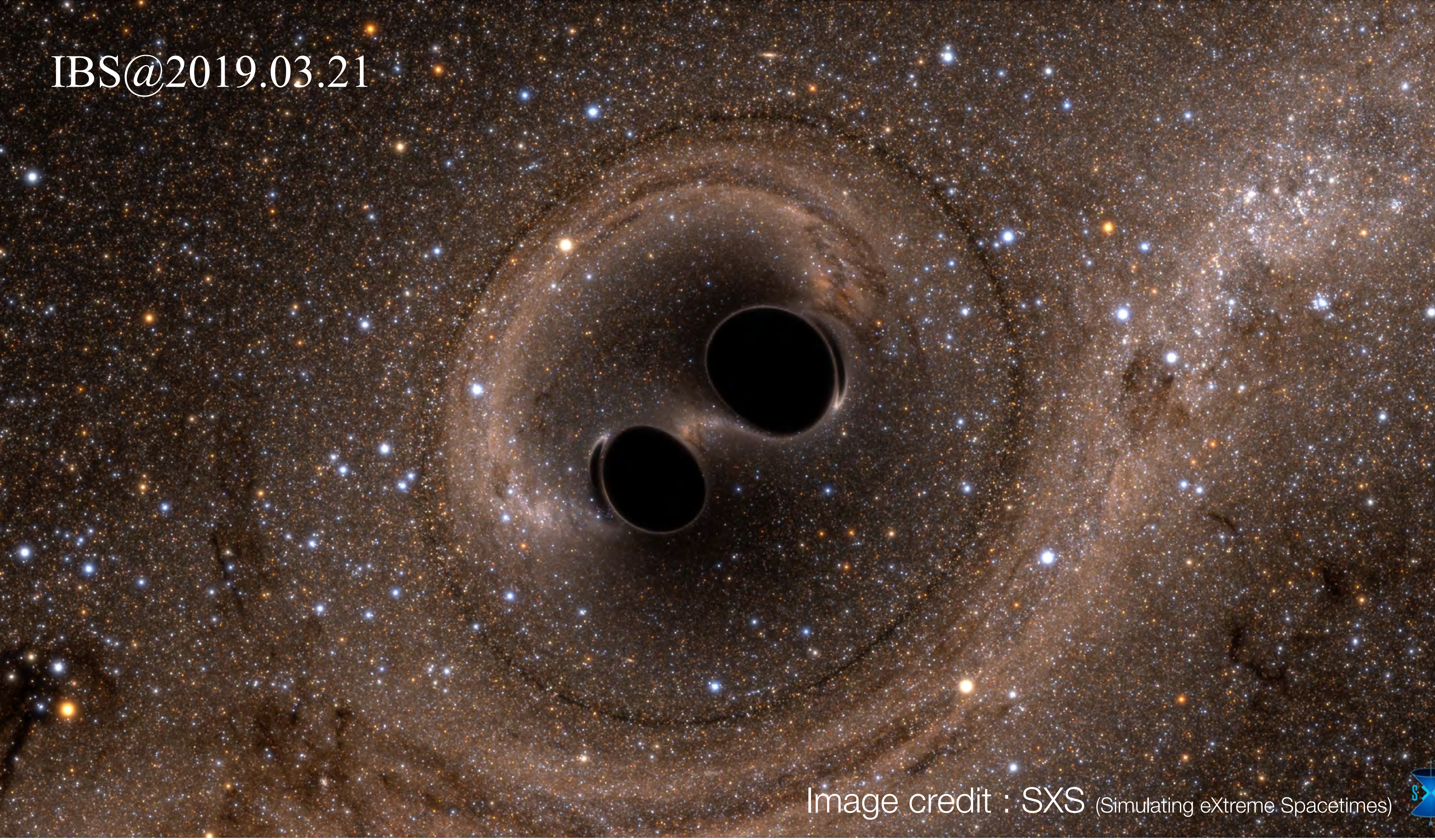


Tidal deformability of neutron stars and gravitational waves

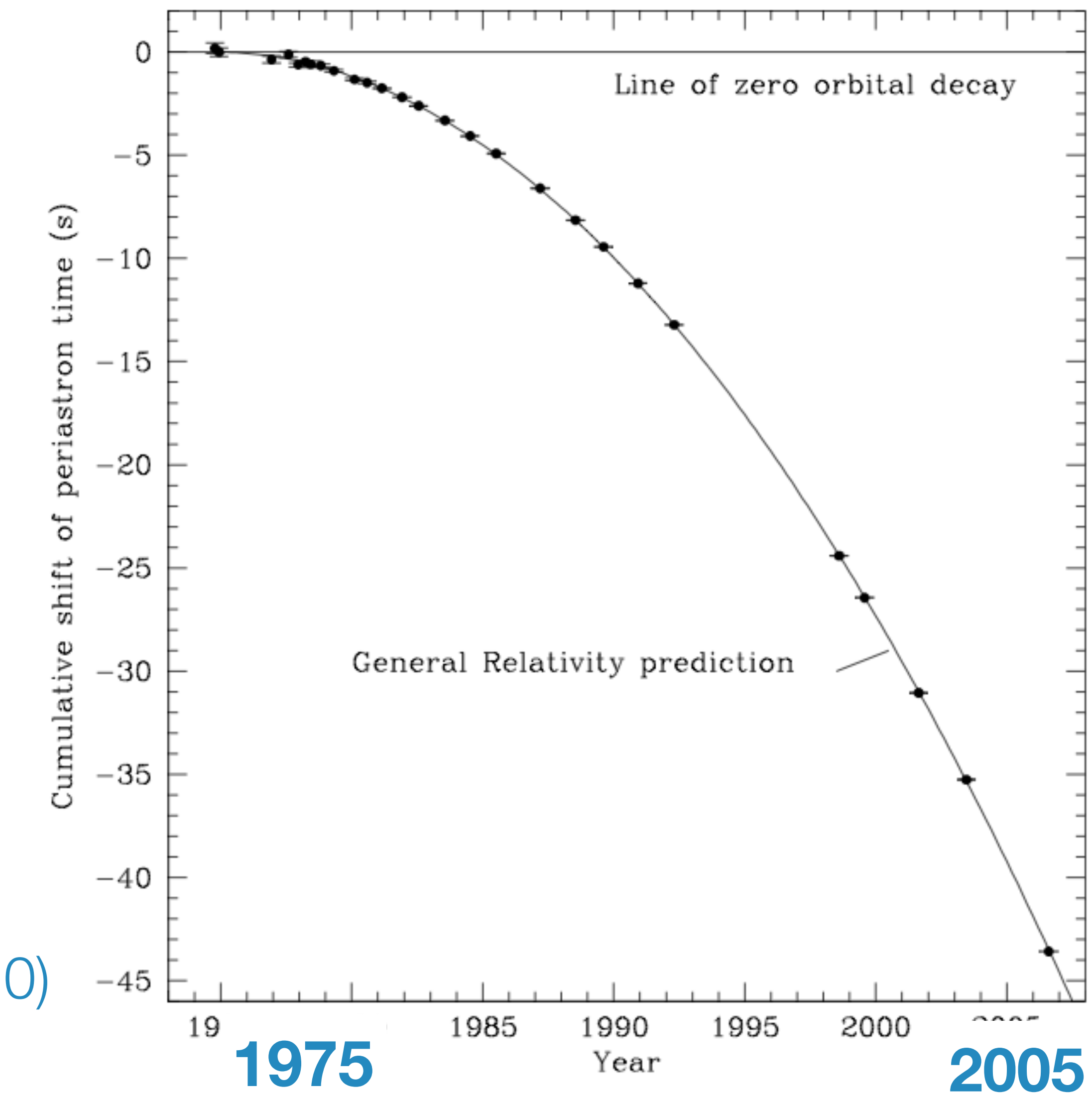
Chang-Hwan Lee
Pusan National University

Contents

- **Motivation**
- Neutron star physics before GW detection
- NS in new era of GW & multi-messenger astronomy
  - Direct measurement of NS mass from GW
  - Tidal Love number/deformability of NS from GW
- Prospects

Gravitational waves from neutron star binaries

- B1913+16 / Hulse & Taylor (1975)
- change in the orbital period due to GW radiation
- 1993 Nobel Prize
- LIGO is based on
  NS binary mergers
- GW expected in **2019**
  d = O(100 Mpc)



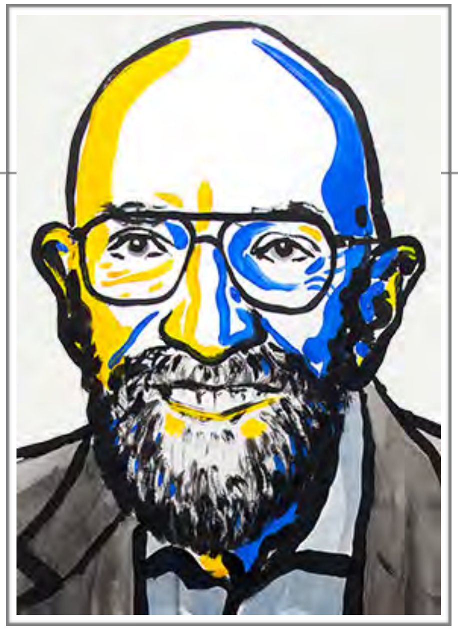
Weisberg, Nice, Taylor, ApJ (2010)

NS (radio pulsar) which will coalesce within Hubble time

PSR	P (ms)	P_b (hr)	e	Total Mass $M_\odot$	τ_c (Myr)	$\tau_{\rm GW}$ (Myr)	
J0737−3039A	22.70	2.45	0.088	2.58	210	87	(2003)
J0737−3039B	2773	2.45	0.088	2.58	50	87	(2004)
B1534+12	37.90	10.10	0.274	2.75	248	2690	(1990)
J1756−2251	28.46	7.67	0.181	2.57	444	1690	(2004)
B1913+16	59.03	7.75	0.617	2.83	108	310	(1975)
B2127+11C	30.53	8.04	0.681	2.71	969	220	(1990)
J1141−6545†	393.90	4.74	0.172	2.30	1.4	590	(2000)

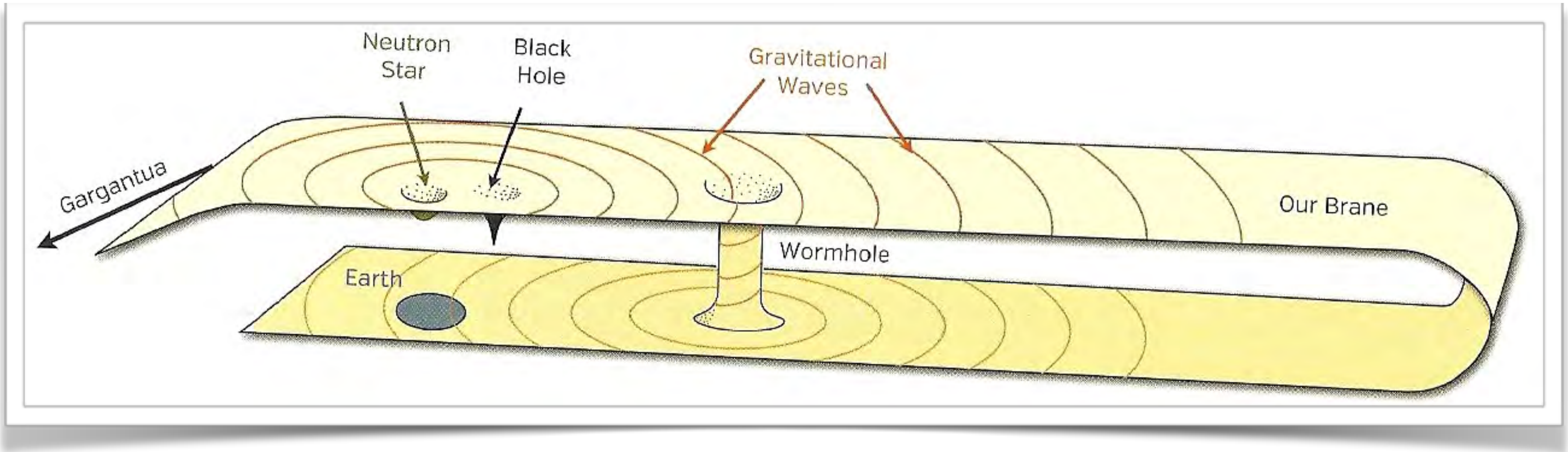
Interstellar original scenario by kip Thorne

2017 Nobel Prize

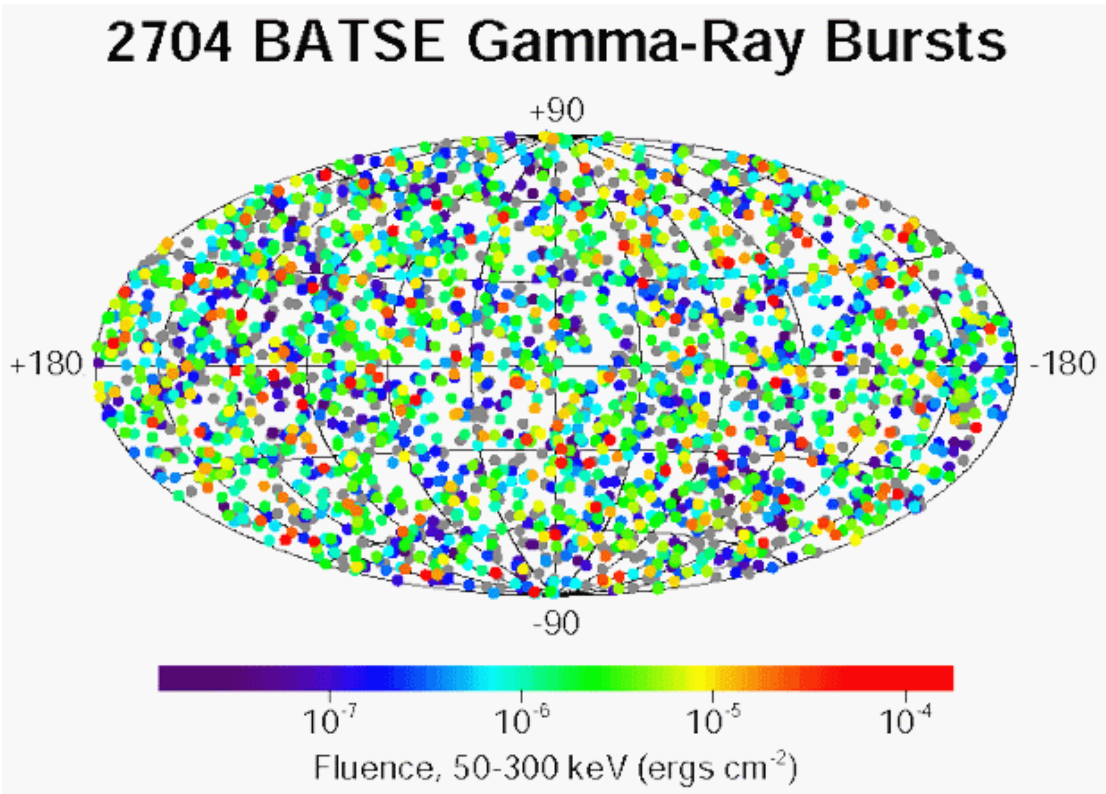


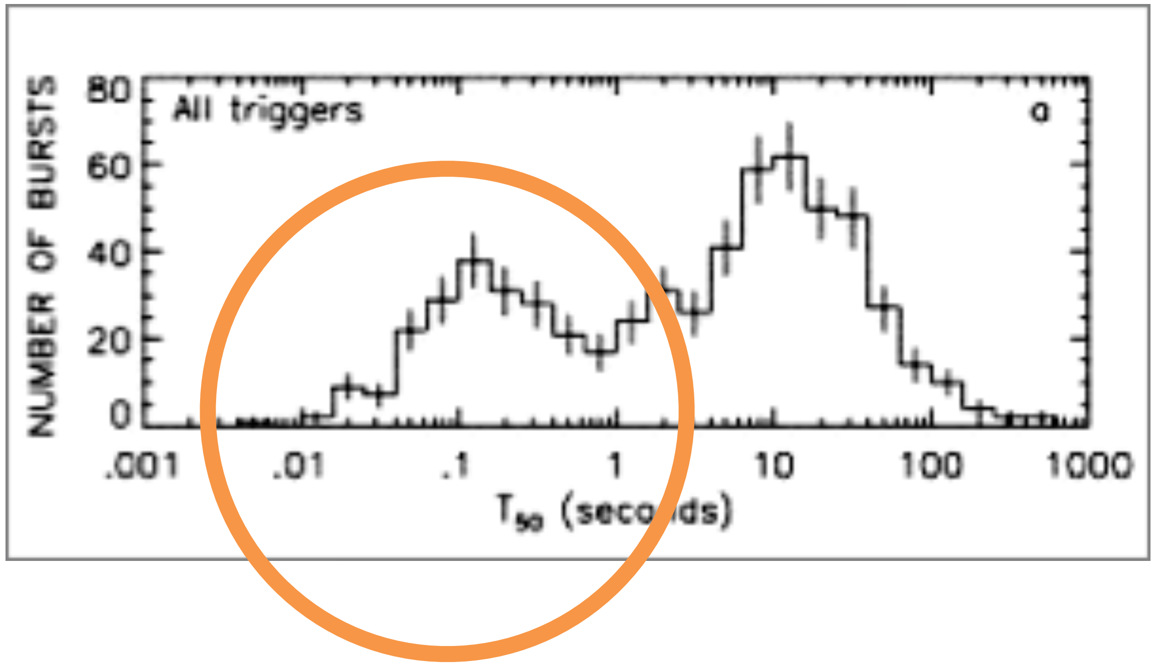
- 2019 LIGO detected GW from Saturn
  - GW from BH/NS binary mergers
  - No BH/NS near Saturn
  - Existence of a Warm Hole near Saturn

- Interstellar starts 40 years after GW detection from Saturn

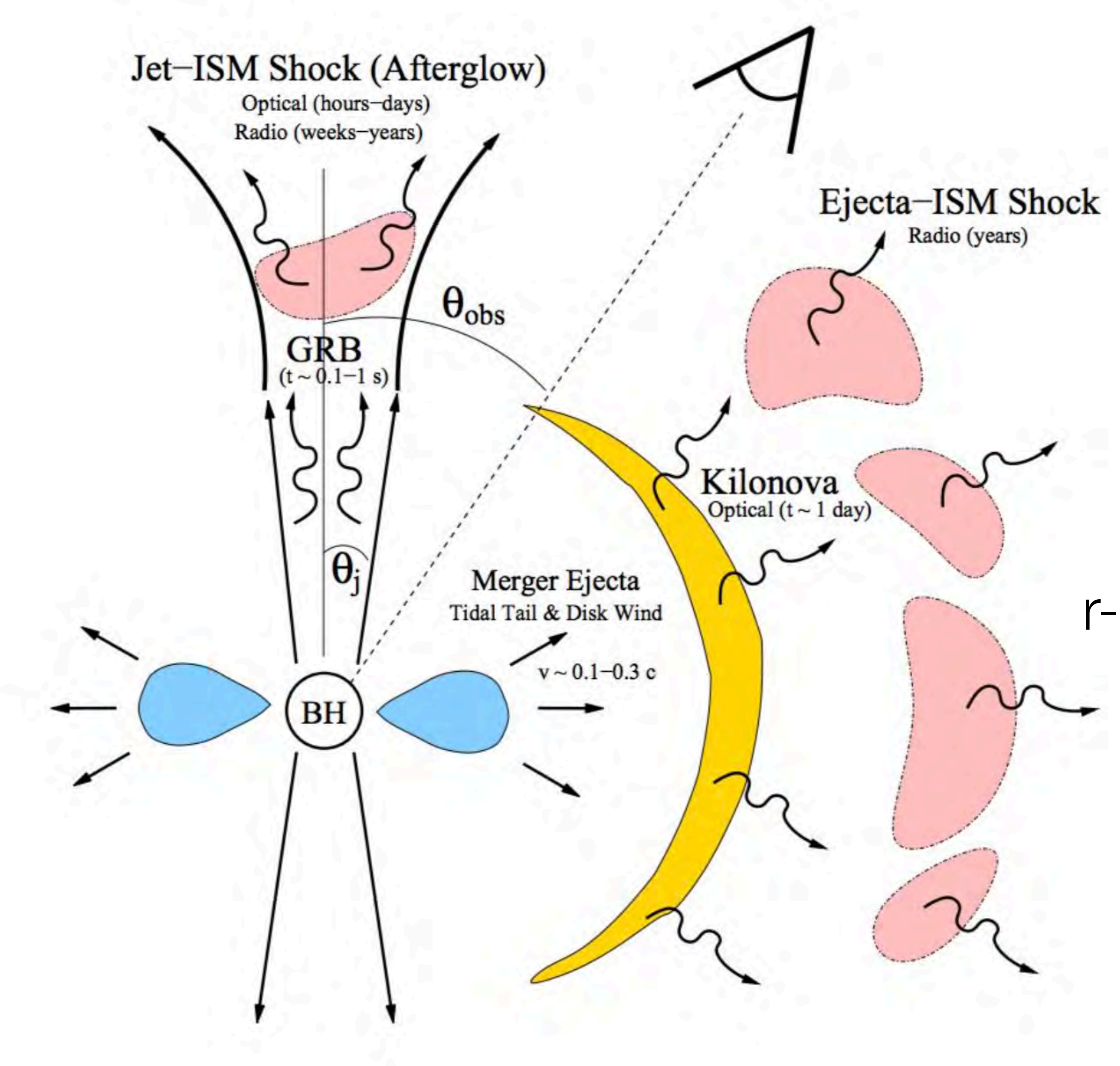


sGRB short-hard gamma-ray bursts from NS mergers





GRB and Kilonova from NS binaries



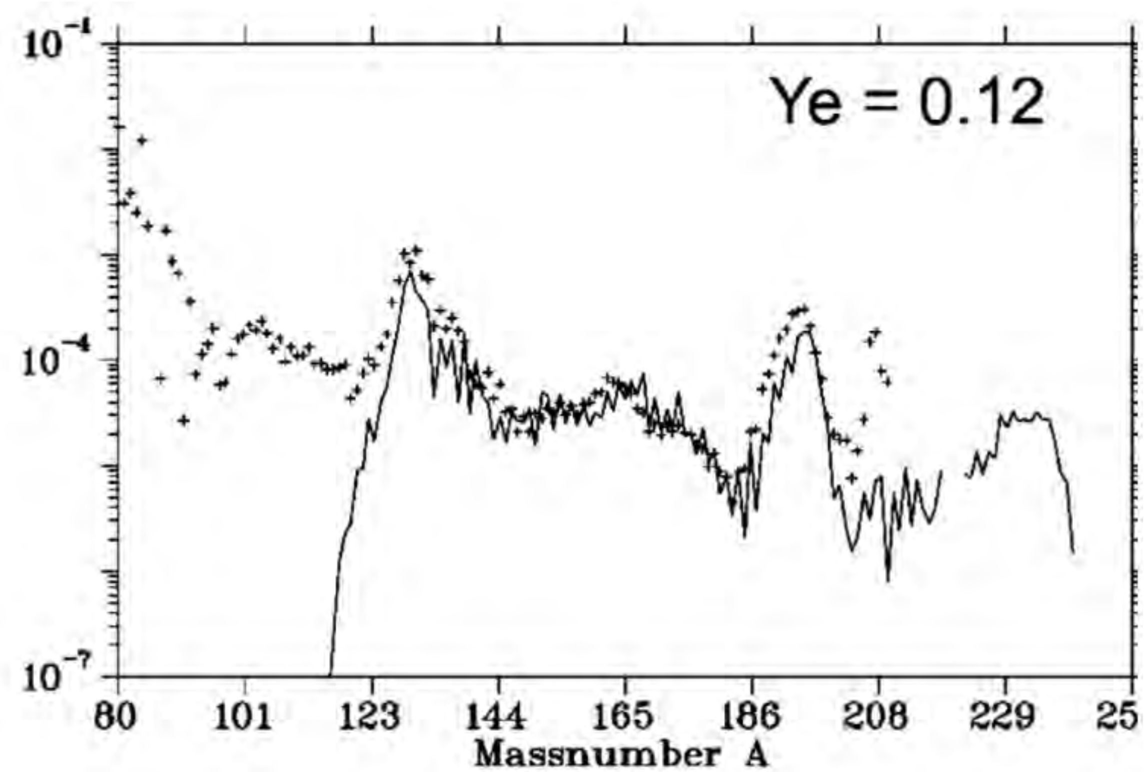
r-process **peak at A~195**

Metzger and Berger 2012

Heavy Elements from NS mergers

Sources of Heavy Elements

S Rosswog 2015



solar pattern vs NS-merger

- **Supernovae:**
  neutrino-driven wind
  r-process **peak at A~130**
- **NS mergers:**
  r-process **peak at A~195**

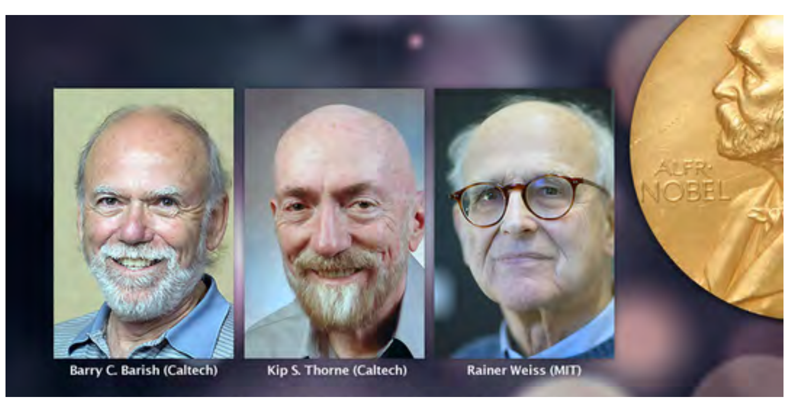
Press Release Oct 16, 2017

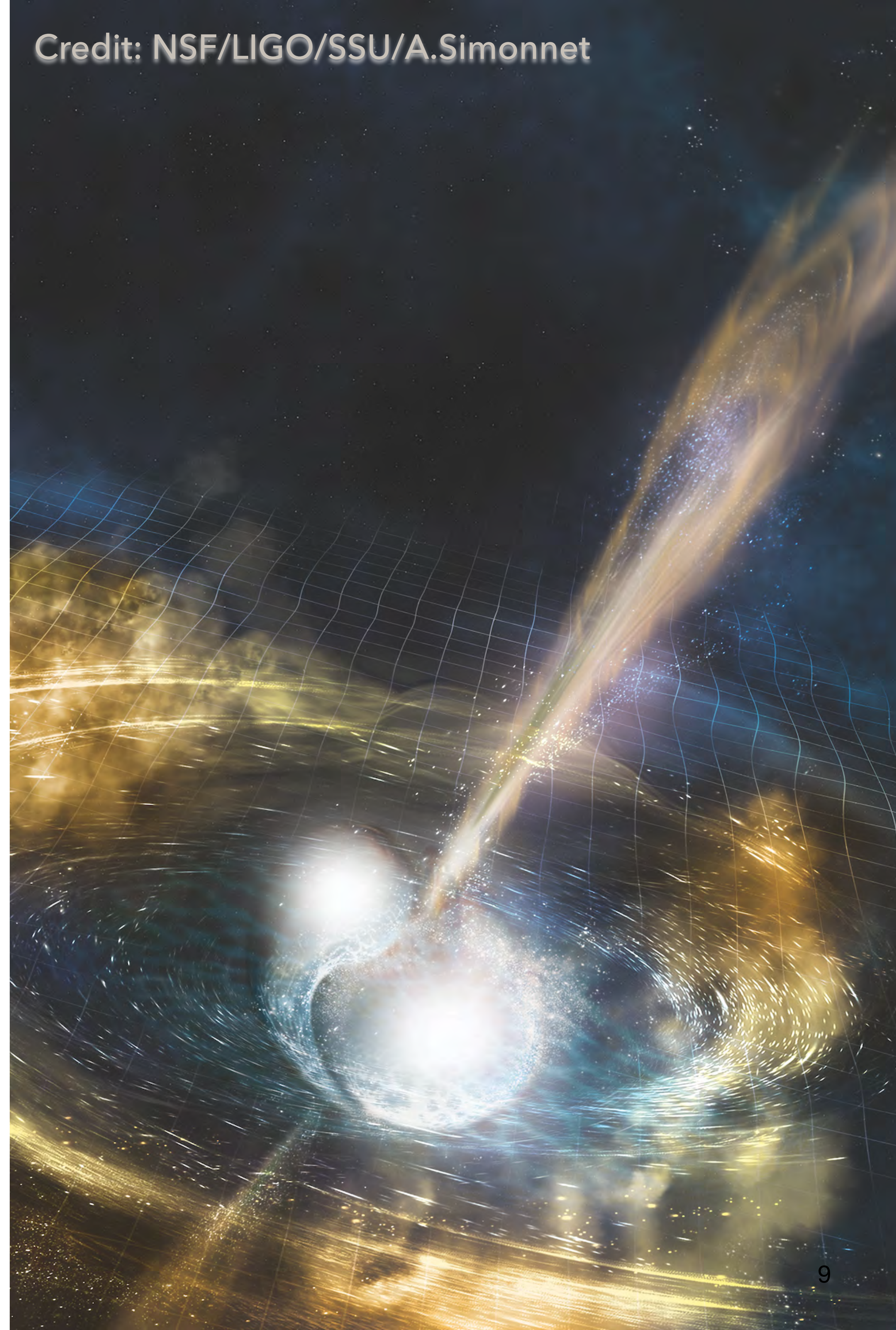
GW from Binary NS Mergers

*GW 170817 (**d=40 Mpc**)*
GRB 170817A by Fermi-GBM
Kilonova/X-ray/Optical Afterglows

