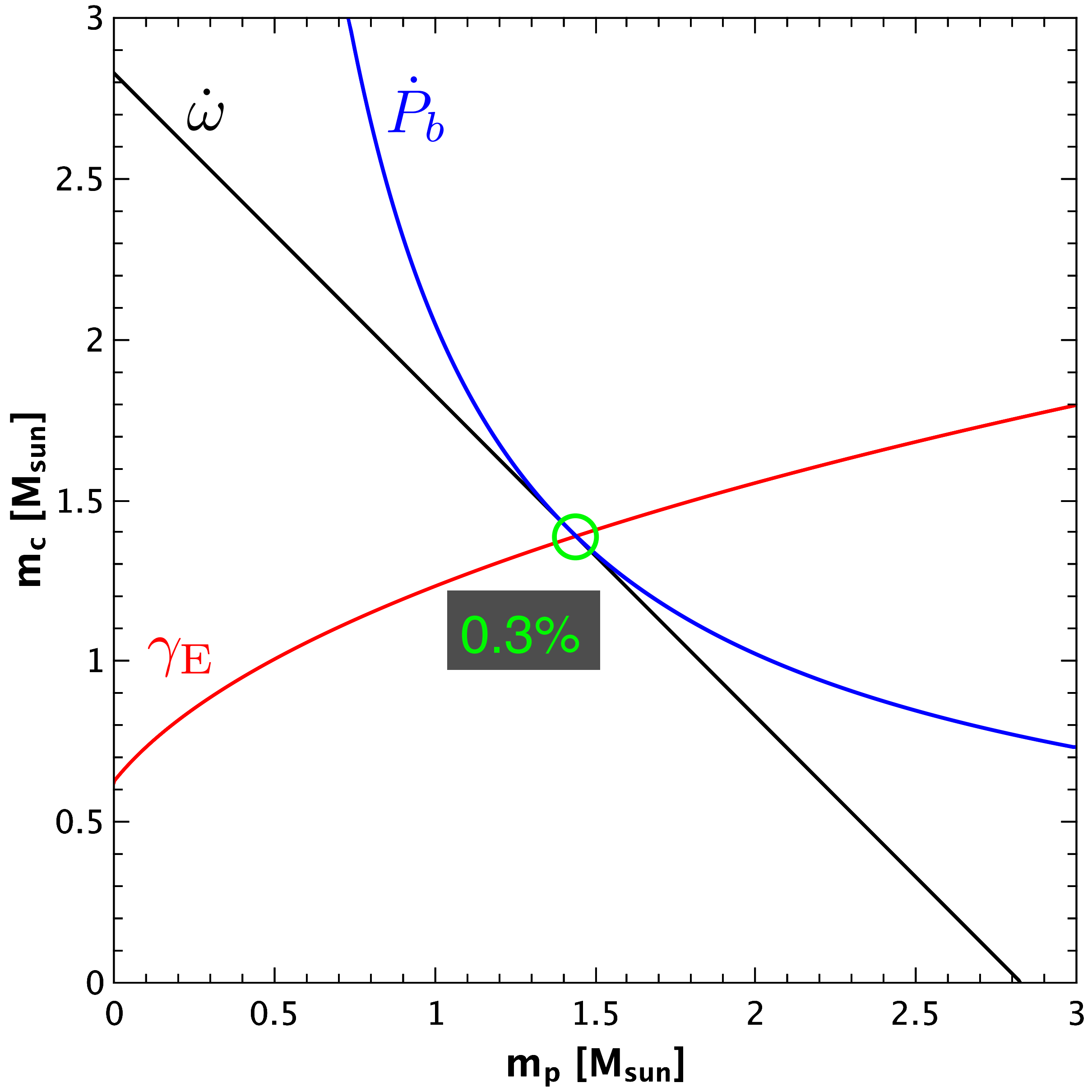
Hulse & Taylor 1975, ApJ 195:L51

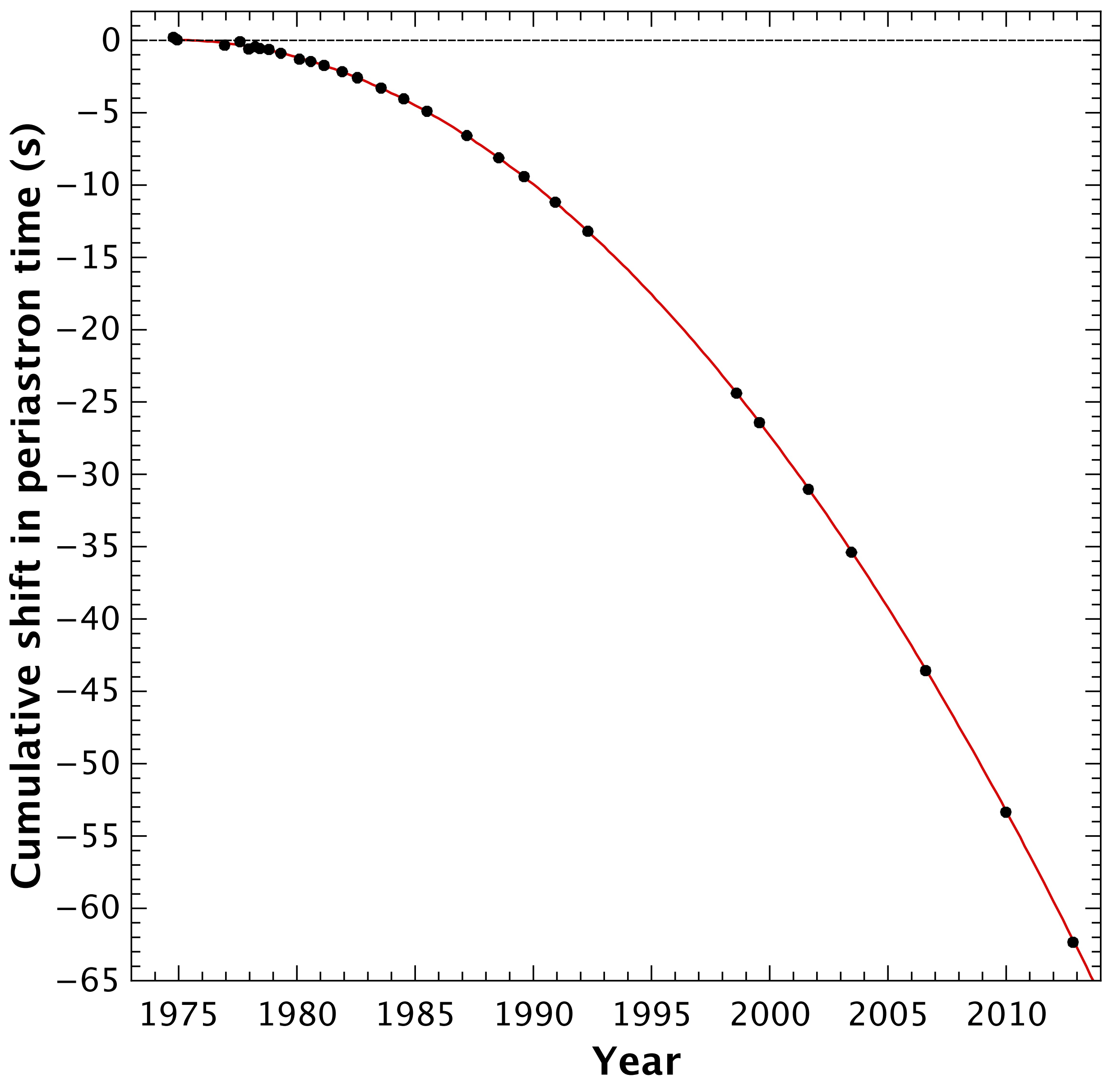


© Larson

**Radio pulsar timing provided the first evidence of GWs, and started a new era to test Einstein's gravity in strong field**

