Lecture 1
Multi-Messenger Observations of Neutron Stars

From Electromagnetic Waves to Gravitational Waves

Chang-Hwan Lee
Pusan National University

Dense Nuclear & Stellar Matter Studies

for **RAON** New Rare Isotope Accelerator & **MMA** Multi-Messenger Astrophysics

BUD^2 Collaboration

Busan (CHL, Myungkuk KIM)
Ulsan (Kyujin KWAK, Young-Min KIM)
Daegu (Chang Ho HYUN)
Daejeon (Youngman KIM)
Montreal (Sangyong JEON, McGill)

History of BUD^2 Collaboration *my personal point of view*

Hadron Physics		*Astrophysics*
NS EoS with **Effective Field Theories** (with D.P.Min, **M.Rho** & G.E.Brown)	**1990s**	NS Binary as a source of GW (with **G.E.Brown**@Stony Brook)
	2003	**Korean Gravitational Wave Group**
Science-Business-Belt Project initiated by **D.P. Min**	**2006**	Nuclear physics + Astrophysics + Mathematics + Artificial Intelligence
RAON project was approved	**2009**	**KGWG** joined LIGO Scientific Collab.
Transport Studies **DJBUU** (new transport code) **BUD^2-McGill Collaboration**	**2017**	**GW from NS-NS mergers** (Multi-messenger Astrophysics) Tidal deformability of NS
First run of RAON Symmetry Energy	**2021**	

BUD^2 Collaboration
for Astro-Hadron Physics

Plan

1. Lecture 1: Observations
   - Electromagnetic Waves (Radio, X-ray, …)
   - Gravitational Waves

2. Lecture 2: Neutron Star Equations of State
   - Thermodynamic principles
   - Polytropic structure

3. Lecture 3: Dense Matter Physics
   - Nuclear & Particle Physics
   - Remaining Problems / Prospects

Why Neutron Stars ?

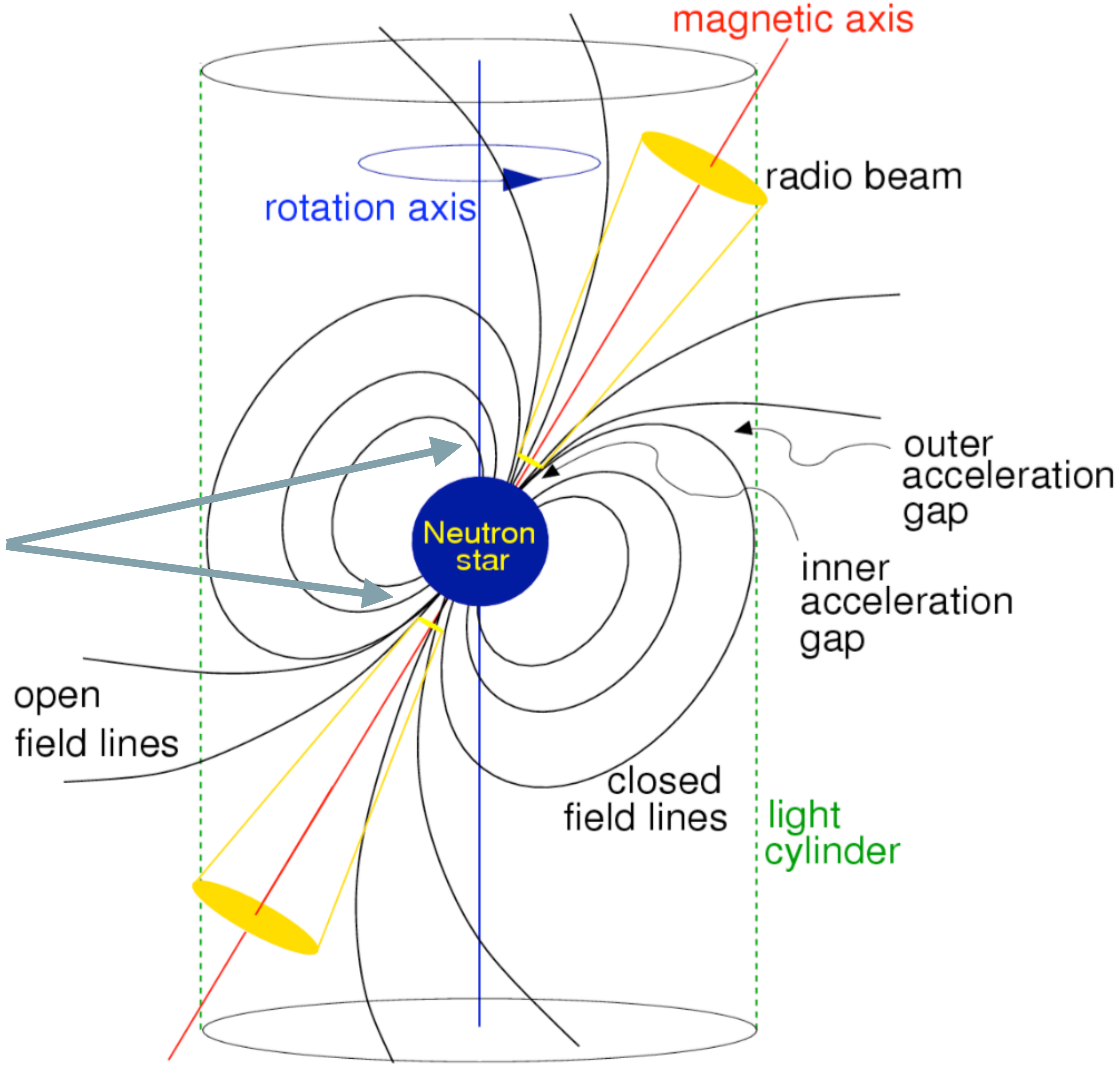
Ultimate testing place for physics of dense matter

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

$$\rho_{\text{center}} \approx \text{several} \times \rho_0$$

$$n_0 \approx 0.16 \text{ fm}^{-3}$$
$$\approx 1.6 \times 10^{44} \text{m}^{-3}$$
$$\rho_0 \approx 2.04 \times 10^{17} \text{kg} \cdot \text{m}^{-3}$$

e^+e^- pair creation

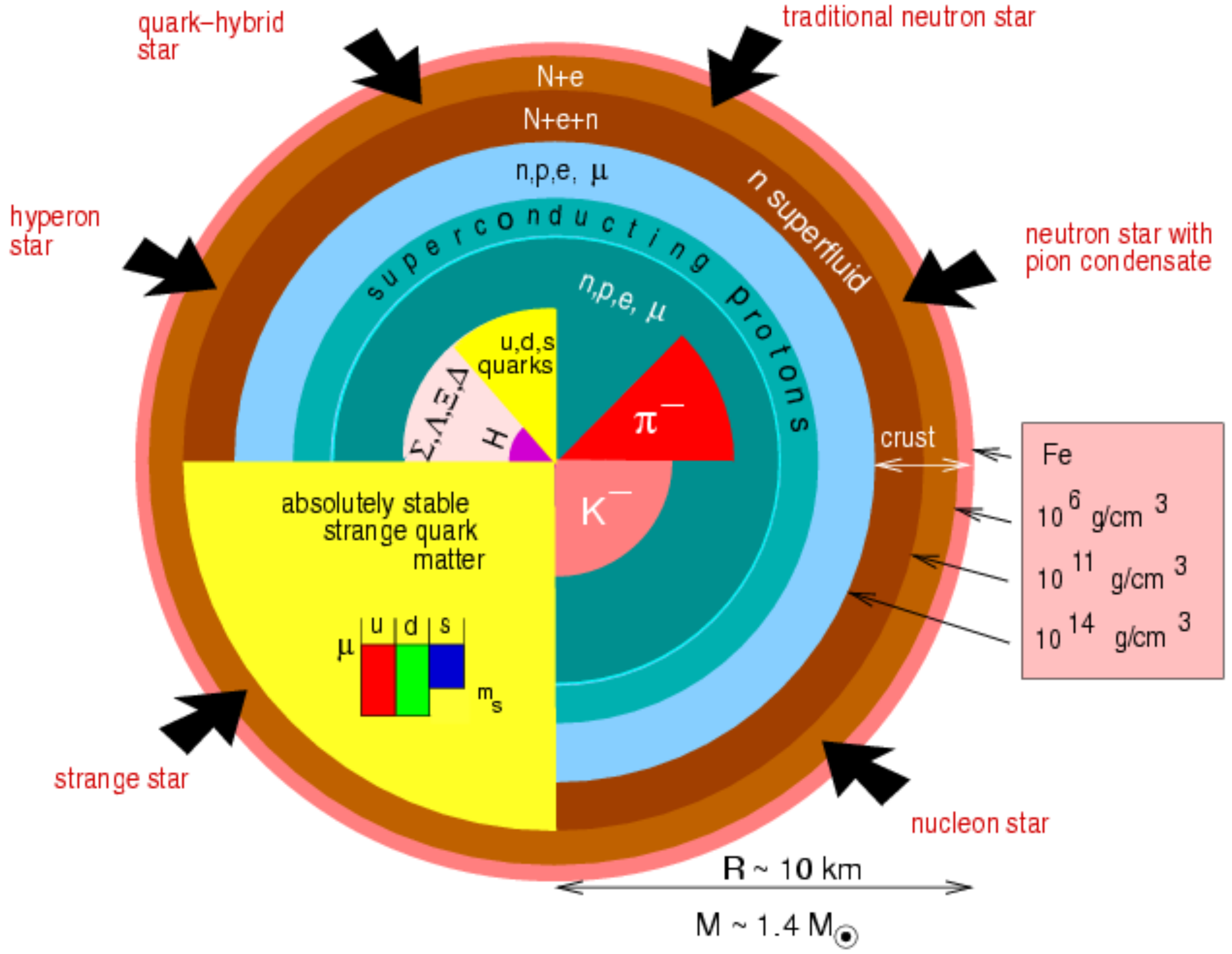


Nuclear matter is not an ideal gas

F. Weber 2005

White Dwarf / Condensed Matter:
- electron degeneracy
- EM interaction

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

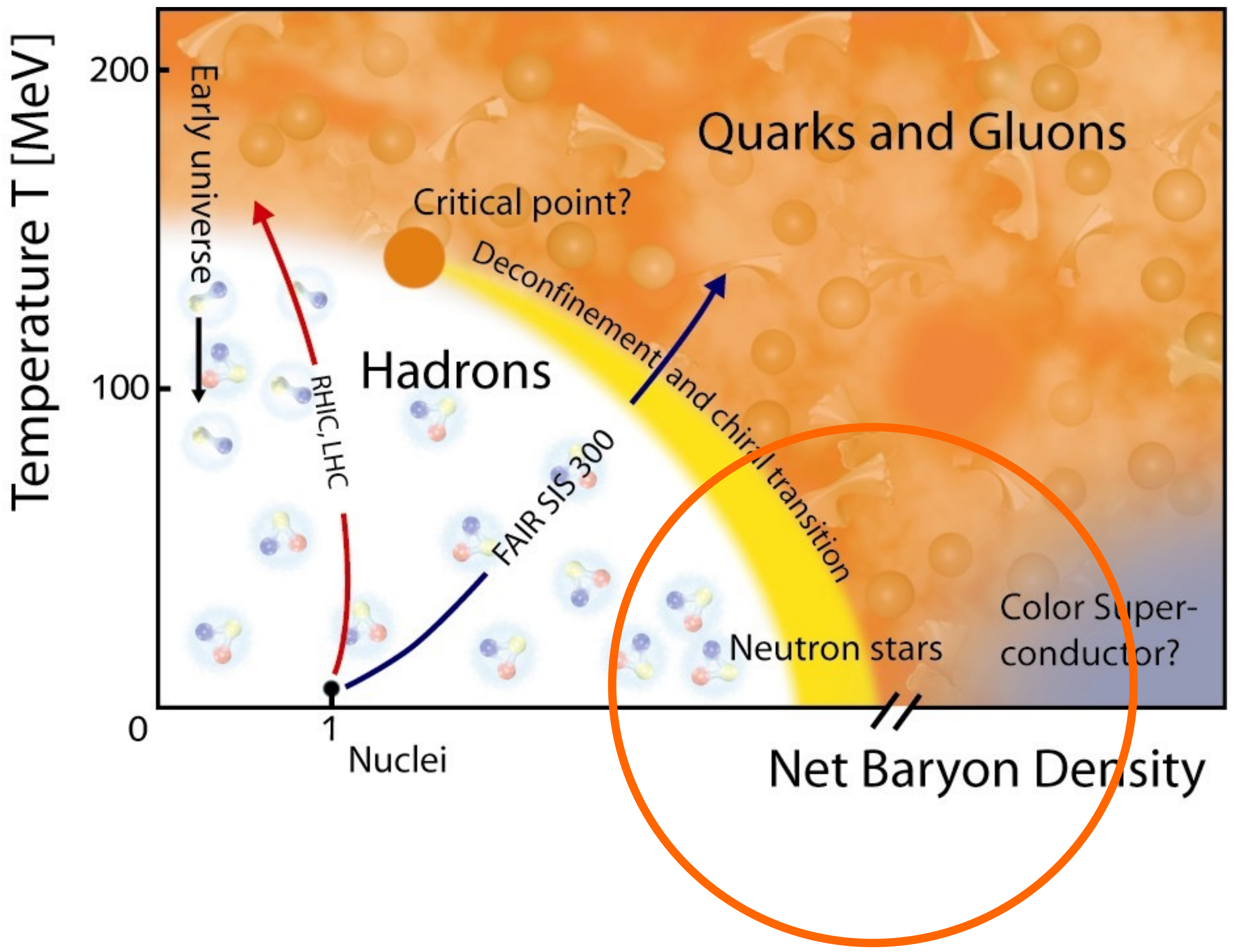


- **still uncertain due to the nature of strong interactions**
- **introduction of 3 body forces**
- **exotic states with strangeness**
- **… …**

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
- ✓ … …



Neutron Star Observations

- Electromagnetic Waves
- Gravitational Waves

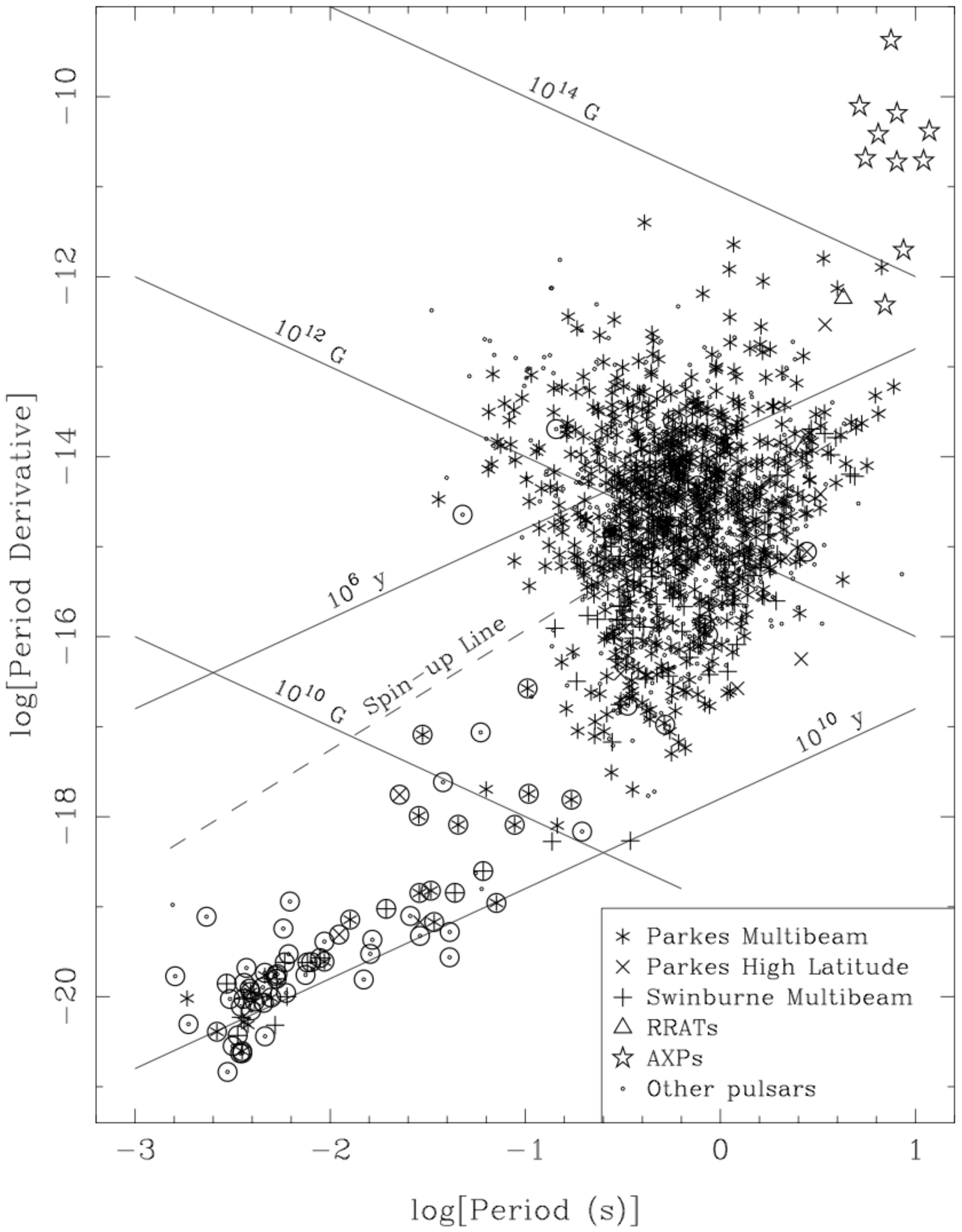
Millisecond Pulsars

Dipole Radiation

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

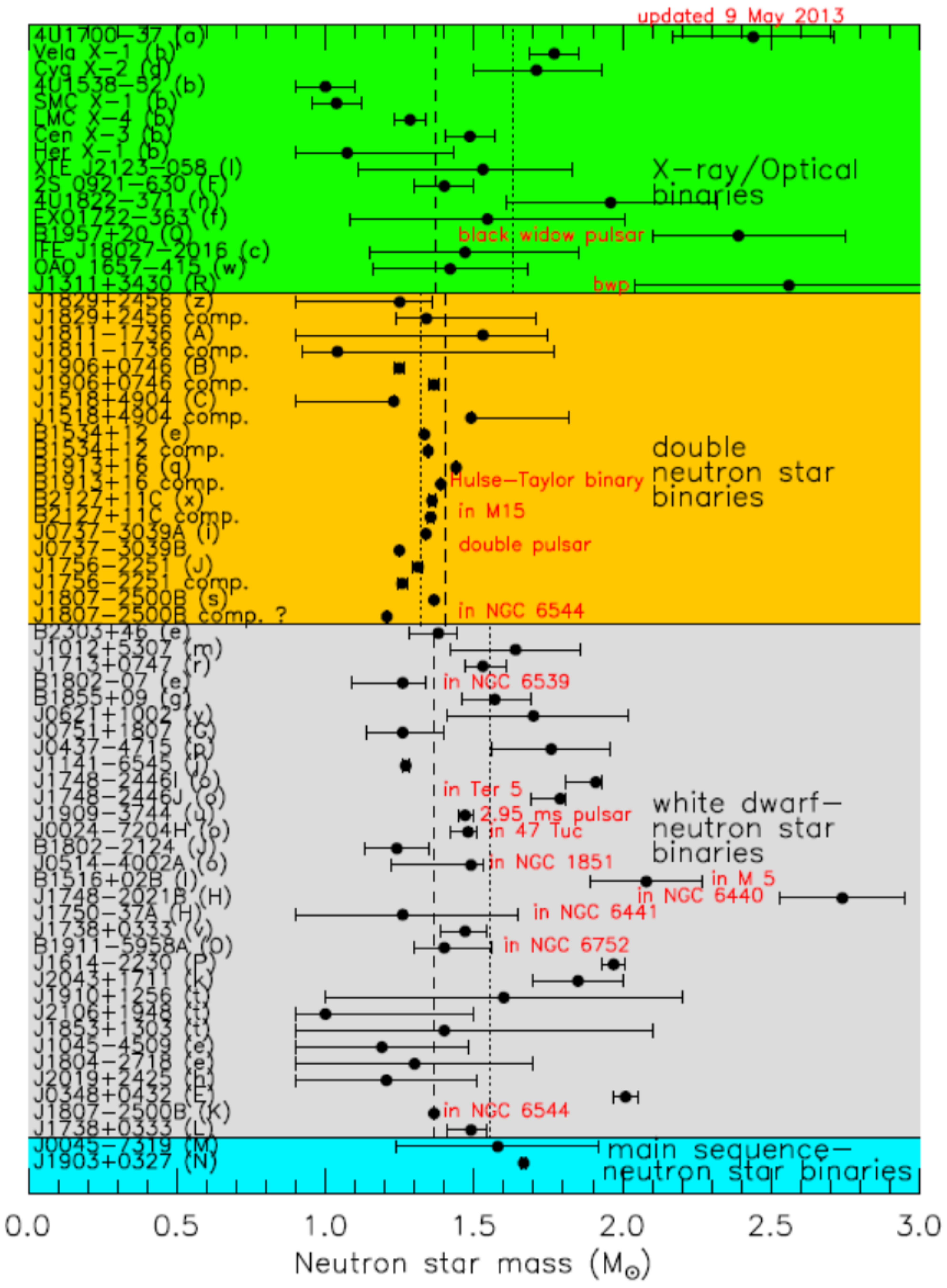
$$\dot{E}_{\rm dipole} = -\frac{B_{\perp}^2 R^6 \Omega^4}{6c^3}$$