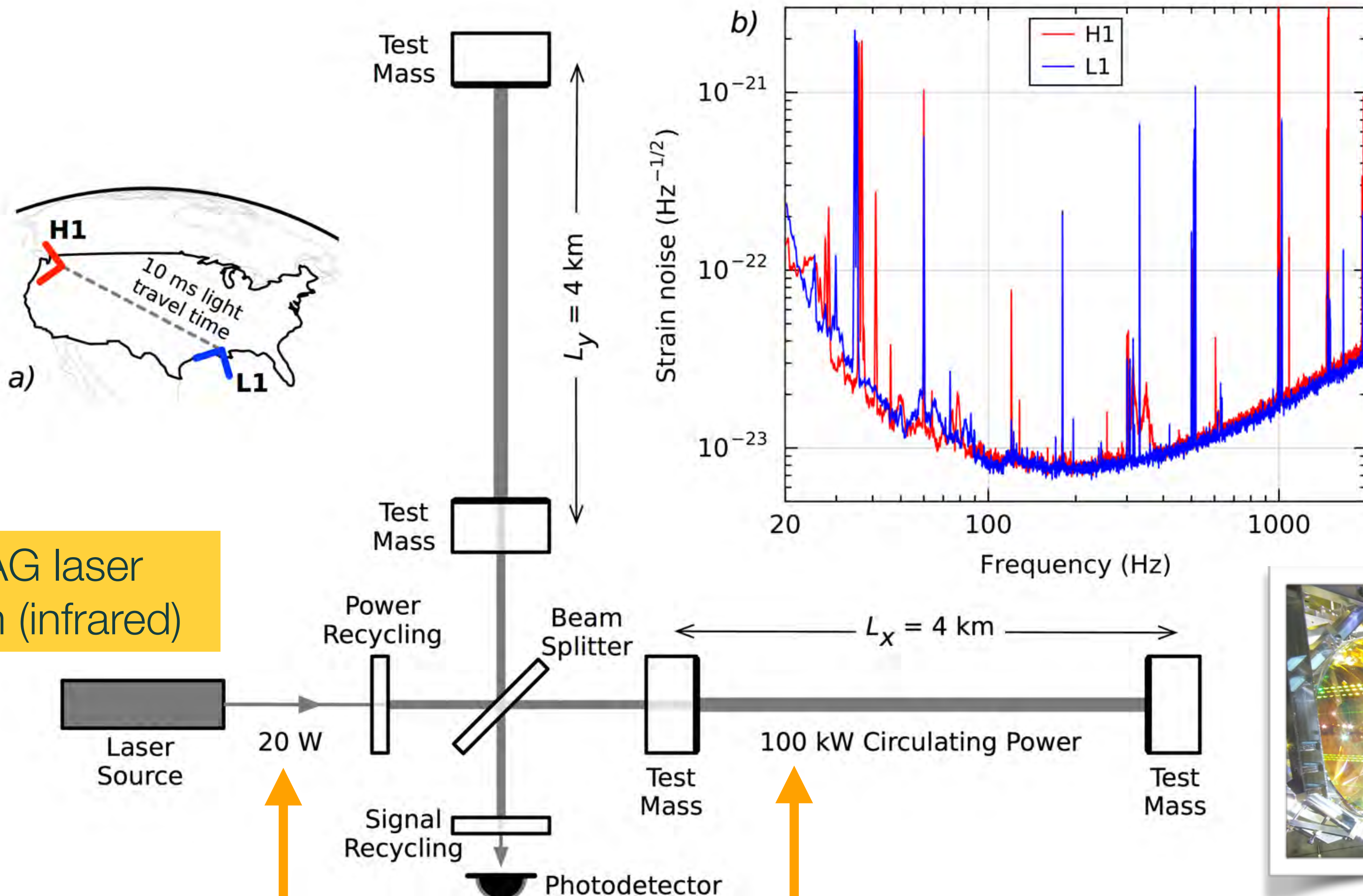
---

soon after the announcement of 2017 Nobel Prize





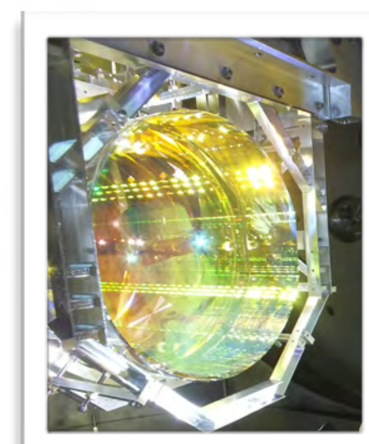
Laser Interferometer Gravitational-wave Observatory



Nd:YAG laser
1064nm (infrared)

Goal 200 W

Goal 750 kW



40kg fused Silica (SiO_2)
(absorption < 1ppm)

Sensitivity of Interferometers

한국 중력파 연구 협력단
Open Collaboration for the Gravitational Wave Detection and its Application

If the length resolution is λ_{laser}, detectable strain is

$$h \equiv \frac{\Delta l}{l} = \frac{\lambda_{laser}}{l} = \frac{10^{-6}\mathrm{m}}{10^{3}\mathrm{m}} = 10^{-9}$$

Fabry-Perot cavity (~ 250 bounces) : $\lambda_{\mathrm{GW}} \sim 1000 \text{ km for } 300 \text{ Hz}$

$$h \sim \frac{\Delta l}{l_{eff}} \sim \frac{\lambda_{laser}}{\lambda_{GW}} \sim \frac{10^{-6}\mathrm{m}}{10^{6}\mathrm{m}} = 10^{-12}$$

Due to quantum nature of the photons, the length resolution could be reduced

$$h \sim \frac{1}{\sqrt{N_{photons}}} \frac{\lambda_{laser}}{\lambda_{GW}}$$

Measuring the phase shift by averaging over some period τ

Poisson distribution

$$p(N) = \frac{\bar{N}^N \exp\left(-\bar{N}\right)}{N!}, \quad \Delta N = \sqrt{\bar{N}}$$

N: measured number of photons over period τ

$$E = \hbar \frac{2\pi c}{\lambda_l} N \rightarrow \Delta E = \hbar \frac{2\pi c}{\lambda_l} \sqrt{\bar{N}}$$

Uncertainty in the phase measurement : $\Delta \Phi = 2\pi c \frac{\Delta t}{\lambda_l}$

$$\Delta t \Delta E \geq \frac{\hbar}{2} \rightarrow \Delta t \Delta E = \frac{\Delta \Phi \lambda_l}{2\pi c} \hbar \frac{2\pi c}{\lambda_l} \sqrt{\bar{N}} \geq \frac{\hbar}{2}$$

$$\rightarrow \Delta \Phi \geq \frac{1}{\sqrt{\bar{N}}} \rightarrow N \geq \frac{1}{2(\Delta \Phi)^2}$$

Shot noise

Collect photons for a time of the order of the period of GW wave

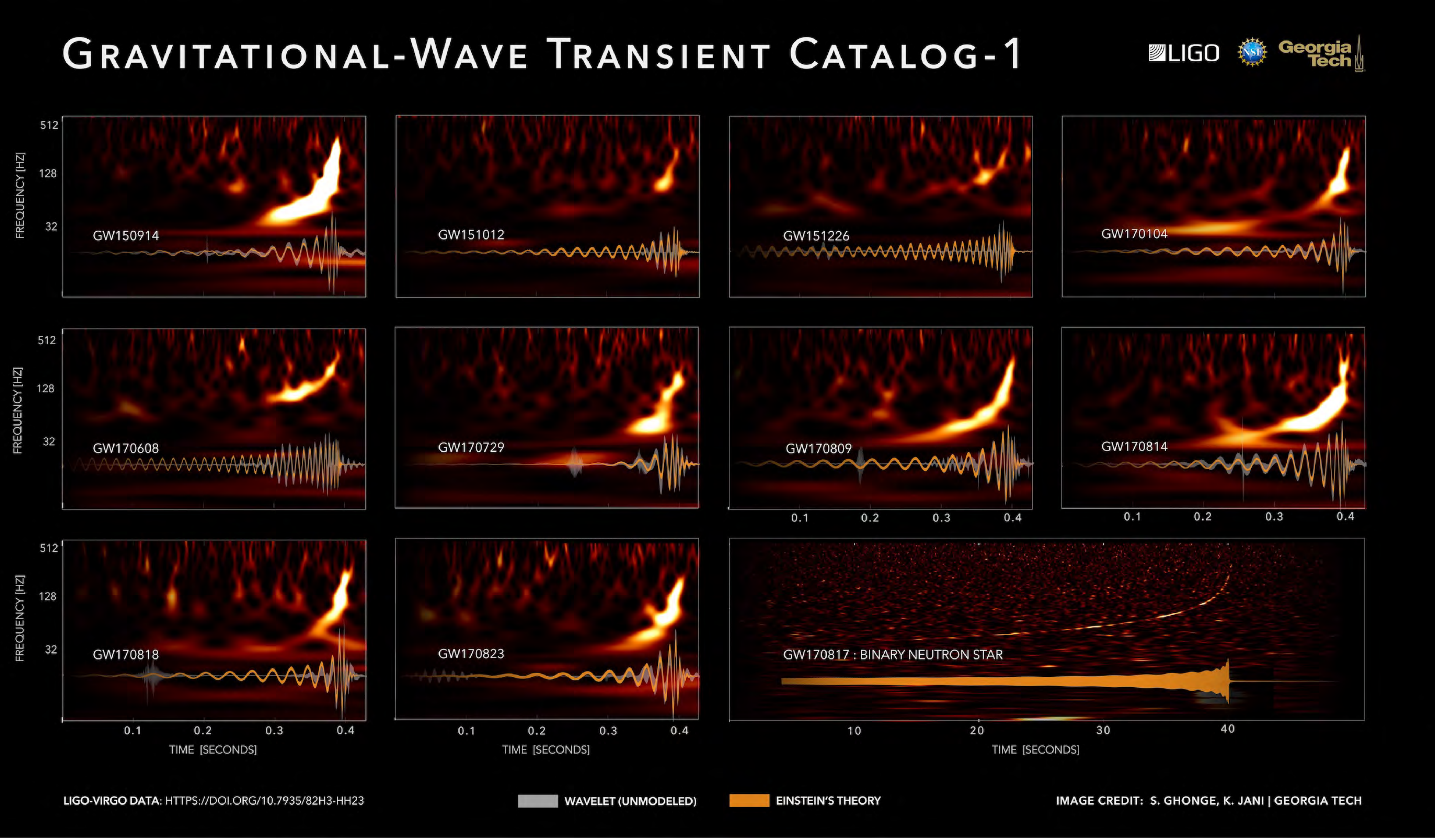
$$\tau \sim 1/f_{GW}$$

$$N_{photons} = \frac{P_{laser}}{hc/\lambda_{laser}}\tau \sim \frac{P_{laser}}{hc/\lambda_{laser}}\frac{1}{f_{GW}}$$

For 1W laser with λ_{laser}=1 μm, f_{GW}=300Hz, $N_{photons}$=10^{16}

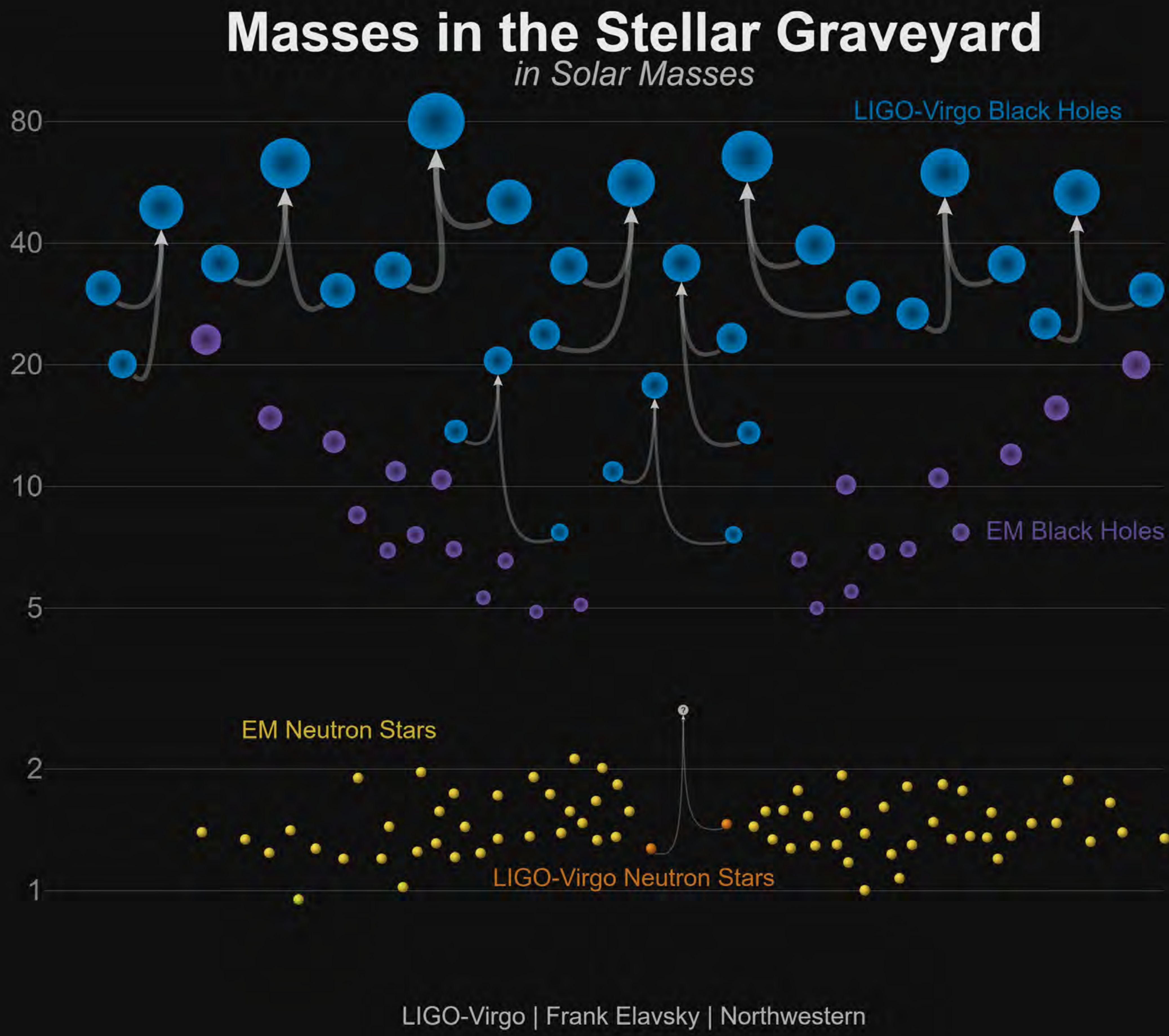
$$h \sim \frac{\Delta l}{l_{eff}} \sim \frac{N_{photons}^{-1/2}\lambda_{laser}}{\lambda_{GW}} \sim \frac{10^{-8} \times 10^{-6}\mathrm{m}}{10^{6}\mathrm{m}} = 10^{-20}$$

By adopting high power laser (20W for O1) and Power Recycling, we can reach 'astrophysical sensitivity' of ~10^{-22}.

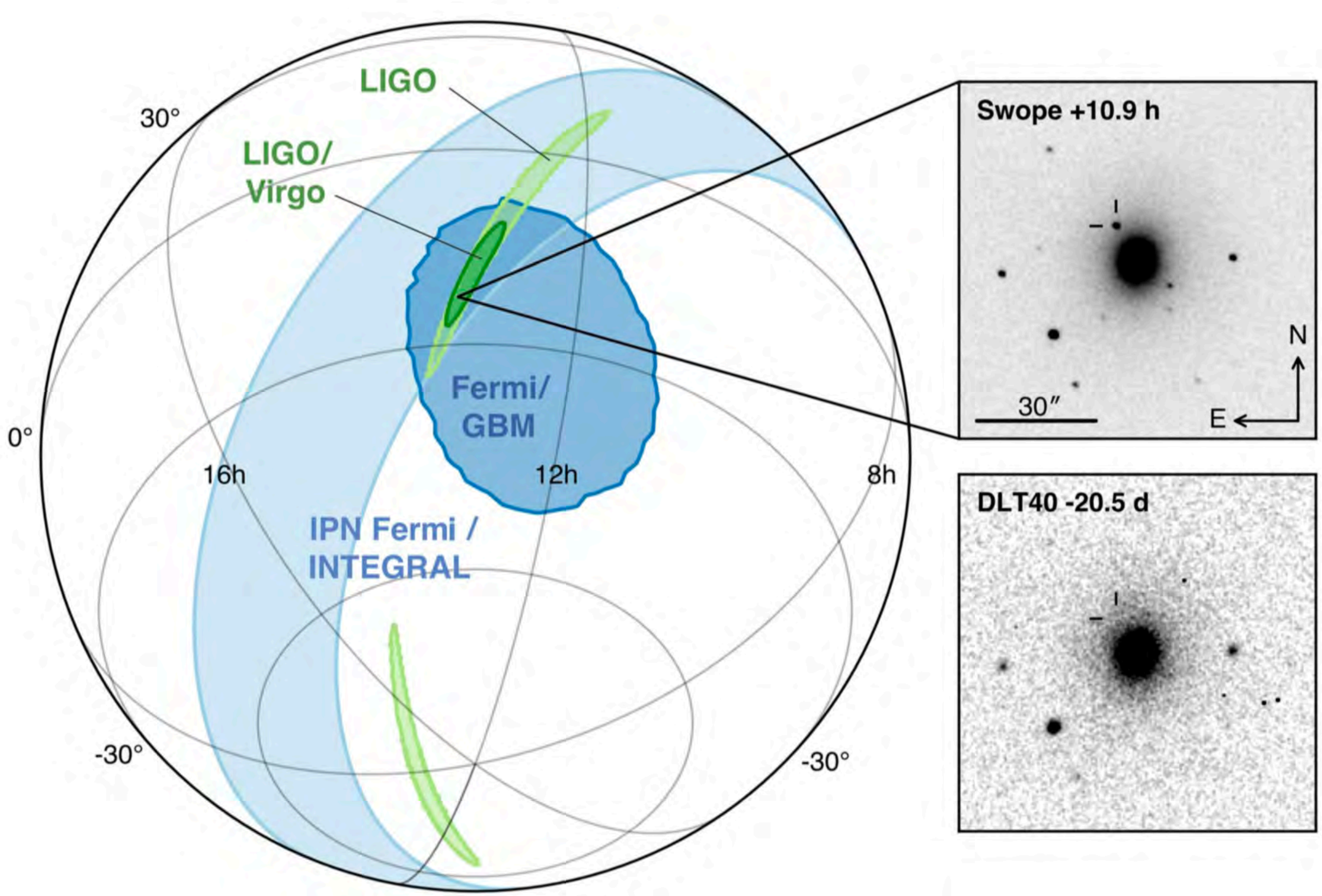


GW Catalog

2018.12.05


Masses in the Stellar Graveyard
in Solar Masses
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
80
40
20
10
5
2
1
LIGO-Virgo | Frank Elavsky | Northwestern

GW170817 / GRB170817A

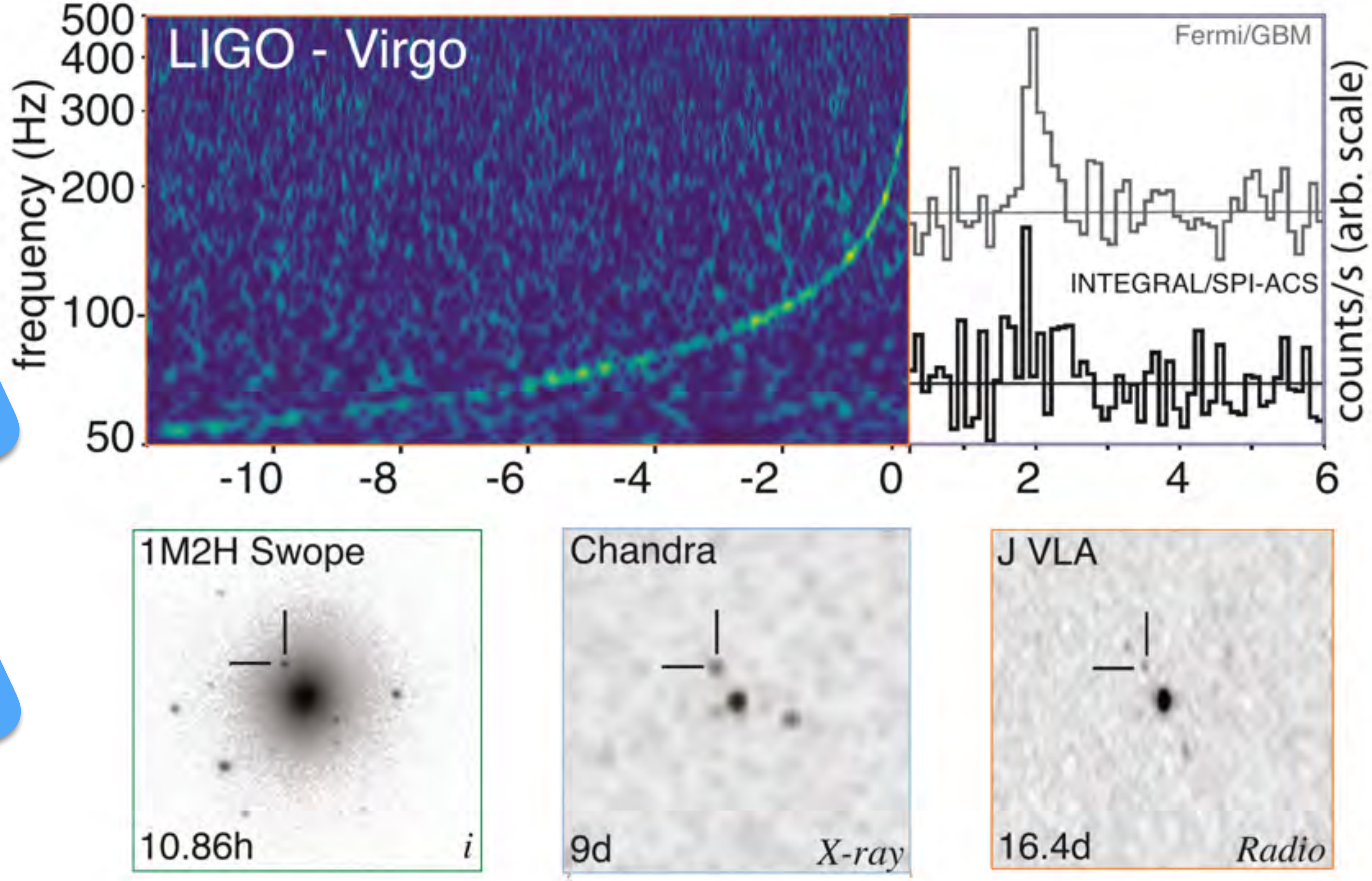


First event of Multi-messenger Astronomy

GW170817

GRB170817A

SSS17a/
AT2017gfo



ApJL.848.L12(2017)

TIMELINE

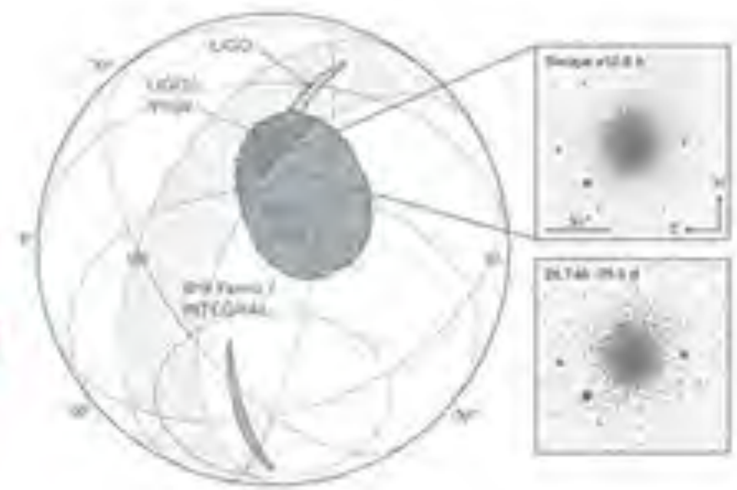
중성자별 충돌에서 발생한 중력파, 감마선, 가시광선, 엑스선 및 전파 관측

2017.08.17.
12:41:04 UTC

라이고 및 비르고
중력파 신호
포착

+2
seconds

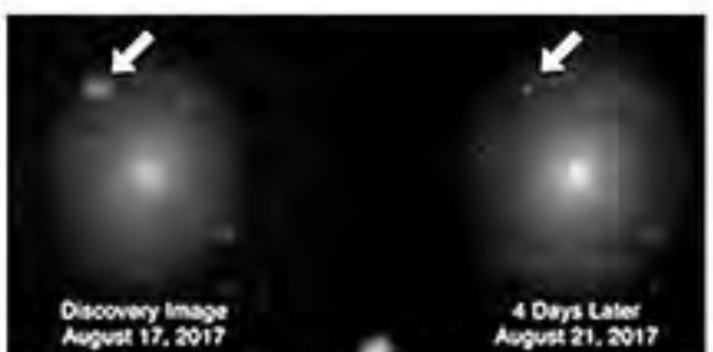
페르미 및 인티그랄
감마선 신호
포착



Fermi/Integral gamma-ray

+11
hours

칠레 천문대
망원경들이
가시광선 신호
포착



Telescopes in Chile

http://horizon.kias.re.kr

Korean Telescopes
Nature 551, 71 (2017)

+21 hours

국내연구진 호주
이상각망원경으로
추적 관측 시작
이후 약 4주간
추적 관측
(KMTNet, BOOTES-5
망원경 등)