# Mass-mass diagram and GW radiation

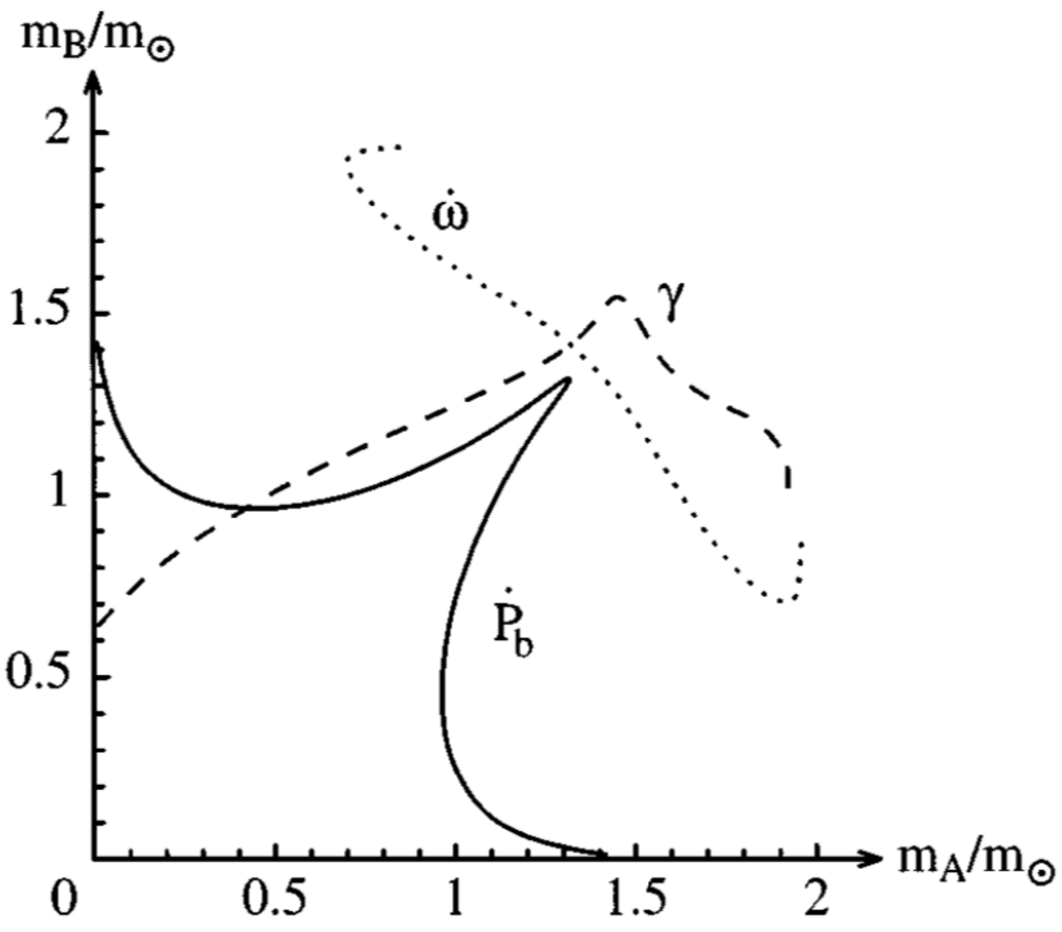




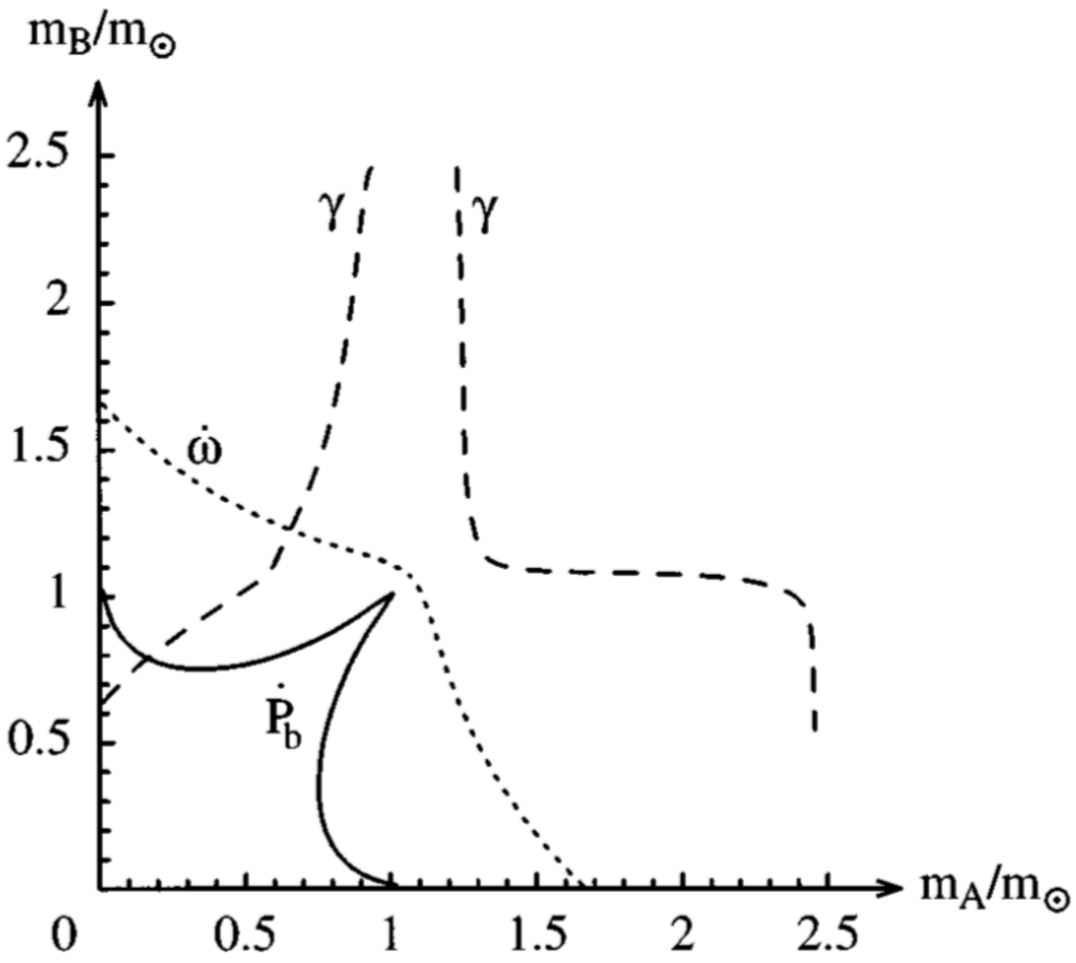
**In GR, observations of post-Keplerian parameters agree within 0.3%**