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



Masses

- High-mass neutron stars in X-ray binaries & white dwarf-NS binaries (2010 & 2013)
- Less than 1.5 solar mass in double NS binaries
- Maximum NS mass is still uncertain

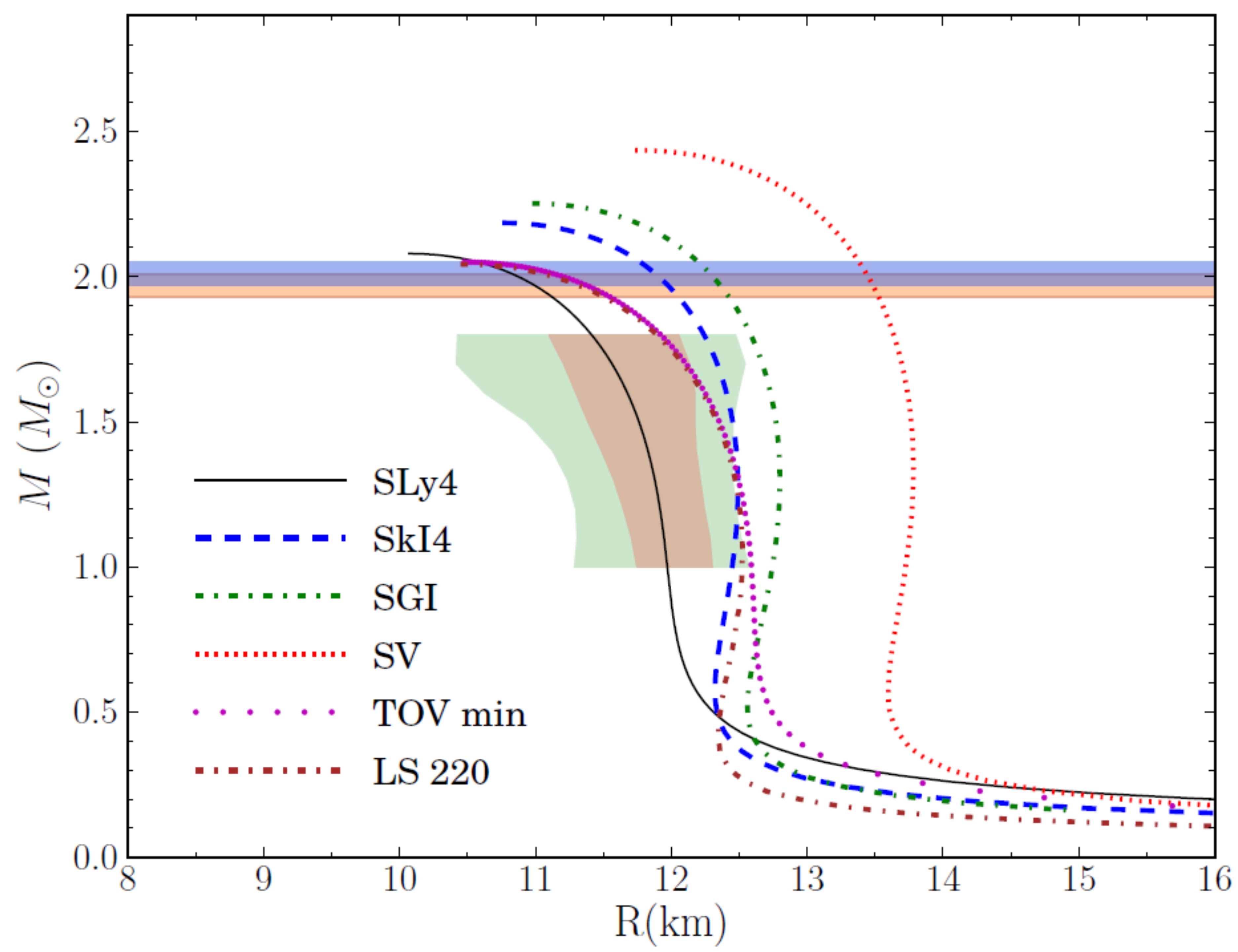


Prakash 2013

Maximum Mass of Neutron Stars

Neutron Star-White Dwarf Binaries

[Nature 467 (2010) 1081; Science 340 (2013) 6131]



$2.01 M_\odot$

$1.97 M_\odot$

Moment of Inertia / Glitches

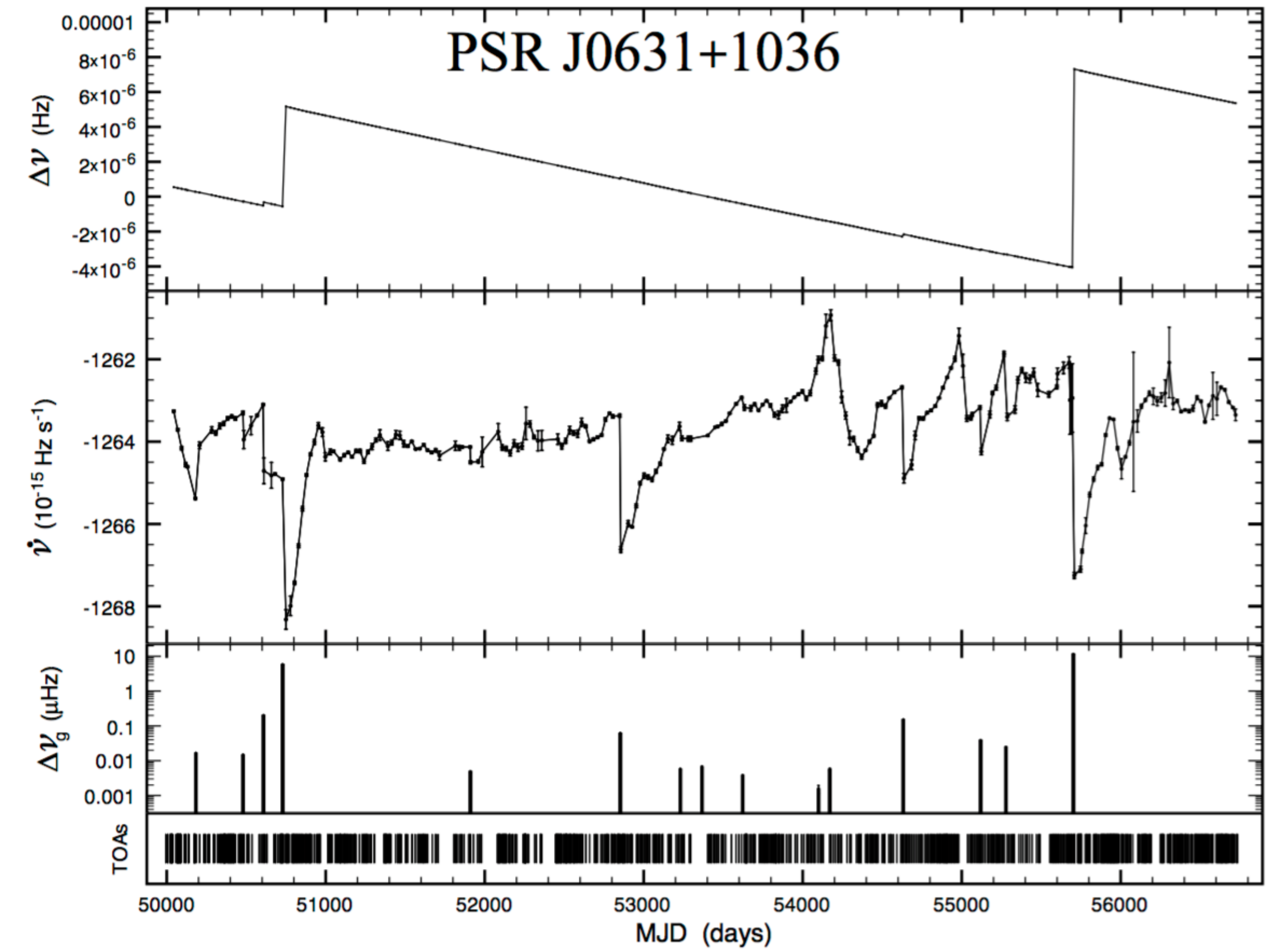
$$\dot{E}_{\rm rot} = I\Omega\dot{\Omega}$$

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

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

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

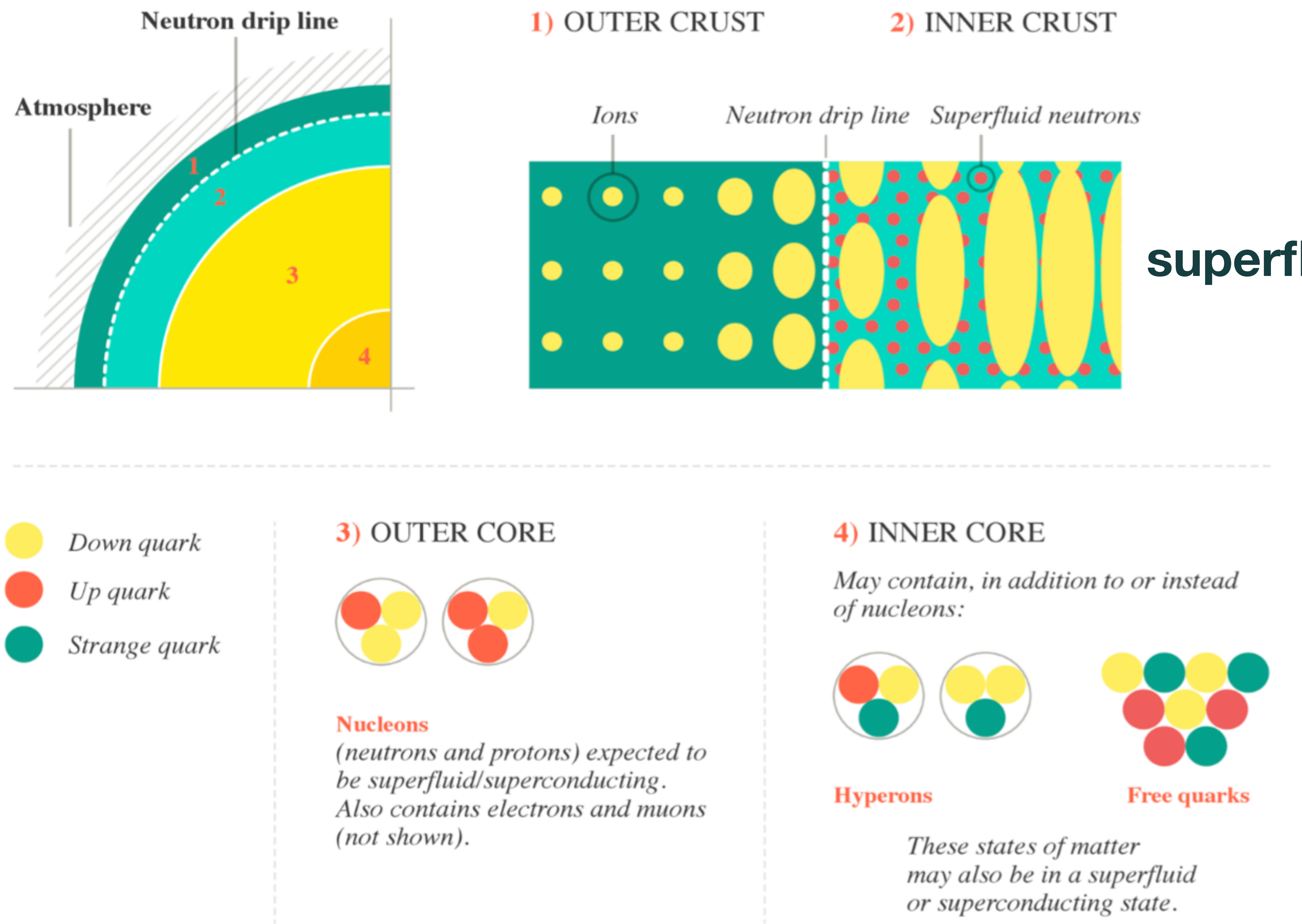
$$\tau_{\rm pulsar} = \frac{\Omega}{(1-n)\dot{\Omega}}$$



D. Antonopoulou (U. Amsterdam, 2015)

Superfluid Neutrons

D. Antonopoulou (U. Amsterdam, 2015)



superfluid

Low-Mass X-ray Binaries (LMXB)

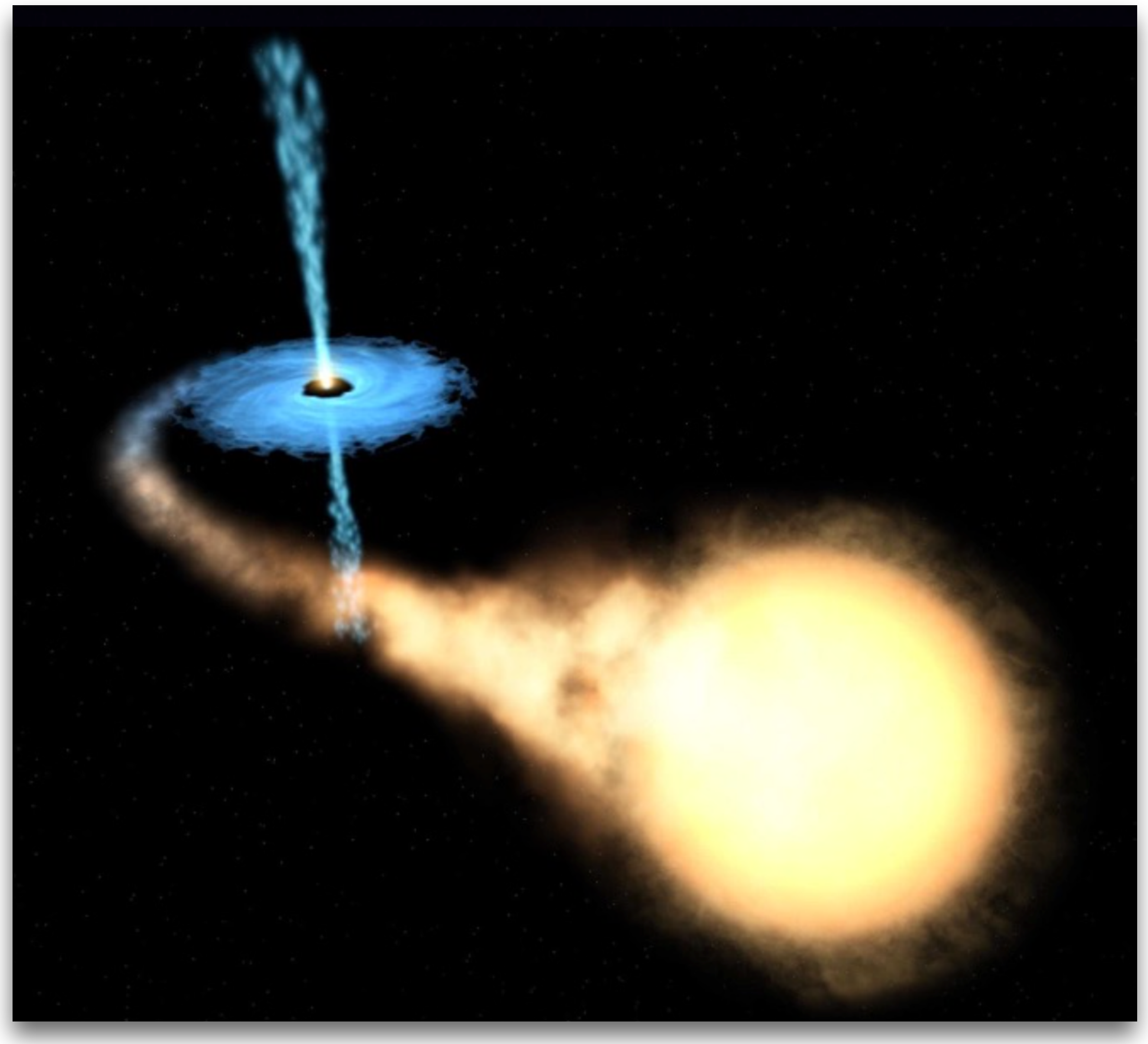
Accreting Object: NS or BH

Companion: Low-Mass Main Sequence

Age: Old (> 10^9 year)

Accretion timescale: 10^7 - 10^9 year

X-ray energy: Soft (< 10 keV)