Chandra X-ray

+9 Days

찬드라
우주망원경
X선 신호
포착

VLA radio

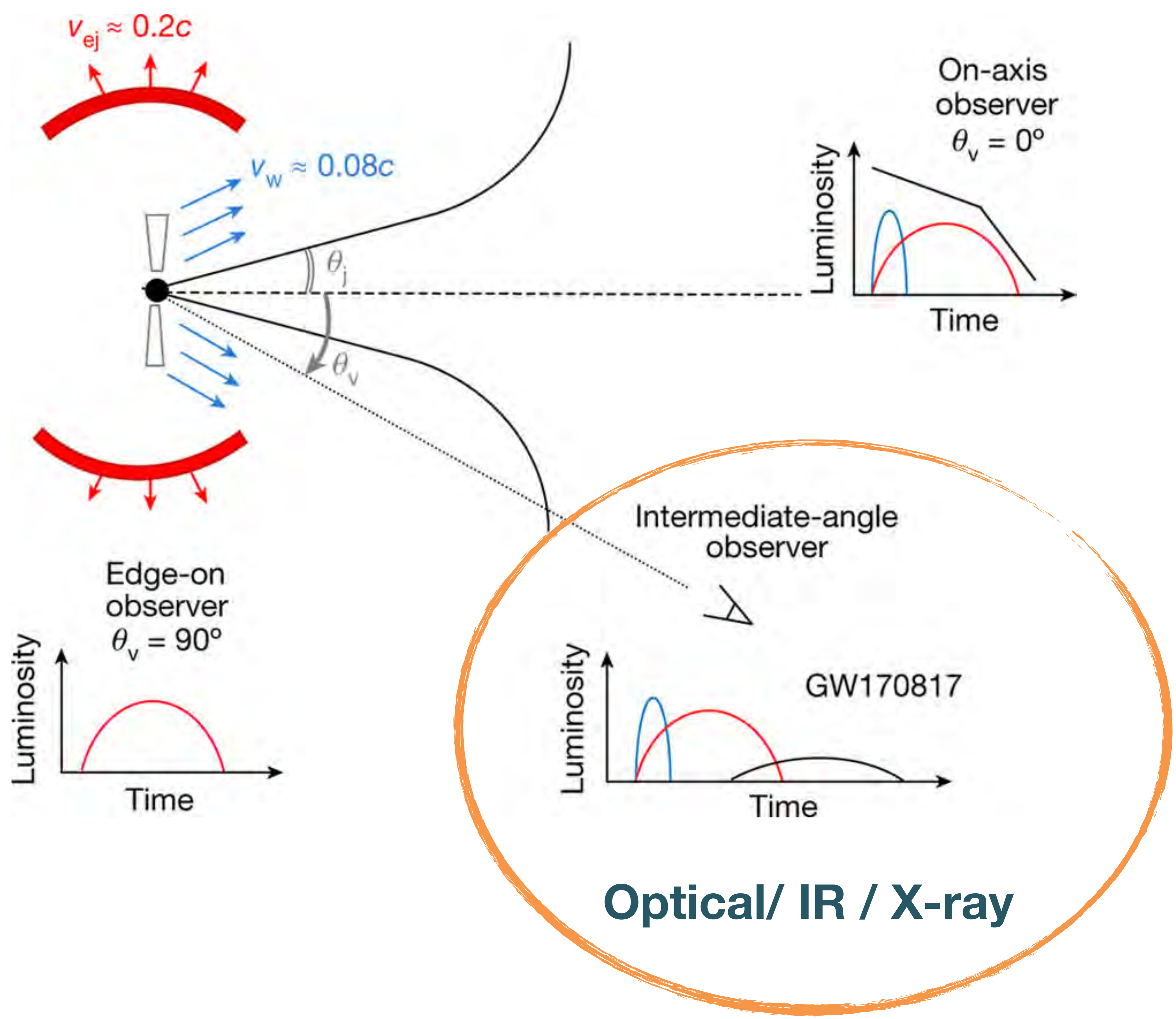
+16 Days

지상 전파 망원경
전파 신호
포착

http://horizon.kias.re.kr

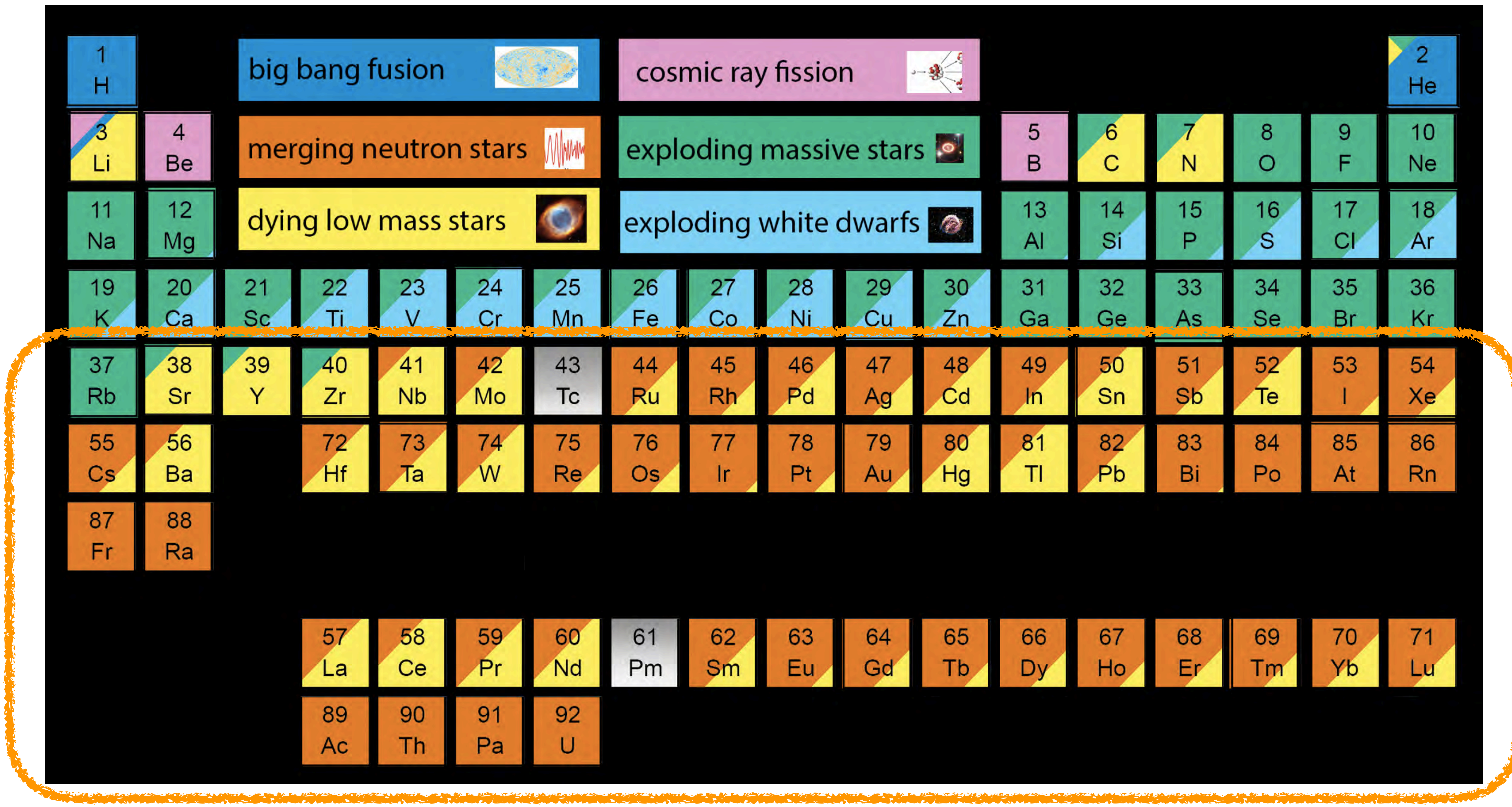
Kilonova / Geometry of GW170817

Nature 551, 71 (2017)



Origin of Solar System Elements

merging neutron stars



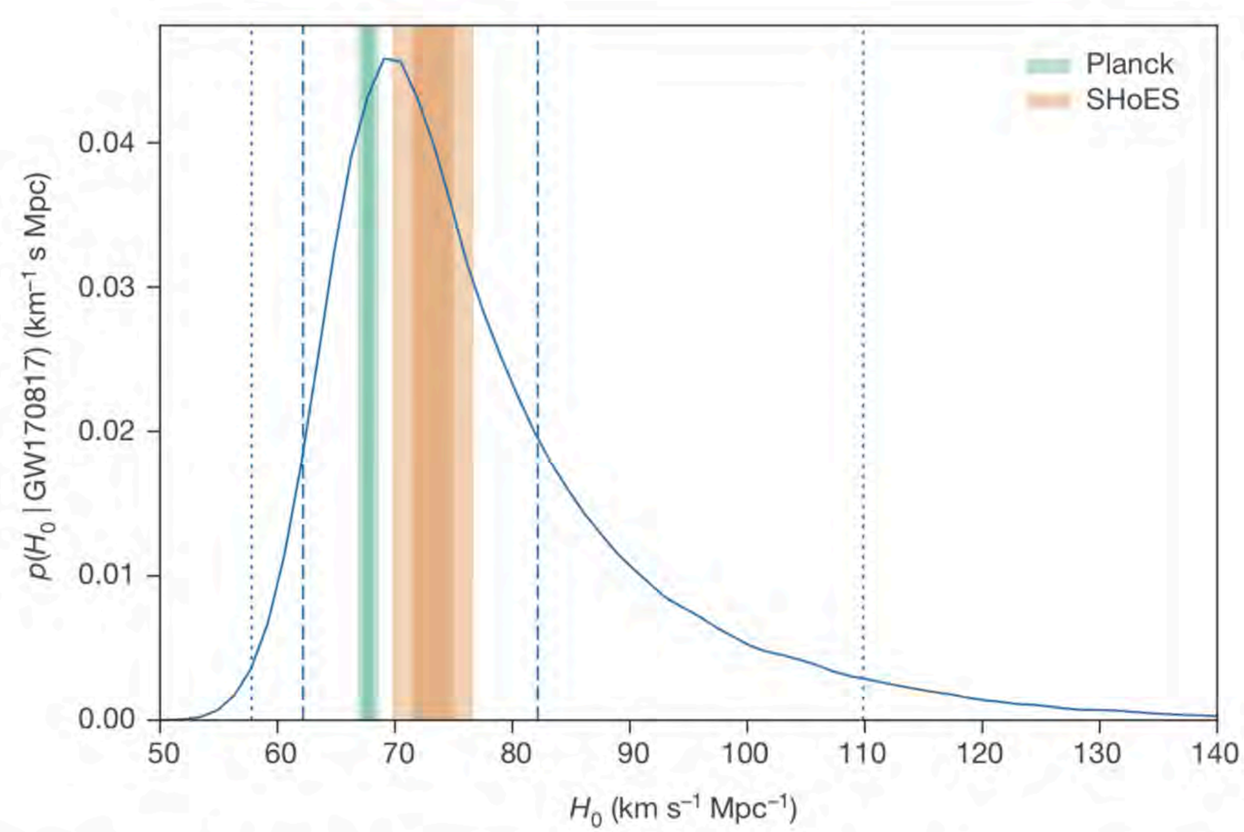
LETTER

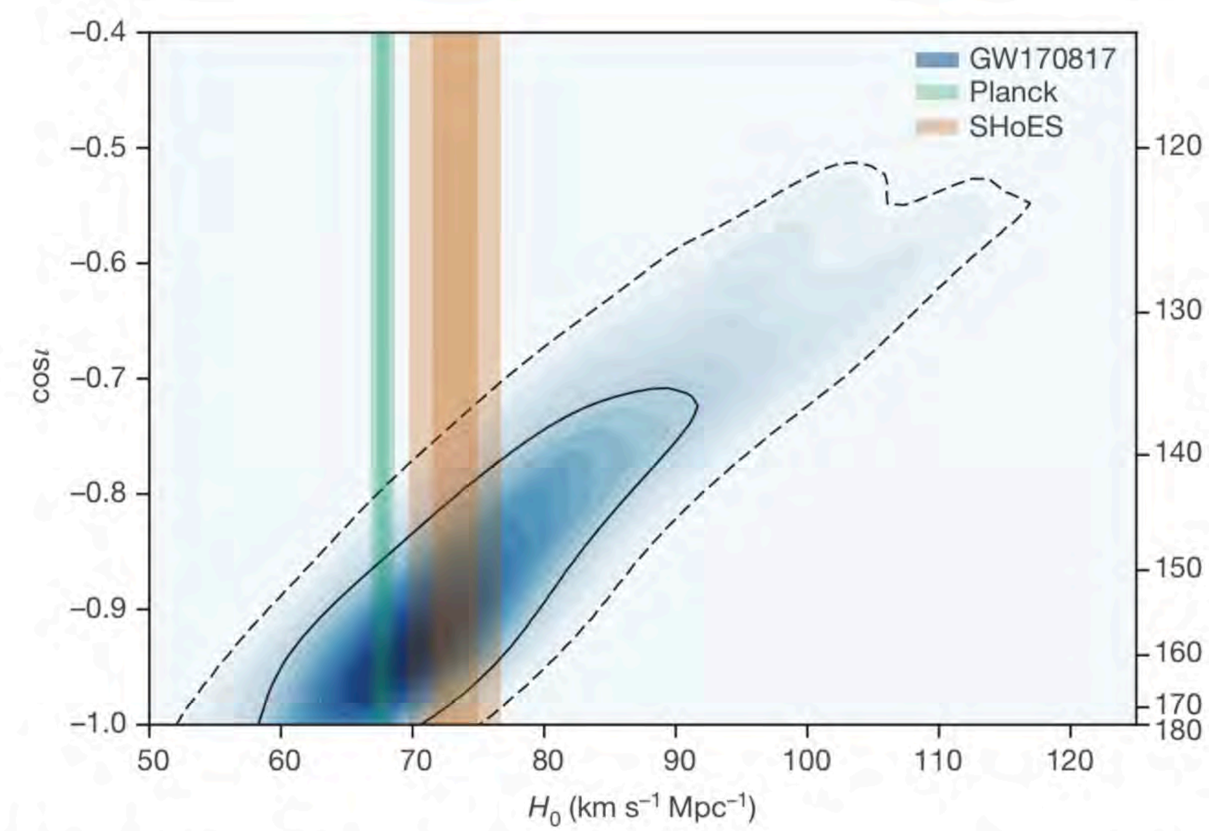
doi:10.1038/nature24471

A gravitational-wave standard siren measurement of the Hubble constant

The LIGO Scientific Collaboration and The Virgo Collaboration*, The 1M2H Collaboration*, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration*, The DLT40 Collaboration*, The Las Cumbres Observatory Collaboration*, The VINROUGE Collaboration* & The MASTER Collaboration*

$$H_0 = 70.0^{+12.0}_{-8.0}\ \mathrm{km\ s^{-1}\,Mpc^{-1}}$$

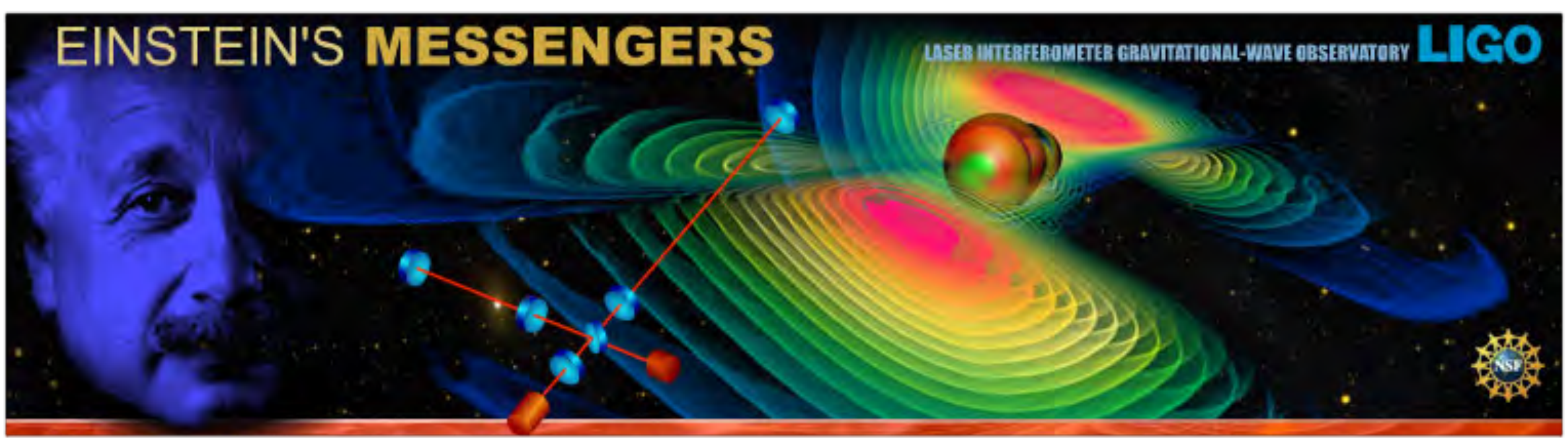




2 NOVEMBER 2017 | VOL 551 | NATURE | 85

Gravitational-Wave & Multi-Messenger Astronomy

- First direct detection of GW in 2015
- First detection of BHs with masses 30 ~ 60 solar mass
- **GW, Gamma-ray, Optical, X-ray, Radio from NS mergers**
- New era for GW Astronomy & **Multi-Messenger Astronomy**



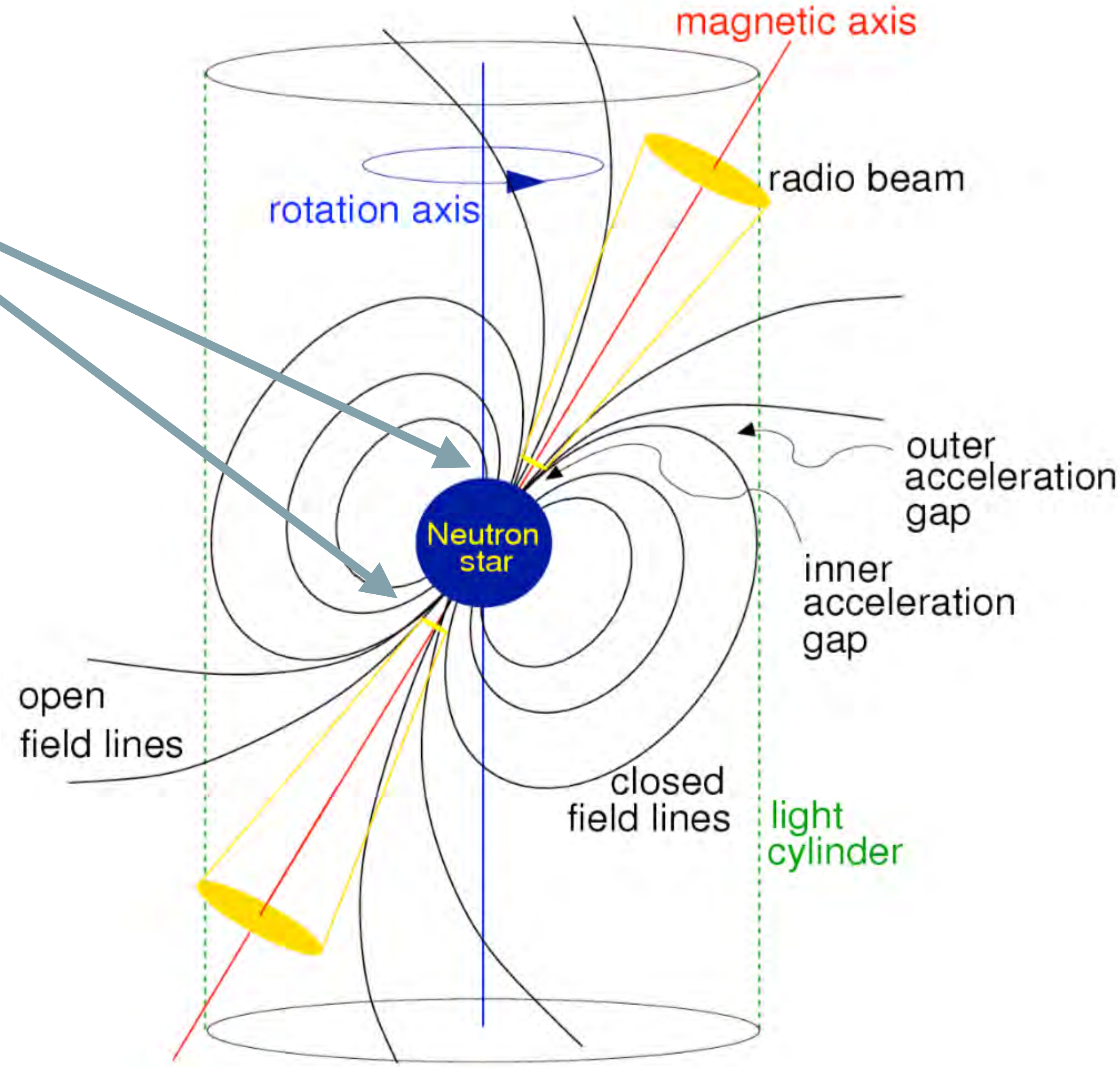
Contents

- Motivation
- **Neutron star physics before GW detection**
- NS in new era of GW & multi-messenger astronomy
  - Direct measurement of NS mass from GW
  - Tidal Love number/deformability of NS from GW
- Prospects

Why Neutron Stars ?

Ultimate testing place for physics of dense matter

e^+e^- pair creation



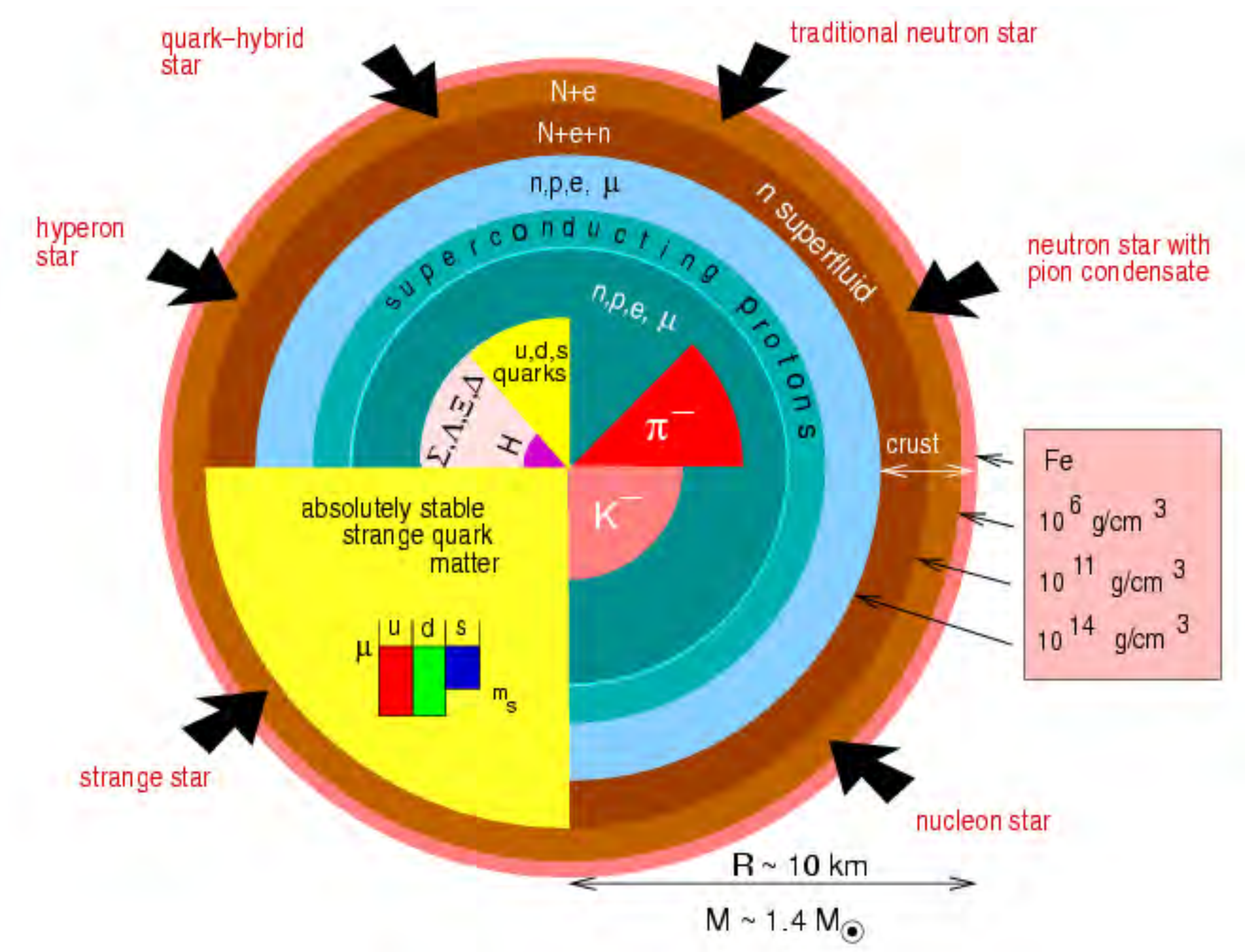
$$M = 1.5 \sim 2.0 M_\odot$$
$$R = 10 \sim 15 \text{ km}$$
$$A \sim 10^{57} \text{ nucleons}$$

Nuclear matter is not an ideal gas

F. Weber 2005

Condensed Matter:
- *electron degeneracy*
- *EM interaction*

Neutron Star:
- *hadron (p,n) degeneracy*
- *strong interaction*

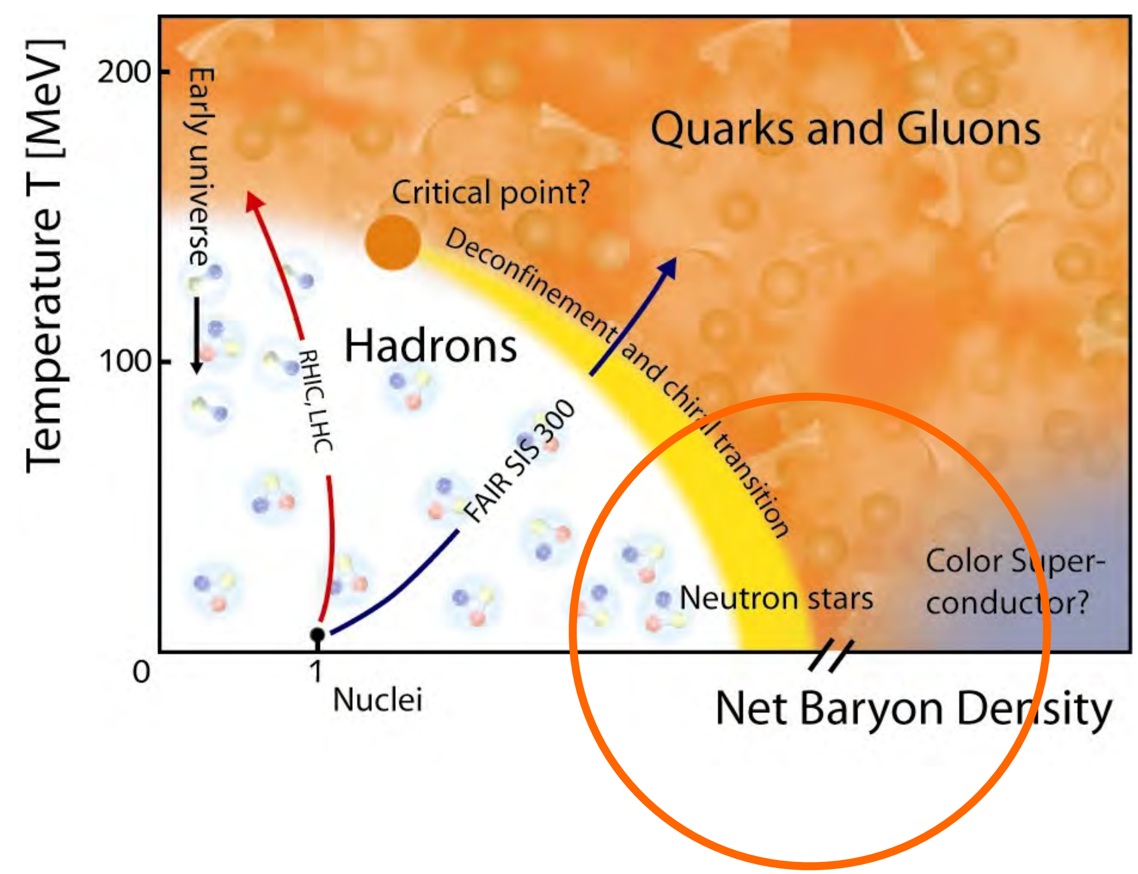


- **still uncertain due to the nature of strong interactions**
- **introduction of 3 body forces**
- **exotic states with strangeness**
- **… …**

Why Neutron Stars ?