Weisberg & Huang 2016, ApJ 829:55

# Examples: Hulse-Taylor pulsar with SFG



**Scalar-tensor theory with $\beta_0 = -4.5$**

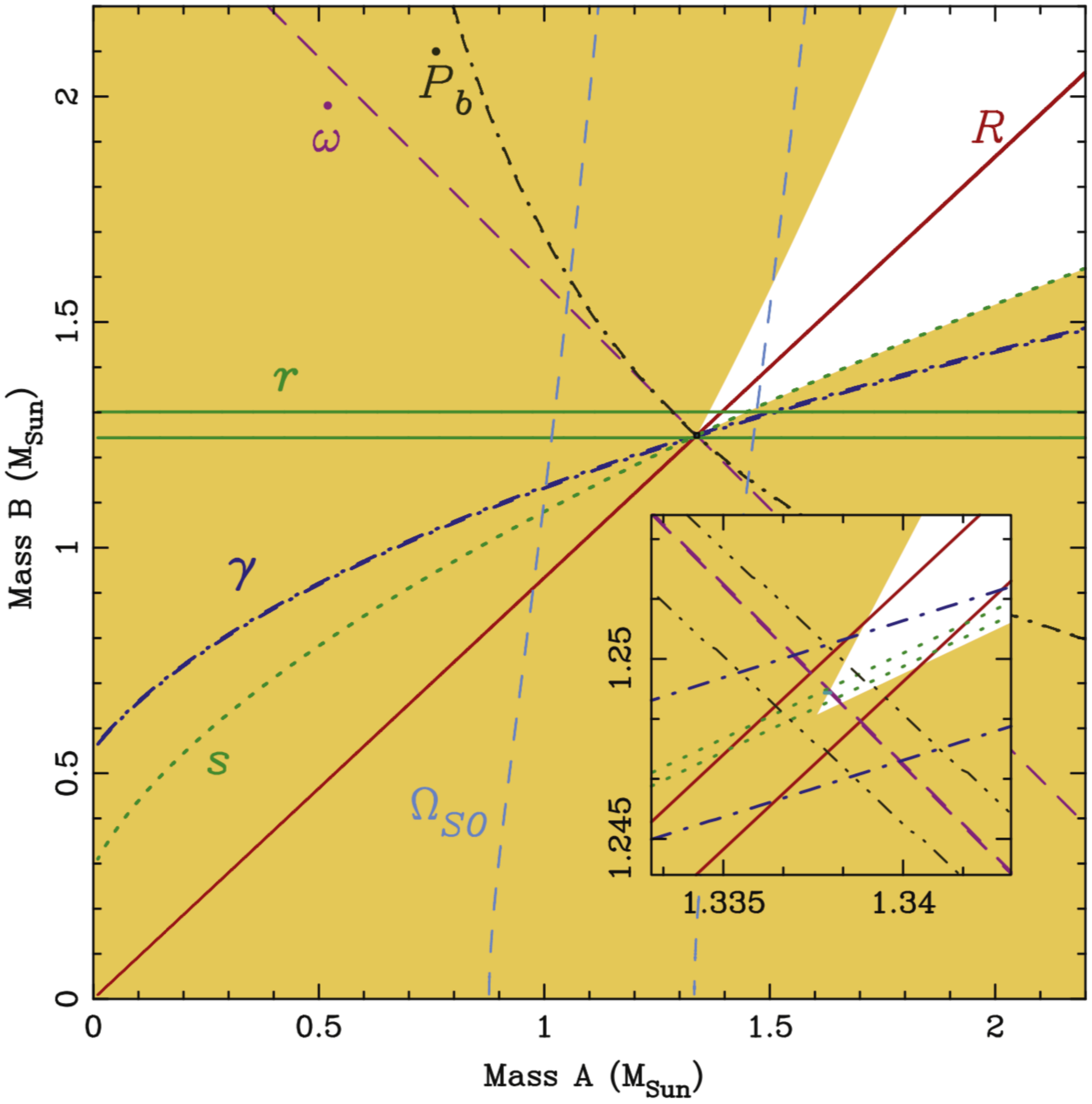


**Scalar-tensor theory with $\beta_0 = -6$**

**Binary pulsars are extremely sensitive probes of SFG!**

Damour & Esposito-Farèse 1996, PRD 54:1474

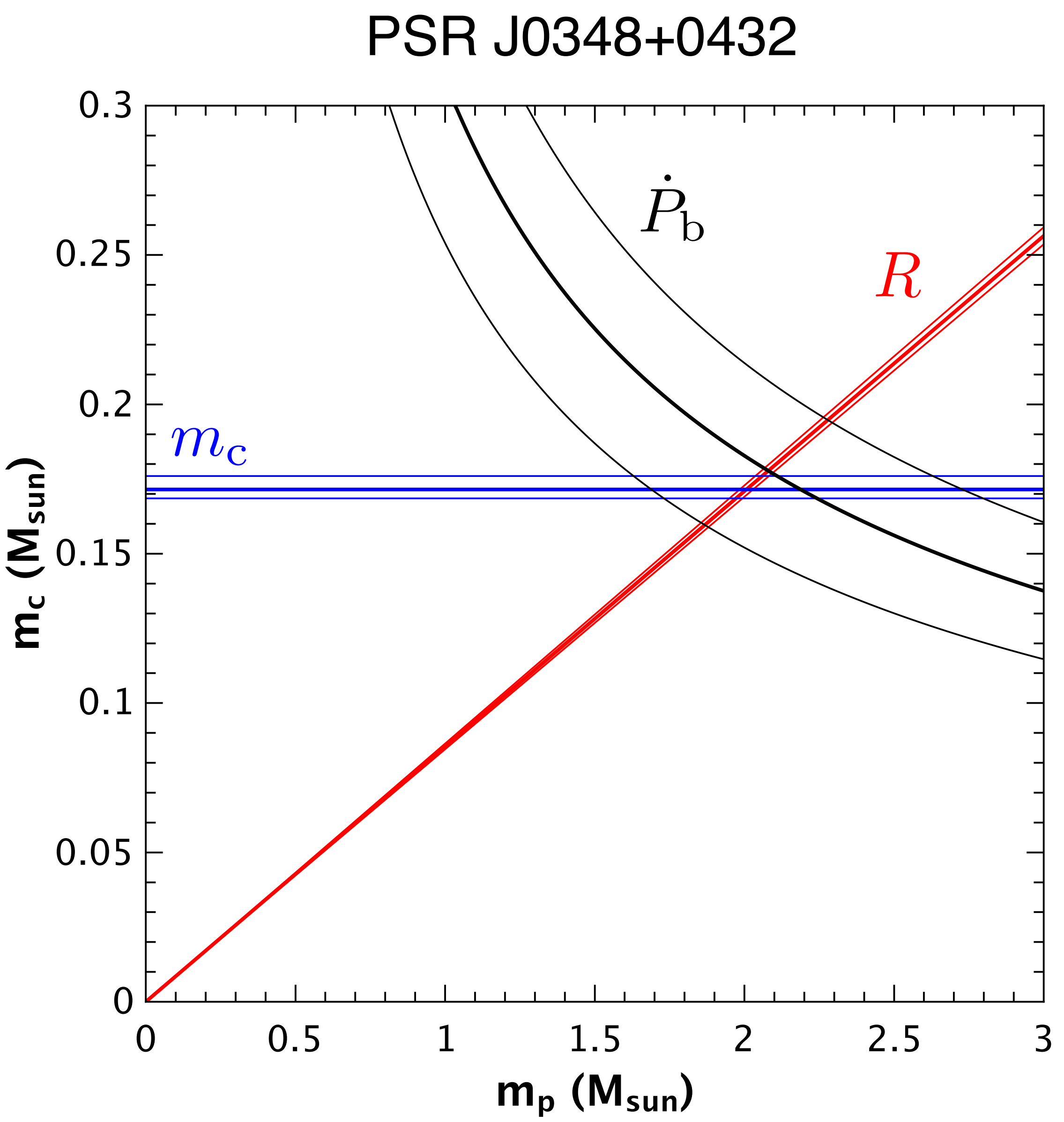
# The Double Pulsar J0737-3039



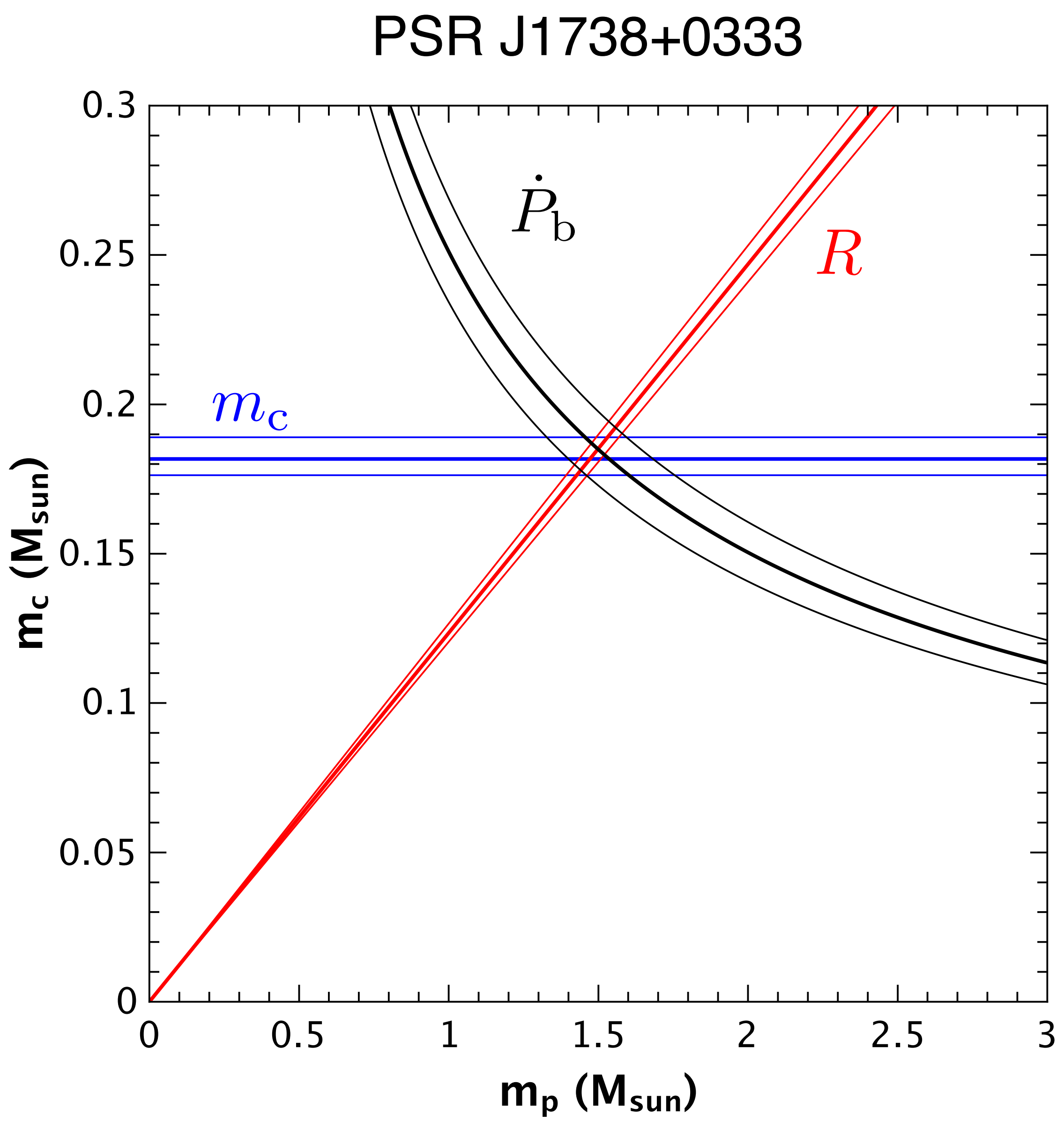
**Double Pulsar agrees with GR significantly better than the Hulse-Taylor pulsar**

Kramer et al. 2006, Science 314:97
Kramer 2016, IJMPD 25:1630029
Kramer et al., in prep.