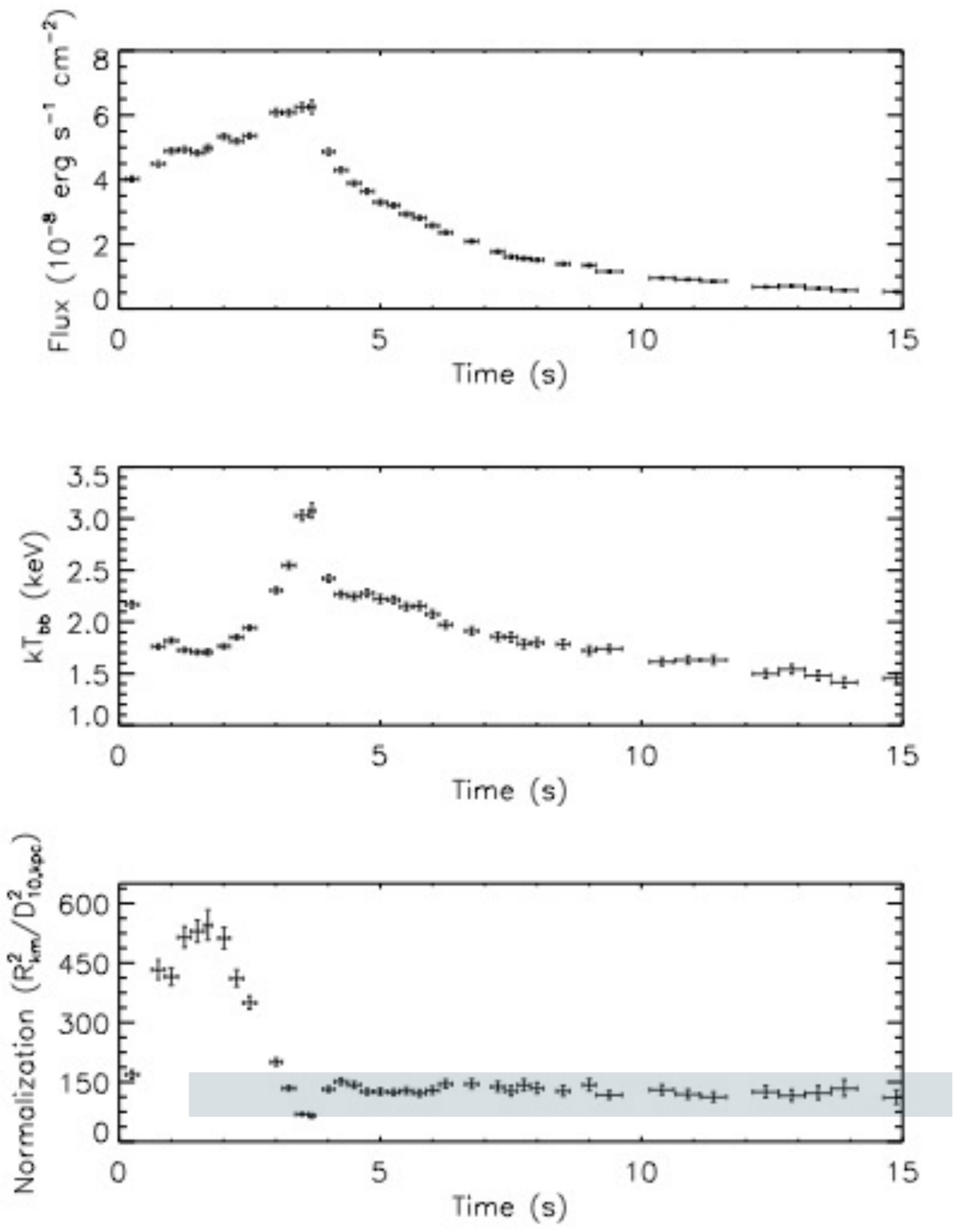
M & R from LMXB

with Myungkuk Kim, Young-Min Kim, Kyujin Kwak

flux

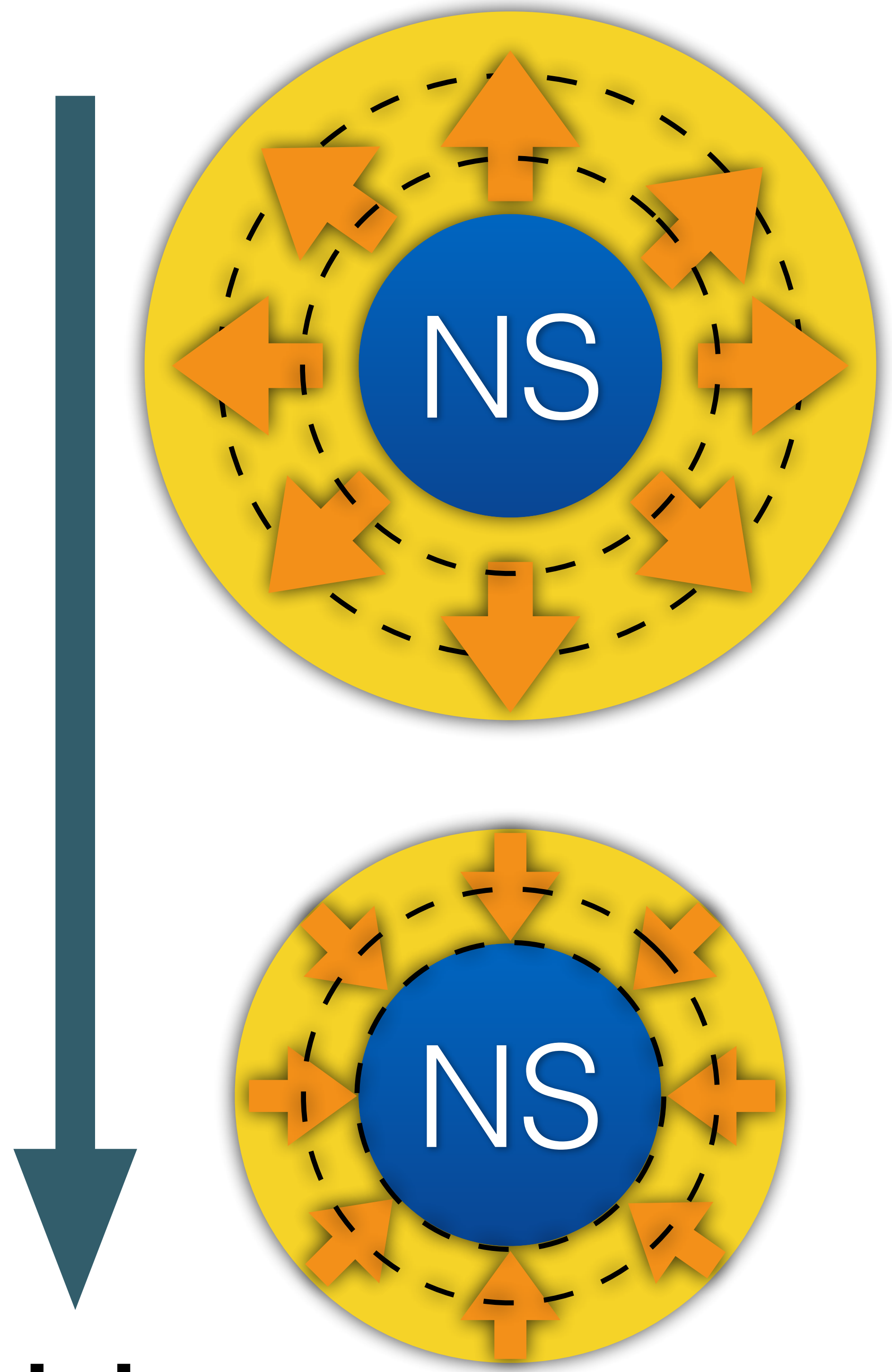
temperature

radius



Ozel et al. 2009

expansion



touchdown

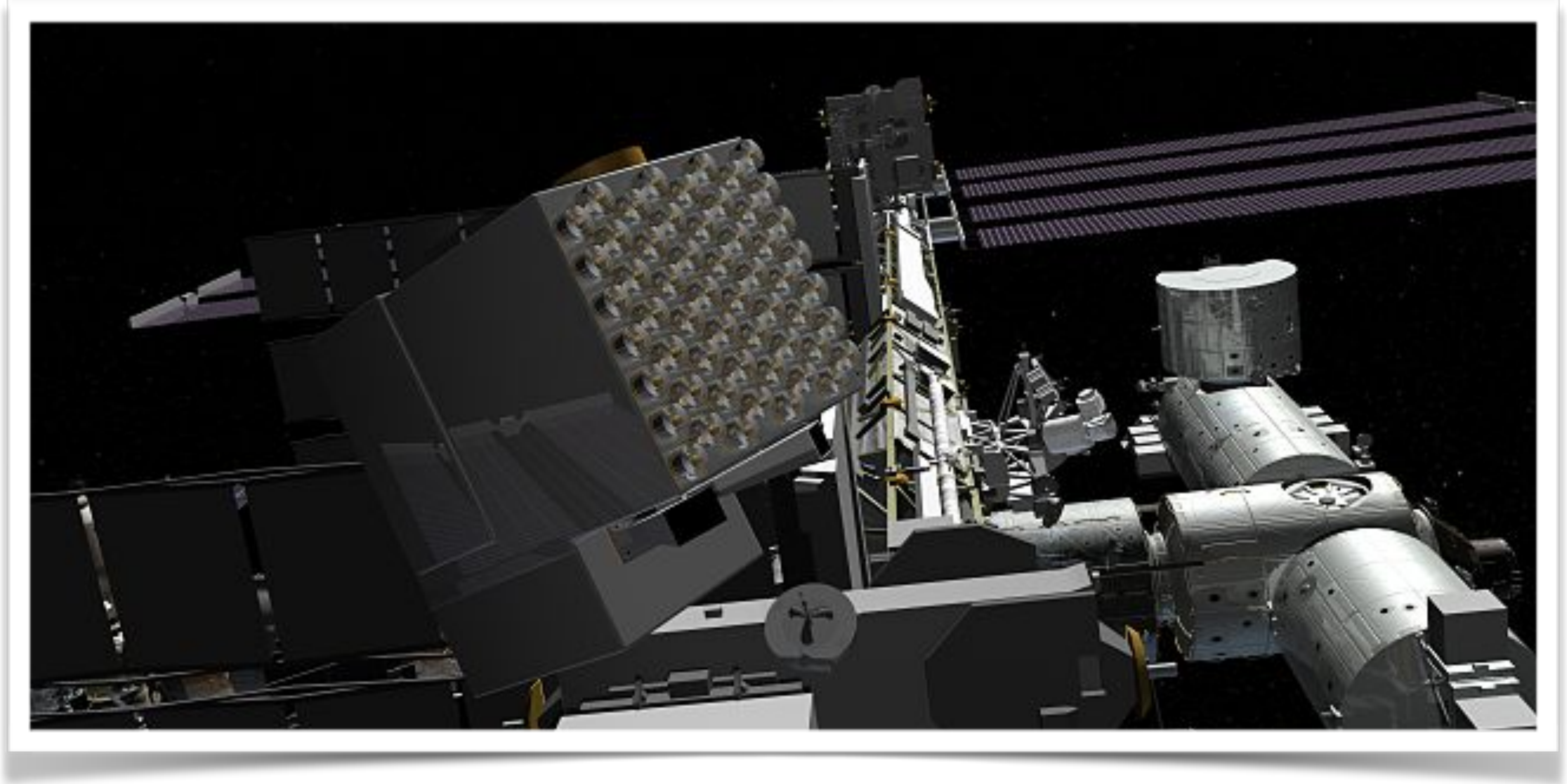
Low-Mass X-ray Binaries (LMXB)

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	$0.832^{+1.19}_{-0.051}$	$13.25^{+1.37}_{-3.50}$	$1.98^{+0.10}_{-0.36}$	$11.3^{+0.95}_{-1.03}$

NICER Neutron star Interior Composition ExploreR

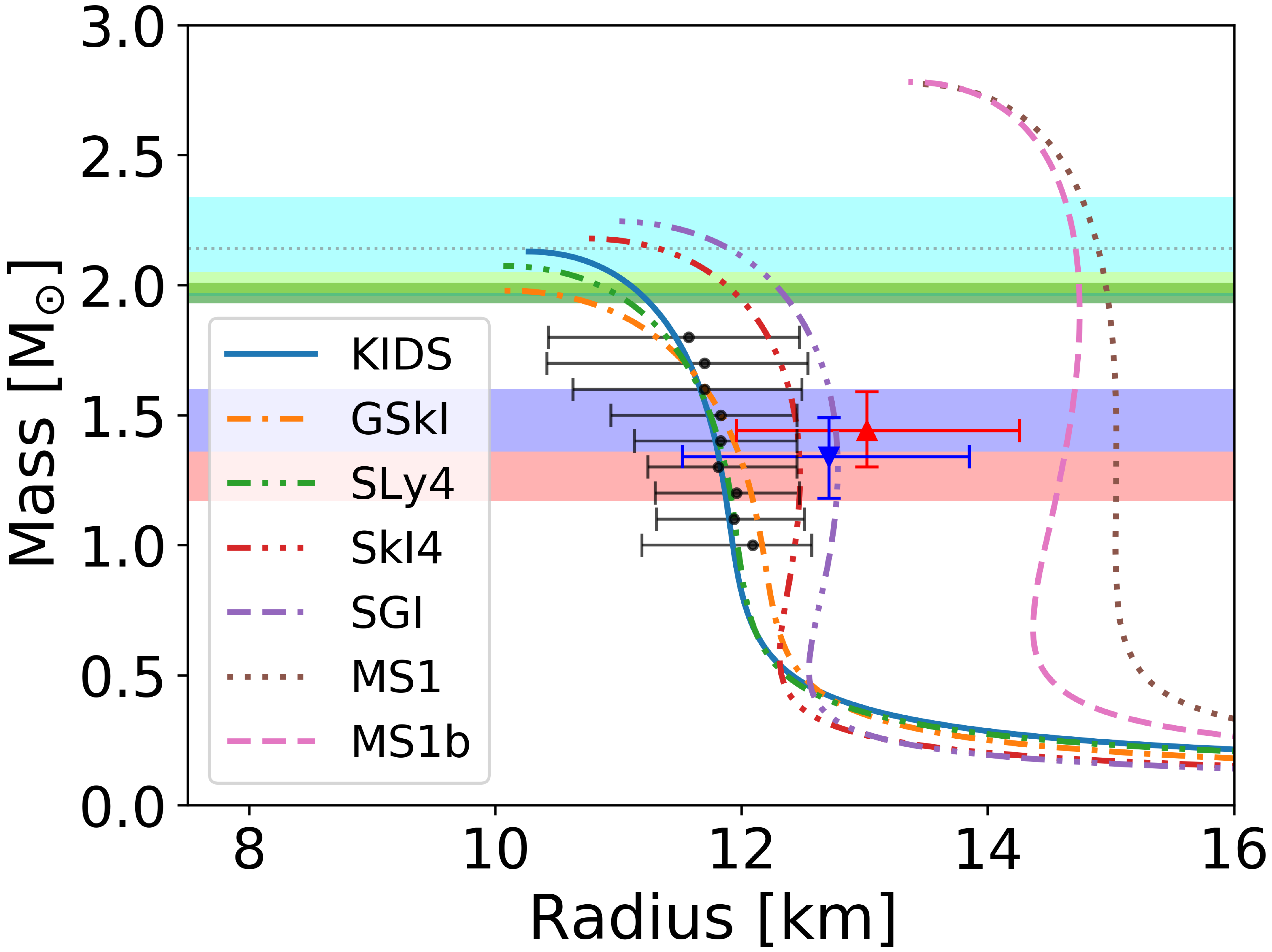
- **launch**: June 2017, SpaceX
- **platform**: ISS ELC (ExPRESS Logistics Carrier)
- **instrument**: X-ray (0.2-12 keV)
- **objective**
  - ***structure***: neutron star radii to 5%, cooling timescales
  - ***dynamics***: stability of pulsars as clocks, properties of outbursts, oscillations, and precession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



Riley 2019 vs. Miller 2019

1. Mass
   - $1.34^{+0.15}_{-0.16}$ Msun vs. $1.44^{+0.15}_{-0.14}$ Msun
2. Radius
   - $12.71^{+1.14}_{-1.19}$ km vs. $13.02^{+1.24}_{-1.06}$ km
3. Methods
   - MultiNest vs. MultNest & emcee (MCMC)
   - X-PSI bayesian code vs. Miller's own code
   - Different heated regions
   - Pulse profile model vs. Pulse waveform model

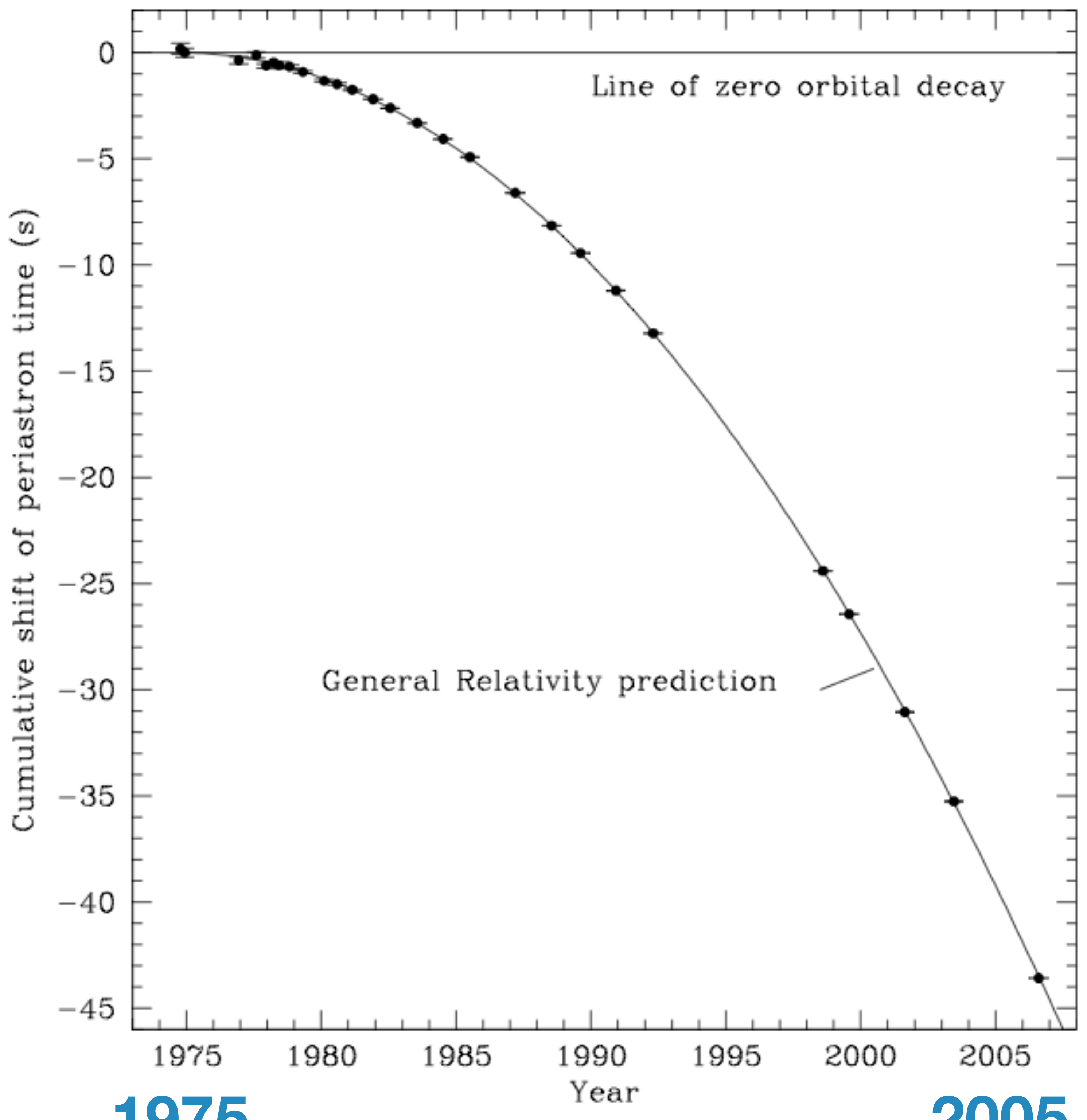
H. T. Cromartie, *et al.*, Nature Astronomy (2019).



$2.14^{+0.20}_{-0.18} M_\odot$

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)