Ultimate testing place for physics of dense matter

- ✓ chiral symmetry restoration
- ✓ color superconductivity
- ✓ color-flavor locking
- ✓ quark-gluon-plasma
- ✓ AdS/QCD
- ✓ symmetry energy
- ✓ tensor forces
- ✓ 3-body forces
- ✓ … …



Theomodynamics with General Relativity

$$P = P(\rho, T, \text{composition})$$
$$\kappa = \kappa(\rho, T, \text{composition})$$
$$\epsilon = \epsilon(\rho, T, \text{composition})$$

Hydrostatic equilibrium

$$\frac{dP}{dr} = -\frac{GM\rho}{r^2}$$

$$\frac{dP}{dr} = -\frac{GM\rho}{r^2}\left(1 + \frac{P}{\rho c^2}\right)\left(1 + \frac{4\pi P r^3}{Mc^2}\right)\left(1 - \frac{2GM}{rc^2}\right)^{-1}$$

Mass continuity

$$\frac{dM}{dr} = 4\pi r^2 \rho$$

$$\frac{dM}{dr} = 4\pi r^2 \left(\frac{\epsilon}{c^2}\right)$$

includes all energy sources

physics of dense nuclear matter (strong interaction)

Radiative energy transport

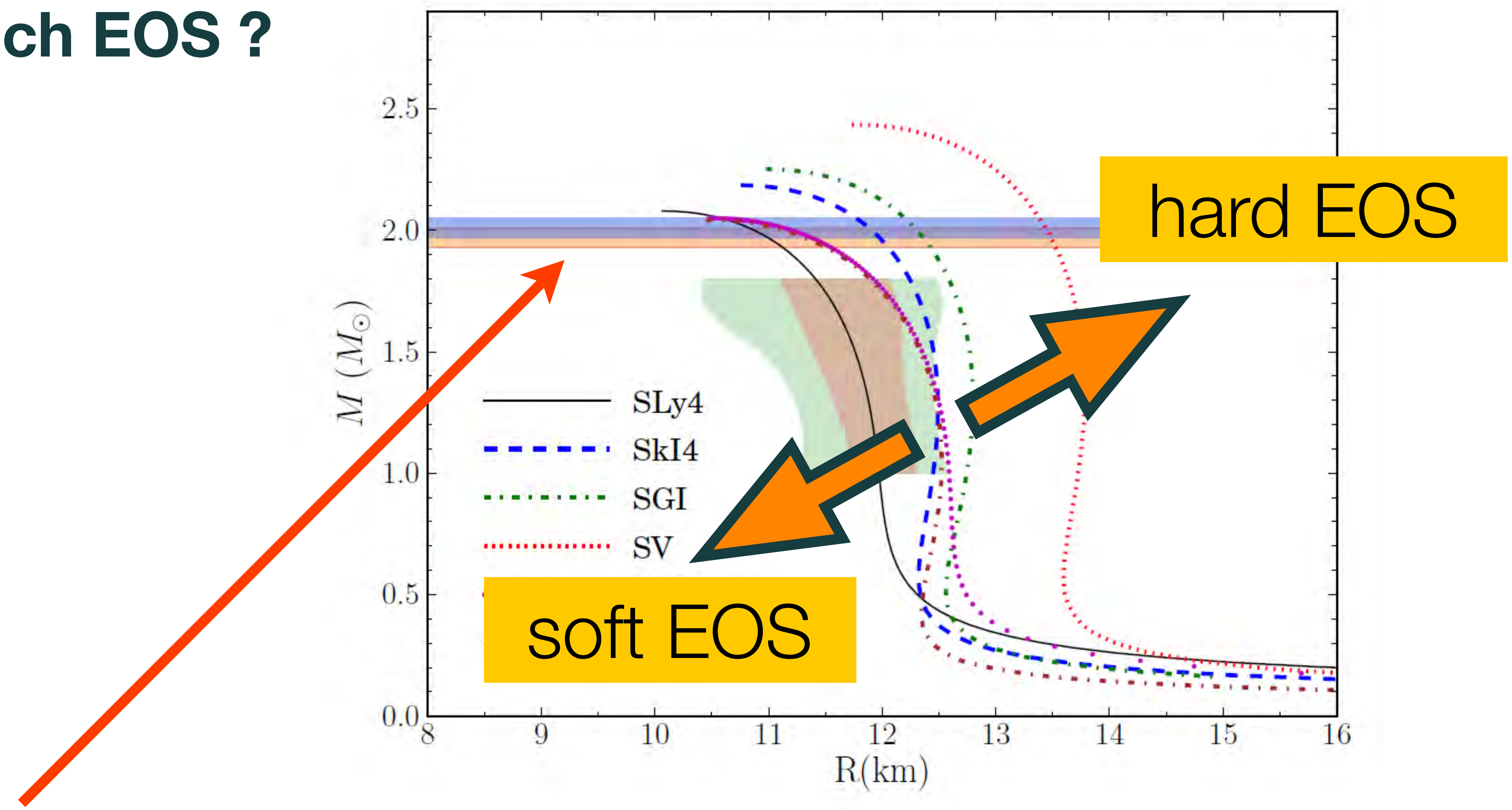
$$\frac{dT(r)}{dr} = -\frac{3L(r)\kappa(r)\rho(r)}{4\pi r^2 4acT(r)^3}$$

Energy conservation

$$\frac{dL(r)}{dr} = 4\pi r^2 \rho(r)\epsilon(r)$$

Mass & radius of neutron star

Q) Which EOS ?



Neutron Star-White Dwarf Binaries

1.97 solar mass NS : Nature 467 (2010) 1081

2.01 solar mass NS : Science 340 (2013) 6131

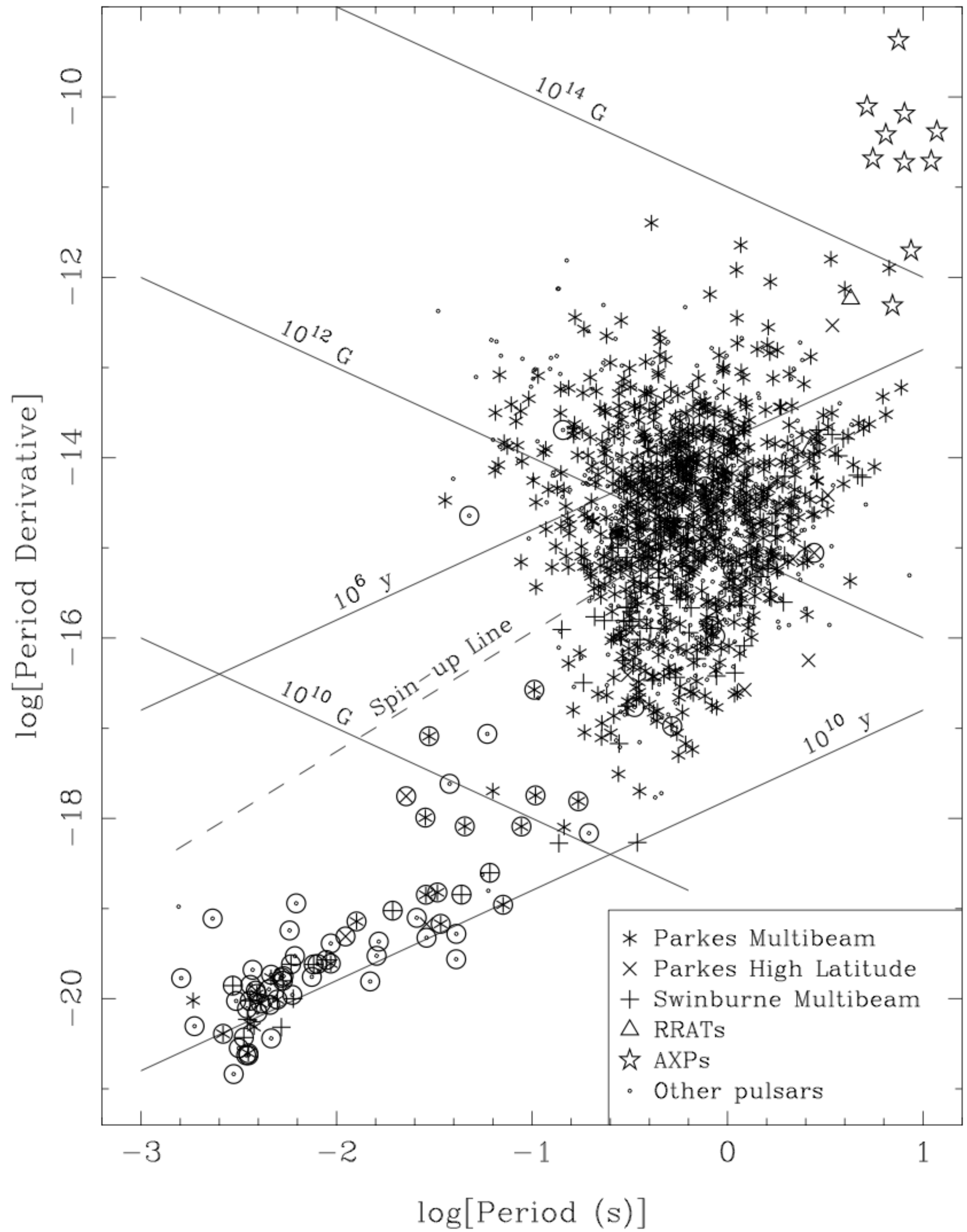
Millisecond Pulsars

Dipole Radiation

$$\dot{E}_{\rm rot} = I\Omega\dot{\Omega}$$

$$\dot{E}_{\rm dipole} = -\frac{B_\perp^2 R^6 \Omega^4}{6c^3}$$

$$\dot{\Omega} = -\frac{B_\perp^2 R^6 \Omega^3}{6Ic^3}$$



Moment of Inertia / Glitches

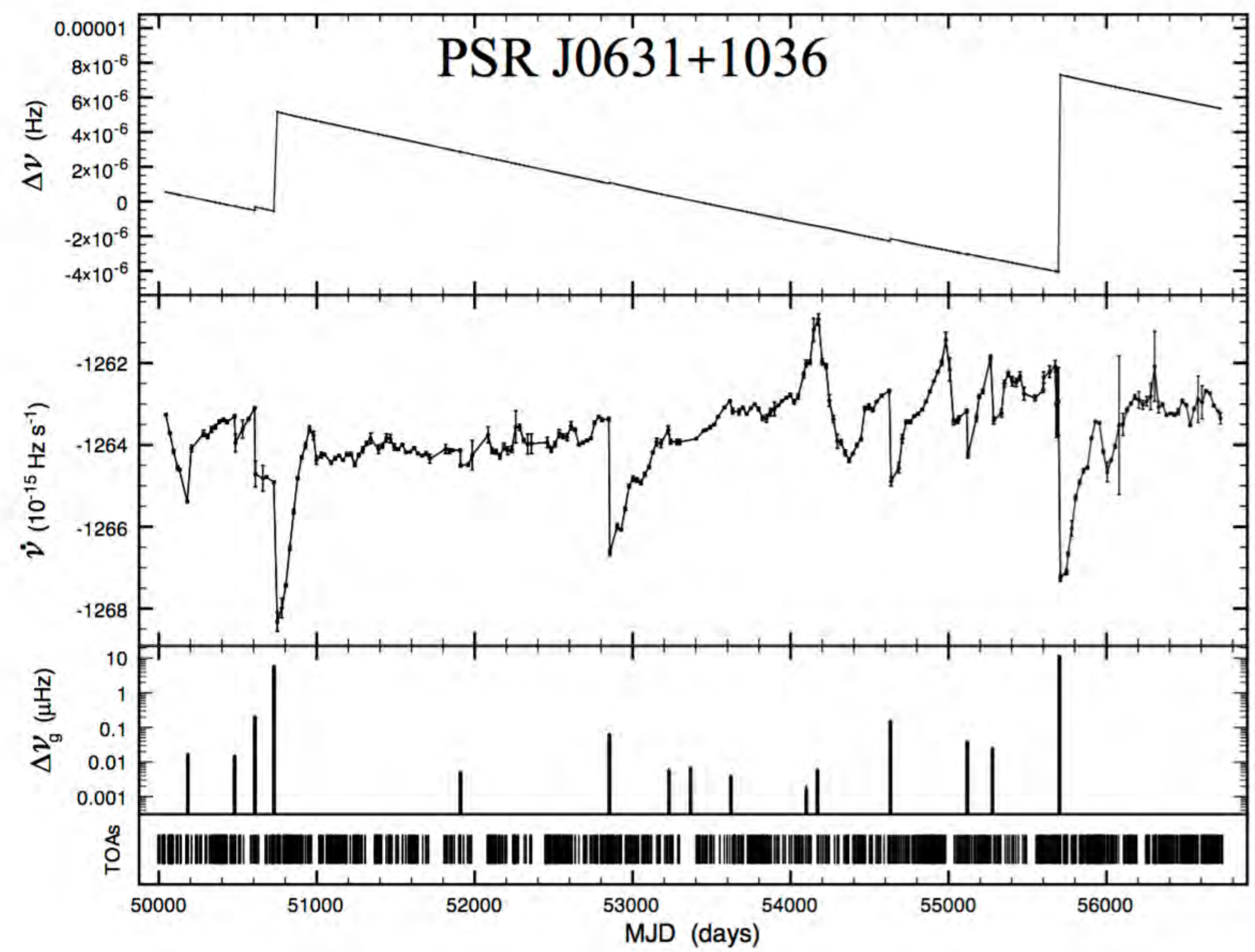
$$\dot{E}_{\rm rot} = I\Omega\dot{\Omega}$$

$$\dot{E}_{\rm dipole} = -\frac{B_\perp^2 R^6 \Omega^4}{6c^3}$$

$$\dot{\Omega} = -\frac{B_\perp^2 R^6 \Omega^3}{6Ic^3}$$

$$\dot{\Omega} \propto -\Omega^n$$

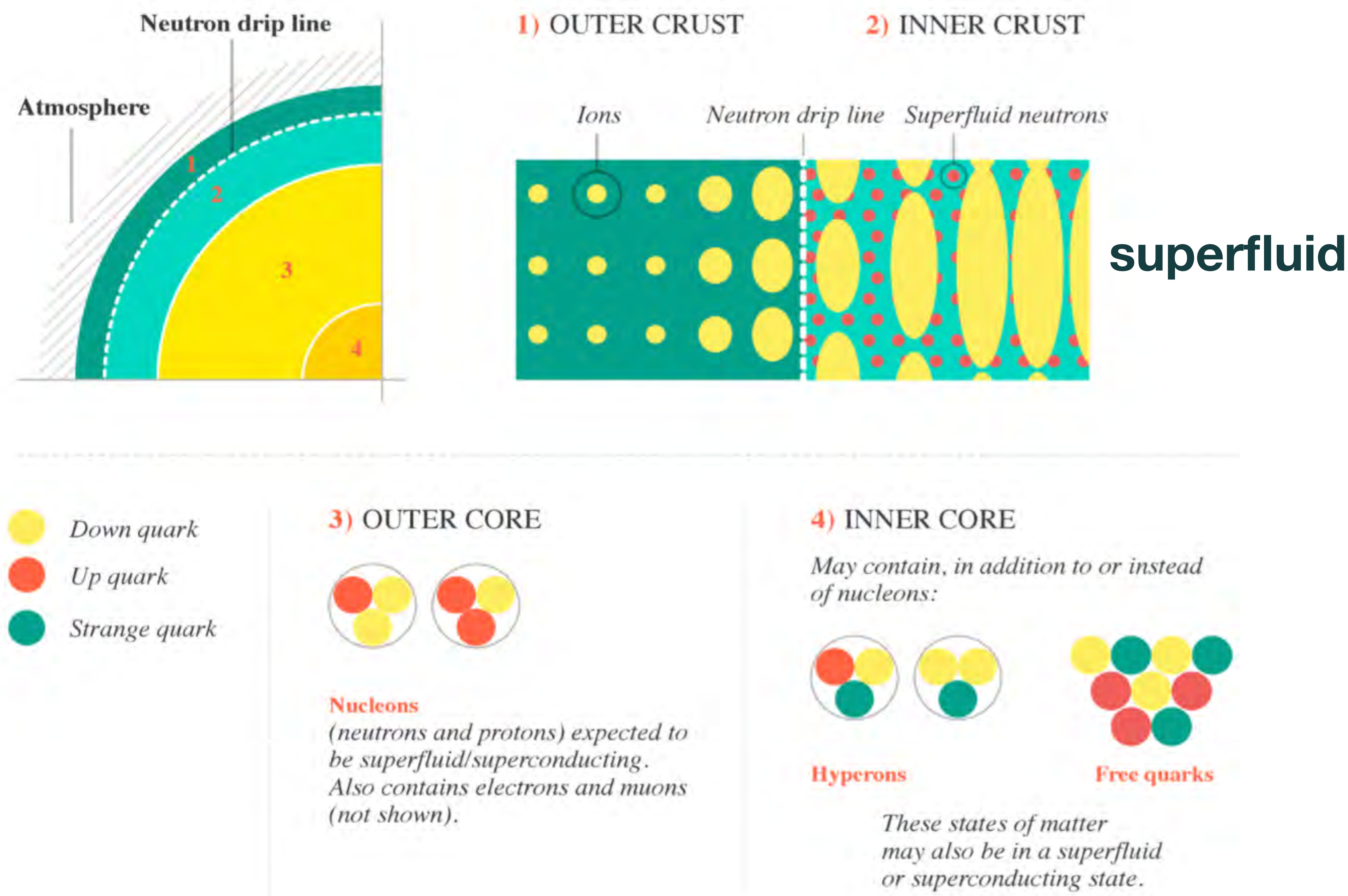
$$\tau_{\rm pulsar} = \frac{\Omega}{(1-n)\dot{\Omega}}$$



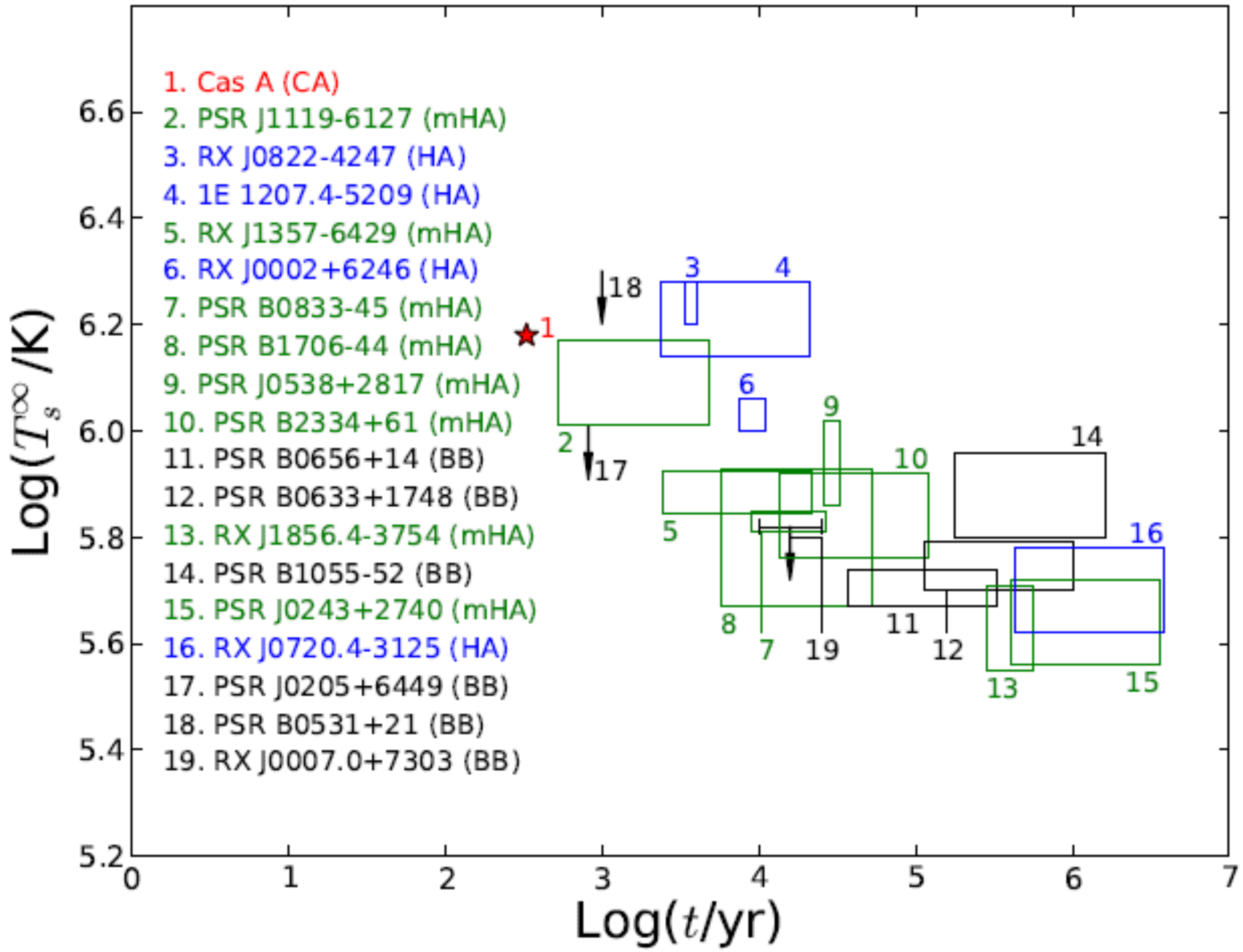
D. Antonopoulou (U. Amsterdam, 2015)

Superfluid Neutrons

D. Antonopoulou (U. Amsterdam, 2015)



Neutron Star Cooling



depends on

- particle fraction
- elements in the envelope
- nuclear superfluidity
- … …

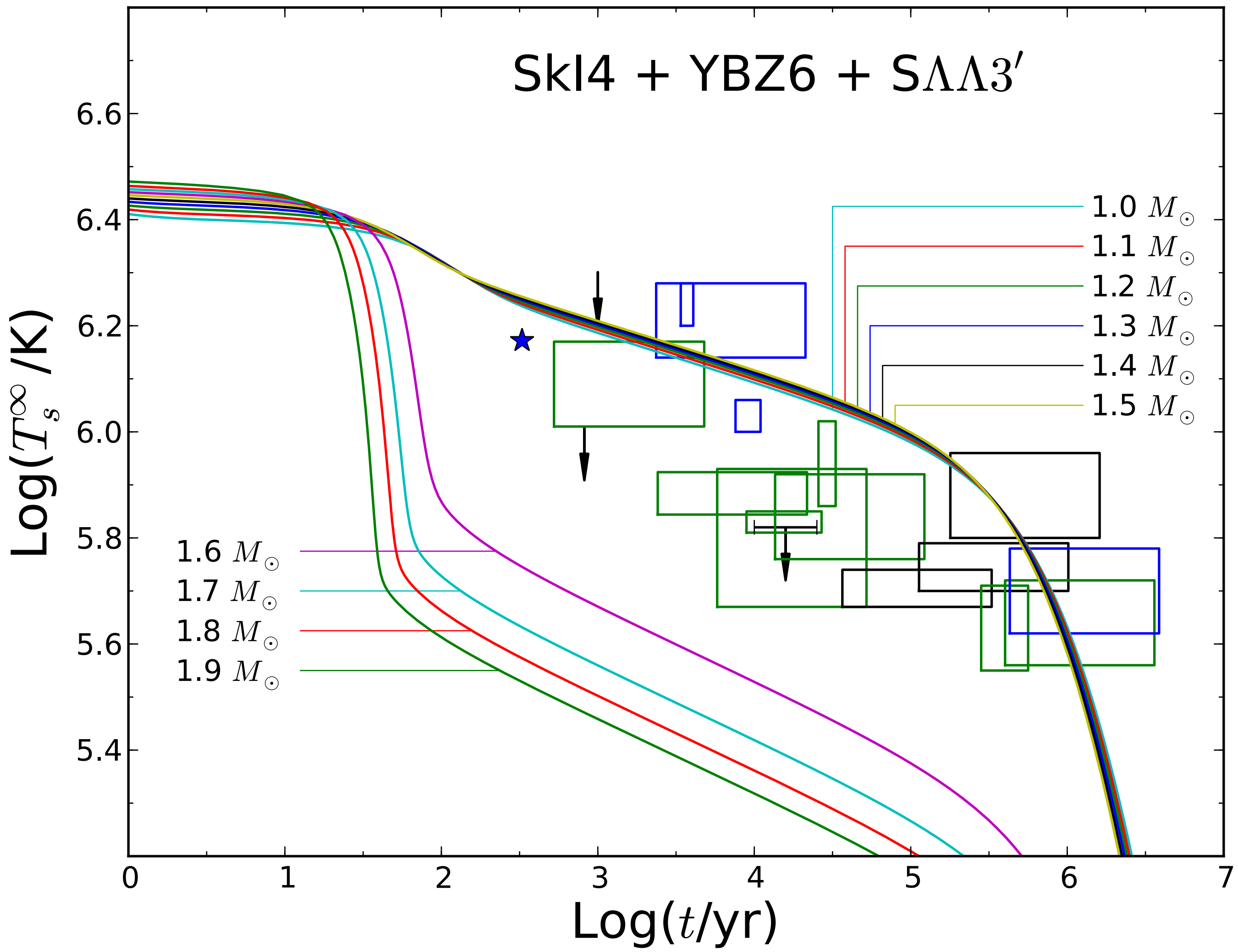
Y.Lim, C H Hyun, CHL, IJMPE (2017)

Cooling Mechanism

- **Photon emission** : mostly on the surface
- **Neutrino emission** : entire region, major energy loss

Name	Process	Emissivity[b] (erg cm^{-3} s^{-1})	
Modified Urca (neutron branch)	$n+n \rightarrow n+p+e^- + \bar{\nu}_e$ $n+p+e^- \rightarrow n+n+\nu_e$	$\sim 2\times 10^{21}\, \mathcal{R}\, T_9^8$	Slow
Modified Urca (proton branch)	$p+n \rightarrow p+p+e^- + \bar{\nu}_e$ $p+p+e^- \rightarrow p+n+\nu_e$	$\sim 10^{21}\, \mathcal{R}\, T_9^8$	Slow
Bremsstrahlung	$n+n \rightarrow n+n+\nu\bar{\nu}$ $n+p \rightarrow n+p+\nu\bar{\nu}$ $p+p \rightarrow p+p+\nu\bar{\nu}$	$\sim 10^{19}\, \mathcal{R}\, T_9^8$	Slow
Cooper pair formations	$n+n \rightarrow [nn]+\nu\bar{\nu}$ $p+p \rightarrow [pp]+\nu\bar{\nu}$	$\sim 5\times 10^{21}\, \mathcal{R}\, T_9^7$ $\sim 5\times 10^{19}\, \mathcal{R}\, T_9^7$	
Direct Urca	$n \rightarrow p+e^- + \bar{\nu}_e$ $p+e^- \rightarrow n+\nu_e$	$\sim 10^{27}\, \mathcal{R}\, T_9^6$	Fast
π^- condensate	$n + <\pi^-> \rightarrow n+e^- + \bar{\nu}_e$	$\sim 10^{26}\, \mathcal{R}\, T_9^6$	Fast
K^- condensate	$n + <K^-> \rightarrow n+e^- + \bar{\nu}_e$	$\sim 10^{25}\, \mathcal{R}\, T_9^6$	Fast