# PSRs J0348+0432 and J1738+0333



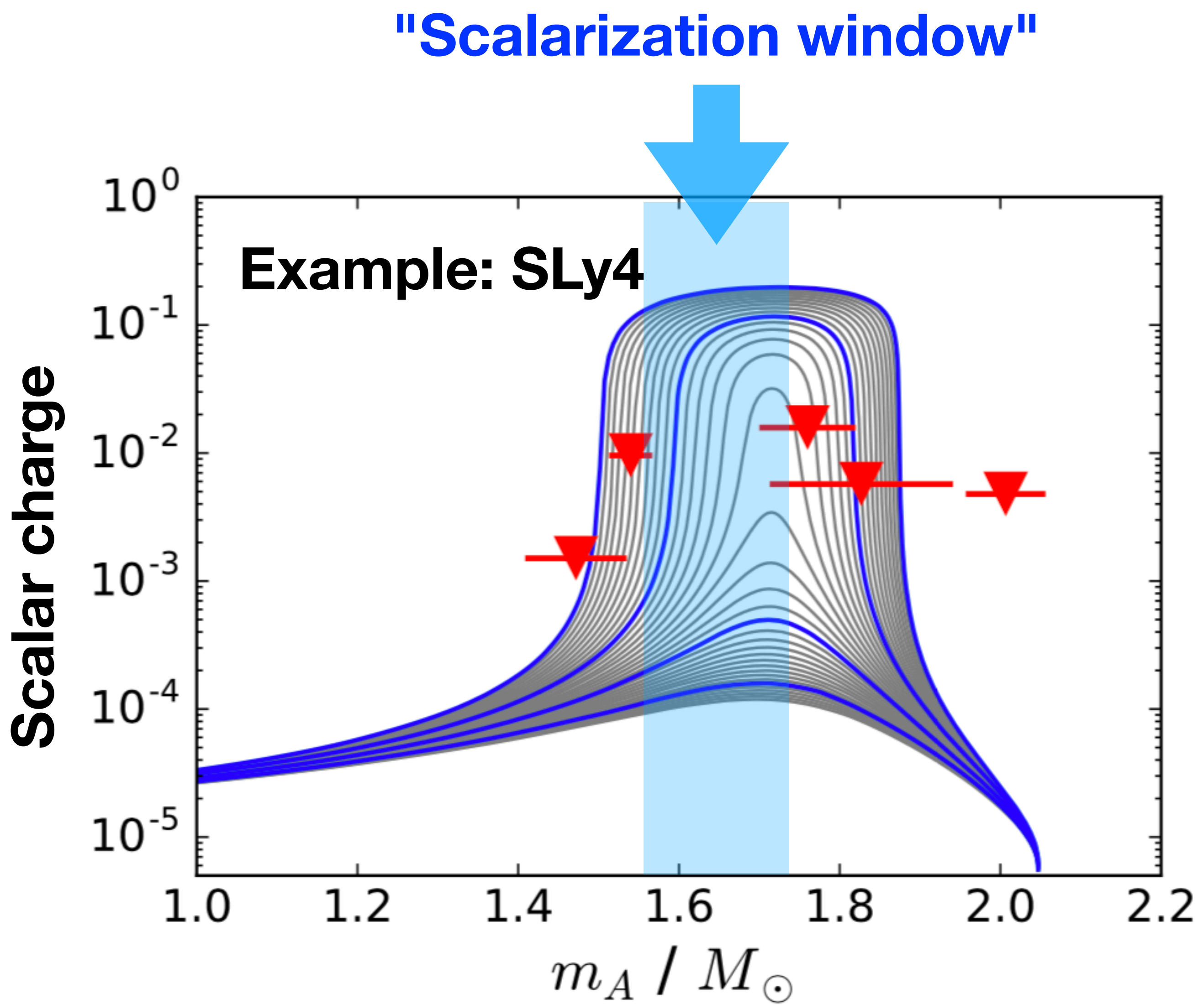
Antoniadis et al. 2013

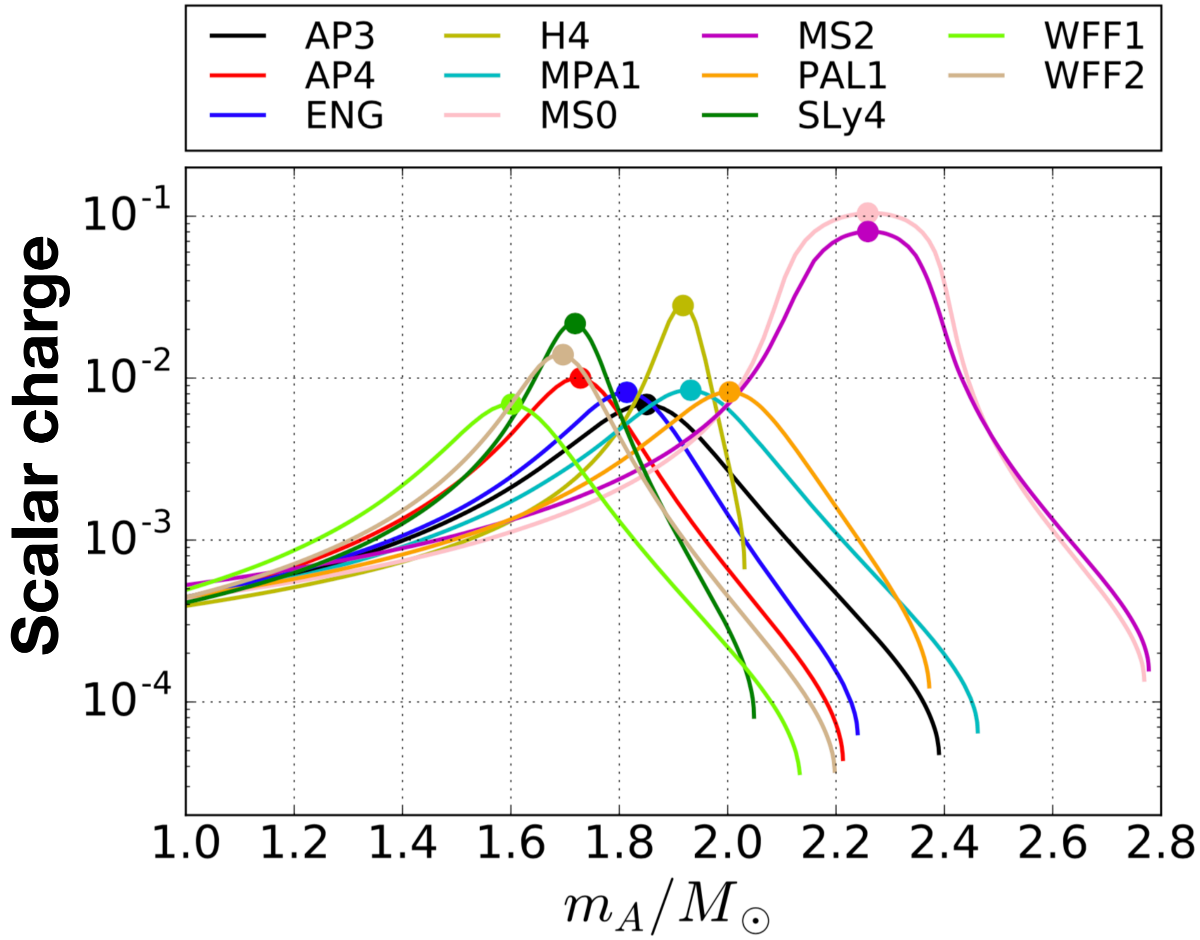


Freire et al. 2012

**Due to their asymmetry, neutron-star white-dwarf systems provide stringent limits on *dipole radiation***

# Combination of five NS-WDs





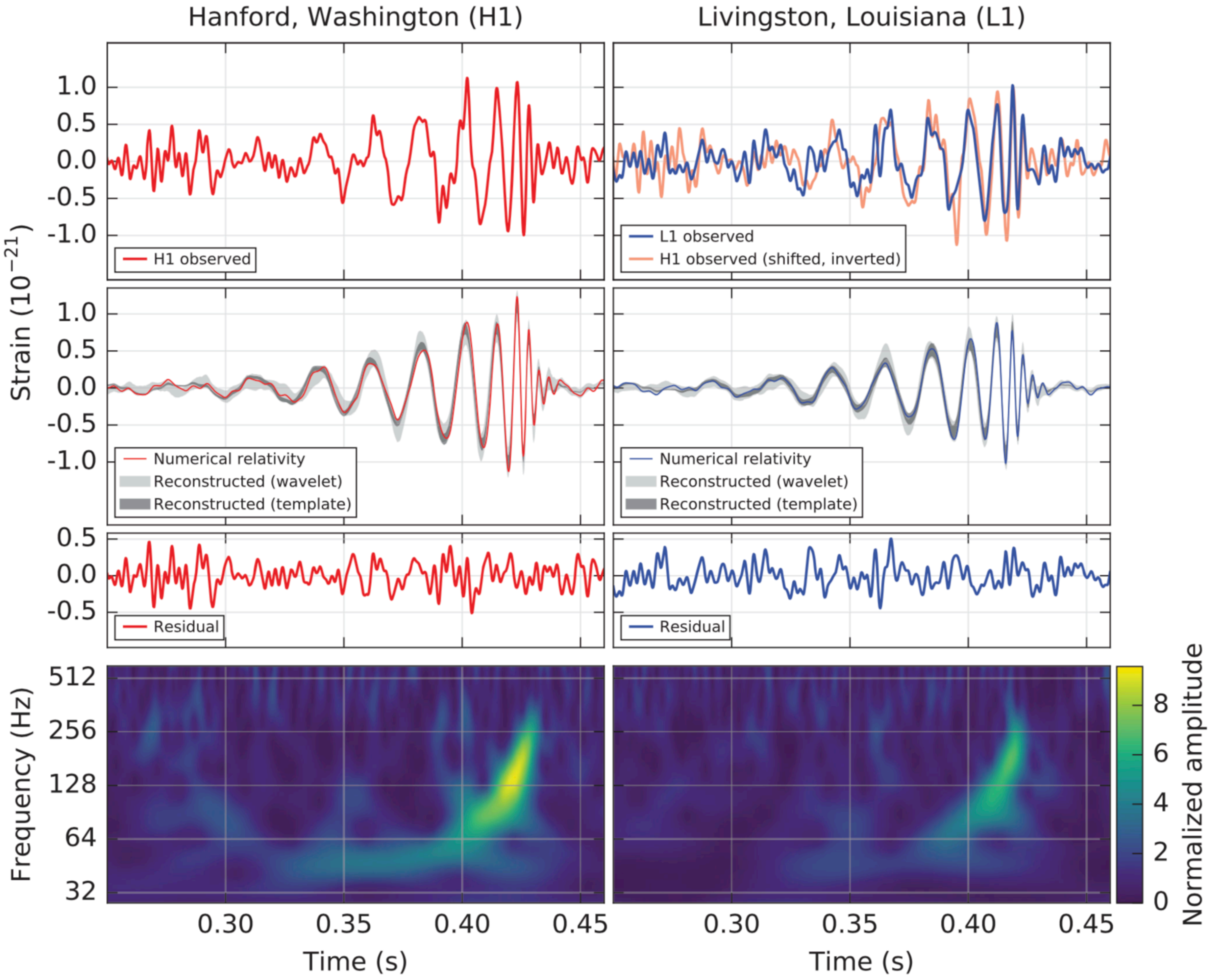
**Strong-field effects could happen at different NS masses for different EOSs**