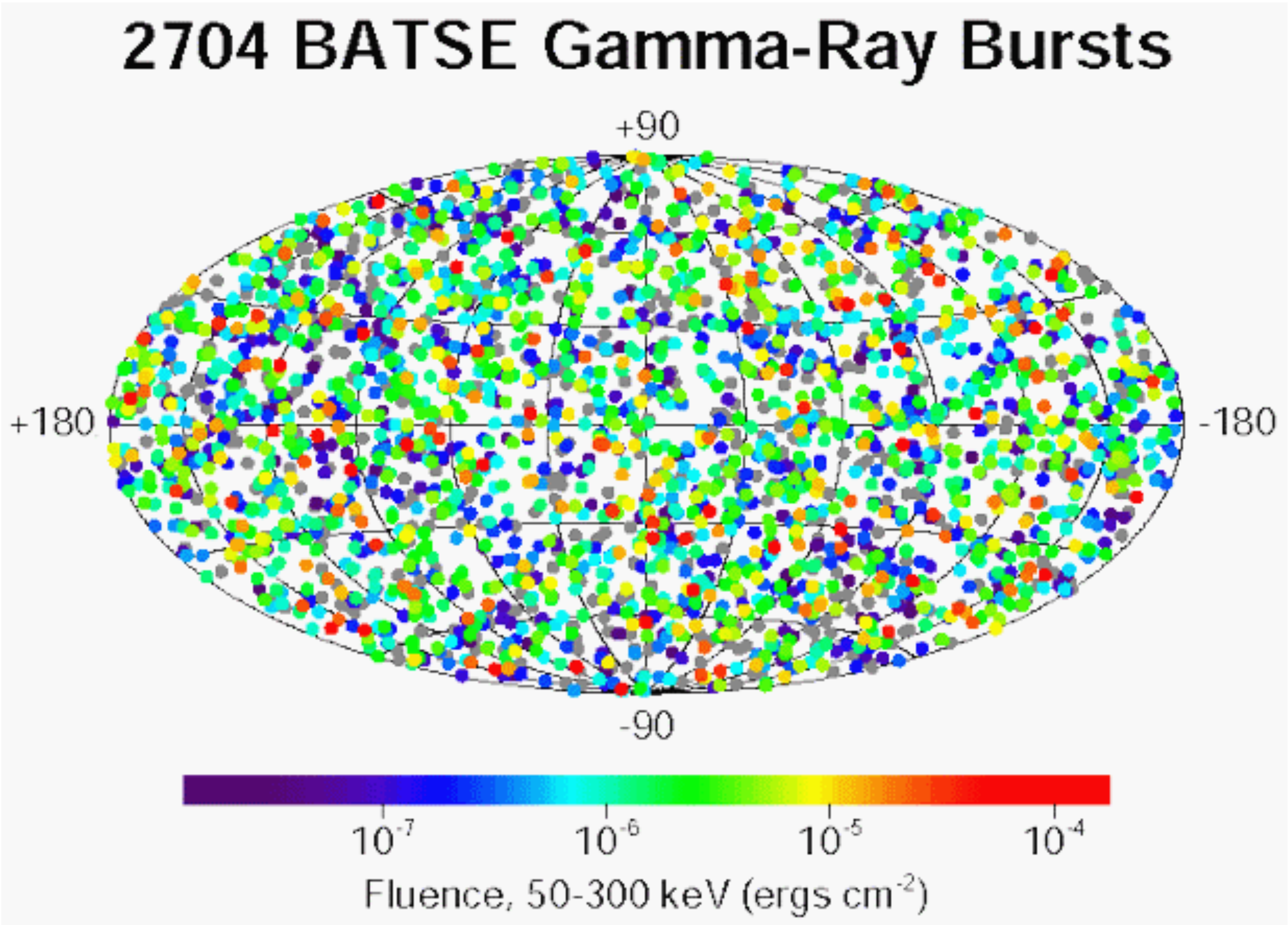
1975 2005

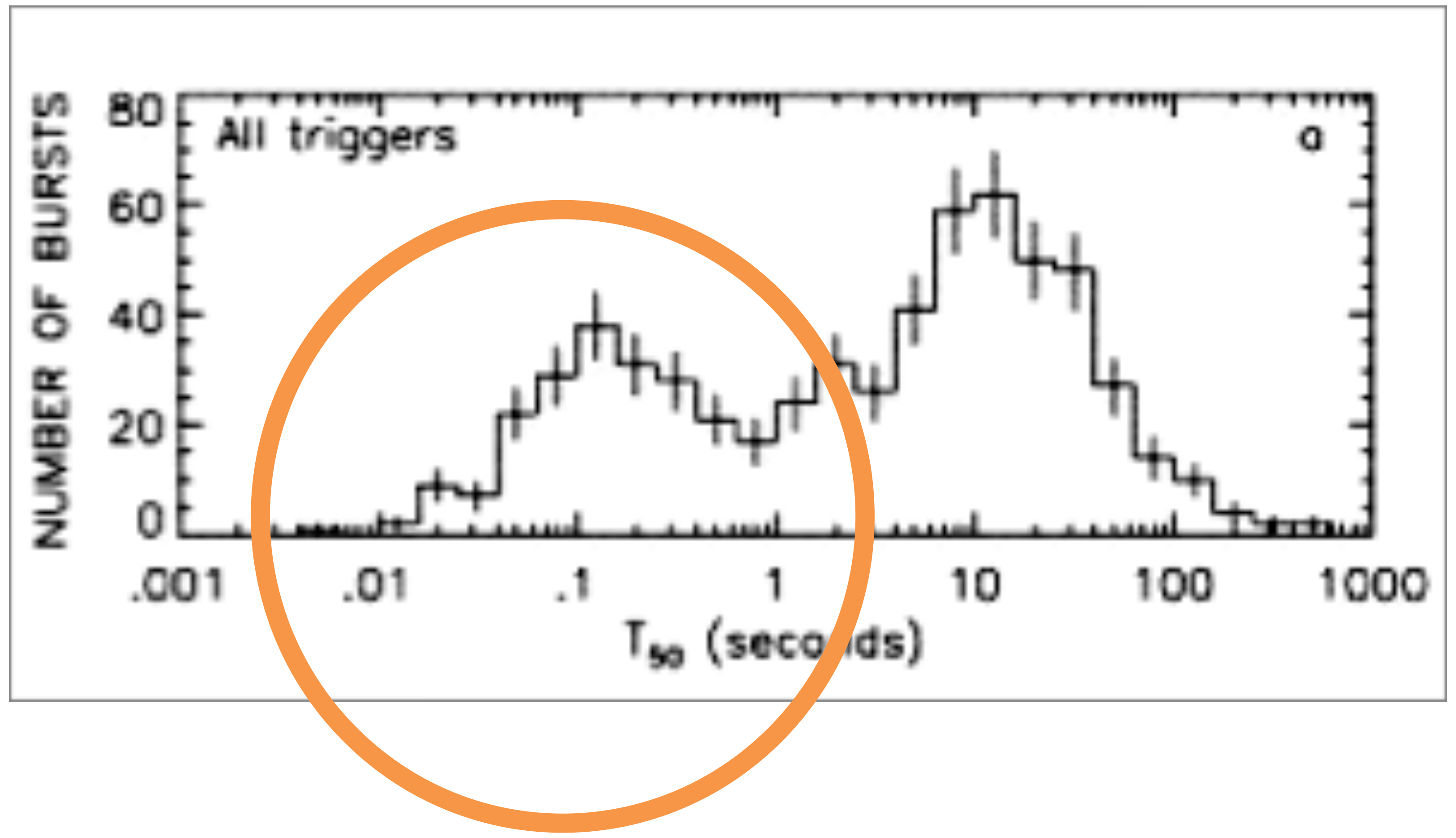
Weisberg, Nice, Taylor, ApJ (2010)

NS (radio pulsar) which will coalesce within Hubble time

PSR	P (ms)	P_b (hr)	e	Total Mass $M_\odot$	τ_c (Myr)	τ_{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)

sGRB short-hard gamma-ray bursts from NS mergers

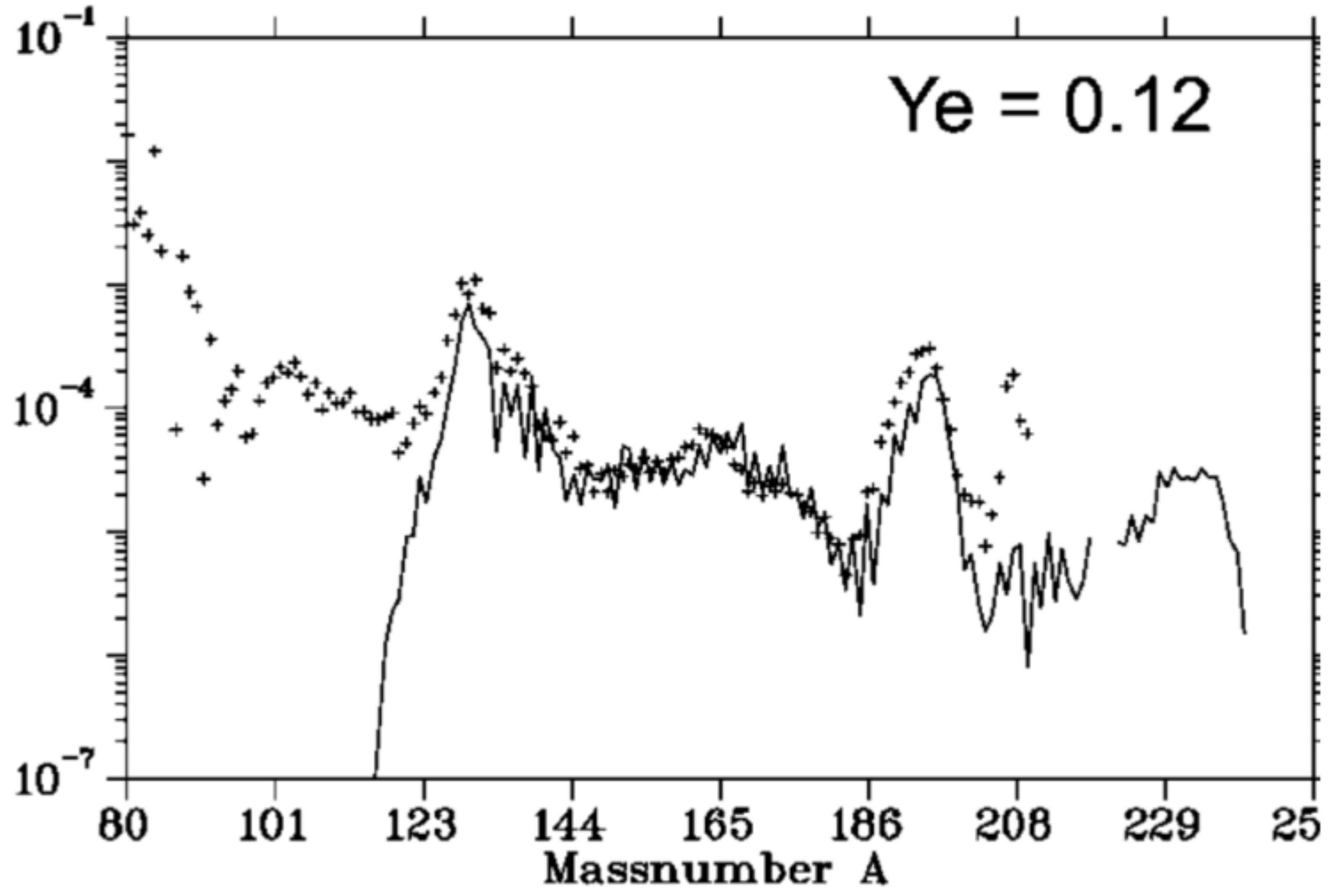




Heavy Elements from NS mergers

Sources of Heavy Elements

S Rosswog 2015

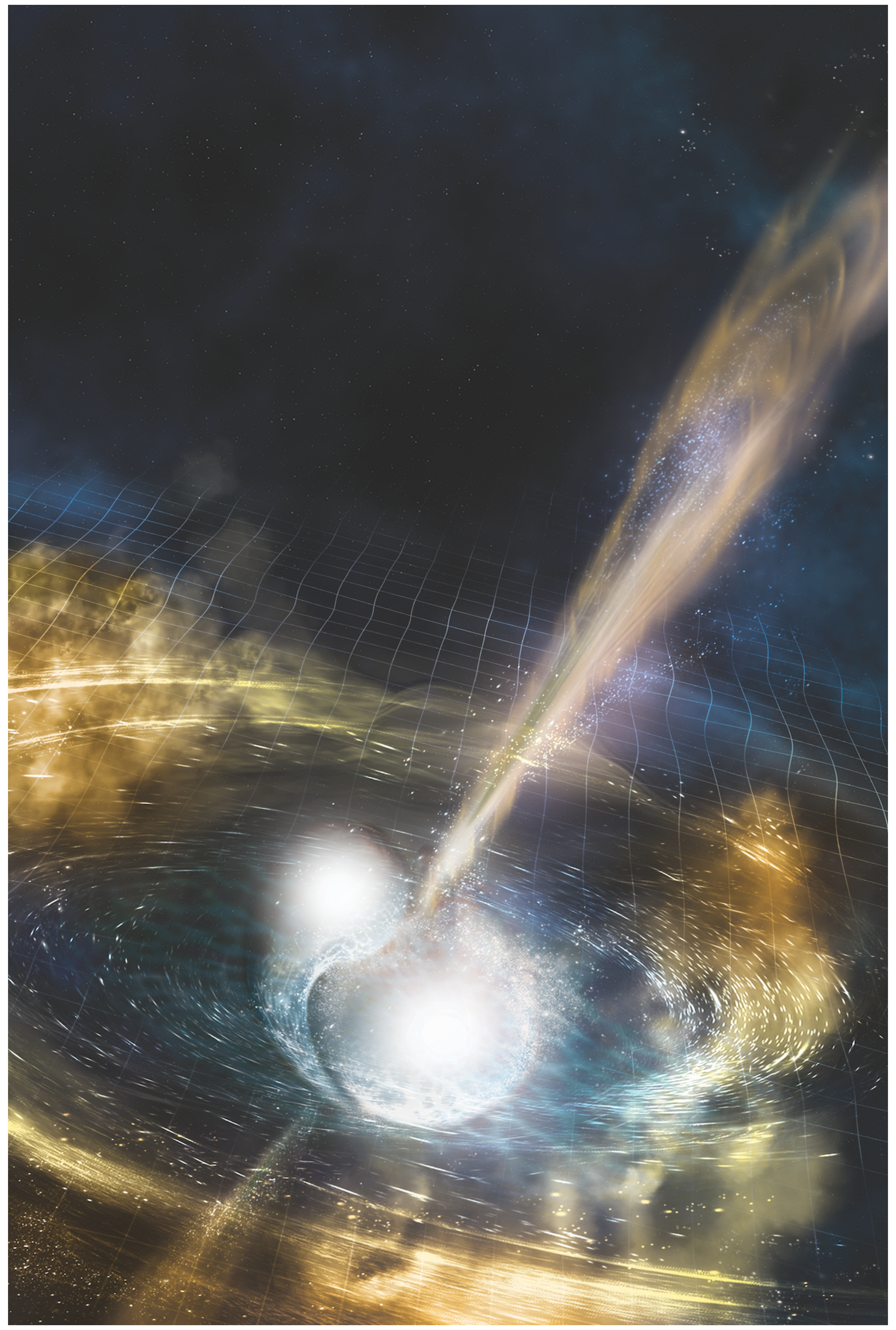


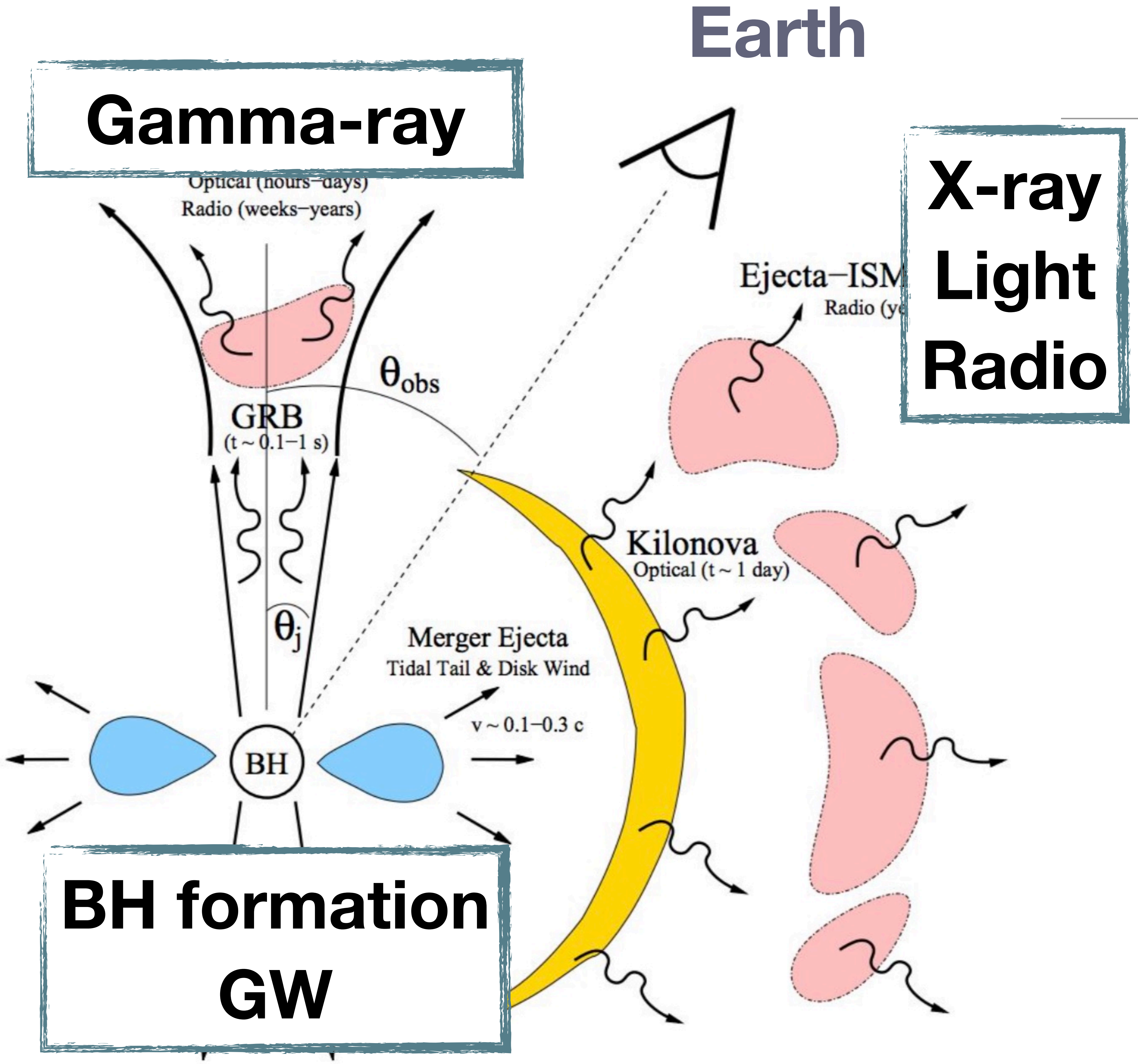
solar pattern vs NS-merger

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

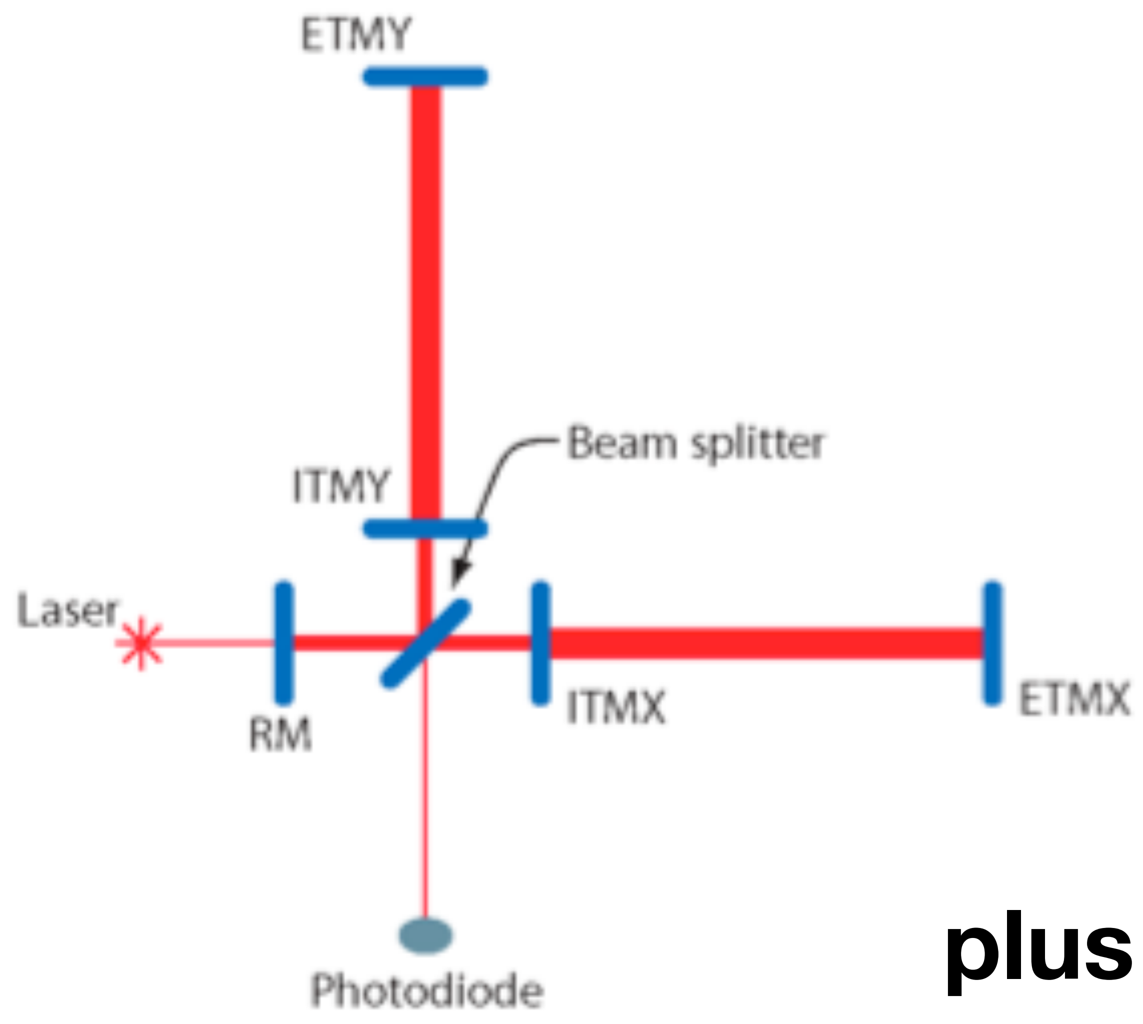
- **NS mergers:**
  r-process **peak at A~195**