Fine-tuning Problem

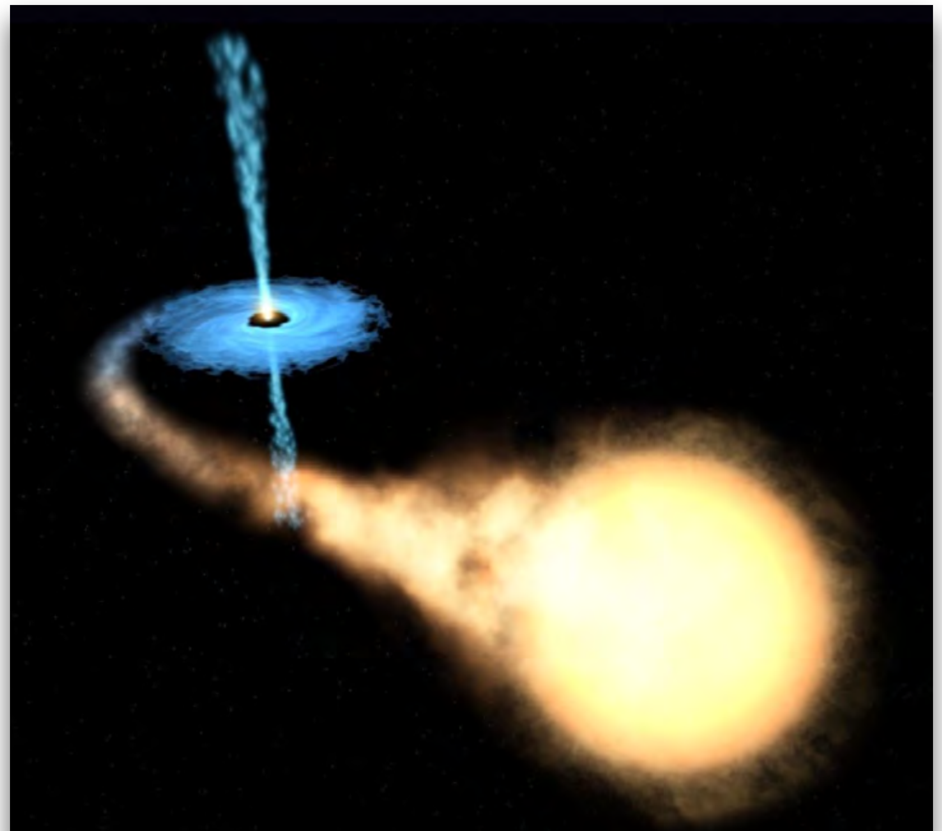


NS mass : 1.0 – 2.0 $M_\odot$

- abrupt drop: ingnition of direct URCA
- stiffer EoS allows early direct Urca
- no calculated-curve can explain middle-age data
- **require real fine-tuning**

with Yeunhwan Lim, Chang Ho Hyun, Kyujin Kwak

Low-Mass X-ray Binaries (LMXB)



Accreting Object: NS or BH

Companion: Low-Mass Main Sequence

Age: Old (> 10^9 year)

Accretion timescale: 10^7 - 10^9 year

X-ray energy: Soft (< 10 keV)

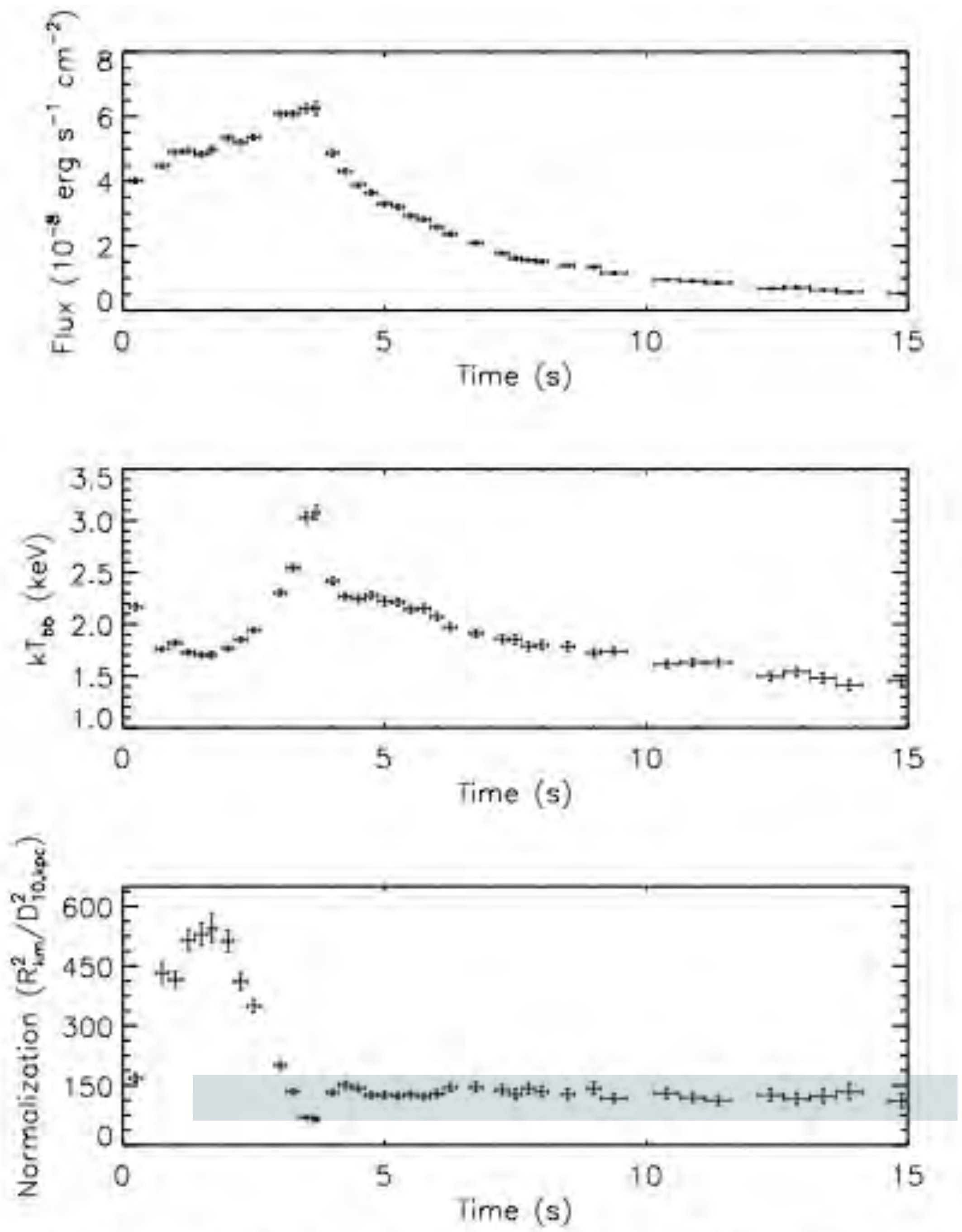
M & R from LMXB

with Myungkuk Kim, Young-Min Kim, Kyujin Kwak

flux

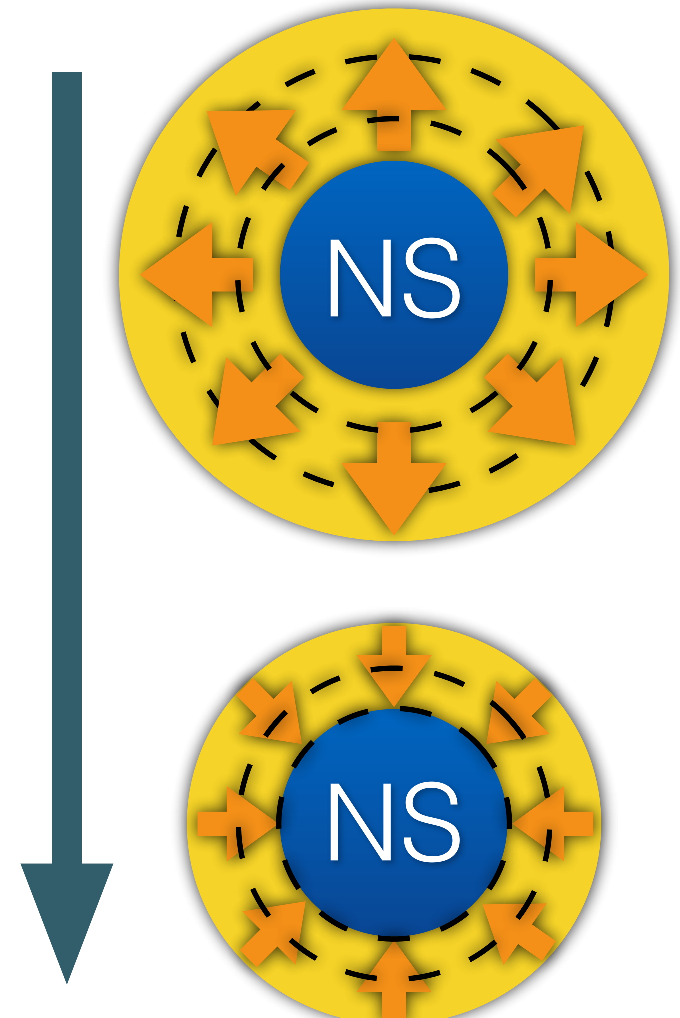
temperature

radius



Ozel et al. 2009

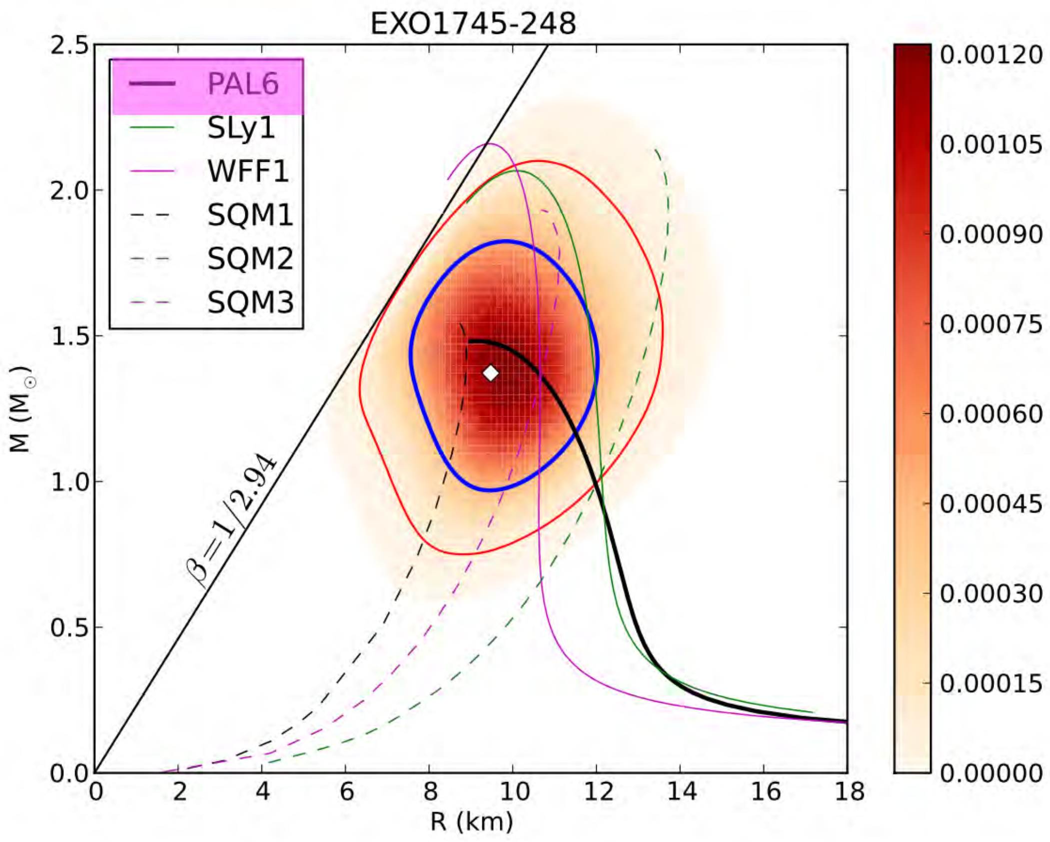
expansion

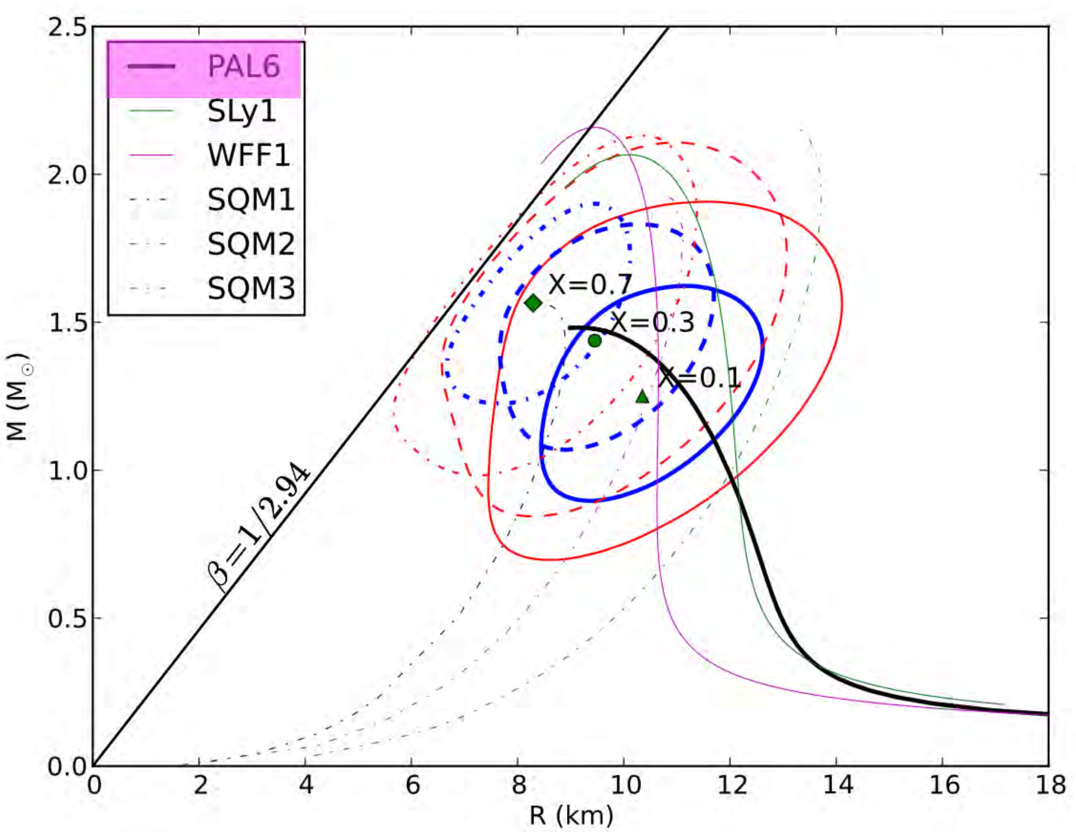


touchdown

Mass & radius from LMXB

- in collaboration with MK Kim, YM Kim, K Kwak





Low-Mass X-ray Binaries (LMXB)

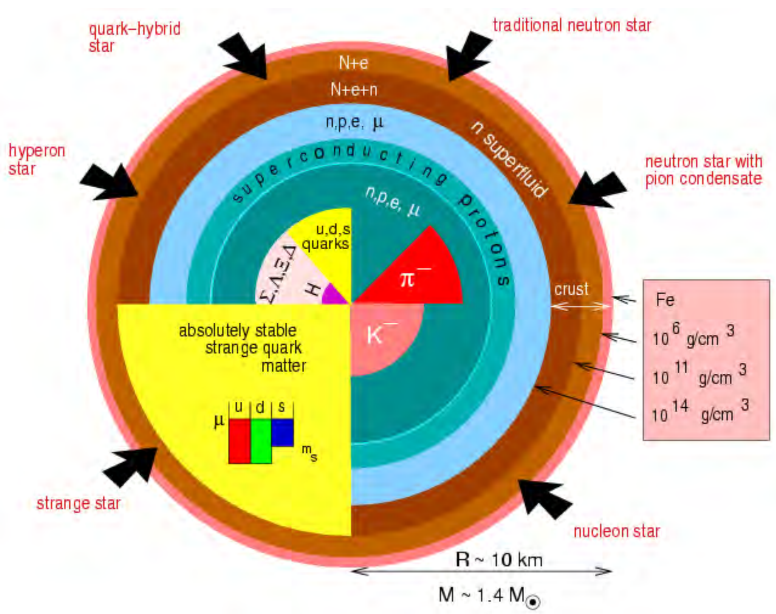
Steiner, Lattimer, Brown, ApJ, 2010

Object	M ($M_\odot$)	R (km)	M ($M_\odot$)	R (km)
	$r_{ph} = R$		$r_{ph} \gg R$	
4U 1608–522	$1.52^{+0.22}_{-0.18}$	$11.04^{+0.53}_{-1.50}$	$1.64^{+0.34}_{-0.41}$	$11.82^{+0.42}_{-0.89}$
EXO 1745–248	$1.55^{+0.12}_{-0.36}$	$10.91^{+0.86}_{-0.65}$	$1.34^{+0.450}_{-0.28}$	$11.82^{+0.47}_{-0.72}$
4U 1820–30	$1.57^{+0.13}_{-0.15}$	$10.91^{+0.39}_{-0.92}$	$1.57^{+0.37}_{-0.31}$	$11.82^{+0.42}_{-0.82}$
M13	$1.48^{+0.21}_{-0.64}$	$11.04^{+1.00}_{-1.28}$	$0.901^{+0.28}_{-0.12}$	$12.21^{+0.18}_{-0.62}$
ω Cen	$1.43^{+0.26}_{-0.61}$	$11.18^{+1.14}_{-1.27}$	$0.994^{+0.51}_{-0.21}$	$12.09^{+0.27}_{-0.66}$
X7	$0.832^{+1.19}_{-0.051}$	$13.25^{+1.37}_{-3.50}$	$1.98^{+0.10}_{-0.36}$	$11.3^{+0.95}_{-1.03}$

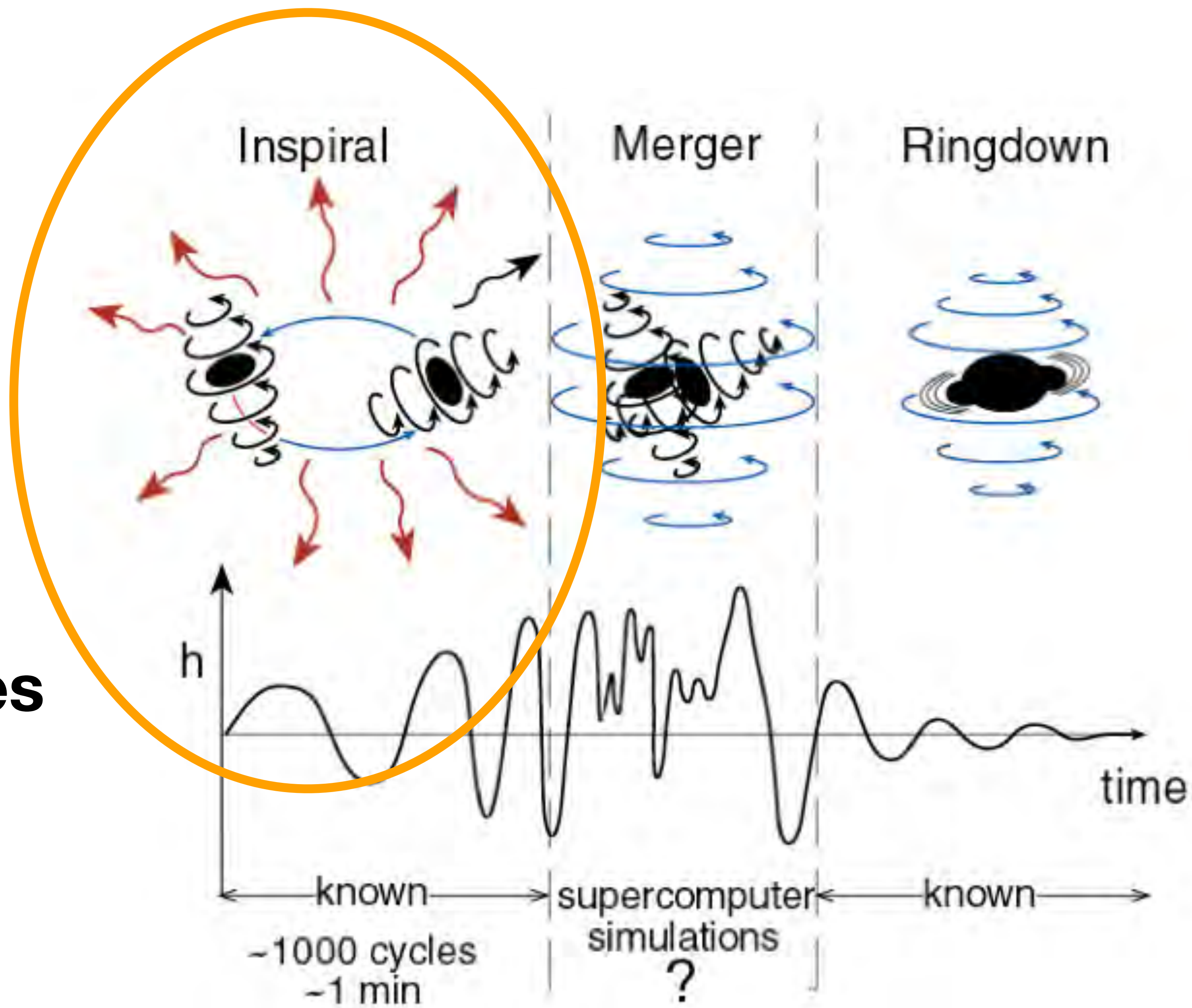
Contents

- Motivation
- Neutron star physics before GW detection
- **NS in new era of GW & multi-messenger astronomy**
  - **Direct measurement of NS mass from GW**
  - **Tidal Love number/deformability of NS from GW**
- Prospects

Response of NS to GW during Inspiral



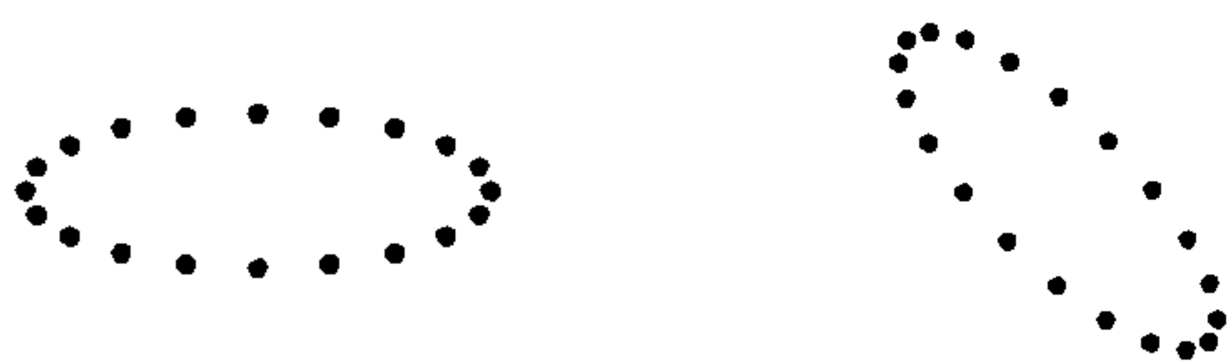
perturbative approaches



Tidal deformability & Love number

Selected references

- **A.E.H. Love** (1909) - The Yielding of the Earth to Disturbing Forces
- **K.S. Thorne** & A. Campolattaro (1967) - non-radial pulsation of NS
- J.B. Hartle & **K.S. Thorne** (1969) - stability of rotating NS
- … …
- **K.S. Thorne** (1998) - Tidal stabilization of rigid rotating, fully relativistic neutron star
- … …



Tidal deformability & Love number

$$-\frac{(1+g_{tt})}{2} = -\frac{m}{r} - \frac{3Q_{ij}}{2r^3}\left(n^i n^j - \frac{1}{3}\delta^{ij}\right) + \mathcal{O}\left(\frac{1}{r^3}\right) + \frac{\mathcal{E}_{ij}}{2} r^2 n^i n^j + \mathcal{O}(r^3)$$

$\mathcal{E}_{ij}$: external quadrupole tidal field

Q_{ij} : quadrupole moment of NS

$\lambda :$ Tidal deformability

$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$

$$Q_{ij} = \int d^3x \delta\rho(x) \left(x_i x_j - \frac{1}{3} r^2 \delta_{ij}\right)$$

$$n^i = \frac{x^i}{r}$$

dimensionless parameter

$k_2 :$ $l = 2$ Tidal Love number

$$k_2 = \frac{3}{2} G \lambda R^{-5}$$

Hinderer et al. PRD 81 (2010)

PRL 112, 101101 (2014) PHYSICAL REVIEW LETTERS week ending 14 MARCH 2014

Systematic Parameter Errors in Inspiraling Neutron Star Binaries

Marc Favata*

$$\tilde{h}_{\rm T}(f) = \mathcal{A} f^{-7/6} e^{i\Psi_{\rm T}(f)}$$

$$\Psi_{\rm T}(f) = \varphi_c + 2\pi f t_c + \frac{3}{128\eta v^5}(\Delta\Psi^{\rm pp}_{3.5{\rm PN}} + \Delta\Psi^{\rm spin}_{3{\rm PN}} + \Delta\Psi^{\rm ecc.}_{2{\rm PN}} + \Delta\Psi^{\rm tidal}_{6{\rm PN}} + \Delta\Psi^{\rm tm}_{6{\rm PN}})$$

$$v = (\pi f M)^{1/3}$$

$$v/c = (GM\pi f/c^3)^{1/3}$$

6PN

$$\Delta\Psi^{\rm tidal}_{6{\rm PN}} = -\frac{39}{2}\tilde{\Lambda} v^{10} + v^{12}\left(\frac{6595}{364}\delta\tilde{\Lambda} - \frac{3115}{64}\tilde{\Lambda}\right)$$

5PN

$$\tilde{\Lambda} \equiv 32\frac{\tilde{\lambda}}{M^5} = \frac{8}{13}[(1+7\eta-31\eta^2)(\hat{\lambda}_1+\hat{\lambda}_2) - \sqrt{1-4\eta}(1+9\eta-11\eta^2)(\hat{\lambda}_1-\hat{\lambda}_2)].$$

PRL 112, 101101 (2014) PHYSICAL REVIEW LETTERS week ending 14 MARCH 2014

Systematic Parameter Errors in Inspiraling Neutron Star Binaries

Marc Favata*

phase shift vs deformability

$$\left.\frac{d\Psi_{\rm T}}{dx}\right|_{\rm tidal,5PN} = -\frac{195}{8}\frac{x^{3/2}}{\eta}\frac{\tilde{\lambda}}{M^5} \propto \frac{\tilde{\lambda}}{M^5}$$

$$x = (\omega M)^{2/3} \Rightarrow \left(\omega \frac{GM}{c^3}\right)^{2/3}$$

$$\eta = m_1 m_2 / M^2$$

dimensionless

$$\Lambda = \frac{\lambda}{m^5} \Rightarrow G\lambda\left(\frac{c^2}{Gm}\right)^5 \approx 950.5\left(\frac{m_\odot}{m}\right)^5\left(\frac{\lambda}{10^{36}\ \mathrm{g\ cm^2\ s^2}}\right)$$

$$\Lambda = G\left(\frac{c^2}{Gm}\right)^5 \times \frac{2}{3}\frac{R^5}{G}k_2 = \frac{2}{3}\left(\frac{Rc^2}{Gm}\right)^5 k_2 \approx 9495\left(\frac{R_{10\rm km}}{m_{M_\odot}}\right)^5 k_2$$