**Combining five best-timed NS-WD binaries put the best limits on a class of scalar-tensor theories for different EOSs**

cf. Bastian's talk for EOSs

Shibata et al. 2014, PRD 89:084005
Shao et al. 2017, PRX 7:041025

# The first BBH merger: GW150914

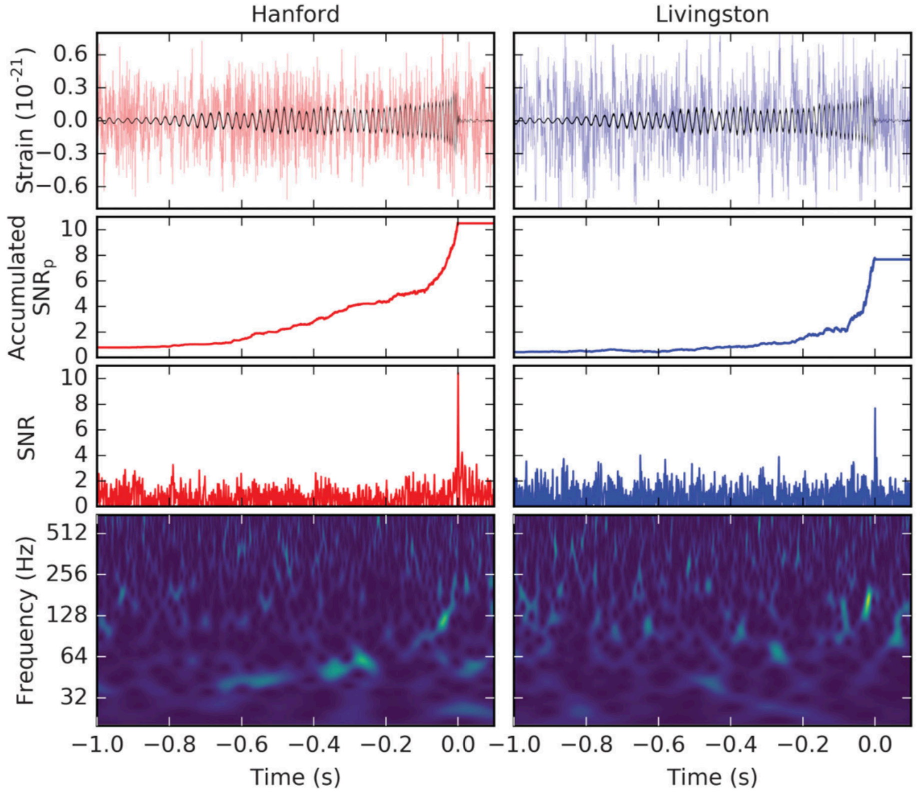


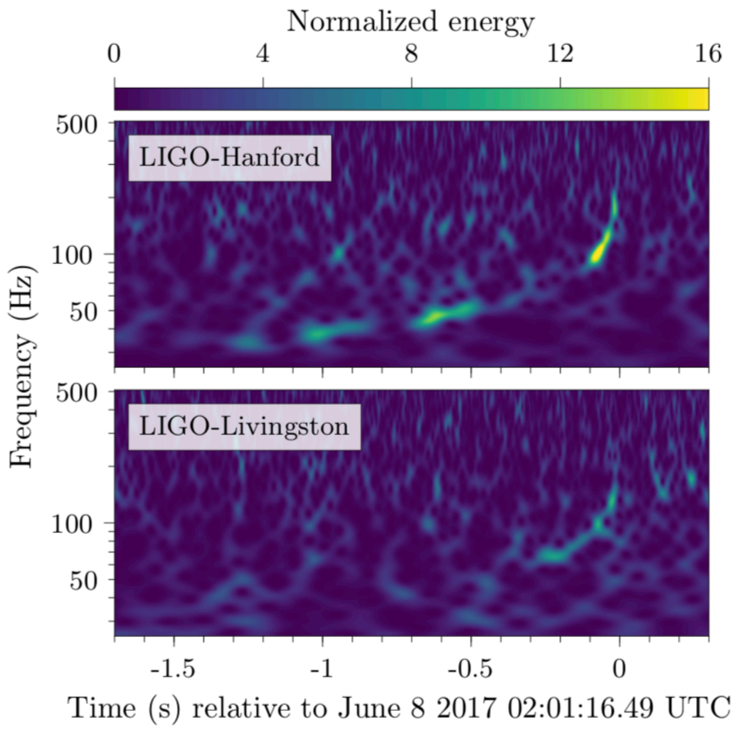
LVC 2016, PRL 116:061102

# A zoo of BBH mergers

## GW151226

LVC 2016, PRL 116:241103