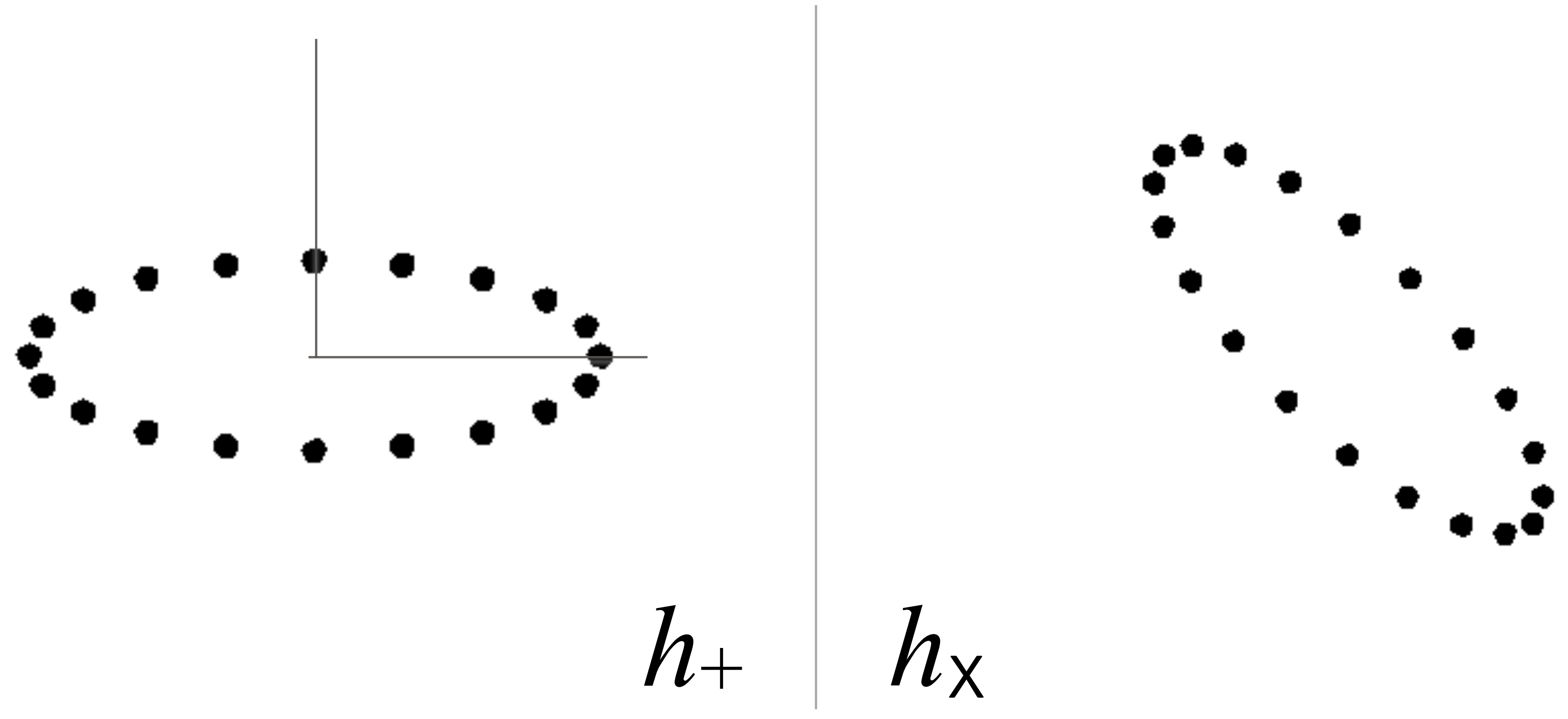
NS binary merger





GW propagating in z-direction

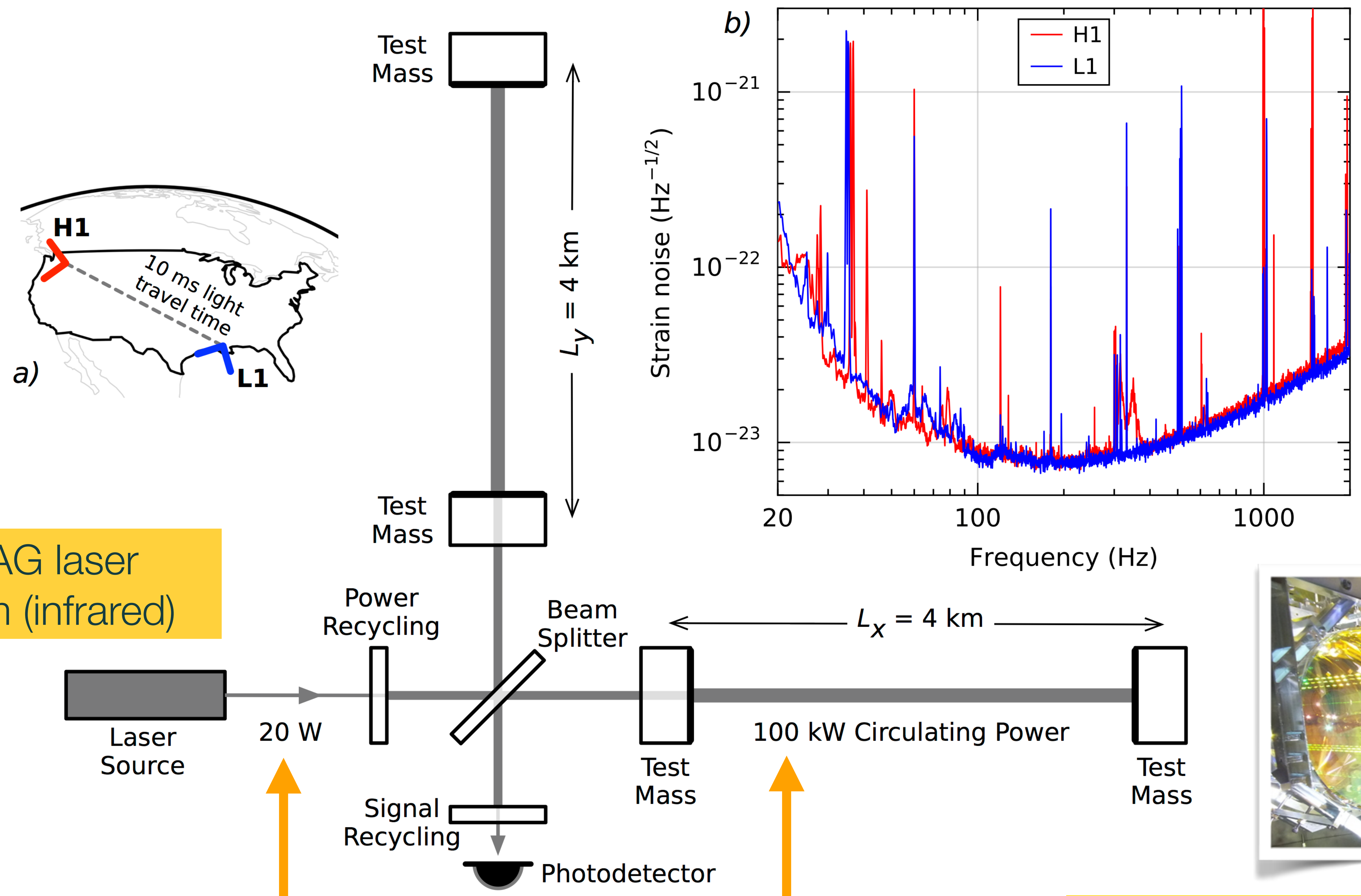




plus polarisation **cross polarisation**

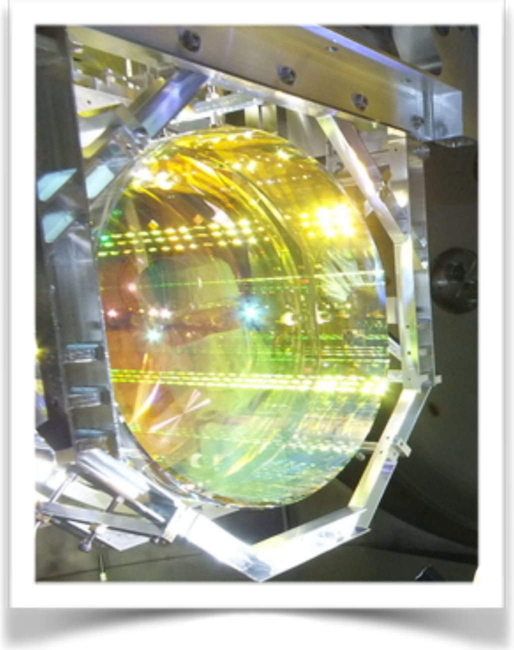
Laser Interferometer Gravitational-wave Observatory

Nd:YAG laser
1064nm (infrared)



Goal 200 W

Goal 750 kW



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

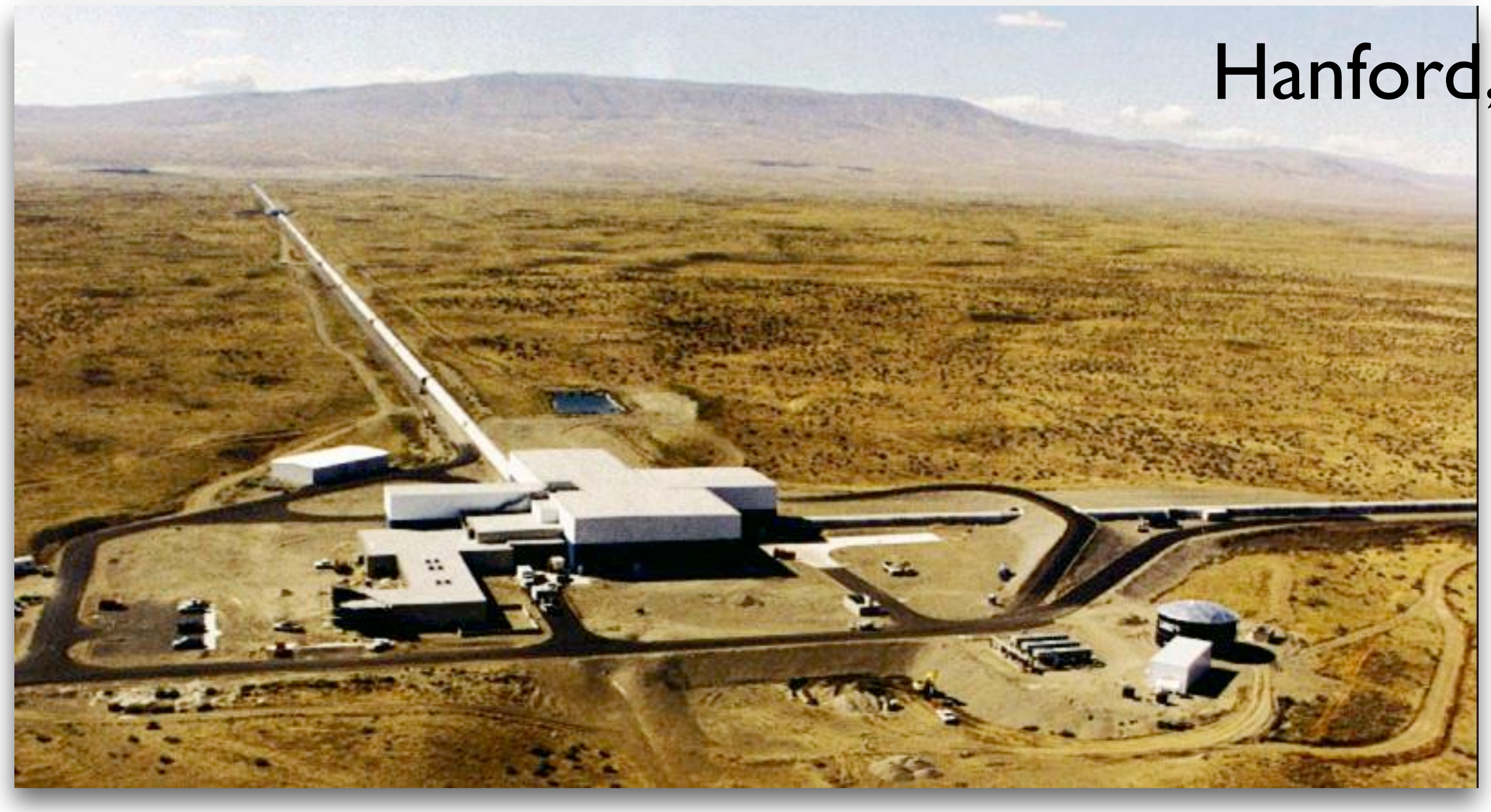
Detectability of LIGO

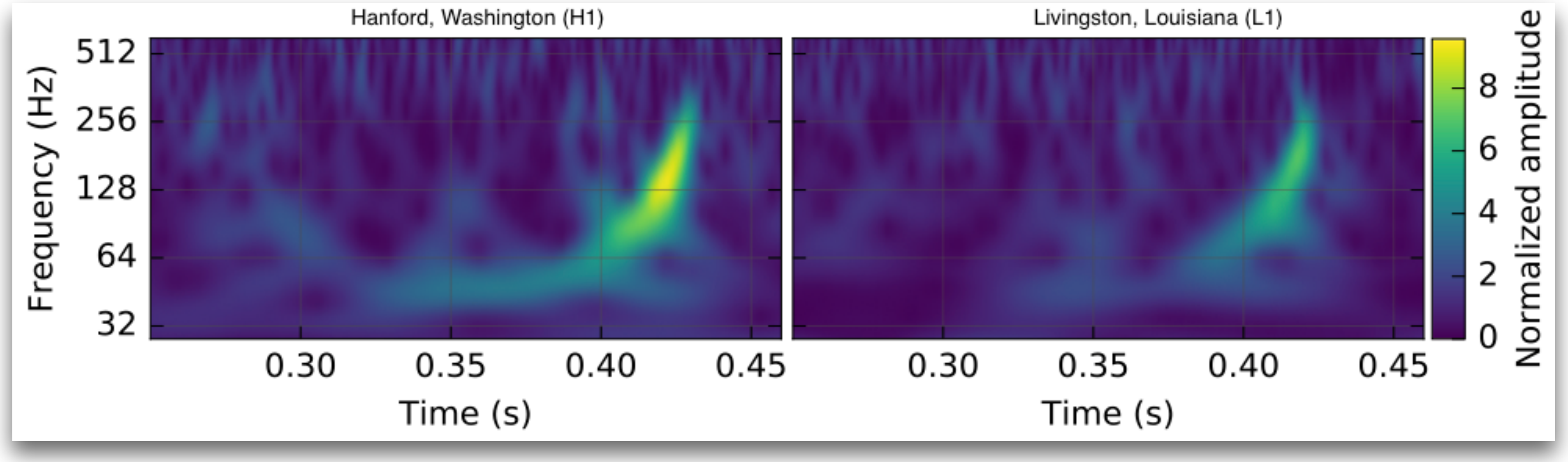
- 1/1000 of proton diameter in a distance of 4km
  (1/10 of hair thickness in a distance of 1 light year)
- Strong LASER power (2015) : 20 W ➔ 700 W ➔ 100 kW
  - design goal : 200 W ➔ 750 kW
- 280 bounces between mirrors (effective distance :1120 km)
- Detection limit :
  NS binary merger - 10 billion light year
  BH binary merger - 30 billion light year

LIGO

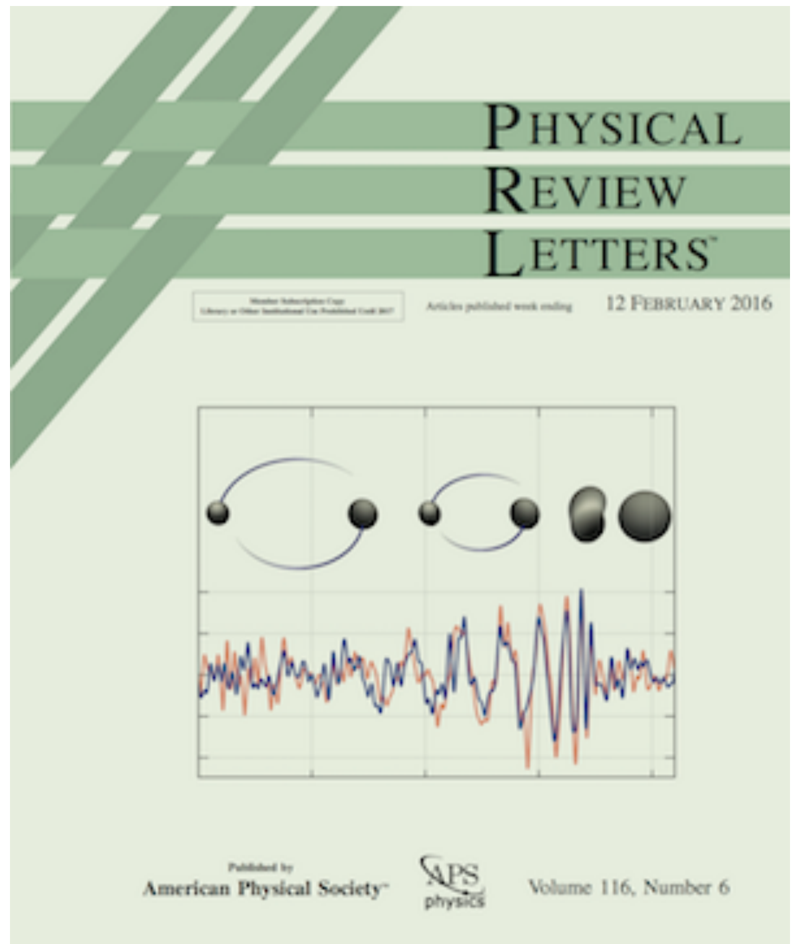
1st detection of GW

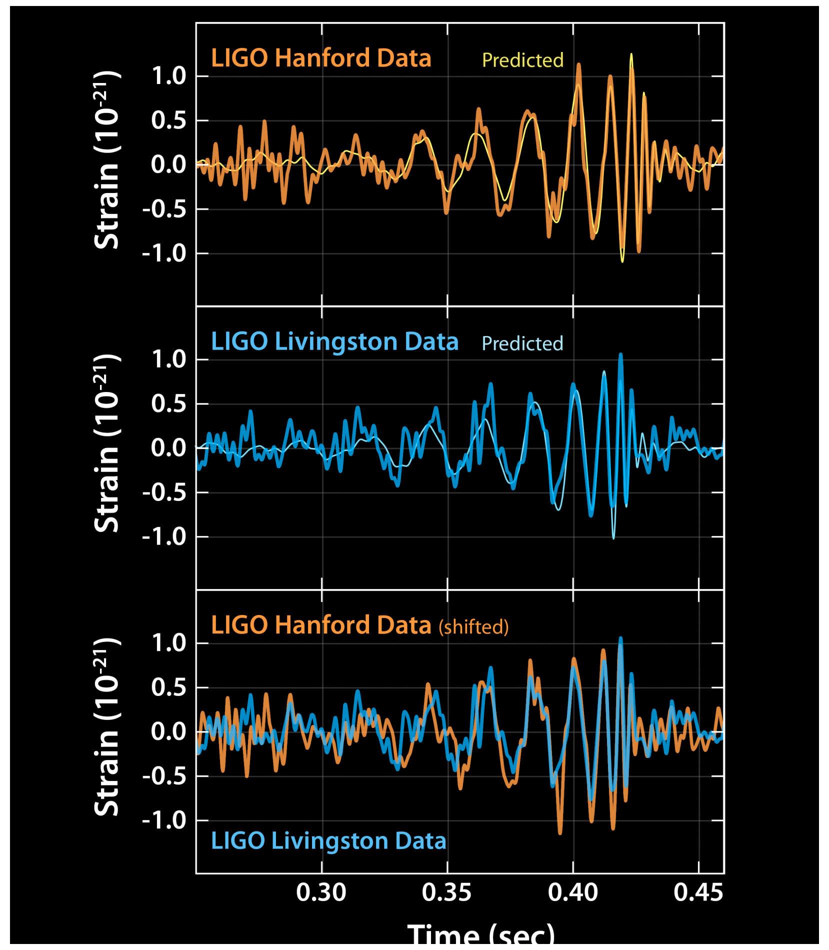
Sep 14th, 2015

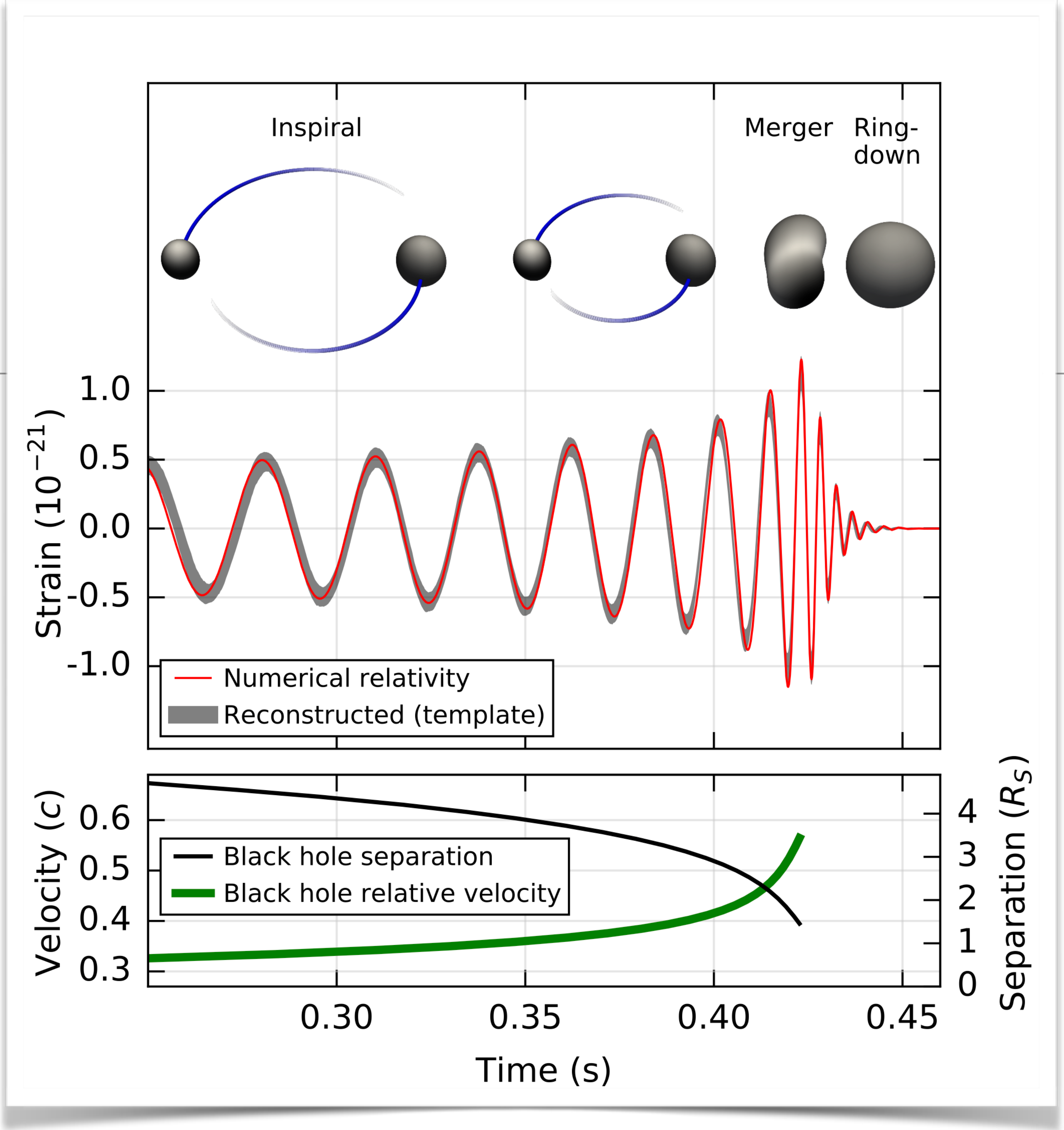



Hanford, Washington (H1)
Livingston, Louisiana (L1)
Frequency (Hz)
512
256
128
64
32
0.30 0.35 0.40 0.45
Time (s)
Normalized amplitude
0 2 4 6 8