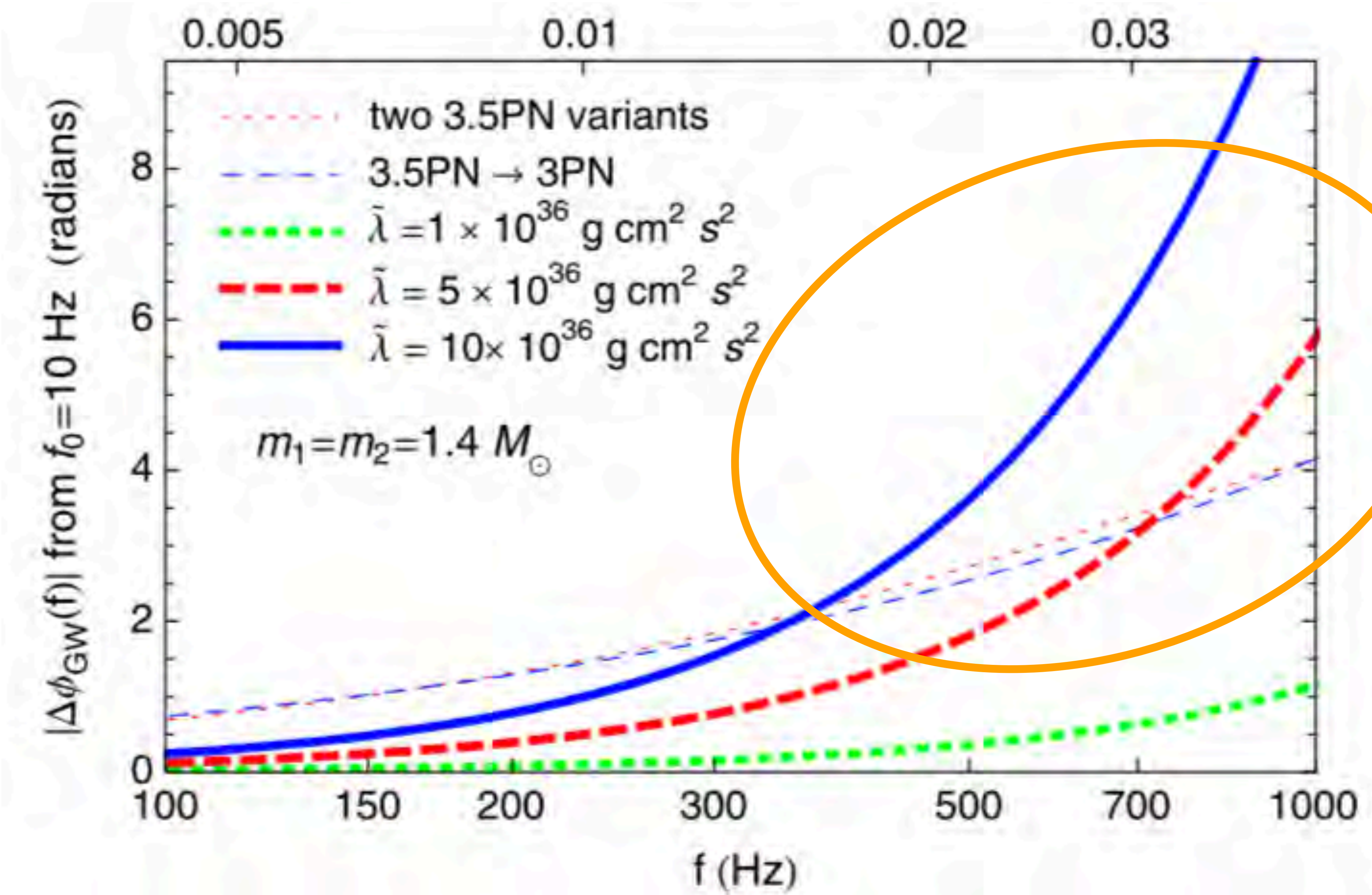
accumulated GW phase

PHYSICAL REVIEW D **81,** 123016 (2010)

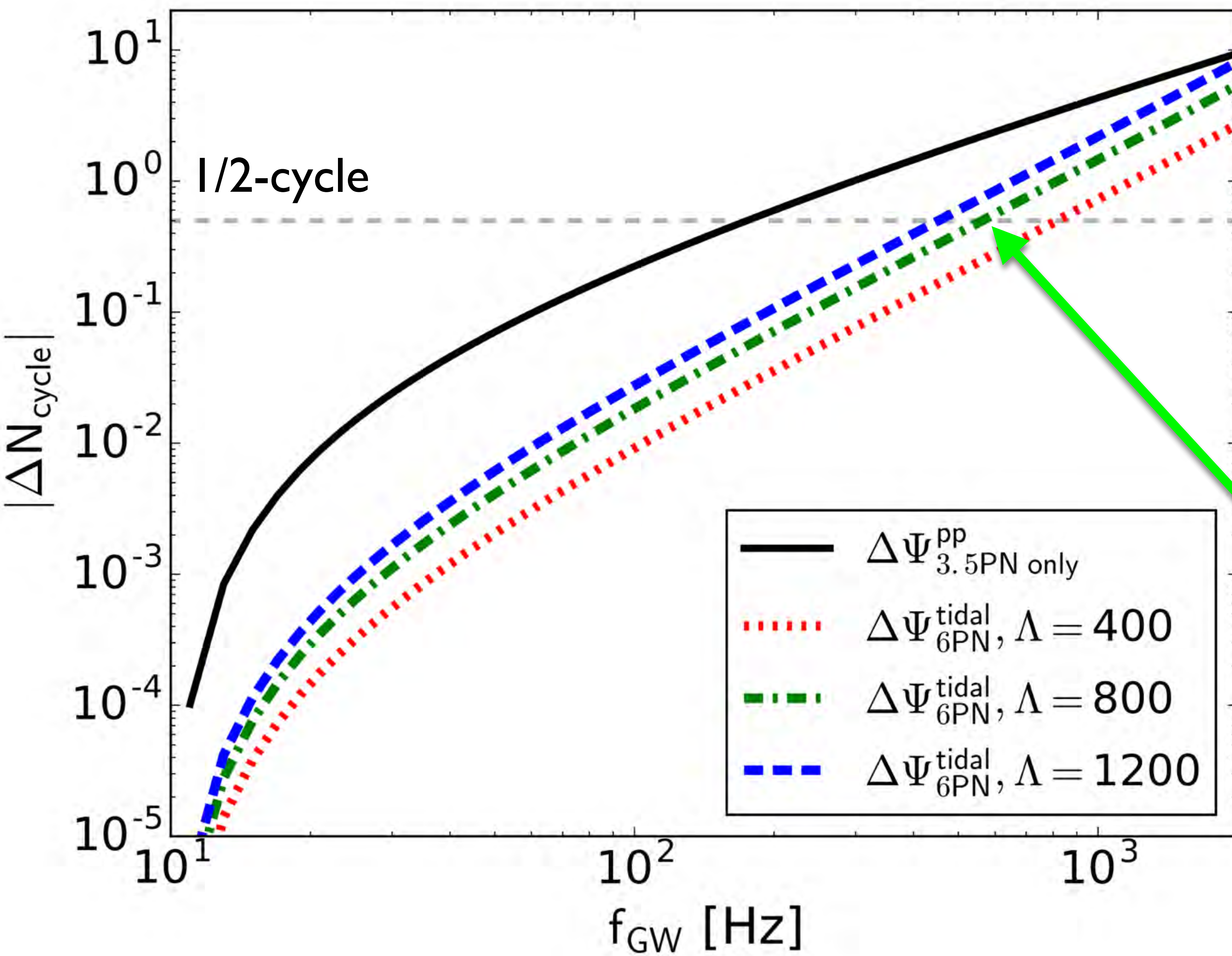
Tidal deformability of neutron stars with realistic equations of state and their gravitational wave signatures in binary inspiral

Tanja Hinderer,[1] Benjamin D. Lackey,[2] Ryan N. Lang,[3,4] and Jocelyn S. Read[5]

$$|\Delta\phi_{\rm GW}(f)| = \left|\Psi(f)_{\rm pp(3.5PN)} - \Psi(f)_{\rm pp(3.5PN)+tidal(5PN)}\right|$$



accumulated GW phase



waveform model:
TaylorF2(SPA)

Mch=1.188$M_\odot$
M1=M2=1.365$M_\odot$

~600 Hz

Measurement error vs. source distance

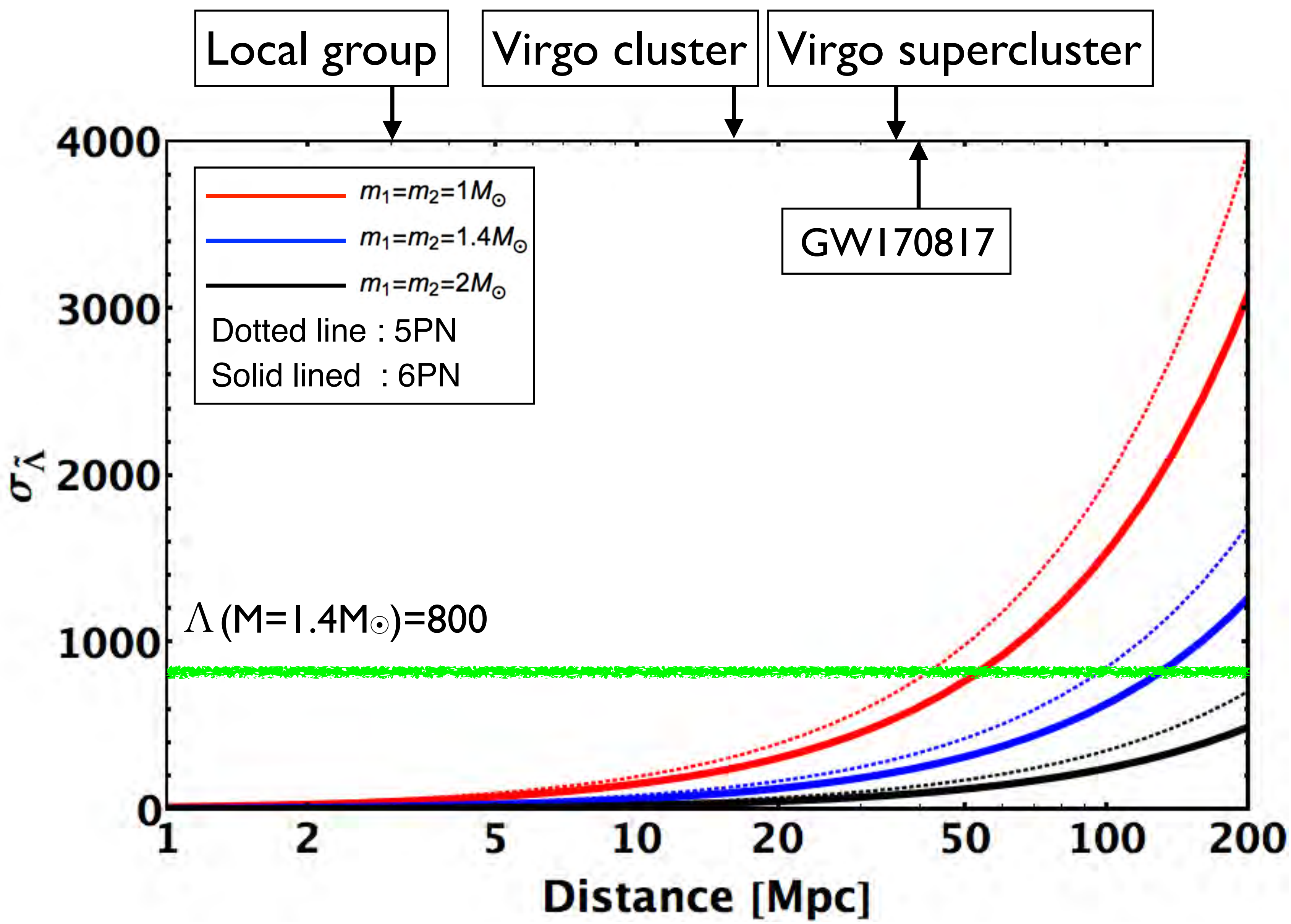


Fig. 1: Tidal deformability measurement error vs distance to the source. distances to galaxy clusters and GW20170817 distance are marked.

Y.B. Choi, H. S. Cho, C.-H. Lee

Press Release Oct 16, 2017

GW from Binary NS Mergers

*GW 170817 (**d=40 Mpc**)*
GRB 170817A by Fermi-GBM
Kilonova/X-ray/Optical Afterglows

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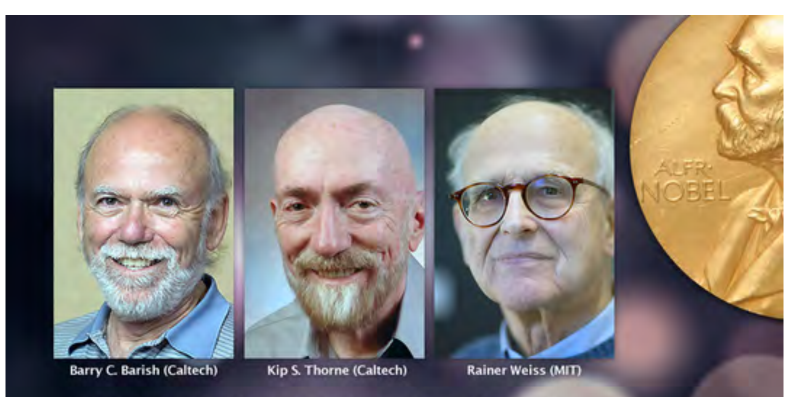
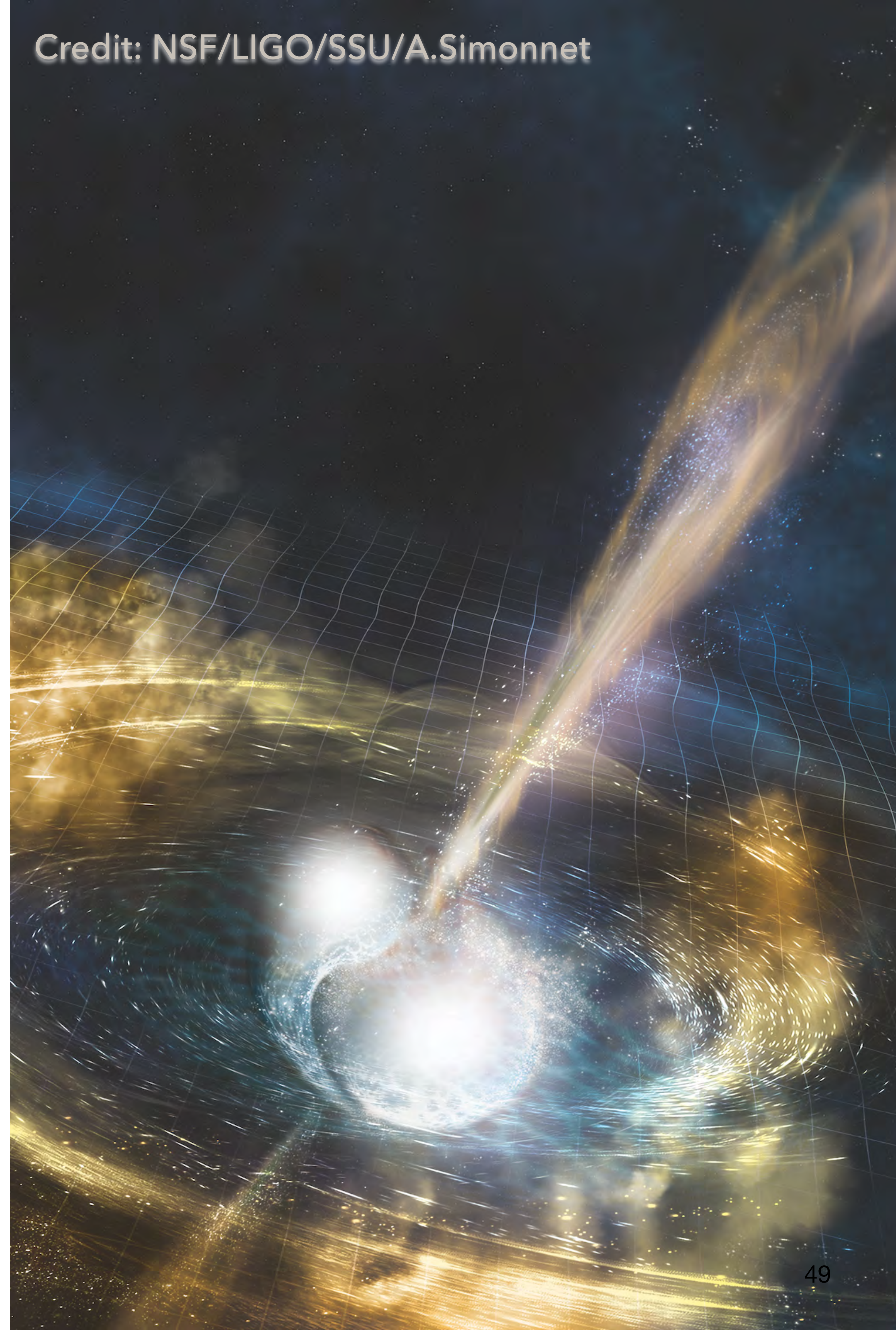
soon after the announcement of 2017 Nobel Prize





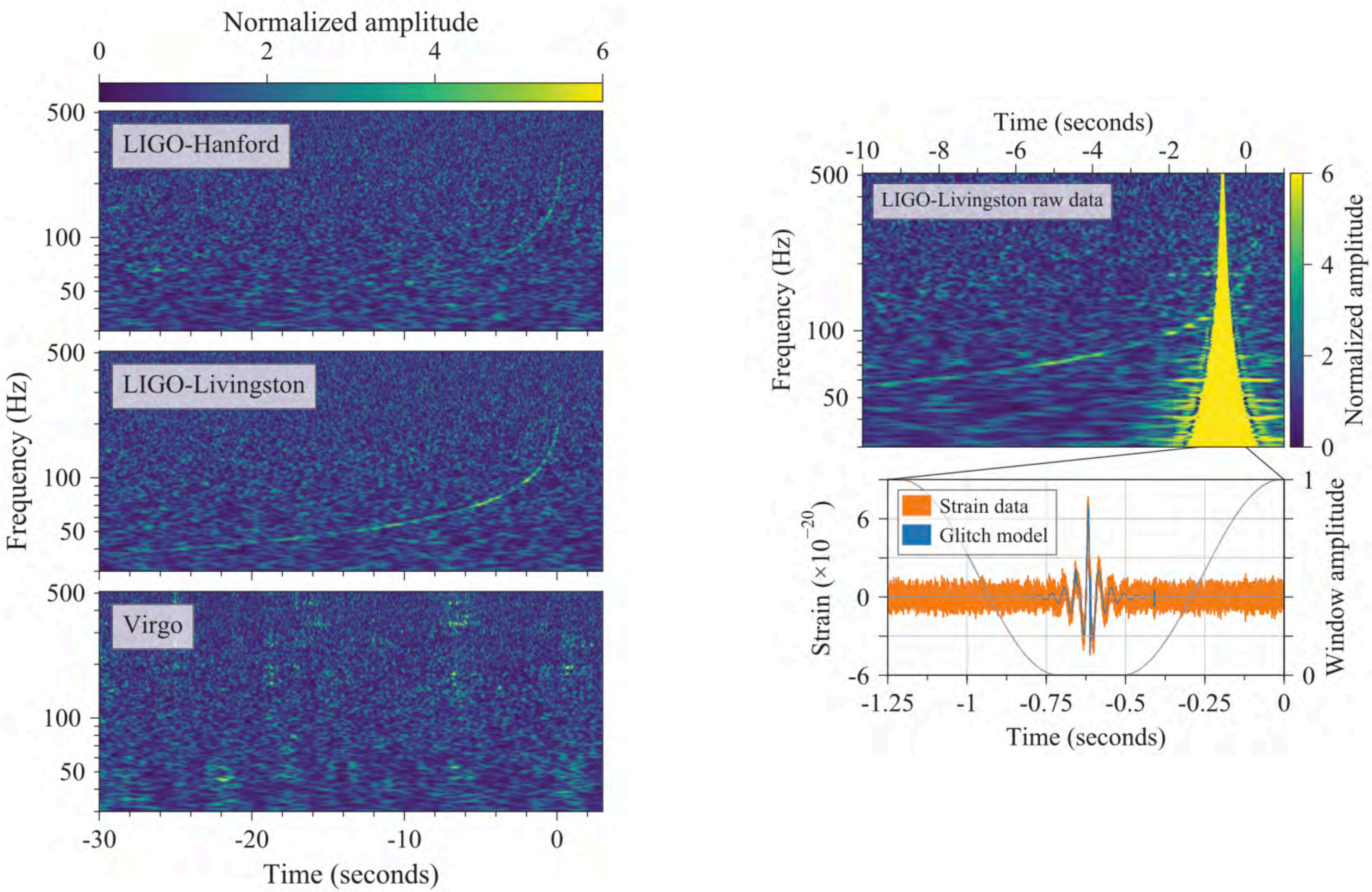
PRL 119, 161101 (2017) | Selected for a Viewpoint in *Physics* | PHYSICAL REVIEW LETTERS | week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)



PRL 119, 161101 (2017)
Selected for a Viewpoint in Physics
PHYSICAL REVIEW LETTERS
week ending 20 OCTOBER 2017

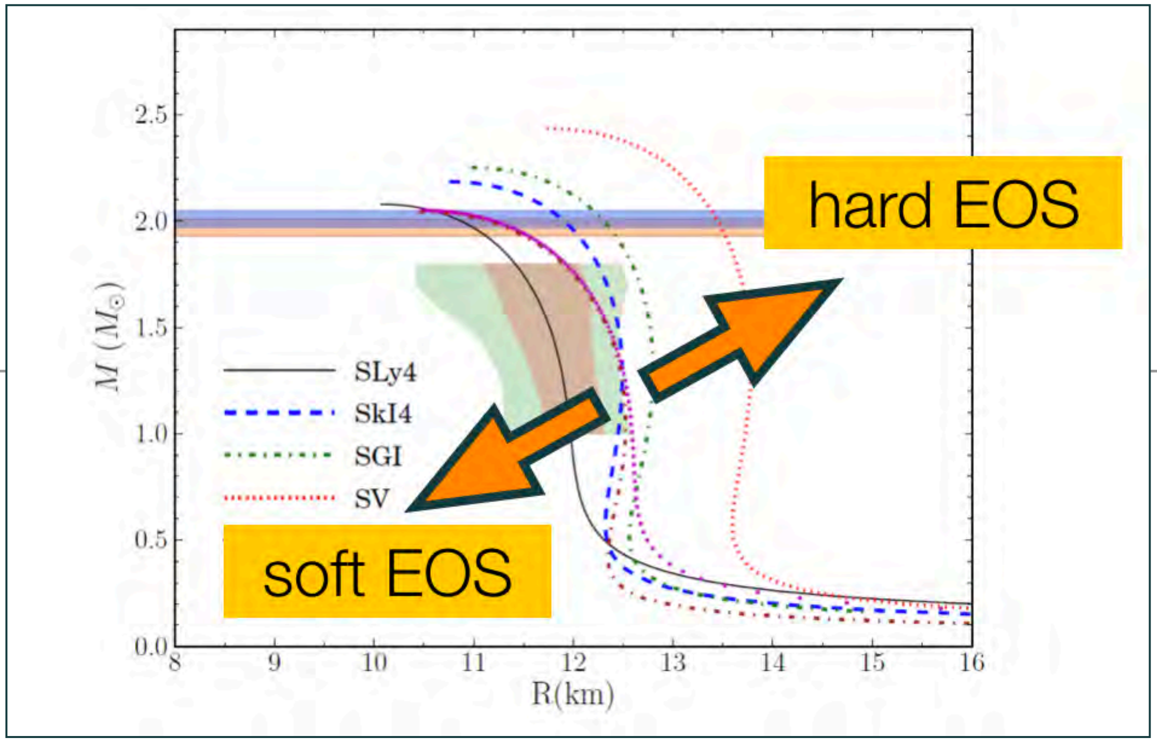
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

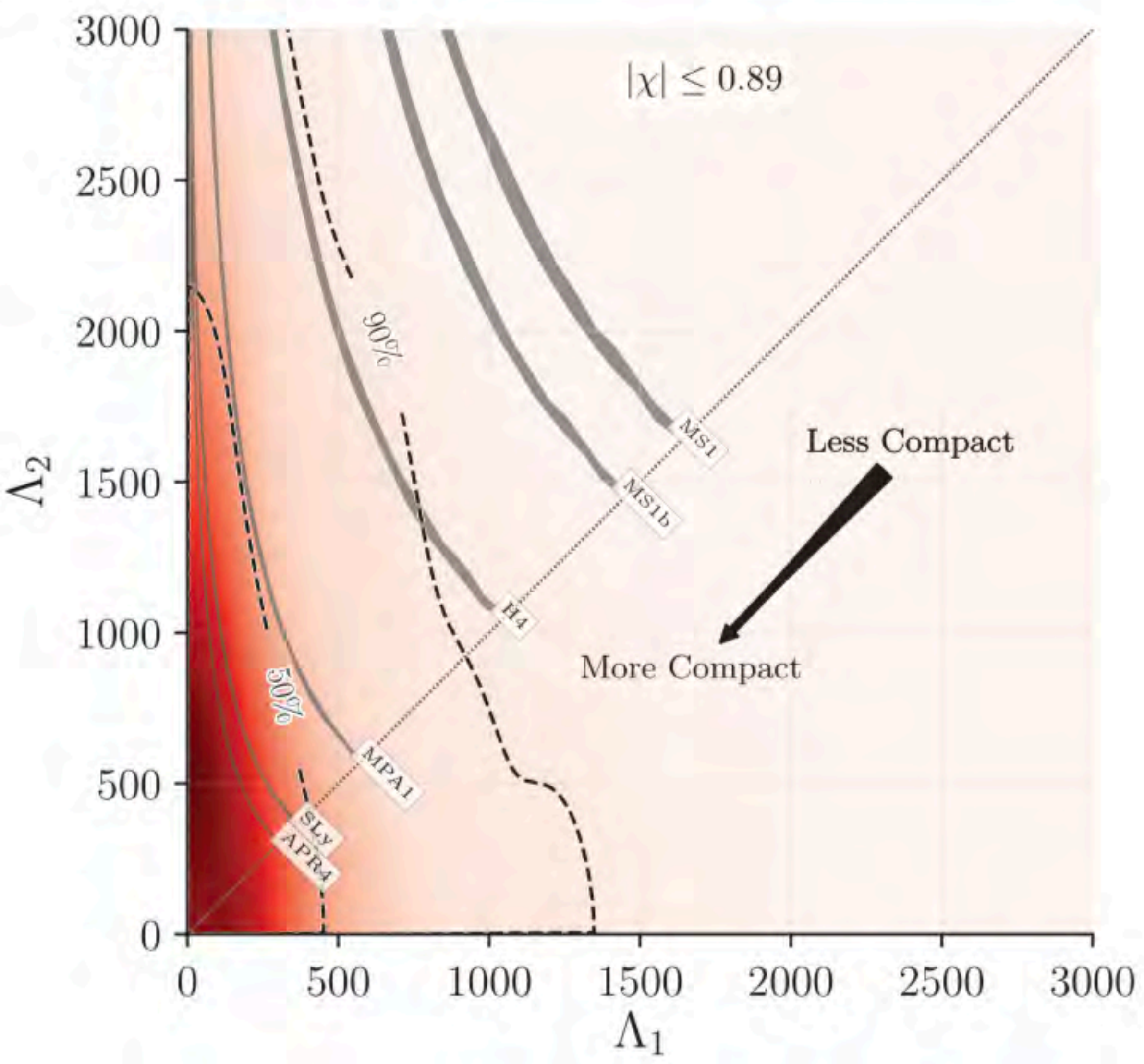
TABLE I. Source properties for GW170817: we give ranges encompassing the 90% credible intervals for different assumptions of the waveform model to bound systematic uncertainty. The mass values are quoted in the frame of the source, accounting for uncertainty in the source redshift.