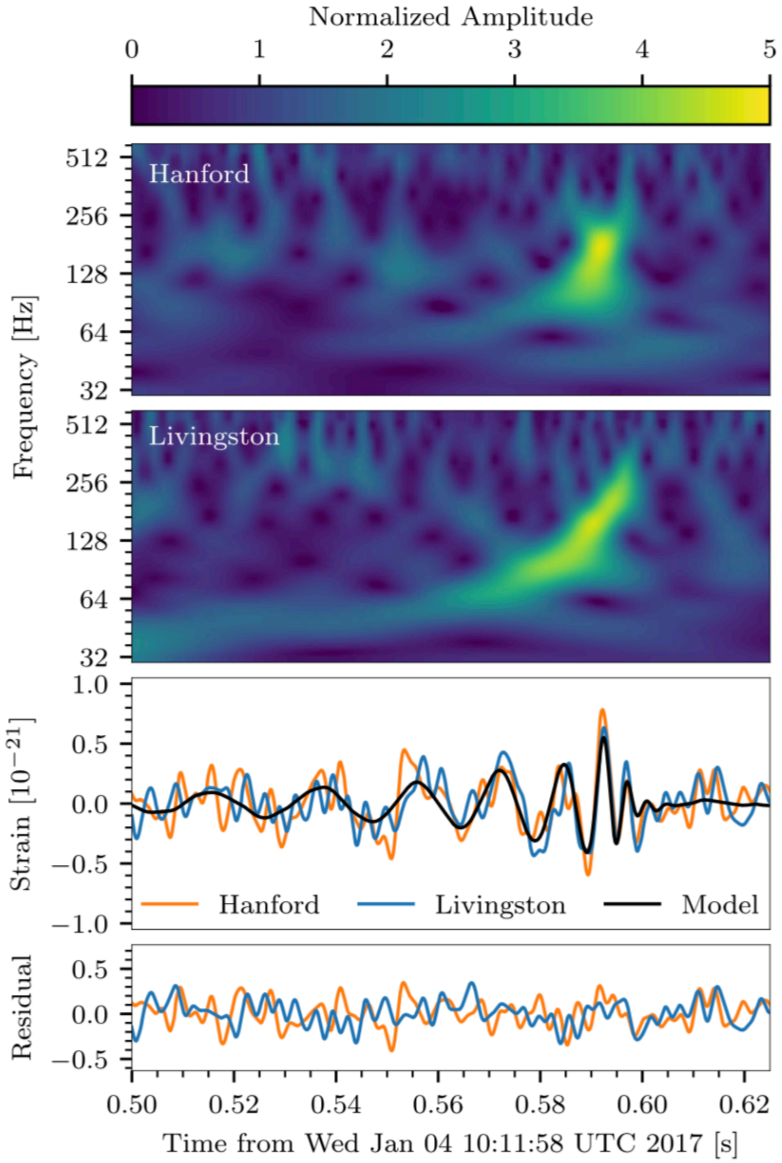


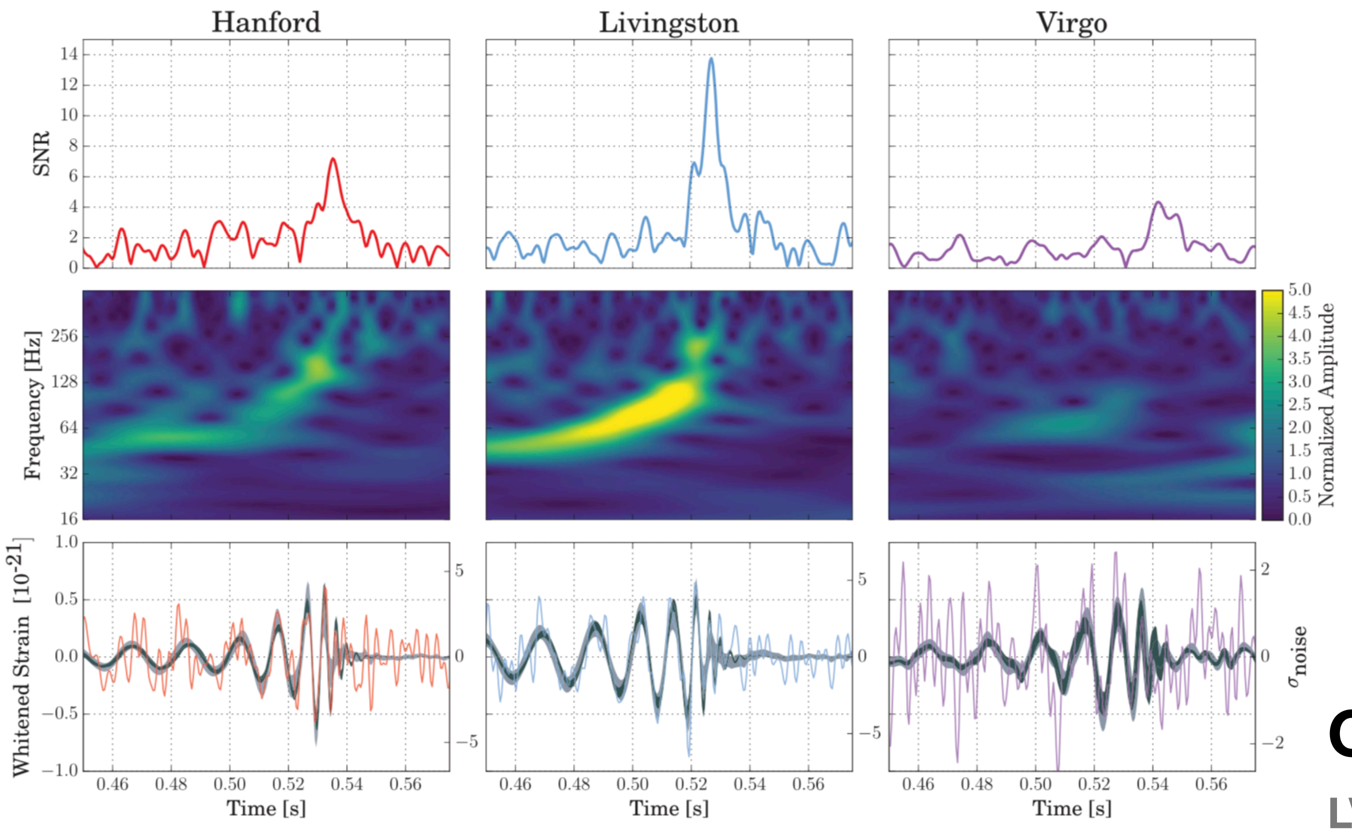
## GW170608

LVC, arXiv:1711.05578

## GW170104

LVC 2017, PRL 118:221101



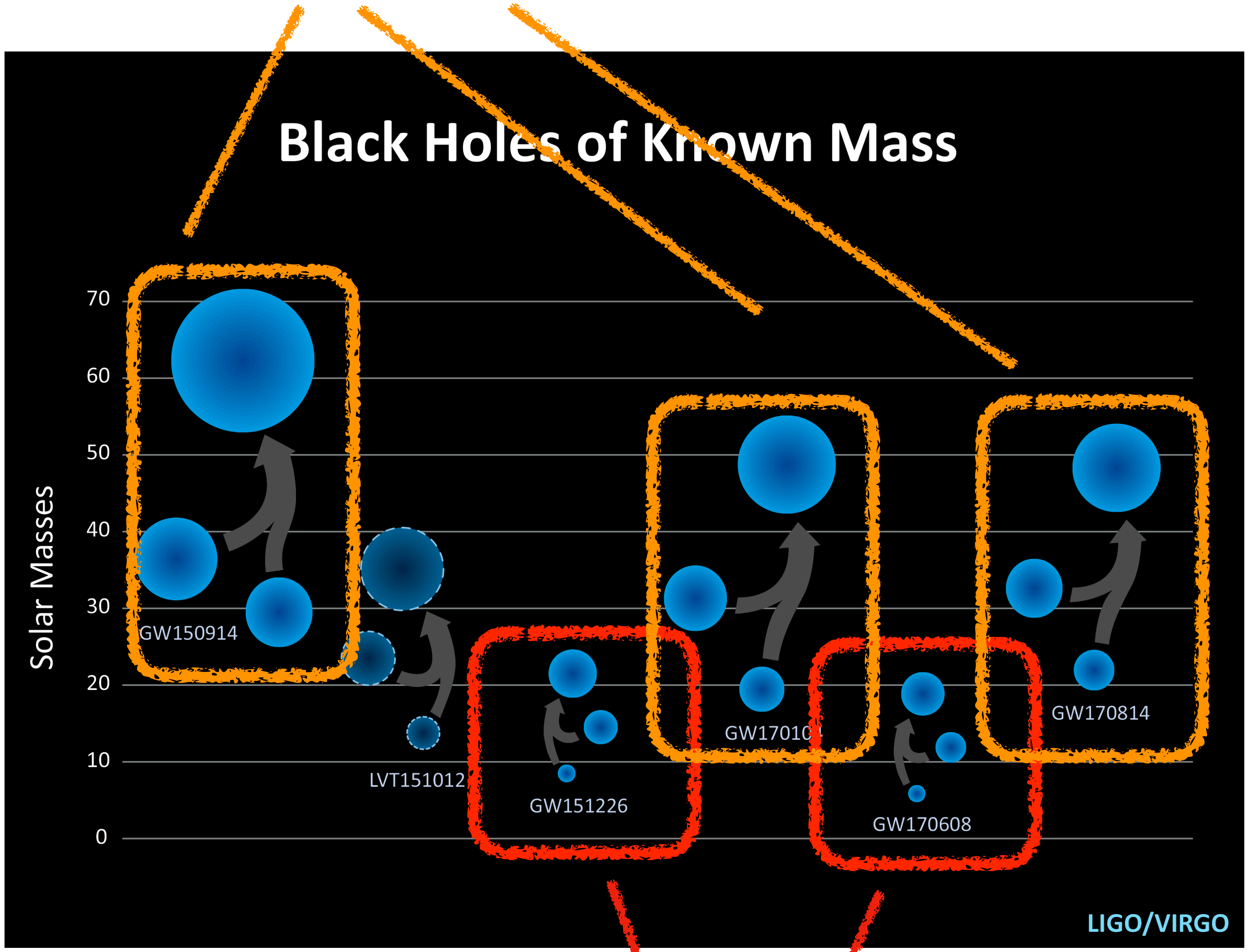


## GW170814

LVC 2017, PRL 119:141101

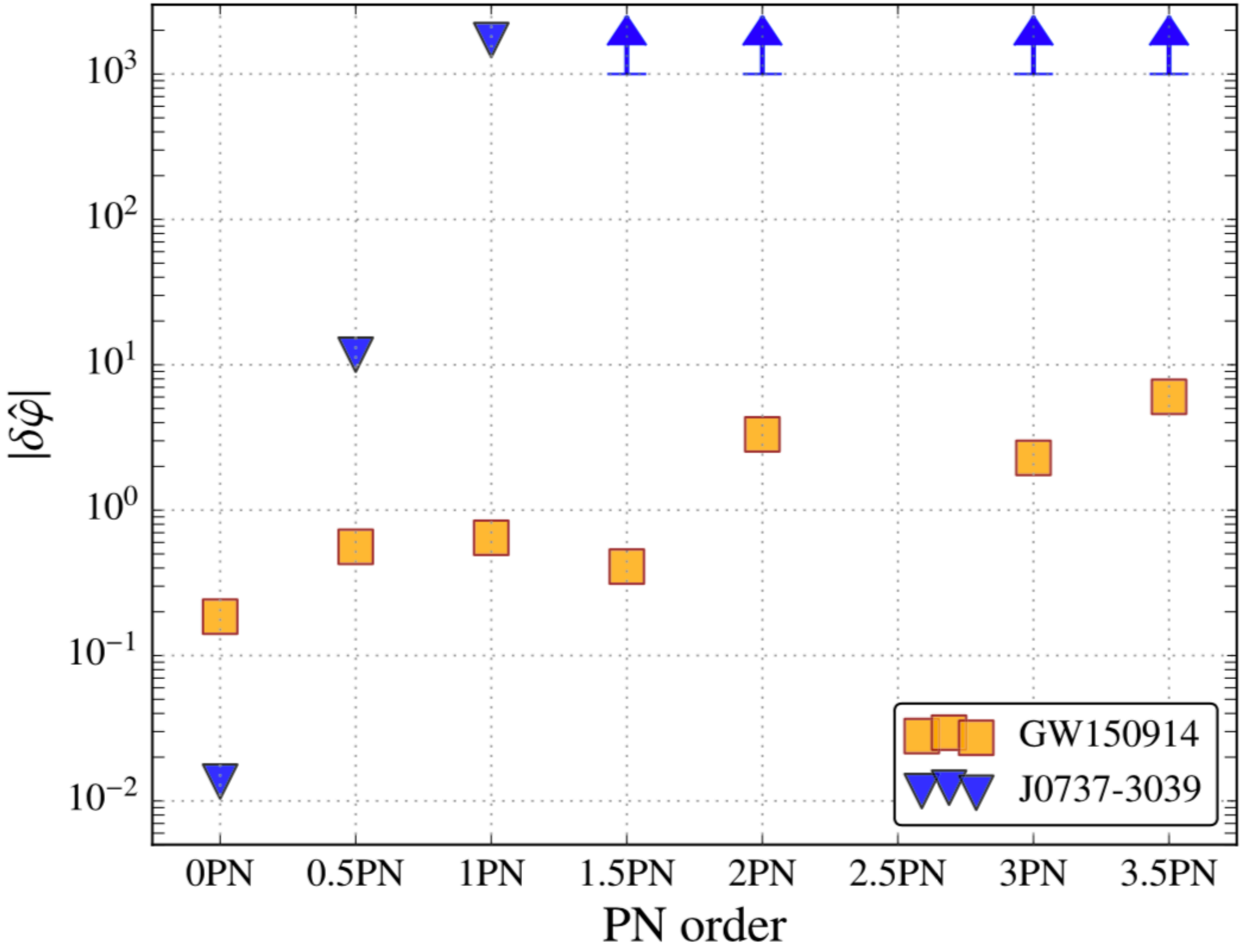
# Masses of BBH mergers

Events with larger masses are in general better at probing merger and ringdown phases