GW150914


PHYSICAL
REVIEW
LETTERS
12 FEBRUARY 2016
American Physical Society
Volume 116, Number 6

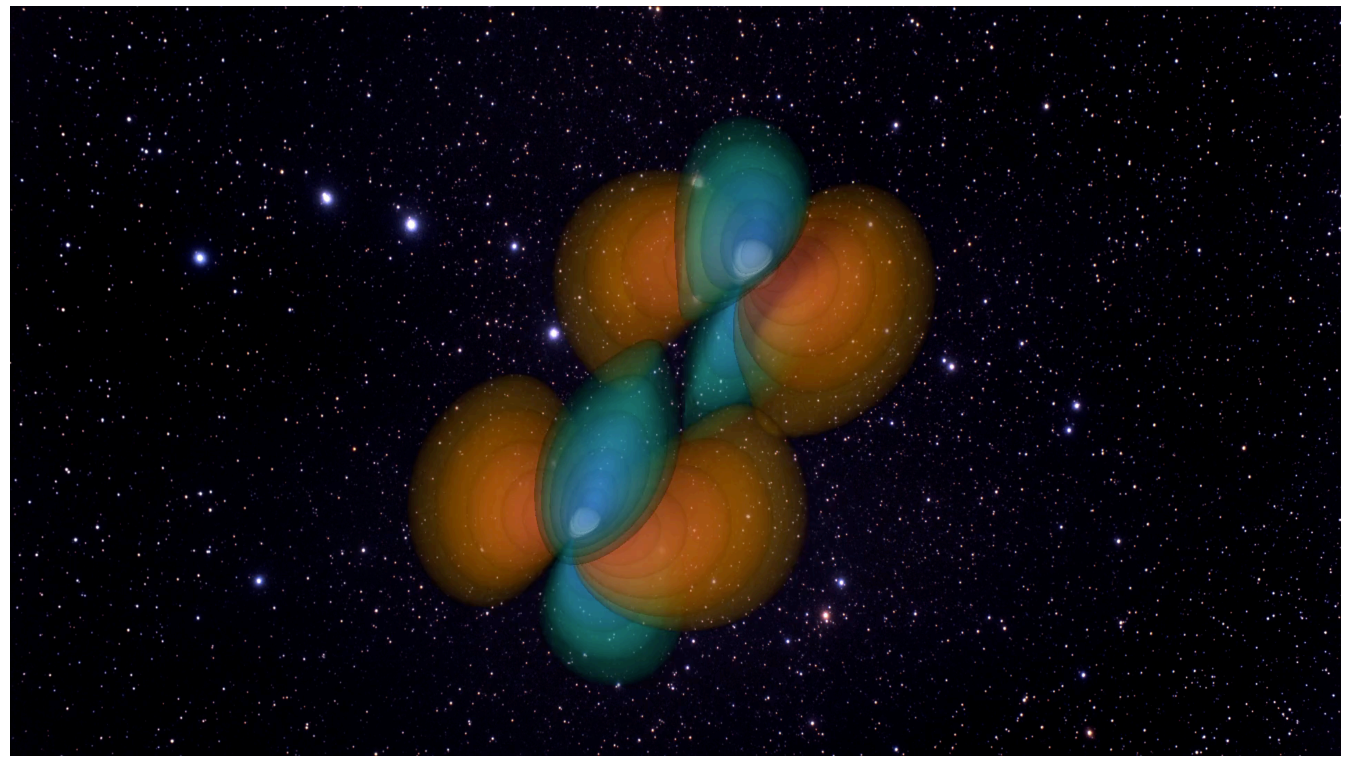

LIGO Hanford Data
Predicted
LIGO Livingston Data
Predicted
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10⁻²¹)
1.0 0.5 0.0 -0.5 -1.0
0.30 0.35 0.40 0.45
Time (sec)


Inspiral
Merger
Ring-
down
Strain (10^{-21})
1.0 0.5 0.0 -0.5 -1.0
Numerical relativity
Reconstructed (template)
Velocity (c)
0.6 0.5 0.4 0.3
Black hole separation
Black hole relative velocity
Separation (R_S)
4 3 2 1 0
0.30 0.35 0.40 0.45
Time (s)

GW150914

- 36 $M_\odot$ BH + 29 $M_\odot$ BH (final BH with 62 $M_\odot$)
- 3 $M_\odot$ in GW energy
  maximum luminosity ~ 50 times of the total light luminosity of the Universe
- distance : 13 billion light year (red shift z=0.09)
- GW frequency : 30-150 Hz
- GW maximum strain : 10^{-21}
  - 4×10^{-16} cm variation in 4km
    (correspond to hair thickness in 1 light year)

$$m = (1 + z)m^{\text{source}}$$



Georgia Tech animation

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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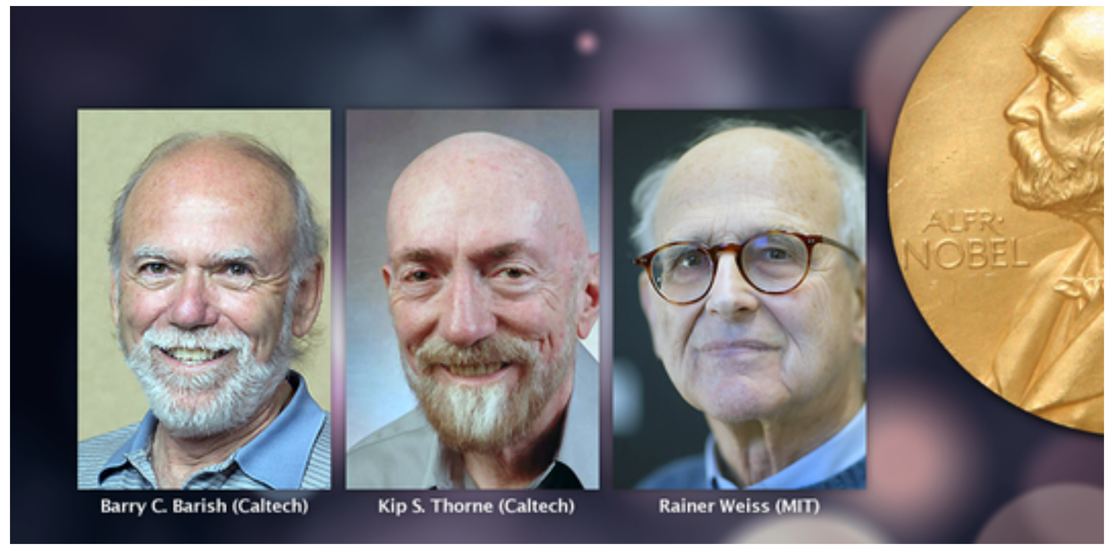
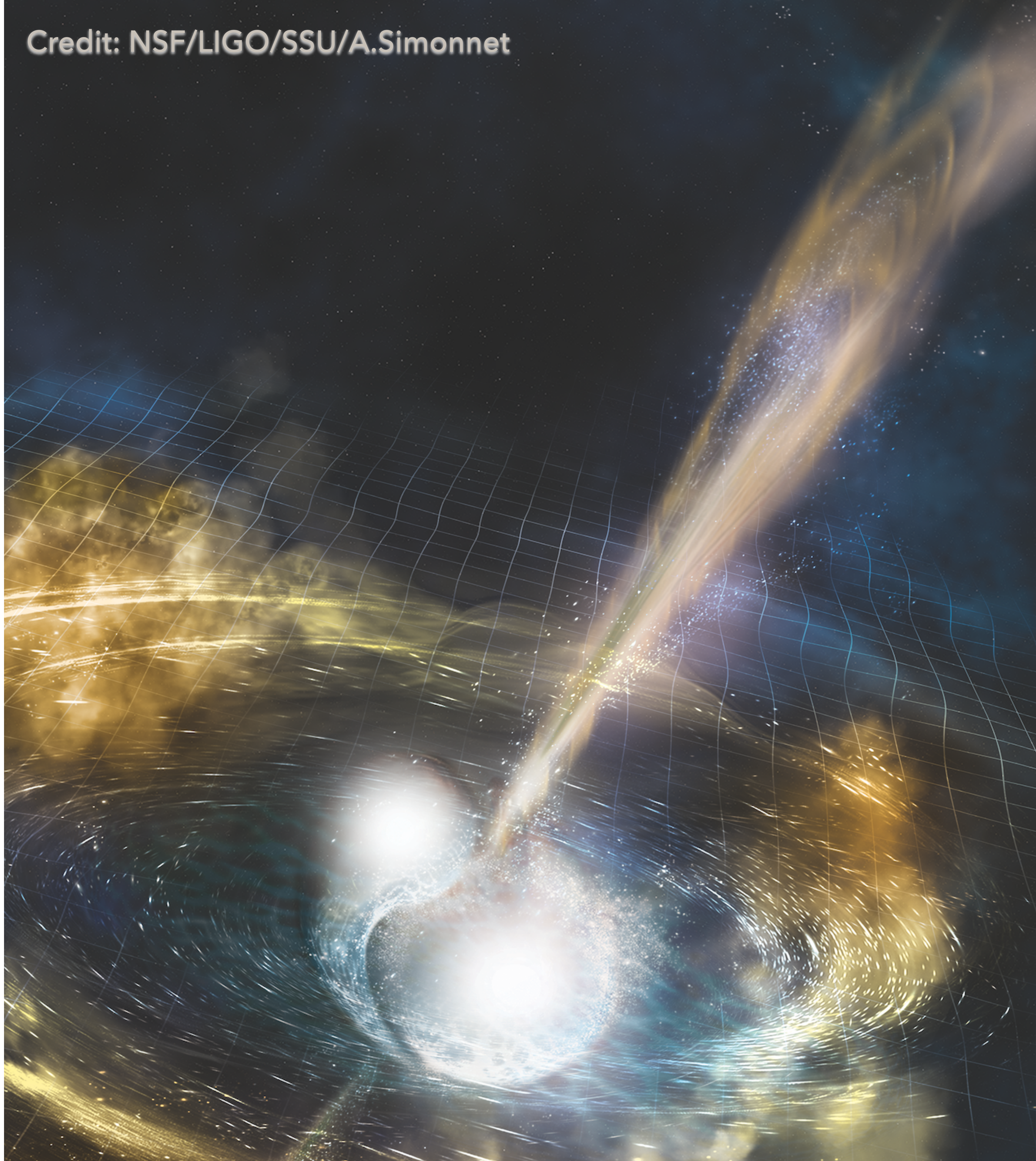
soon after the announcement of

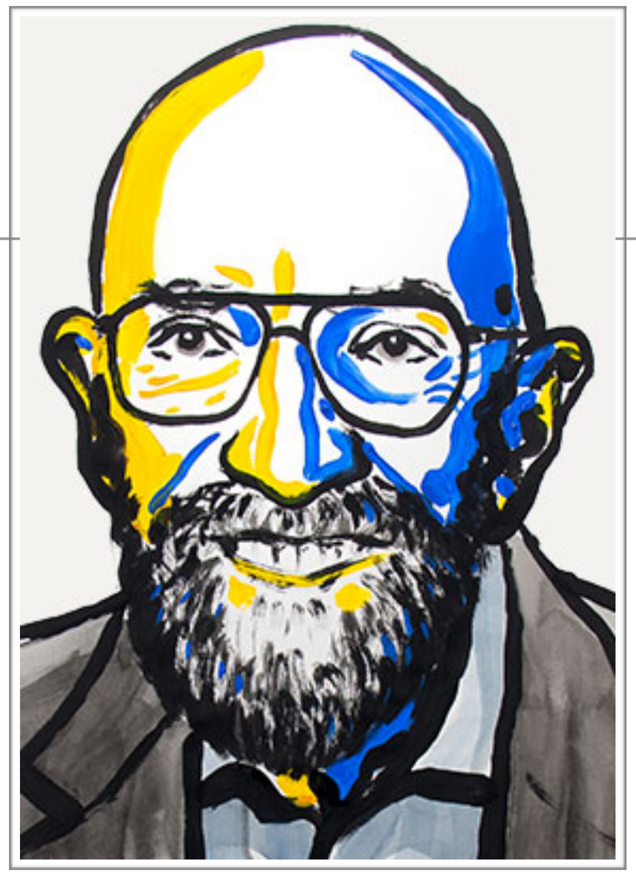
2017 Nobel Prize





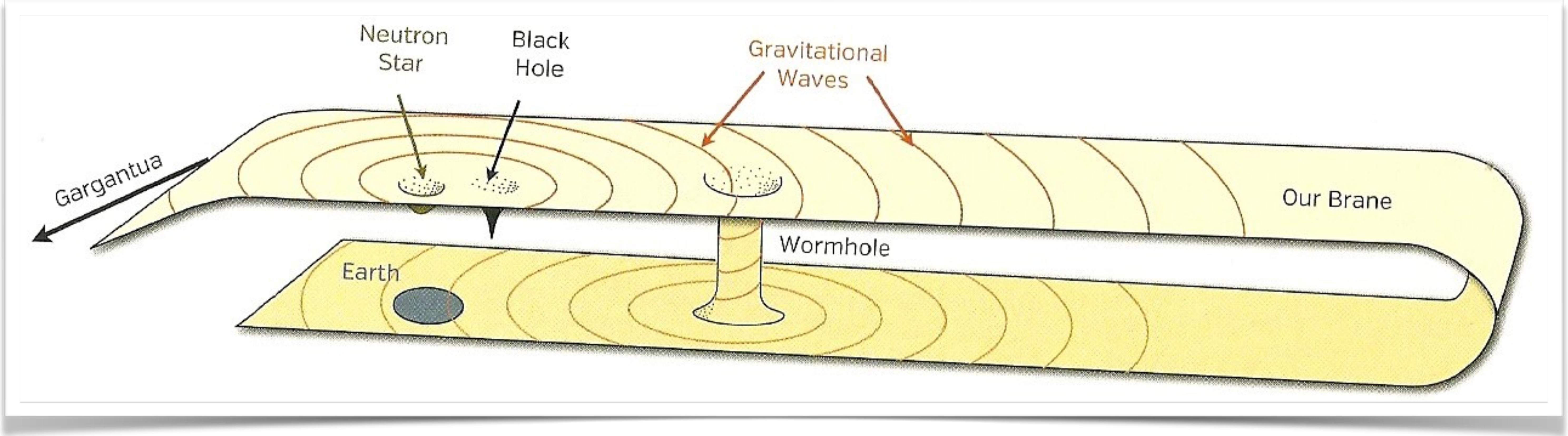
Interstellar original scenario by kip Thorne

2017 Nobel Prize

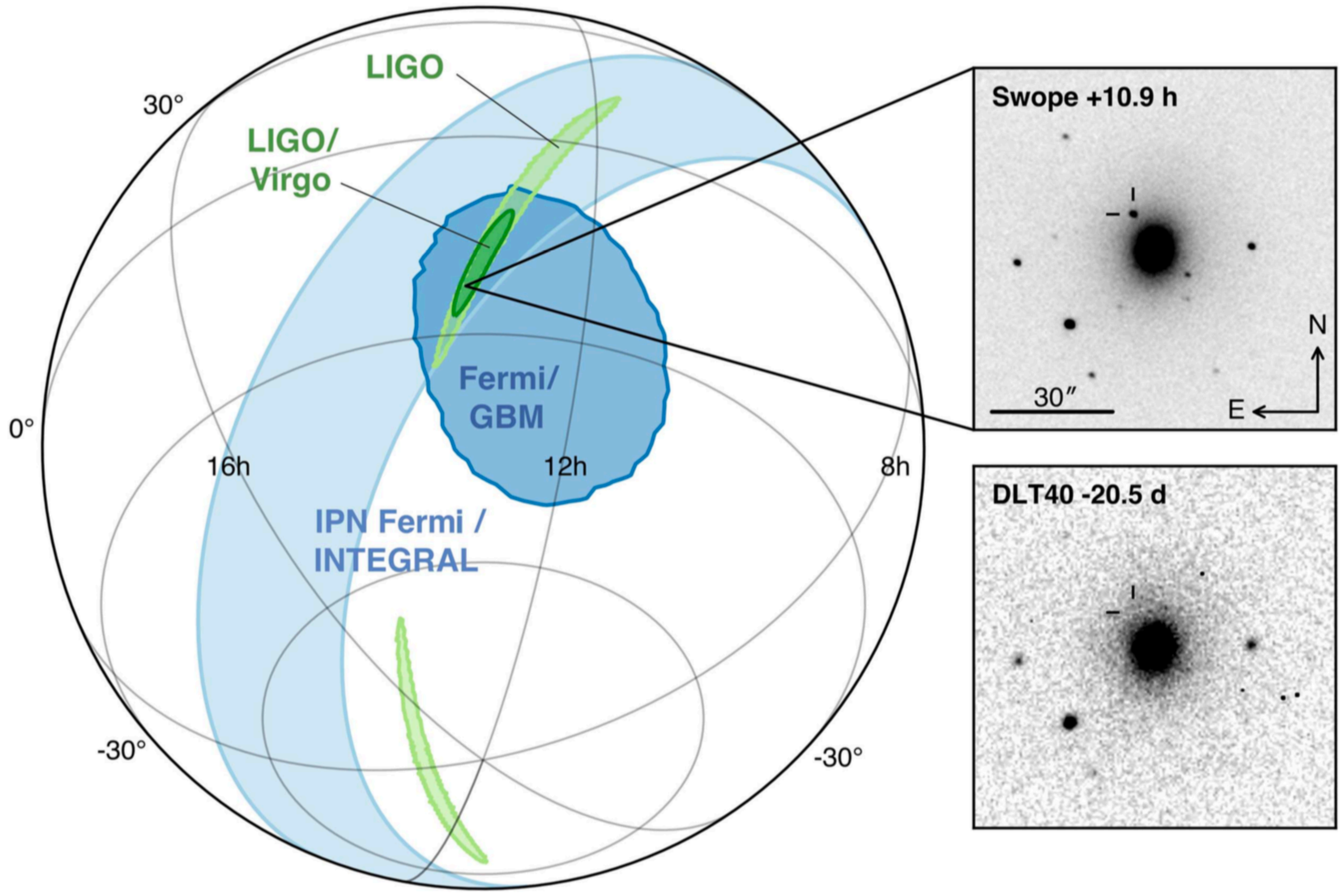


- 2019 LIGO detected GW from Saturn
  - GW from BH/NS binary mergers
  - No BH/NS near Saturn
  - Existence of a Warm Hole near Saturn