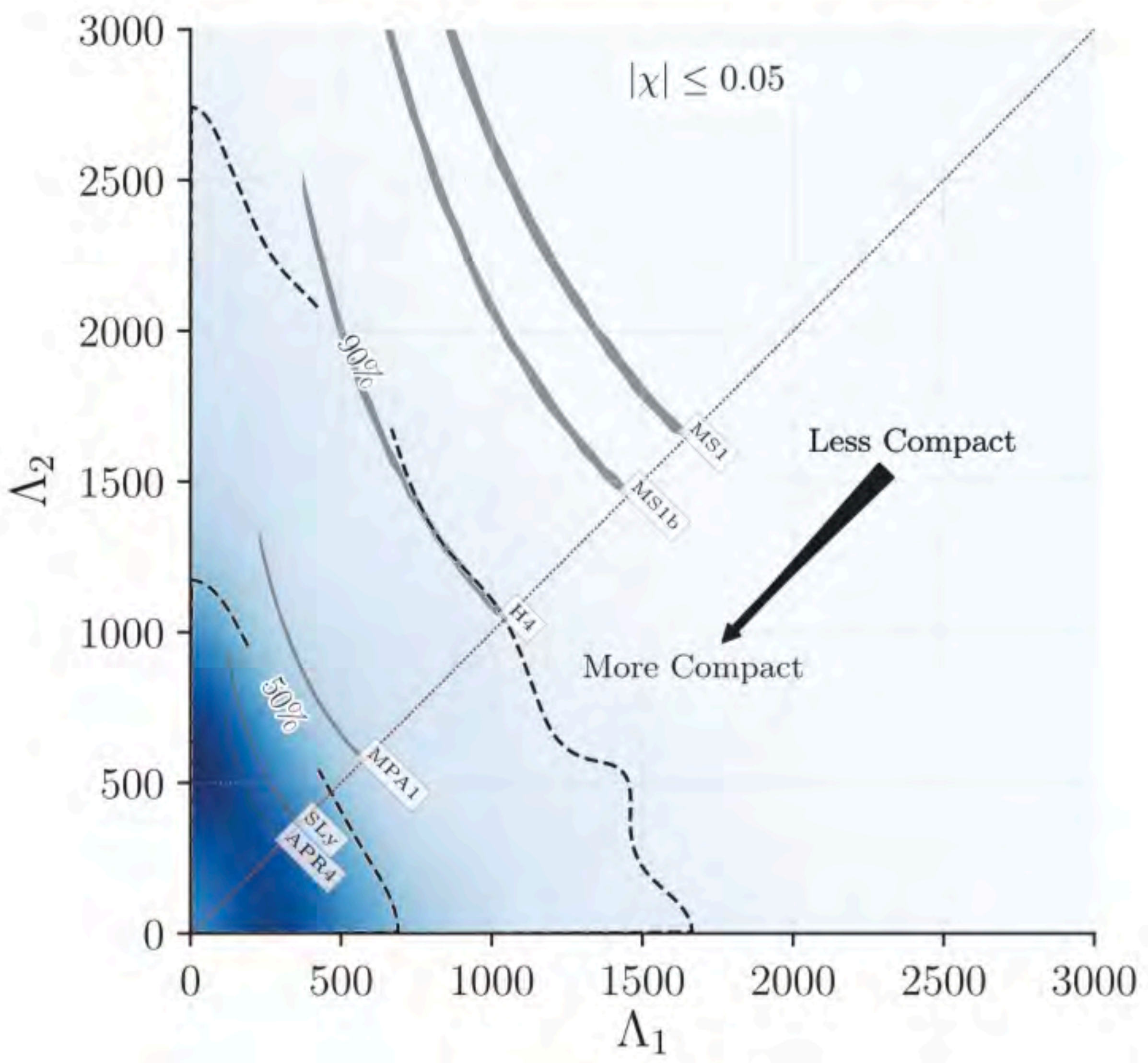
	Low-spin priors ($\|\chi\| \leq 0.05$)	High-spin priors ($\|\chi\| \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance D_{L}	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

GW170817
Information of Neutron Star Structure has been revealed by Gravitational Waves

perfer lower Λ (soft EOS)







(revised) properties of GW170817

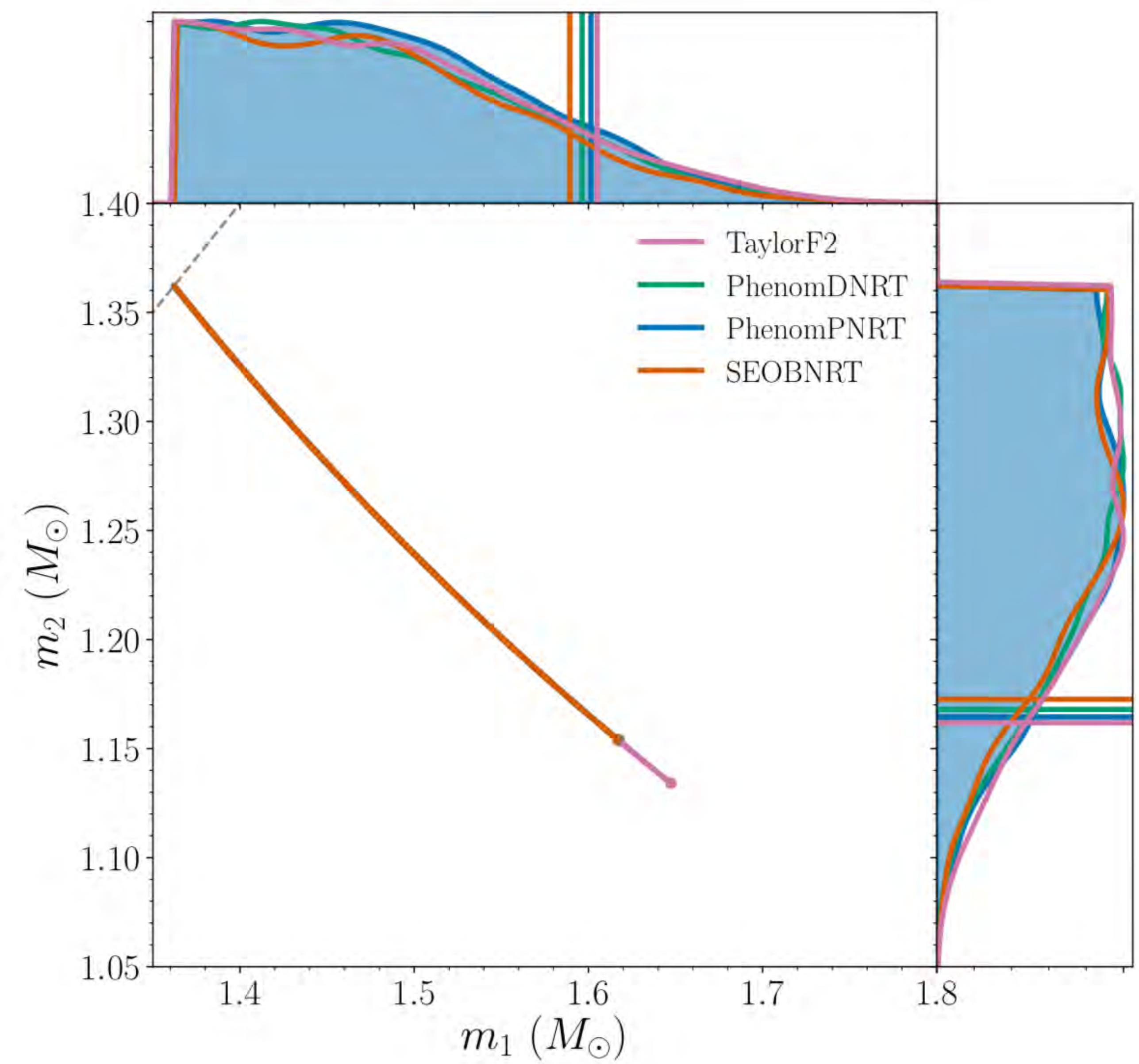
Abbott et al. (LSC and Virgo), arxiv:1805.11579

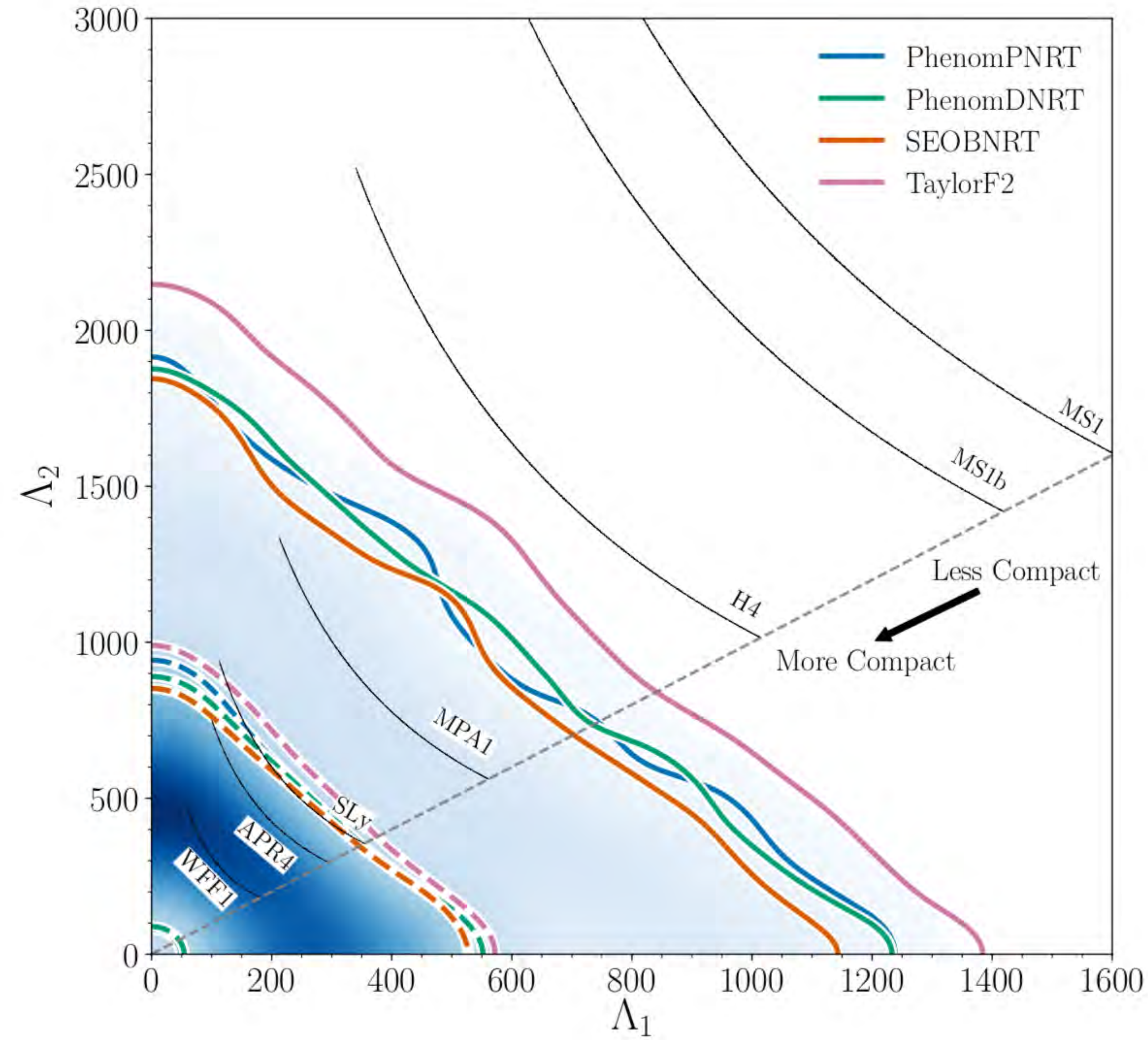
	Low-spin prior ($\chi \leq 0.05$)	High-spin prior ($\chi \leq 0.89$)
Binary inclination θ_{JN}	146^{+25}_{-27} deg	152^{+21}_{-27} deg
Binary inclination θ_{JN} using EM distance constraint [104]	151^{+15}_{-11} deg	153^{+15}_{-11} deg
Detector frame chirp mass $\mathcal{M}^{det}$	$1.1975^{+0.0001}_{-0.0001} M_\odot$	$1.1976^{+0.0004}_{-0.0002} M_\odot$
Chirp mass $\mathcal{M}$	$1.186^{+0.001}_{-0.001} M_\odot$	$1.186^{+0.001}_{-0.001} M_\odot$
Primary mass m_1	(1.36, 1.60) $M_\odot$	(1.36, 1.89) $M_\odot$
Secondary mass m_2	(1.16, 1.36) $M_\odot$	(1.00, 1.36) $M_\odot$
Total mass m	$2.73^{+0.04}_{-0.01} M_\odot$	$2.77^{+0.22}_{-0.05} M_\odot$
Mass ratio q	(0.73, 1.00)	(0.53, 1.00)
Effective spin χ_{eff}	$0.00^{+0.02}_{-0.01}$	$0.02^{+0.08}_{-0.02}$
Primary dimensionless spin χ_1	(0.00, 0.04)	(0.00, 0.50)
Secondary dimensionless spin χ_2	(0.00, 0.04)	(0.00, 0.61)
Tidal deformability $\tilde{\Lambda}$ with flat prior	300^{+500}_{-190}(symmetric)/ 300^{+420}_{-230}(HPD)	(0, 630)

300^{+500}_{-190}(symmetric)/ 300^{+420}_{-230}(HPD) (0, 630)

A new constraint by GW Observation

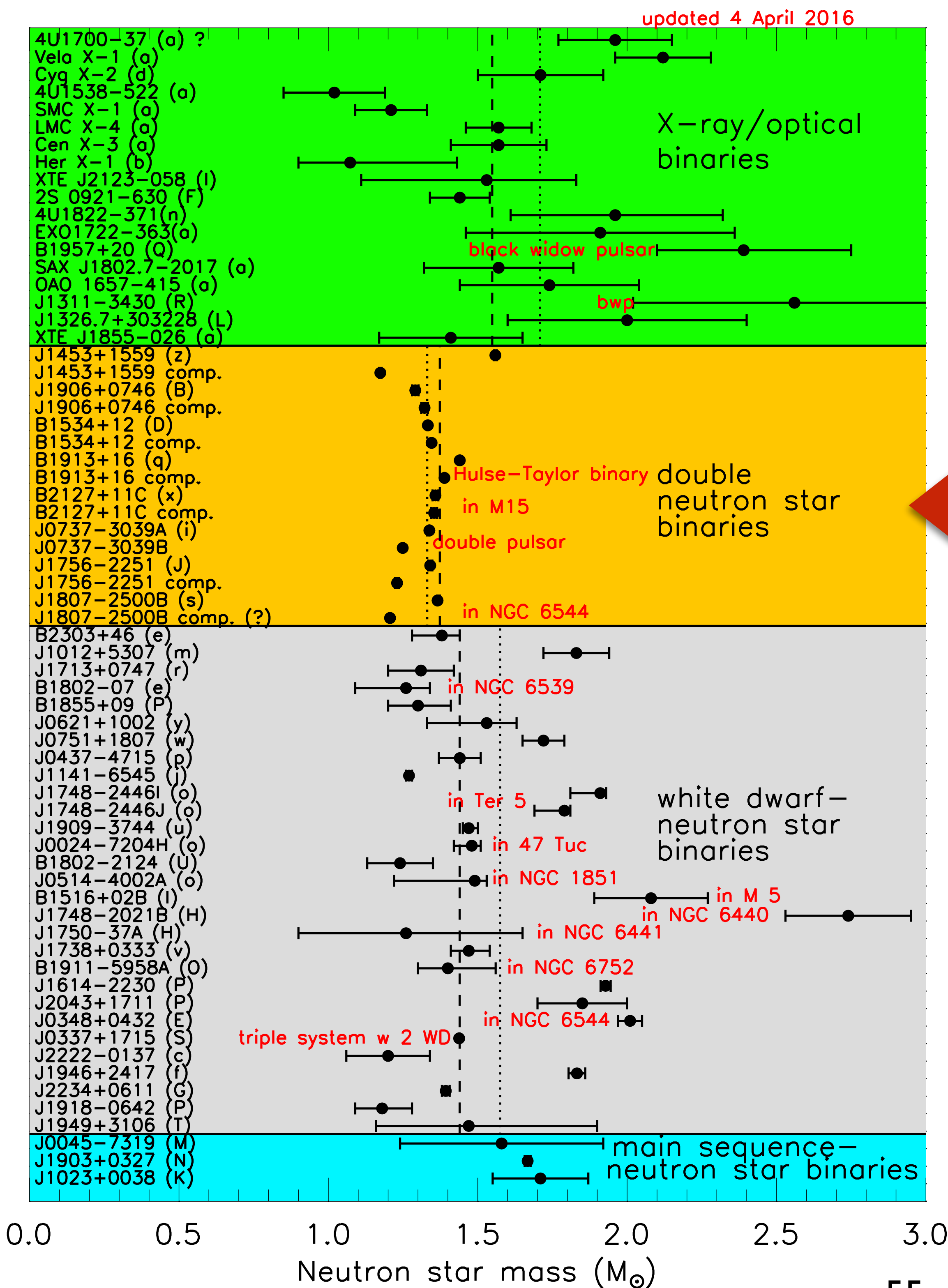
PHYSICAL REVIEW X **9**, 011001 (2019)





Low-spin prior : χ <= 0.05

Neutron Star of Known Mass



GW170817: BNS

M1: 1.36~1.60 $M_\odot$

(1.36~2.26)

M2: 1.17~1.36 $M_\odot$

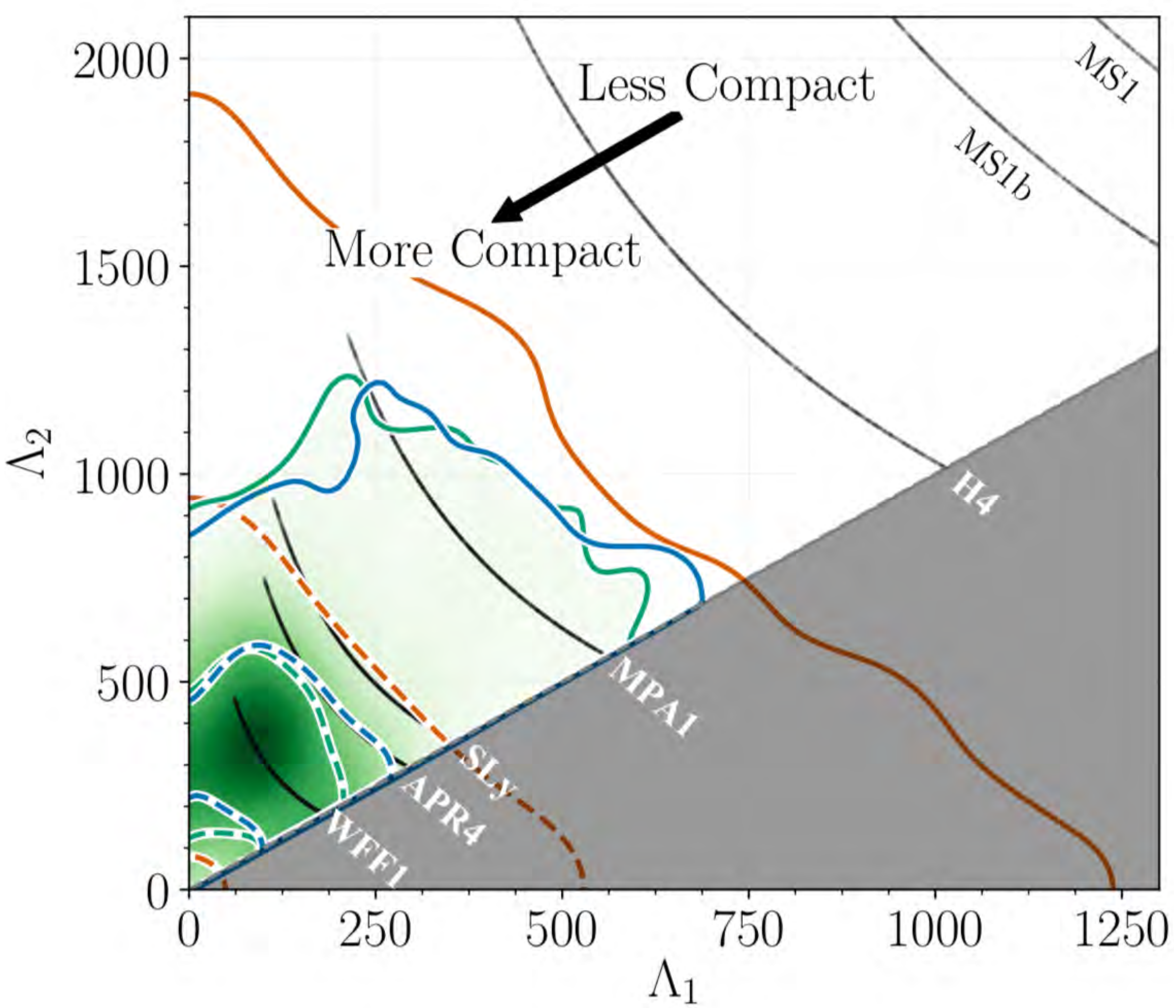
(0.86~1.36)

J. Lattimer, Annu.Rev.Nucl.Part.Sci.62,485(2012) and https://stellarcollapse.org by C. Ott

Slide from YMKim

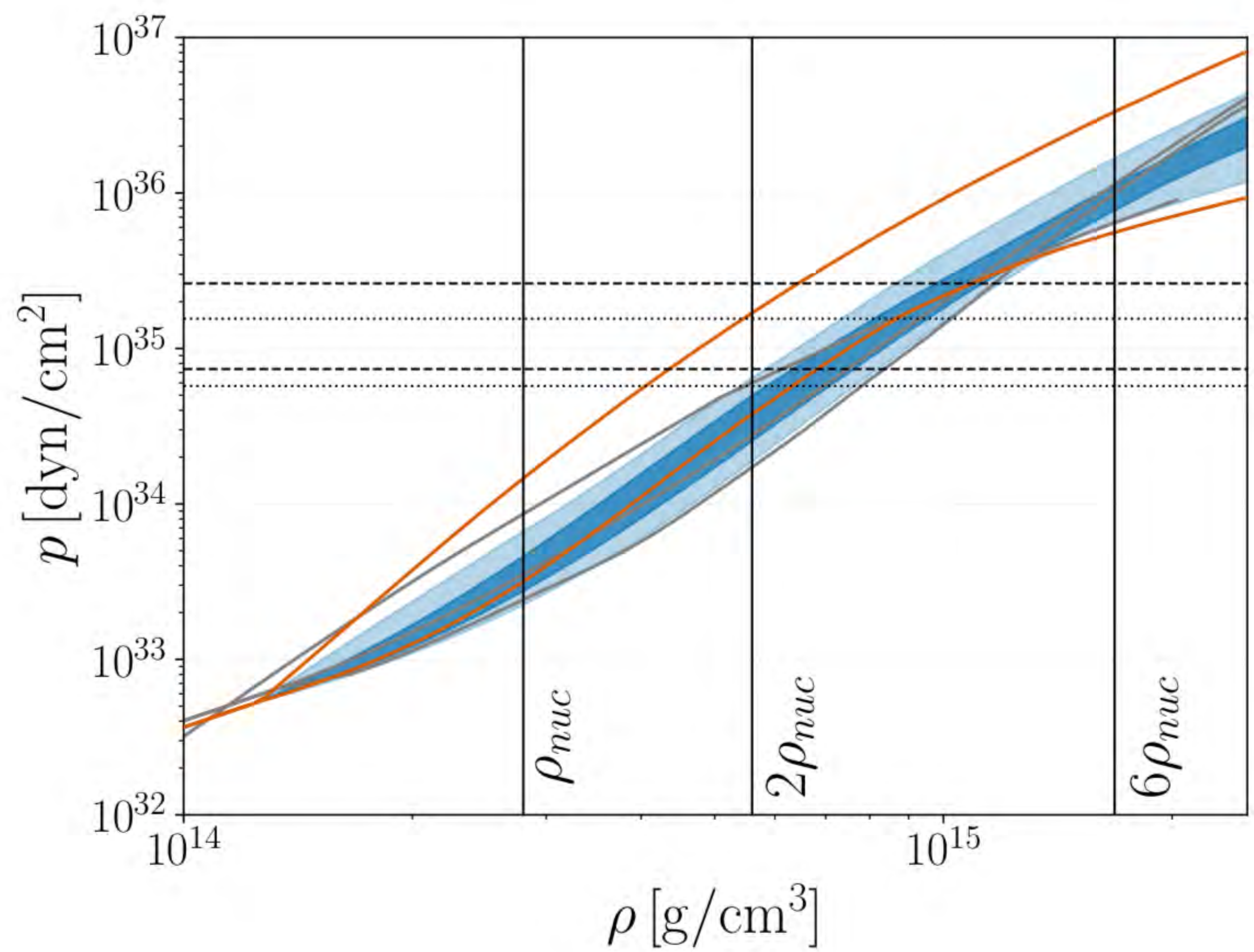
A new constraint by GW Obs. (1)

$\Lambda(1.4M_\odot)=190^{+390}_{-120}$



$P(2\ \rho_{nuc}) = 3.5^{+2.7}_{-1.7} \times 10^{34}$ dyne/cm^2

$P(6\ \rho_{nuc}) = 9.0^{+7.9}_{-2.6} \times 10^{35}$ dyne/cm^2



$\rho_{nuc} = 2.8 \times 10^{14}$ g/cm^3

Abbott et al. (LSC and Virgo), arxiv:1805.11581 (PRL accepted)

Slide from YMKim

Universal (Eos-insensitive) relations

Yagi & Yunes, PR 681, 1 (2017)

I-Love-Q relation, …

- Moment of inertia (I)
- Tital Love number (Love)
- Quardupole moment (Q)

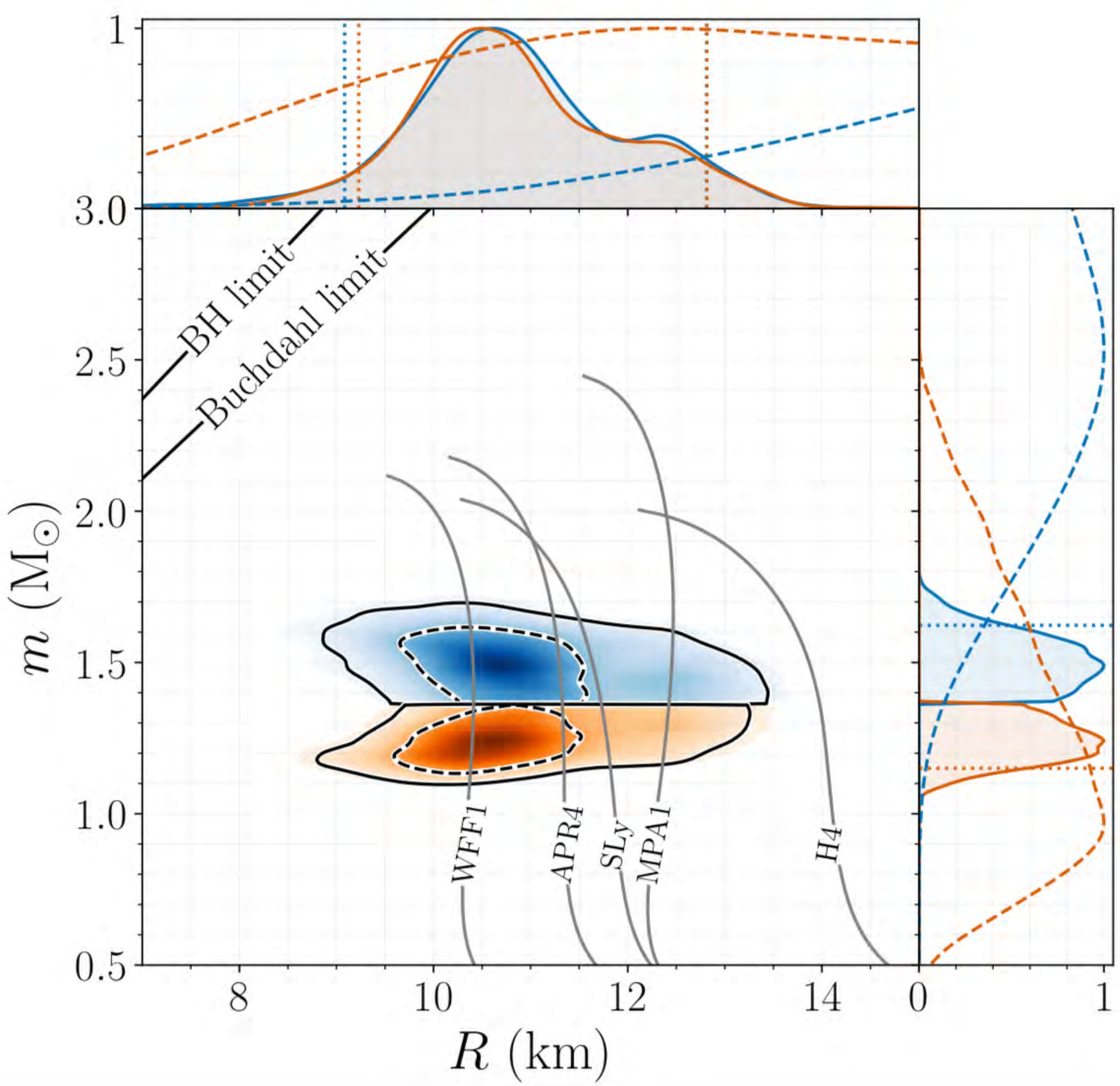
Applications

- X-ray observations
- Gravitational-wave measurements
- Gravitational & astrophysical test of GR