Events with smaller masses are in general better at probing lower-order post-Newtonian gravity

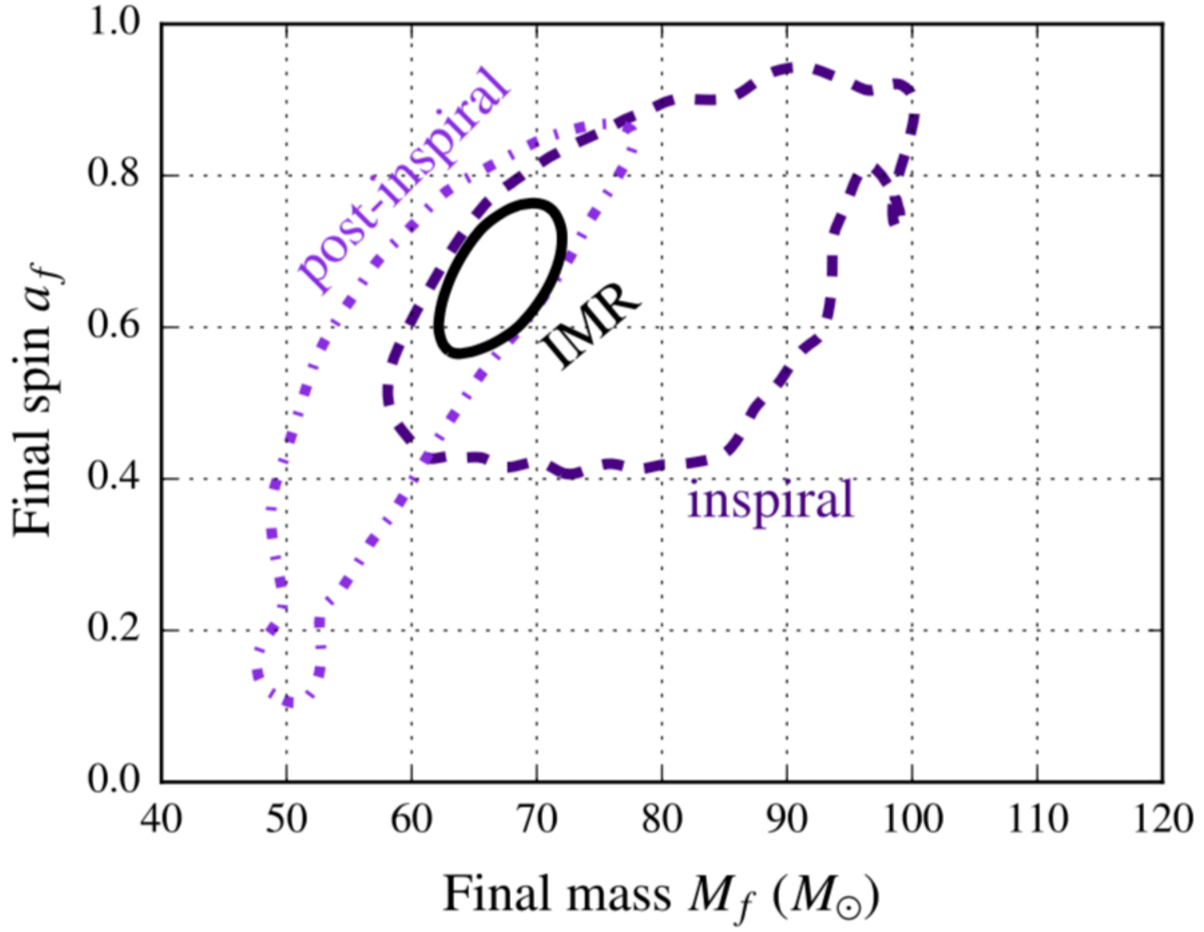
# Tests of post-Newtonian dynamics



**(using Double Pulsar results as of 2006)**

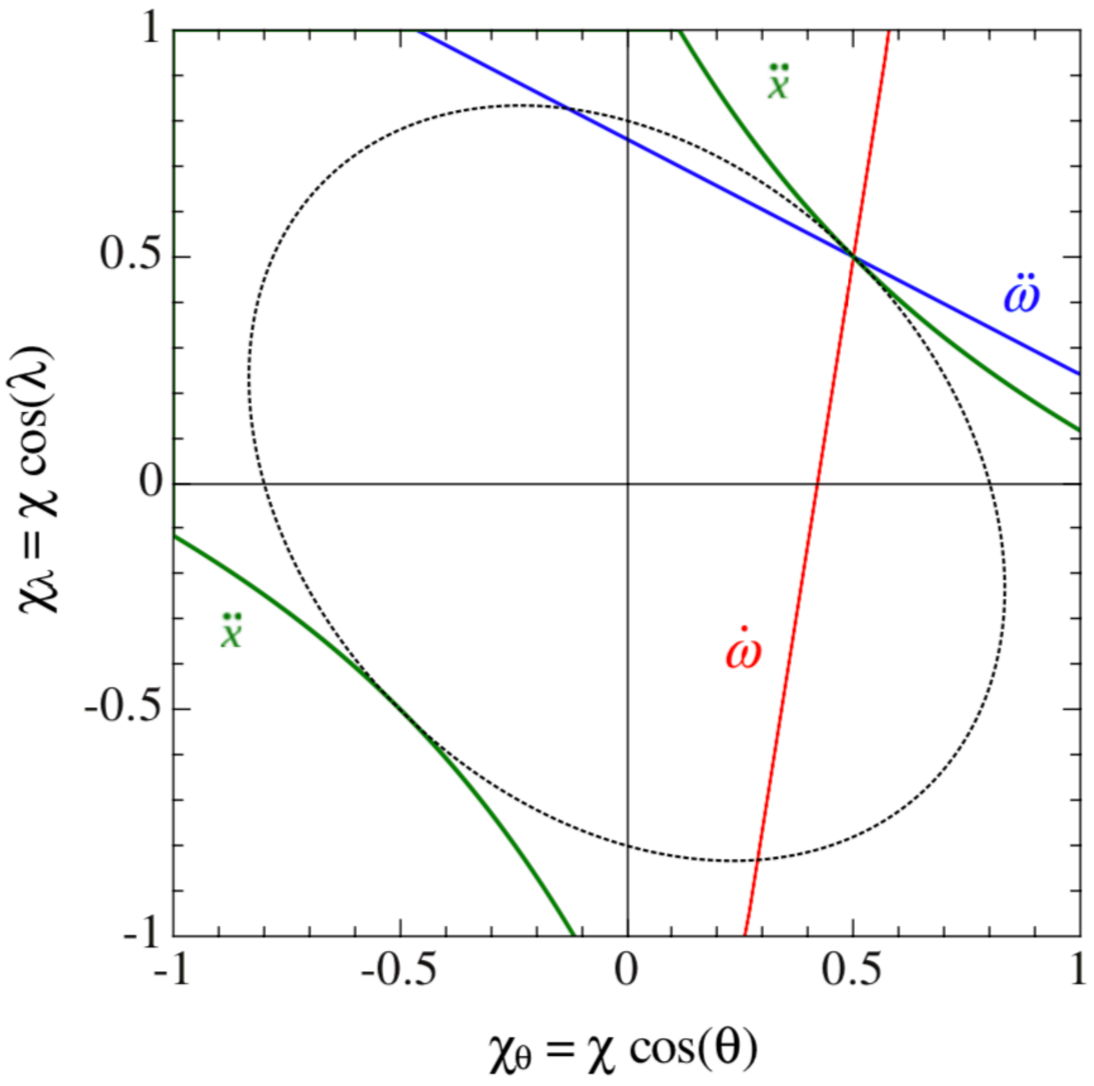
LVC 2016, PRL 116:221101
LVC 2016, PRX 6:041015