- Interstellar starts 40 years after GW detection from Saturn



GW170817 / GRB170817A

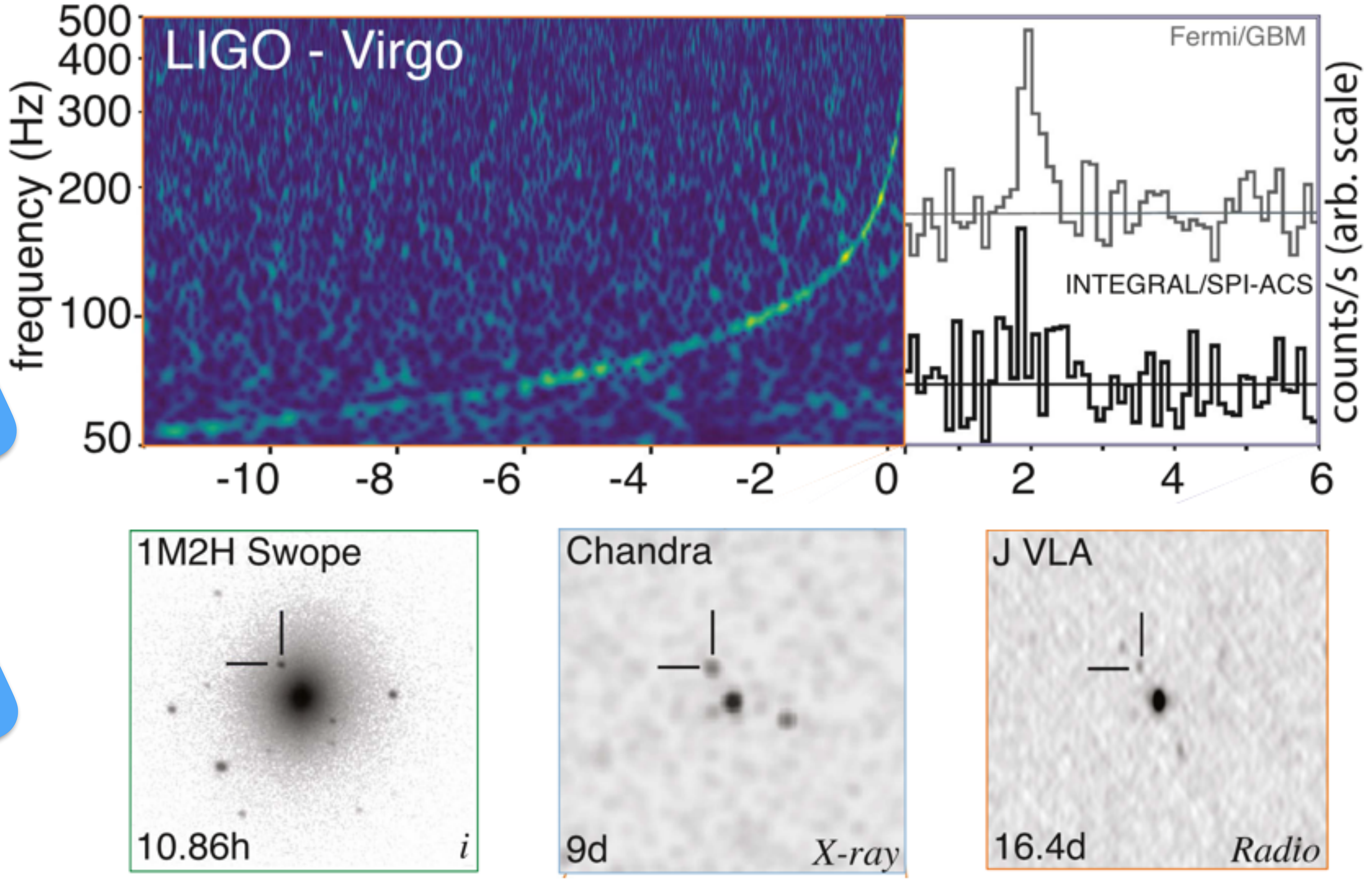


First event of Multi-messenger Astronomy

GW170817

GRB170817A

SSS17a/
AT2017gfo



ApJL.848.L12(2017)

TIMELINE

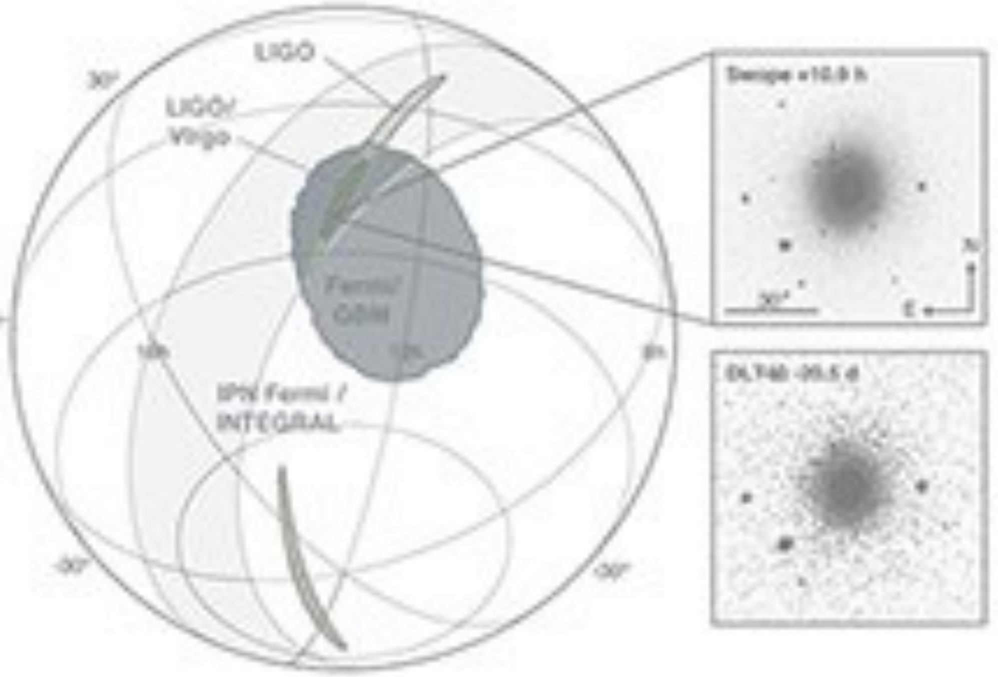
중성자별 충돌에서 발생한 중력파, 감마선, 가시광선, 엑스선 및 전파 관측

2017.08.17.
12:41:04 UTC

라이고 및 비르고
중력파 신호
포착

+2
seconds

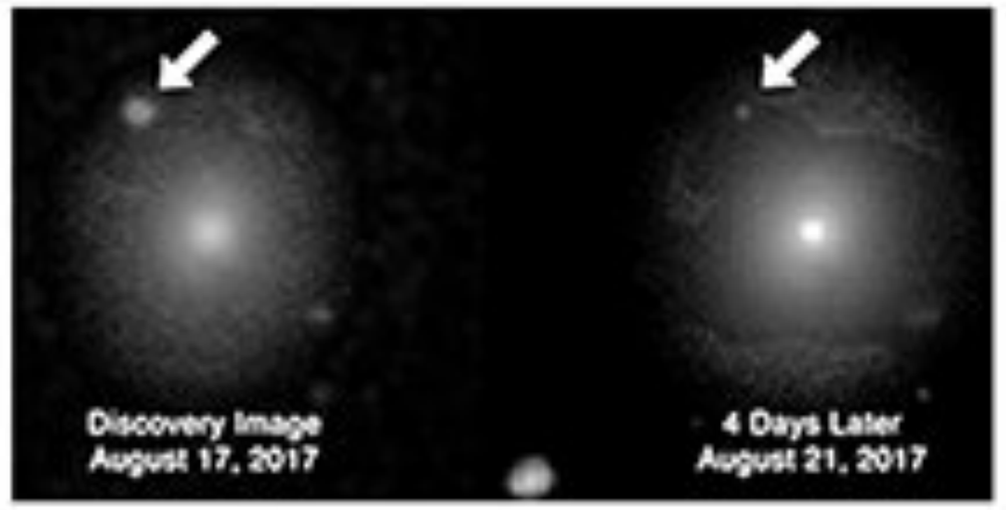
페르미 및 인티그랄
감마선 신호
포착



Fermi/Integral gamma-ray

+11
hours

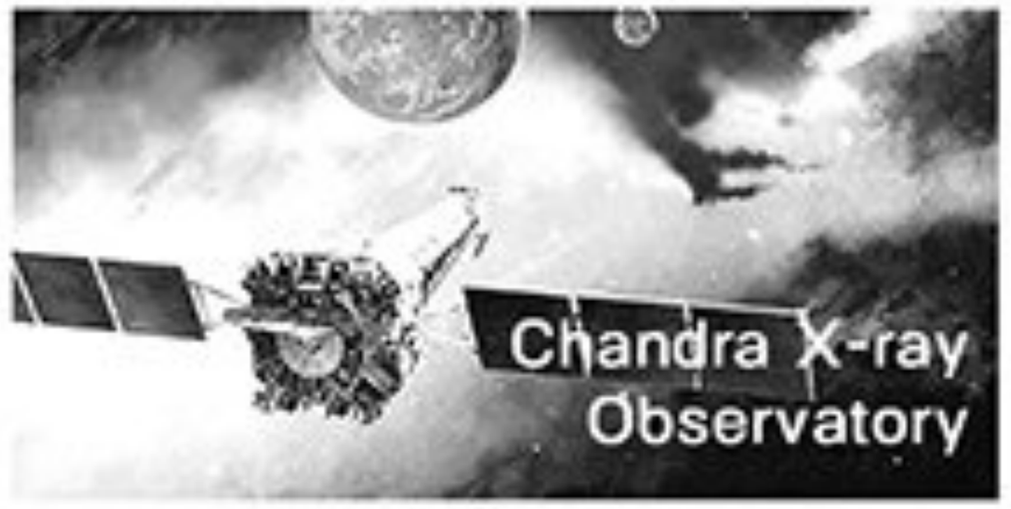
칠레 천문대
망원경들이
가시광선 신호
포착



Telescopes in Chile

http://horizon.kias.re.kr

Korean Telescopes
Nature 551, 71 (2017)



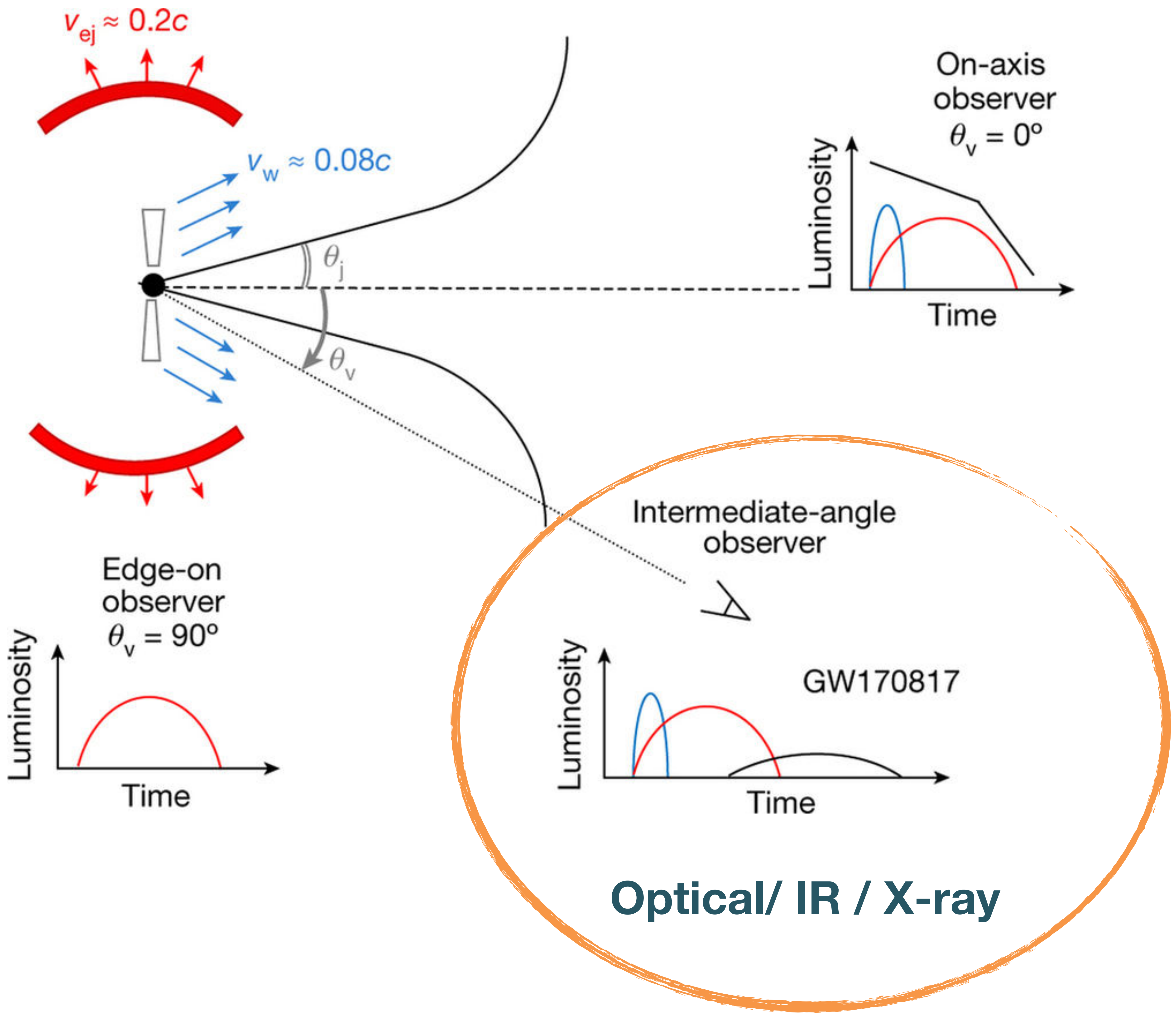
Chandra X-ray

VLA radio

http://horizon.kias.re.kr

Kilonova / Geometry of GW170817

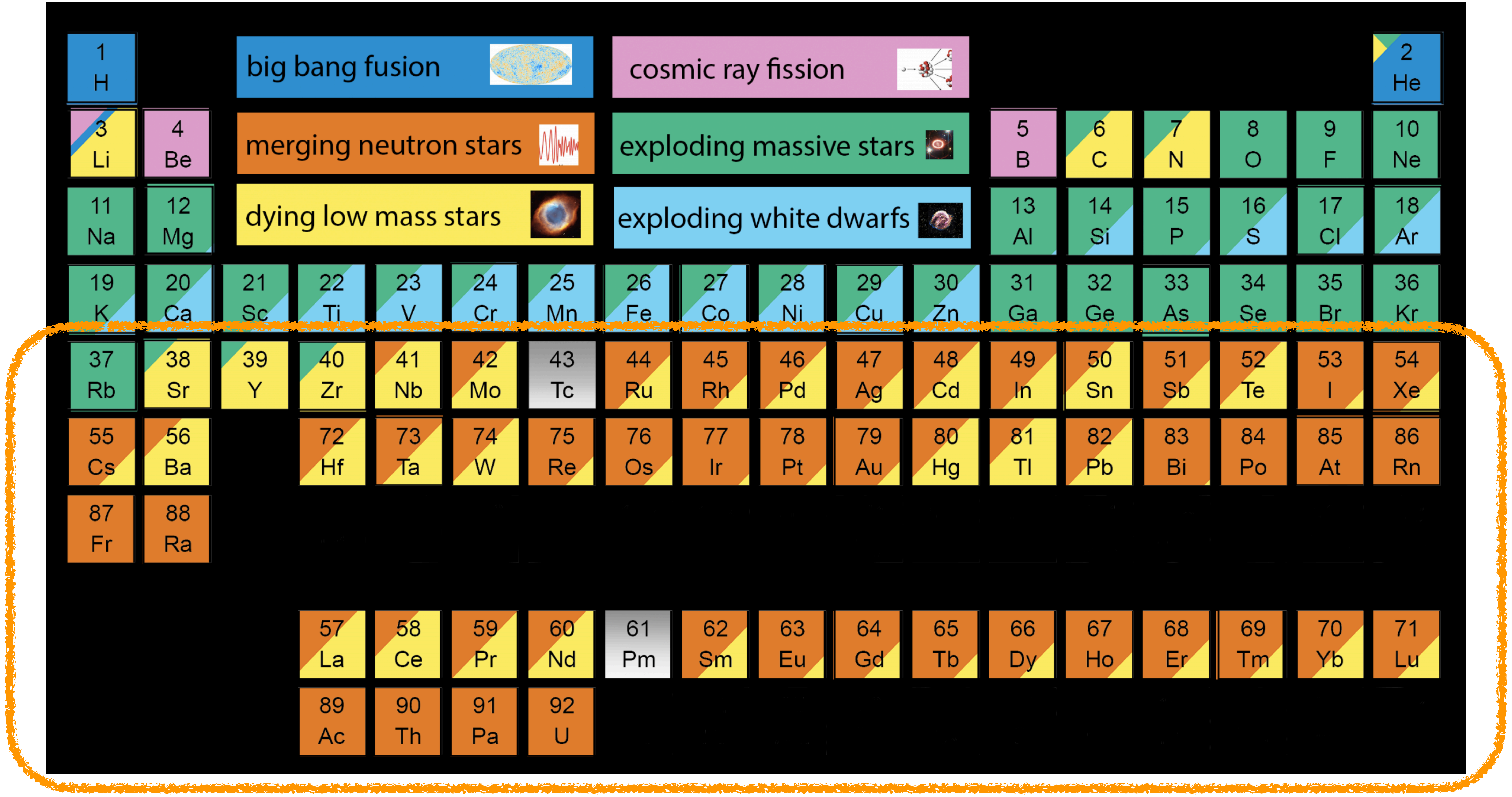
Nature 551, 71 (2017)