A new constraint by GW Obs. (2)

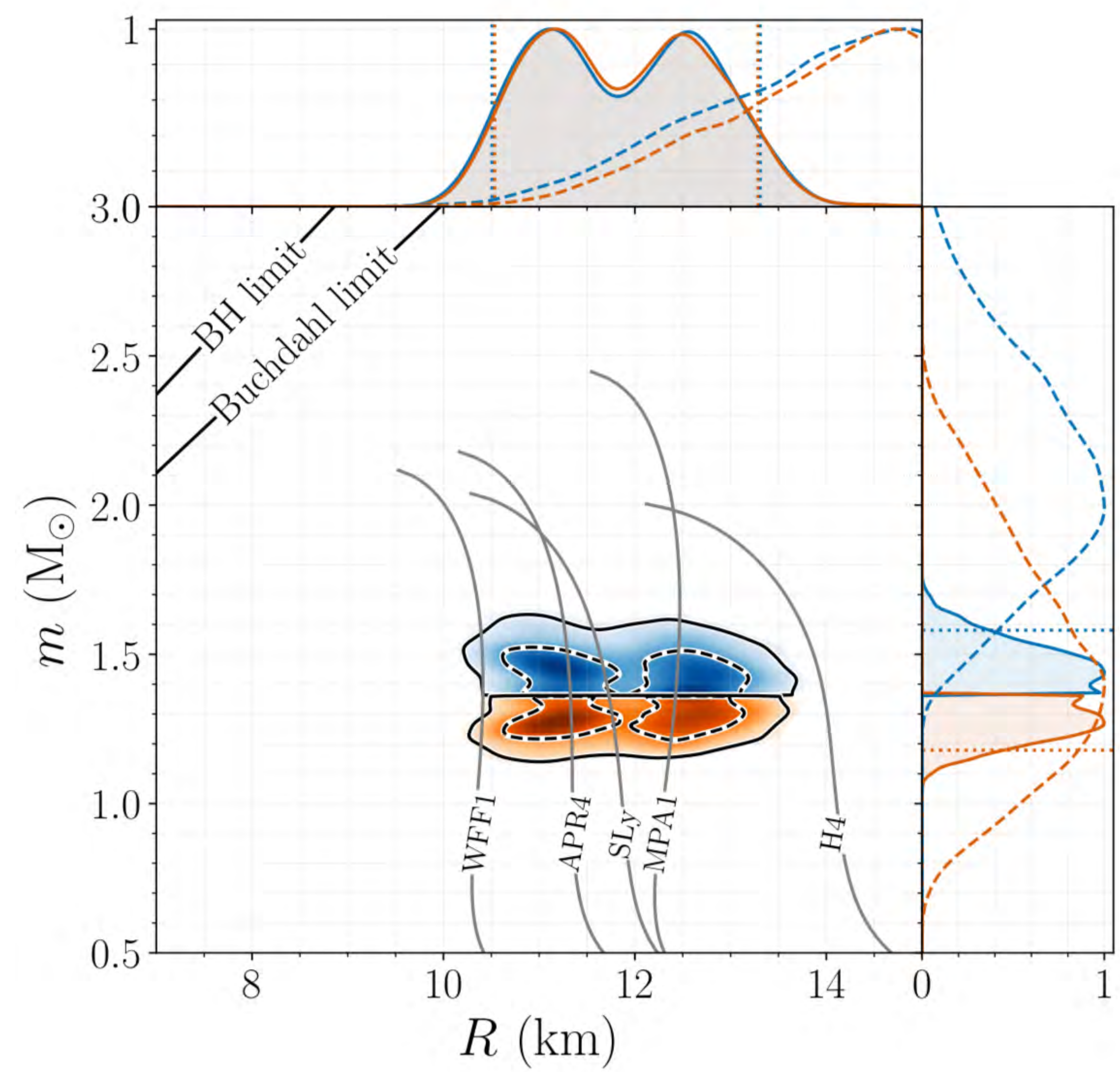
EoS insensitive relations (Yagi&Yunes,PR2017)

R_1=10.8 $^{+2.0}_{-1.7}$ km
R_2=10.7 $^{+2.1}_{-1.5}$ km



Parametrized EoS: M_{max} >= 1.97 $M_\odot$

R_1=11.9 $^{+1.4}_{-1.4}$ km
R_2=11.9 $^{+1.4}_{-1.4}$ km



Abbott et al. (LSC and Virgo), arxiv:1805.11581 (PRL accepted)

Slide from YMKim

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  - Direct measurement of NS mass from GW
  - Tidal Love number/deformability of NS from GW
- **Prospects**

What we have done in Korea

PHYSICAL REVIEW C **98**, 065805 (2018)

Tidal deformability of neutron stars with realistic nuclear energy density functionals

Young-Min Kim,[1] Yeunhwan Lim,[2] Kyujin Kwak,[1] Chang Ho Hyun,[3] and Chang-Hwan Lee[4]
[1] *School of Natural Science, Ulsan National Institute of Science and Technology (UNIST), Ulsan 44919, Korea*
[2] *Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*
[3] *Department of Physics Education, Daegu University, Gyeongsan 38453, Korea*
[4] *Department of Physics, Pusan National University, Busan 46241, Korea*

(Received 1 May 2018; revised manuscript received 14 August 2018; published 26 December 2018)

Nuclear Physics + Astrophysics

Constraints on Nuclear EoS

- Nuclear data: hundreds of models (Skyrme force, RMF, …)
- Neutron star maximum mass

  1.97 ± 0.04 M⊙ [Nature 467, 1081 (2010)]

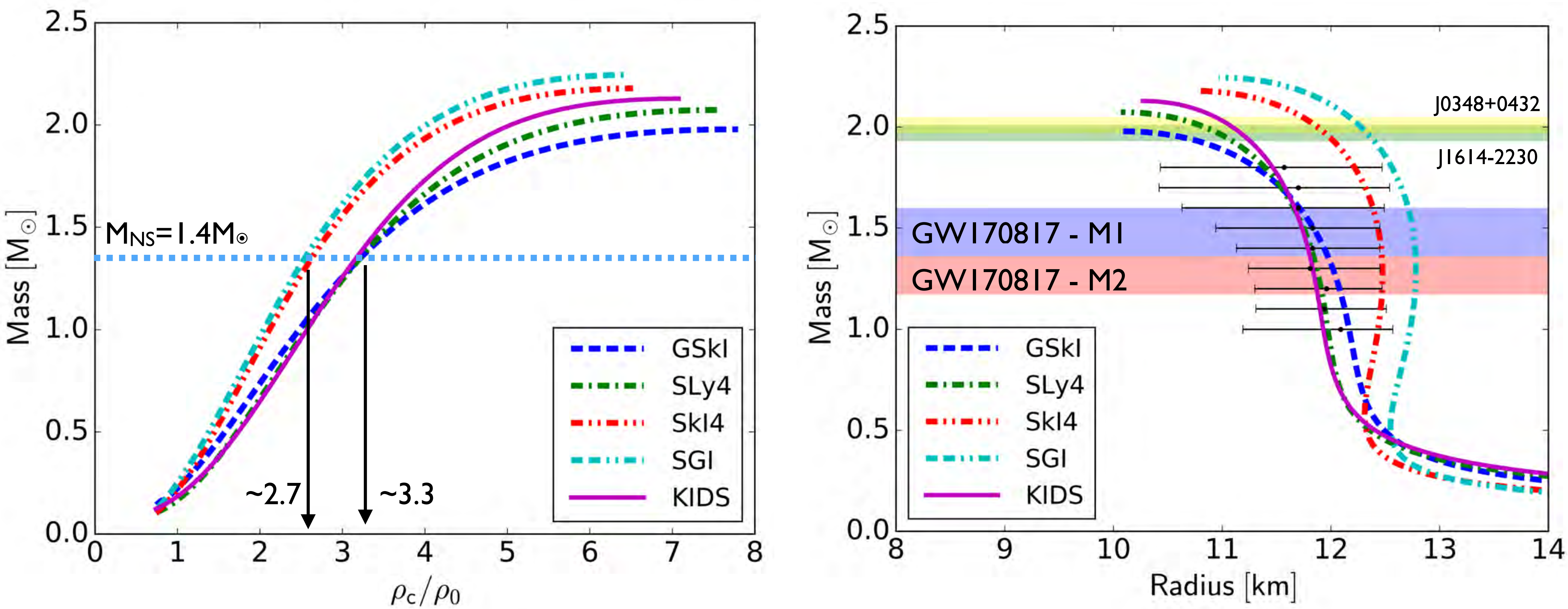
  2.01 ± 0.04 M⊙ [Science 340, 448 (2013)]

- 11 experimental/empirical data for nuclear matter around saturation density [Phys.Rev. C 85, 035201 (2012)]

Constraint	Quantity	Eq.	Density Region	Range of constraint exp/emp	Range of constraint from CSkP	Ref.
SM1	K_o	(7),(15)	ρ_o (fm^{-3})	200 – 260 MeV	202.0 – 240.3 MeV	[64]
SM2	$K' = -Q_o$	(8),(16)	ρ_o (fm^{-3})	200 – 1200 MeV	362.5 – 425.6 MeV	[65]
SM3	$P(\rho)$	(6)	$2 < \frac{\rho}{\rho_o} < 3$	Band Region	see Fig. 1	[78]
SM4	$P(\rho)$	(6)	$1.2 < \frac{\rho}{\rho_o} < 2.2$	Band Region	see Fig. 2	[80]
PNM1	$\frac{E_{PNM}}{E^o_{PNM}}$	(31)	$0.014 < \frac{\rho}{\rho_o} < 0.106$	Band Region	see Fig. 3	[39, 40]
PNM2	$P(\rho)$	(6)	$2 < \frac{\rho}{\rho_o} < 3$	Band Region	see Fig. 5	[78]
MIX1	J	(9)	ρ_o (fm^{-3})	30 – 35 MeV	30.0 – 35.5 MeV	[44]
MIX2	L	(10)	ρ_o (fm^{-3})	40 – 76 MeV	48.6 – 67.1 MeV	[101]
MIX3	$K_{\tau,v}$	(21)	ρ_o (fm^{-3})	-760 – -372 MeV	-407.1 – -360.1 MeV	[107]
MIX4	$\frac{S(\rho_o/2)}{J}$	-	ρ_o (fm^{-3})	0.57 – 0.86	0.61 – 0.67	[110]
MIX5	$\frac{3P_{PNM}}{L\rho_o}$	(41)	ρ_o (fm^{-3})	0.90 – 1.10	1.02 – 1.10	[112]

Mass-Radius relations

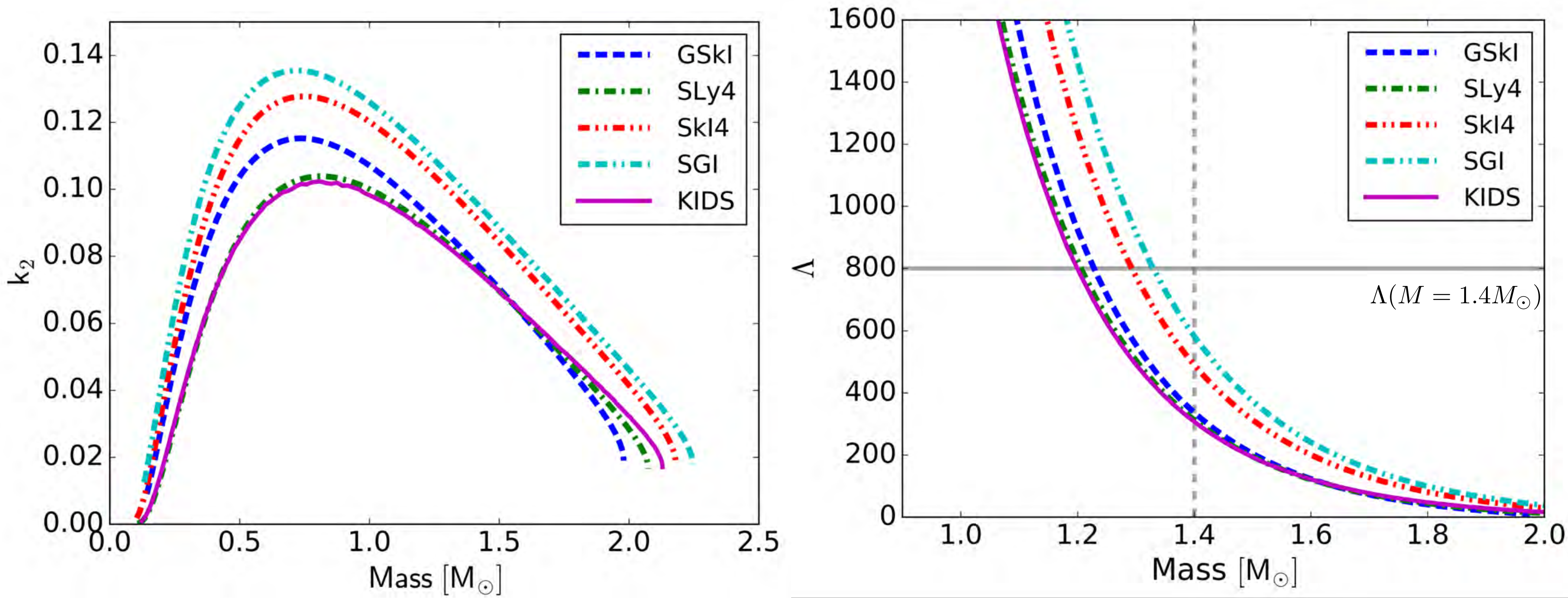
Kim et al., arxiv:1805.00219



GW170817
- Mchirp = 1.188 M⊙
- low spin prior : M1 = 1.36 ~ 1.60 M⊙ , M2 = 1.17 ~ 1.36 M⊙
- high spin prior : M1 = 1.36 ~ 2.26 M⊙ , M2 = 0.86 ~ 1.36 M⊙

Tidal deformability of a NS

Kim et al., arxiv:1805.00219



GW170817, Mchirp = 1.188 M⊙
- low spin prior : Lambda(1.4 M⊙) < 800
- high spin prior : Lambda(1.4 M⊙) < 1400

Prospects of the Observing Runs

"Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA", arXiv:1304.0670v4, LIGO-P1200087-v45, Living Rev. Relativity, 21, 3 (2018)

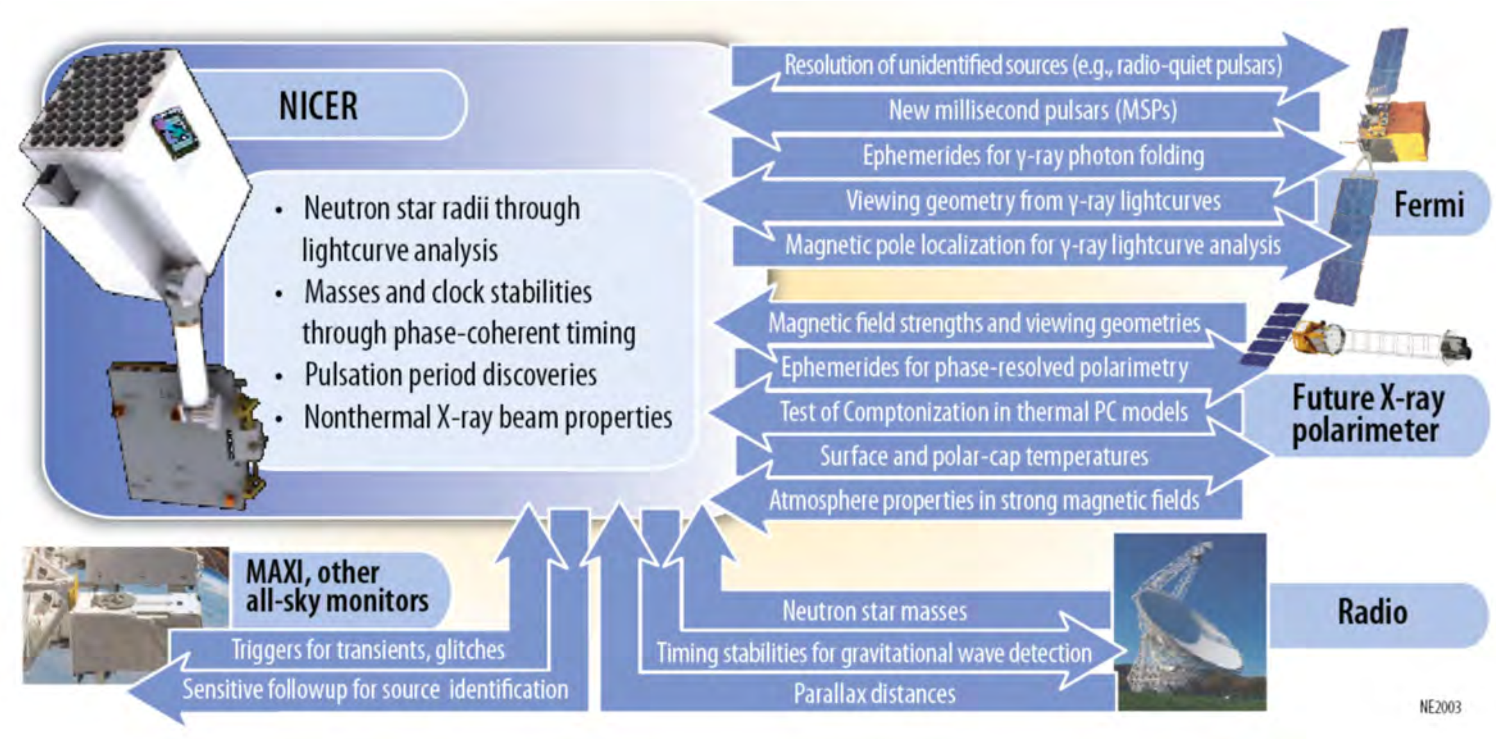
Epoch			2015 – 2016	2016 – 2017	2018 – 2019	2020+	2024+
Planned run duration			4 months	9 months	12 months	(per year)	(per year)
Expected burst range/Mpc		LIGO	40 – 60	60 – 75	75 – 90	105	105
		Virgo	—	20 – 40	40 – 50	40 – 70	80
		KAGRA	—	—	—	—	100
Expected BNS range/Mpc		LIGO	40 – 80	80 – 120	120 – 170	190	190
		Virgo	—	20 – 65	65 – 85	65 – 115	125
		KAGRA	—	—	—	—	140
Achieved BNS range/Mpc		LIGO	60 – 80	60 – 100	—	—	—
		Virgo	—	25 – 30	—	—	—
		KAGRA					
Estimated BNS detections			0.05 – 1	0.2 – 4.5	1 – 50	4 – 80	11 – 180
Actual BNS detections			0	1	—	—	—
90% CR	% within	5 deg^2	< 1	1 – 5	1 – 4	3 – 7	23 – 30
		20 deg^2	< 1	7 – 14	12 – 21	14 – 22	65 – 73
		median/deg^2	460 – 530	230 – 320	120 – 180	110 – 180	9 – 12
Searched area	% within	5 deg^2	4 – 6	15 – 21	20 – 26	23 – 29	62 – 67
		20 deg^2	14 – 17	33 – 41	42 – 50	44 – 52	87 – 90

We expect to observe more BNS and/or NS-BH

Slide by YMKim

NICER Neutron star Interior Composition ExploreR

- **launch**: June 2017, SpaceX
- **platform**: ISS ELC (ExPRESS Logistics Carrier)
- **instrument**: X-ray (0.2-12 keV)
- **objective**
  - ***structure***: neutron star radii to 5%, cooling timescales
  - ***dynamics***: stability of pulsars as clocks, properties of outbursts, oscillations, and precession
  - ***energetics***: intrinsic radiation patterns, spectra, and luminosities



RAON

Rare isotope
Accelerator complex for
ON-line experiments

Nuclear Equation of States

$$x = \frac{\rho_p}{\rho_p + \rho_n}$$

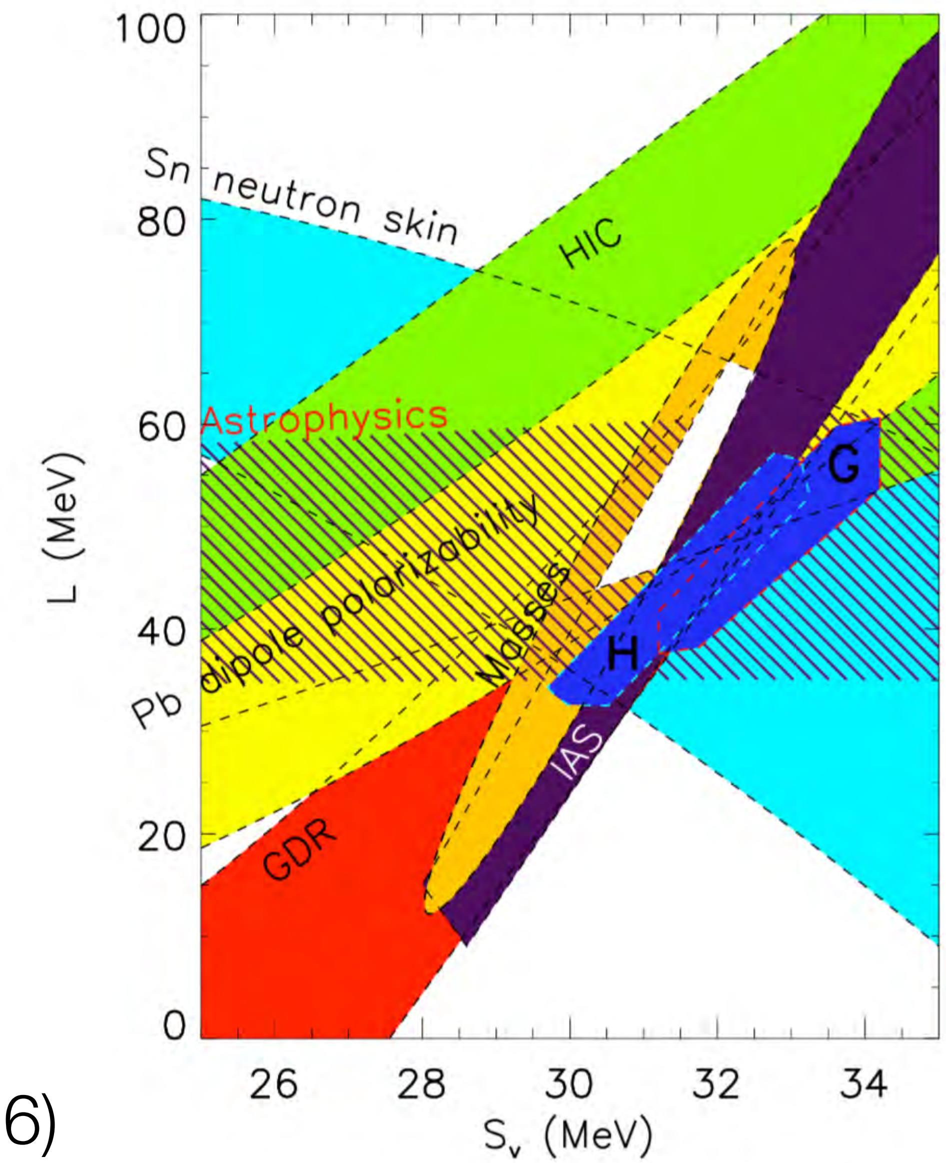
$$E(\rho, x) = -B + \frac{K_0}{18}\left(\frac{\rho}{\rho_0} - 1\right)^2 + \frac{K_0'}{162}\left(\frac{\rho}{\rho_0} - 1\right)^3 + E_{\rm sym}(\rho)(1-2x)^2 + \cdots$$

Incompressibility $K_0 \simeq 230\ \mathrm{MeV}$

Skewness $K_0' \sim -2000\ \mathrm{MeV}$

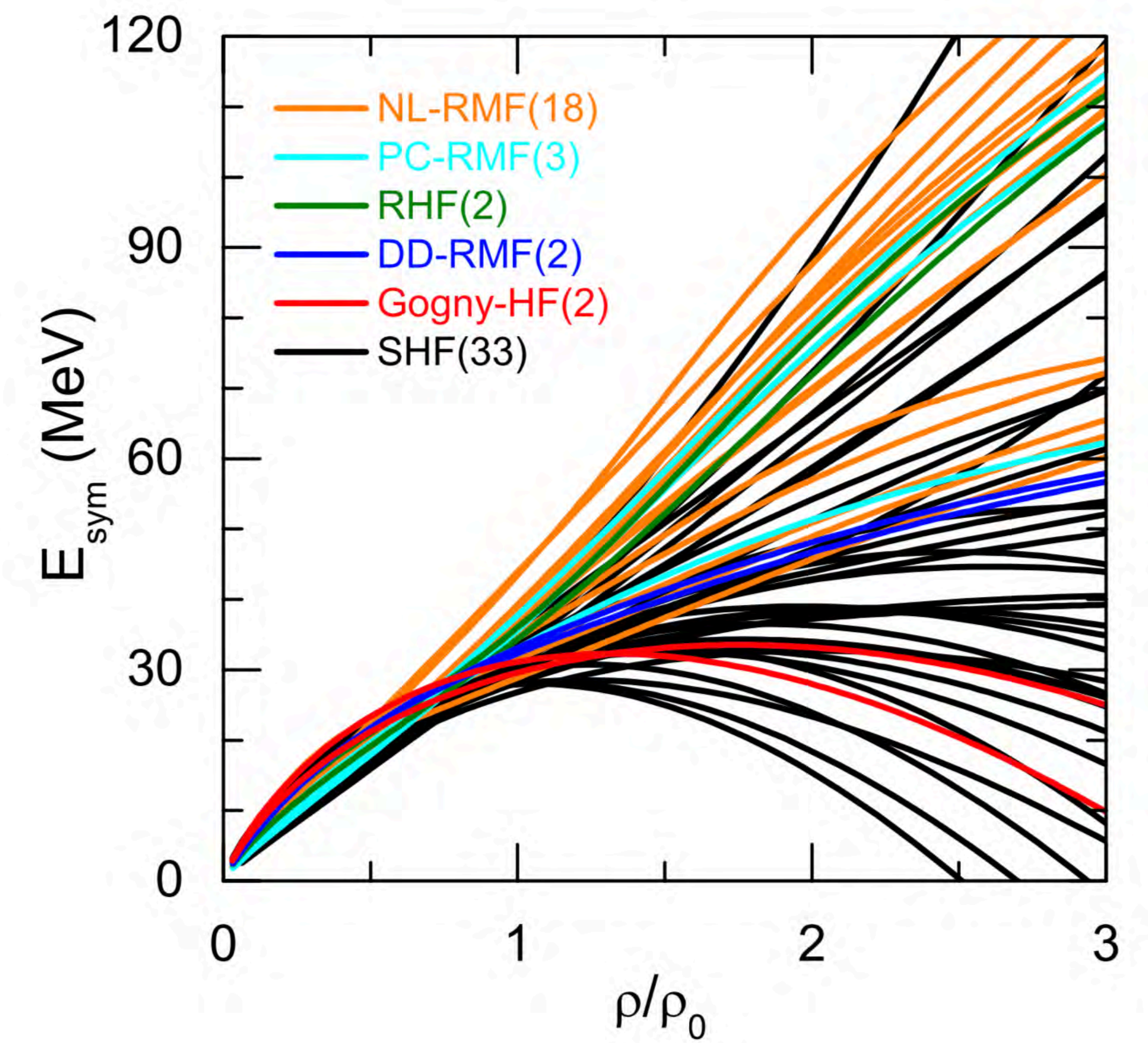
$S_0 \equiv E_{\rm sym}(\rho_0)$ **Symmetry Energy**

$$L \equiv 3\rho \left.\frac{\partial E_{\rm sym}}{\partial \rho}\right|_{\rho_0}$$



J.M. Latter, Y. Lim (2016)

Symmetry energy / Theoretical uncertainties



Courtesy of Lie-Wen Chen

waiting for RAON@IBS

Prospects

- **Expecting more GWs from NS binary mergers !**

  - Mass & tidal deformability of NS can be measured simultaneously by GWs.

  - GWs can give constrains on the radius of NS and high-density EOS.

- **Expecting new results from RAON !**

  - RAON can give constraints on high-density EOS

Binary interactions are always interesting

Thanks