# IMR consistency and no-hair theorem



**GW150914**

Meidam et al. 2014, PRD 90:064009
LVC 2016, PRL 116:221101

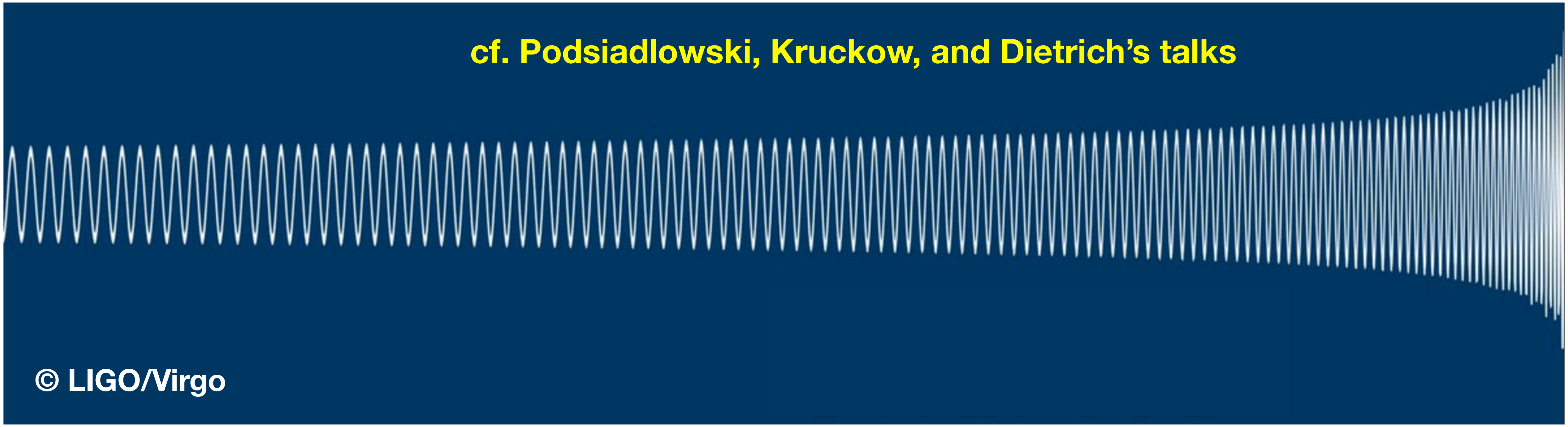


**Pulsar around Sgr A***

Wex & Kopeikin 1999, ApJ 514:388
Liu et al. 2012, ApJ 747:1

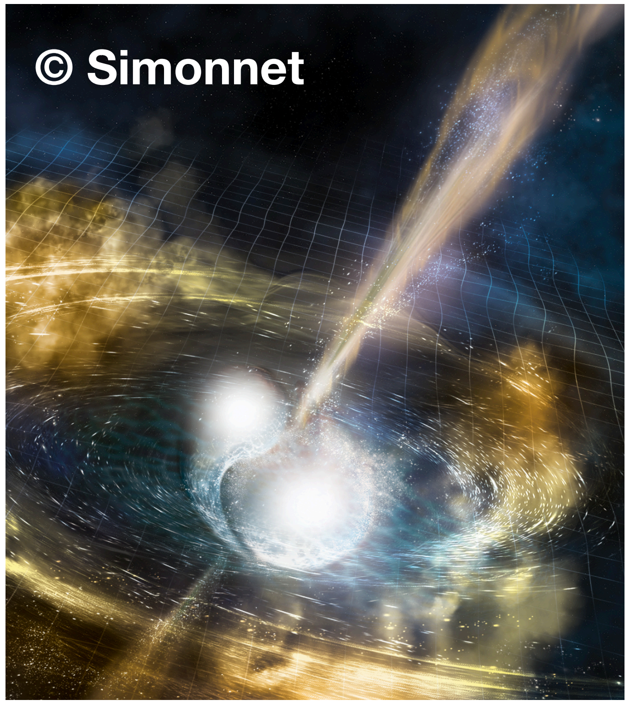
**When higher-order quasinormal modes can be extracted with future GW detectors, no-hair theorem can be tested; it is also true when pulsars closely orbiting Sgr A* are discovered**

# GW170817: binary neutron stars


cf. Podsiadlowski, Kruckow, and Dietrich's talks

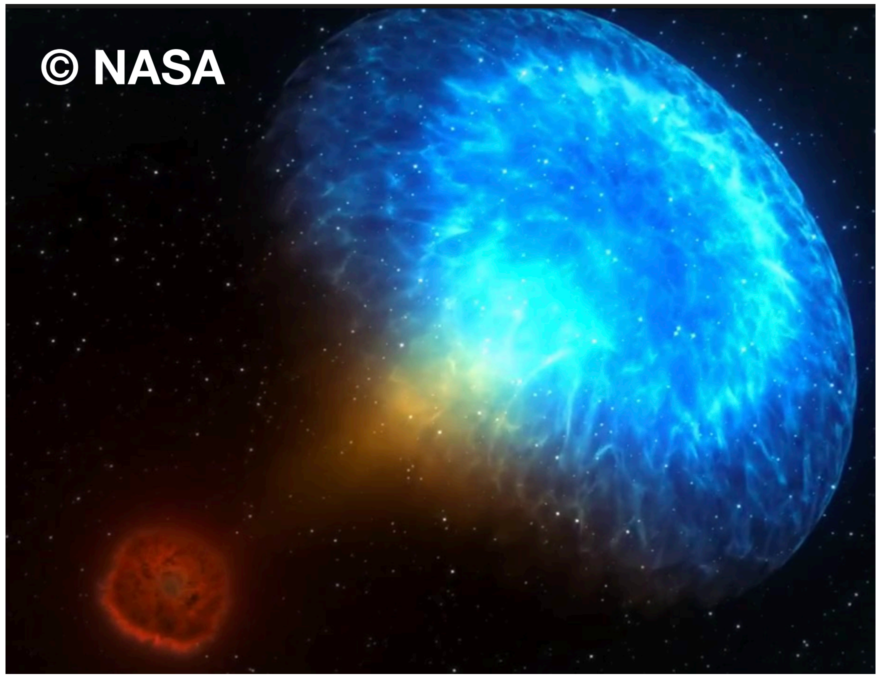
© LIGO/Virgo

**The long inspiral waveform could have imprints from the material of neutron stars ⇨ Testing Einstein's theory with matter**

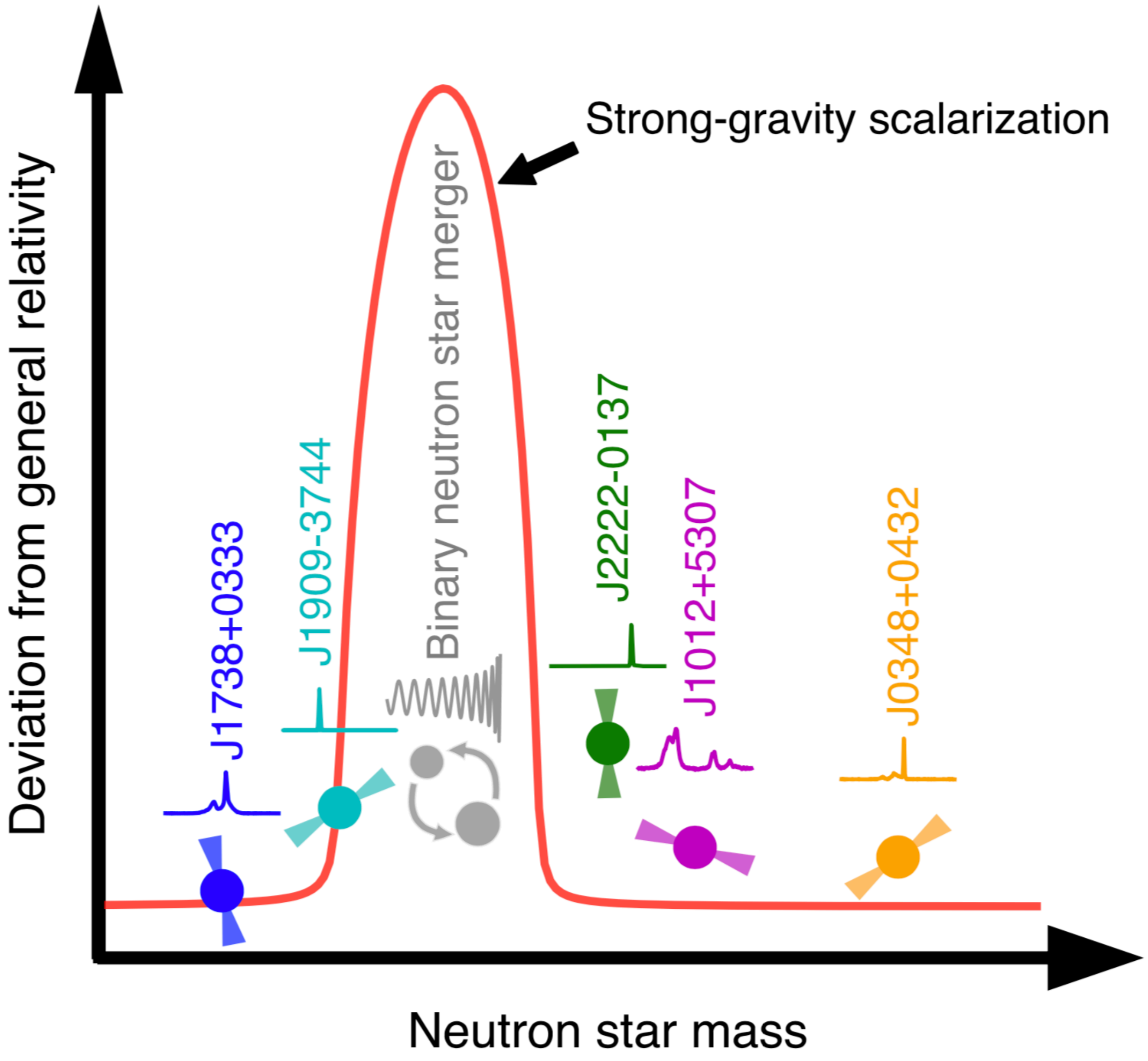

© Simonnet

**In addition, coincident observation with various electromagnetic signals probes the speed of gravity, implicating cosmology**

LVC 2017, PRL 119:161101
LVC, Fermi, INTEGRAL 2017, ApJ 848:L13


© NASA

# Complementarity with pulsars and BNSs



**If future GW detectors can observe BNSs with masses around 1.6—1.7 Msun, a *scalarization window* will be closed**

Shao et al. 2017, PRX 7:041025

# Summary

- ✦ **Despite various confirmation of GR in Solar System, in strong field gravitation might deviate from GR in a noticeable way**

- ✦ **Pulsars and GW detectors are superb laboratories to study SFG**
  - ✓ post-Newtonian dynamics
  - ✓ GW radiation (extra channels)
  - ✓ no-hair theorem
  - ✓ speed of gravity
  - ✓ …

- ✦ **Pulsars and GW detectors are complementary in testing SFG in many ways, and a new horizon of experimental gravity is ahead of us**

# *Thank you!*