Optical/ IR / X-ray

Origin of Solar System Elements

merging neutron stars



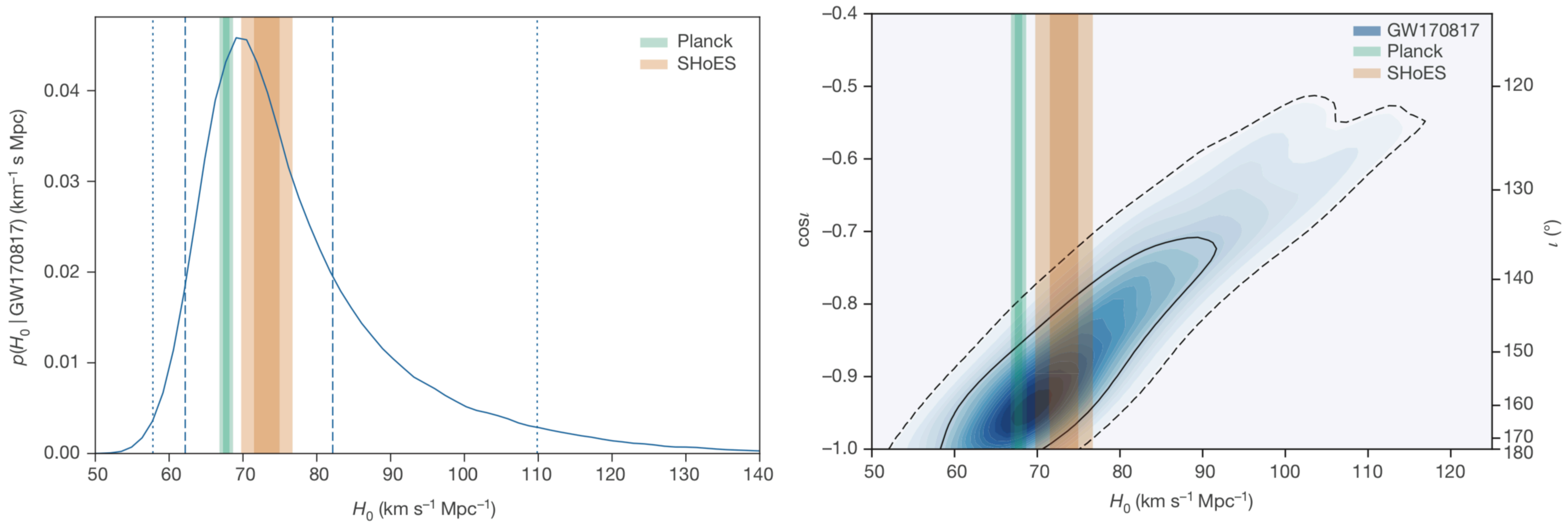
LETTER

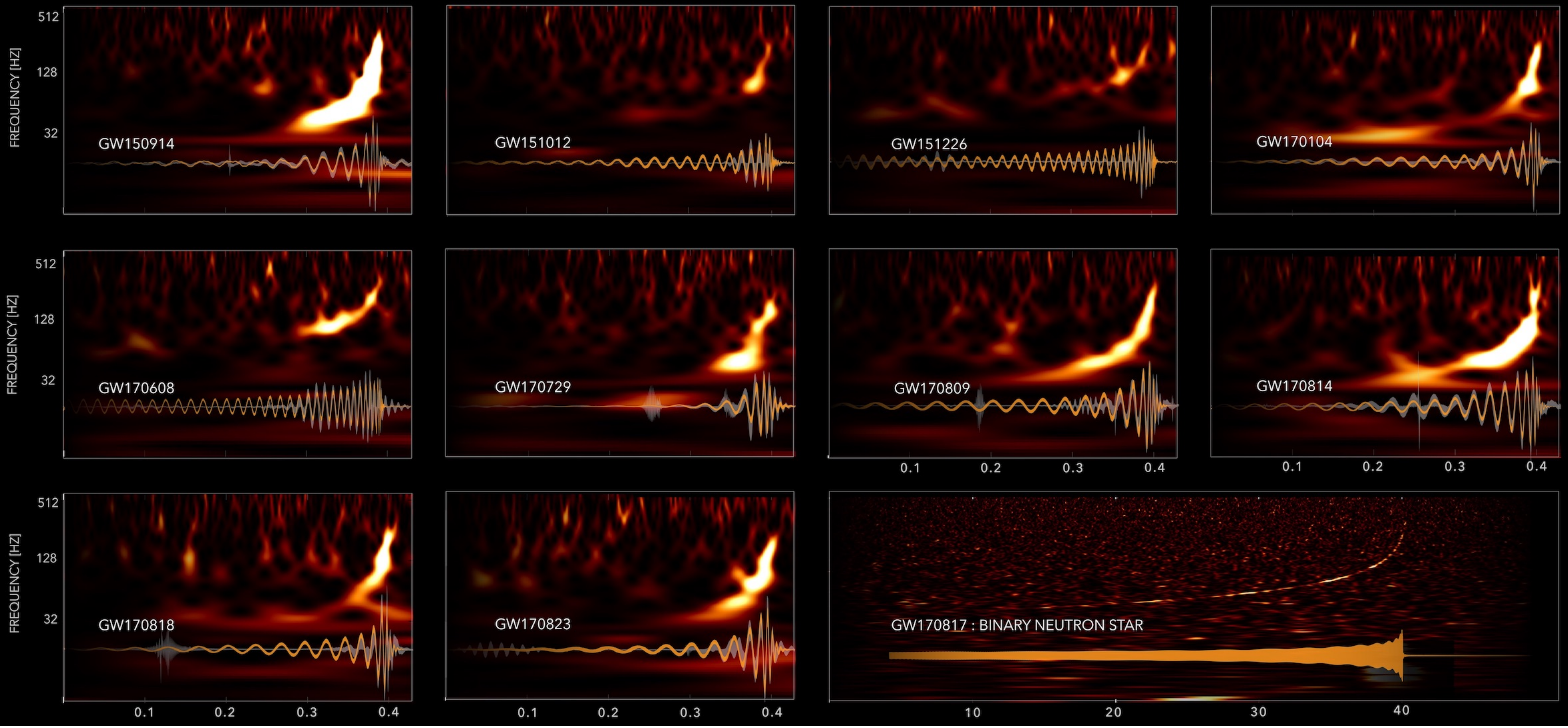
doi:10.1038/nature24471

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*

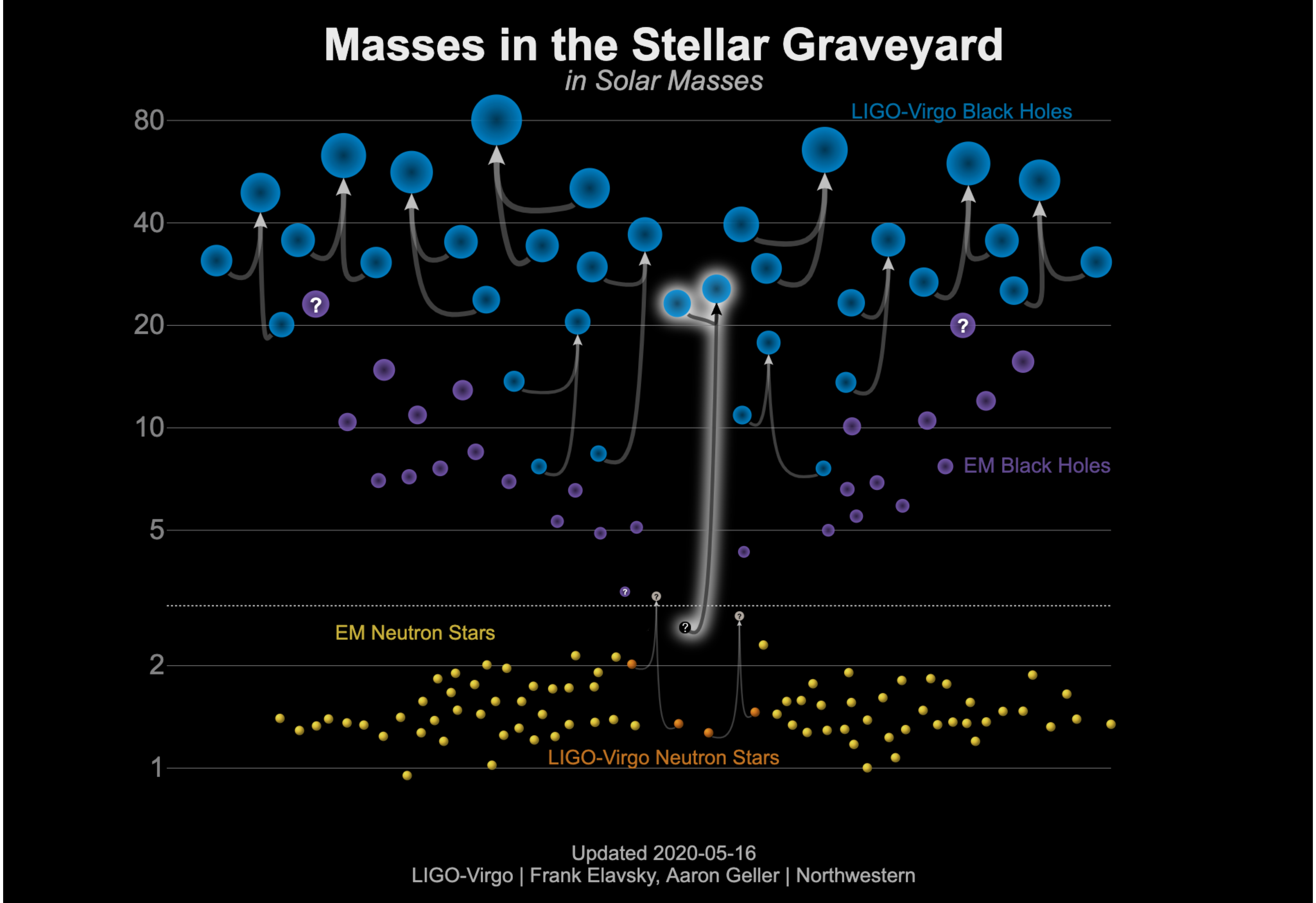
$$H_0 = 70.0^{+12.0}_{-8.0} \text{ km s}^{-1} \text{Mpc}^{-1}$$





GW Catalog

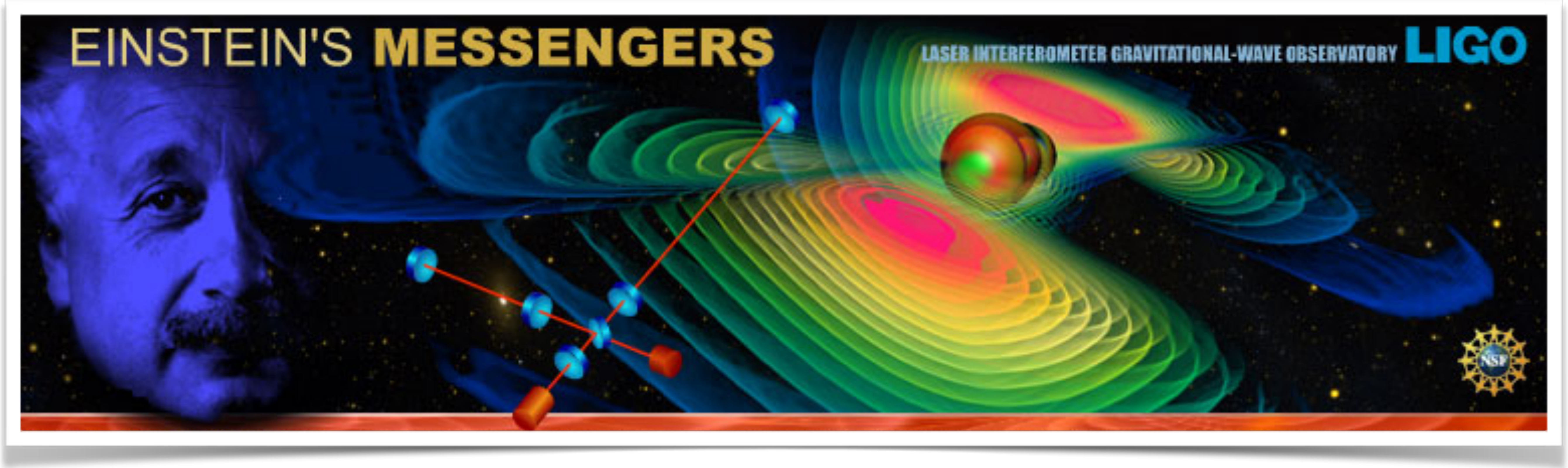
2018.12.05



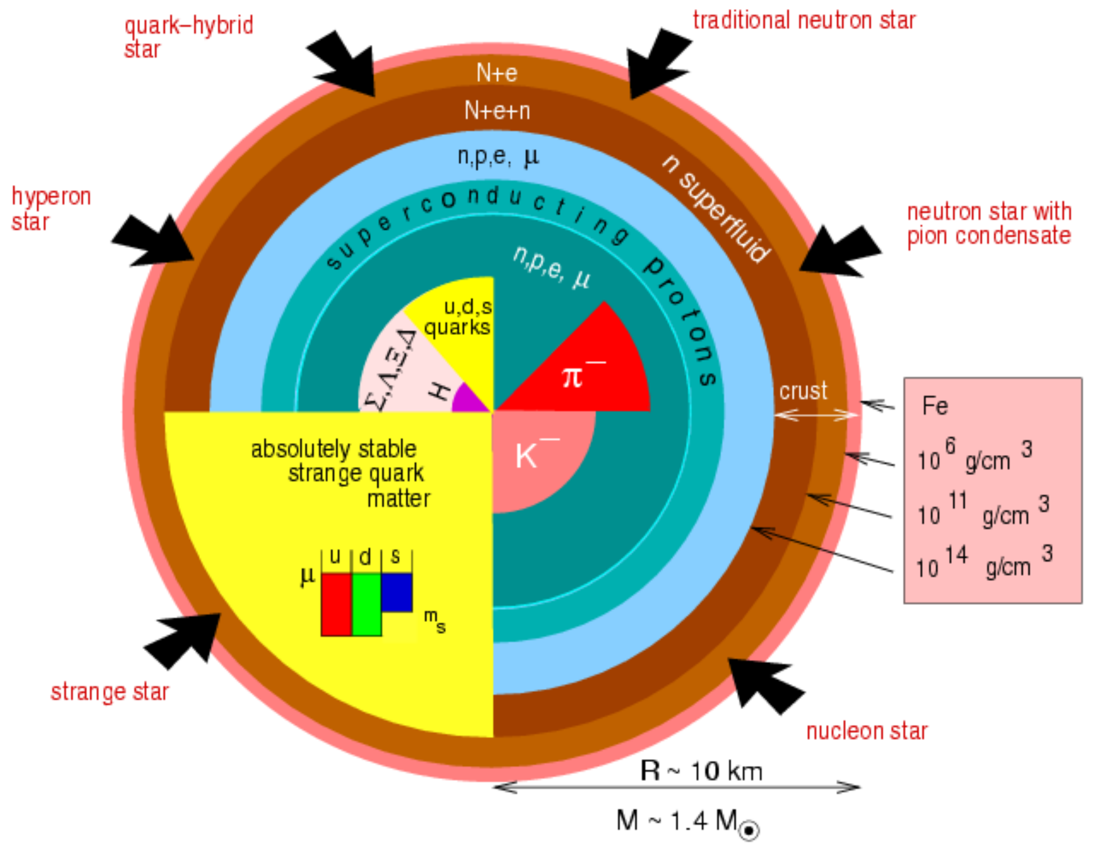
Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
Updated 2020-05-16
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Gravitational-Wave & Multi-Messenger Astronomy

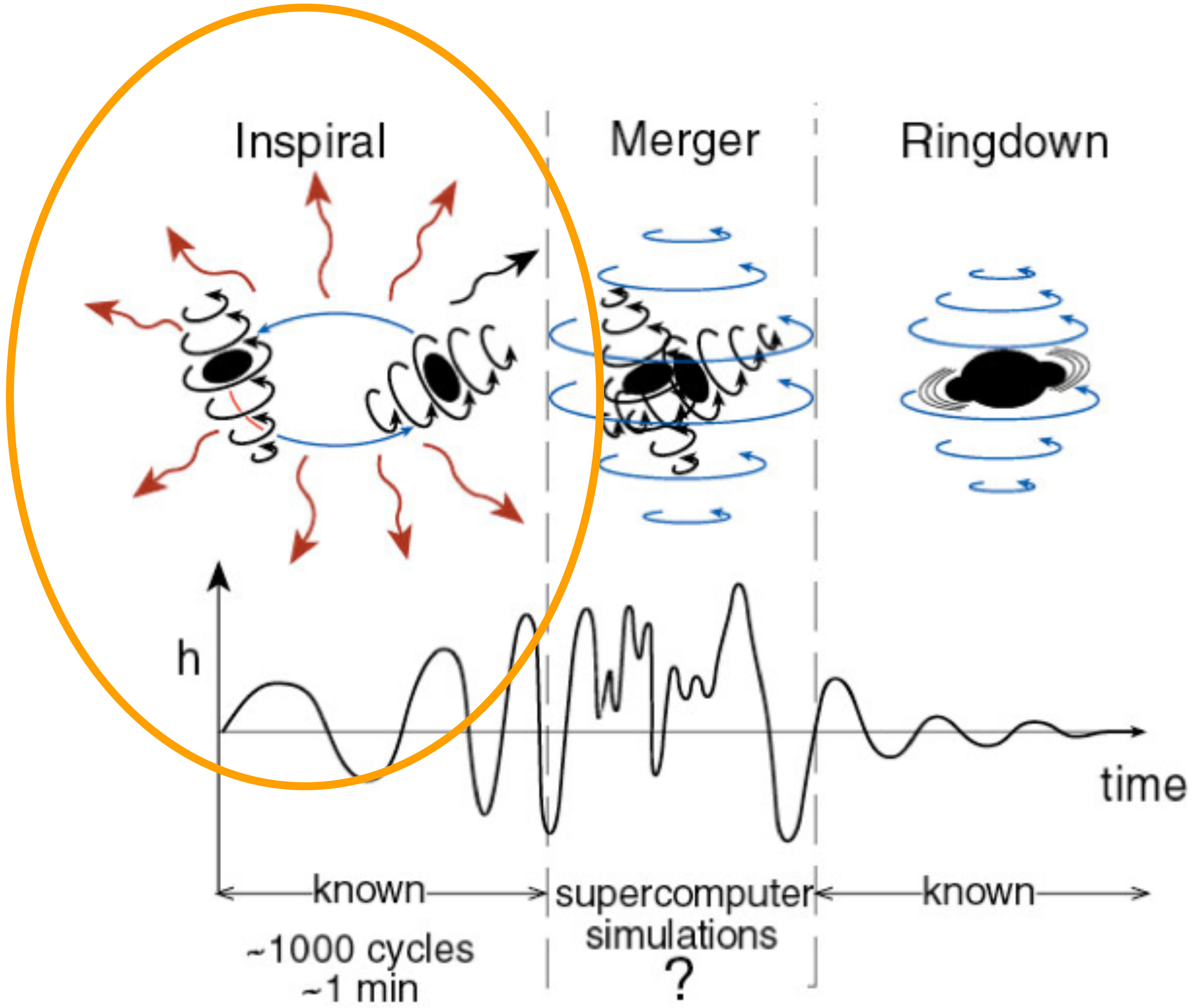
- First direct detection of GW from BH binaries in 2015
- **GW, Gamma-ray, Optical, X-ray, Radio from NS mergers**
- New era for GW Astronomy & **Multi-Messenger Astronomy**



Response of NS to GW during Inspiral



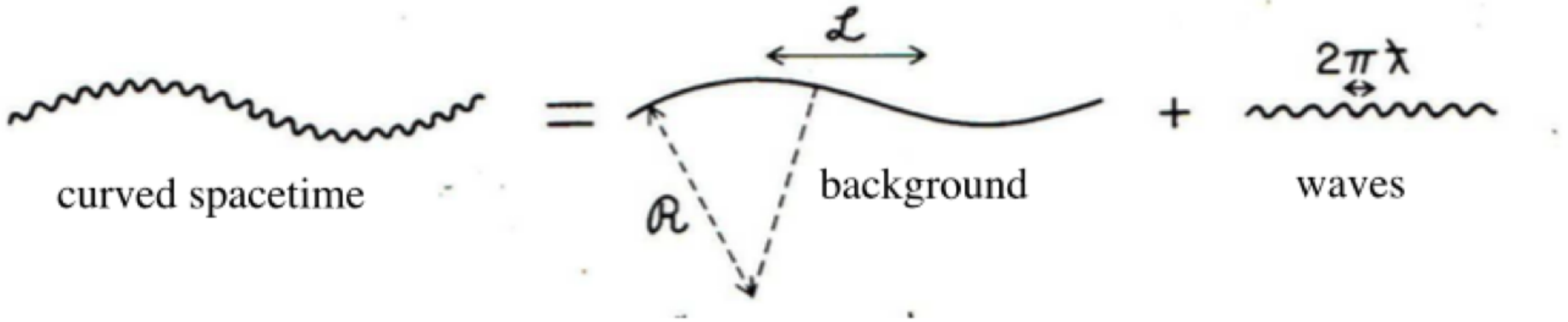
perturbative approaches



Principles of Gravitational Waves

$c = 1$ unit

long timescale change



short timescale oscillation

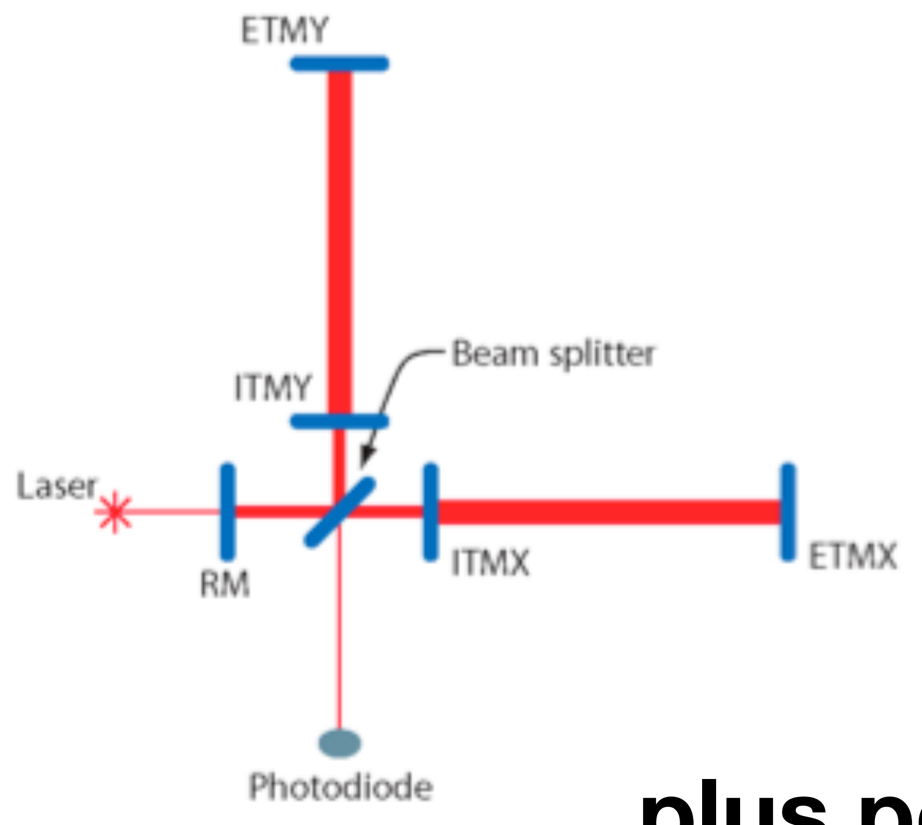
GW propagating in z-direction

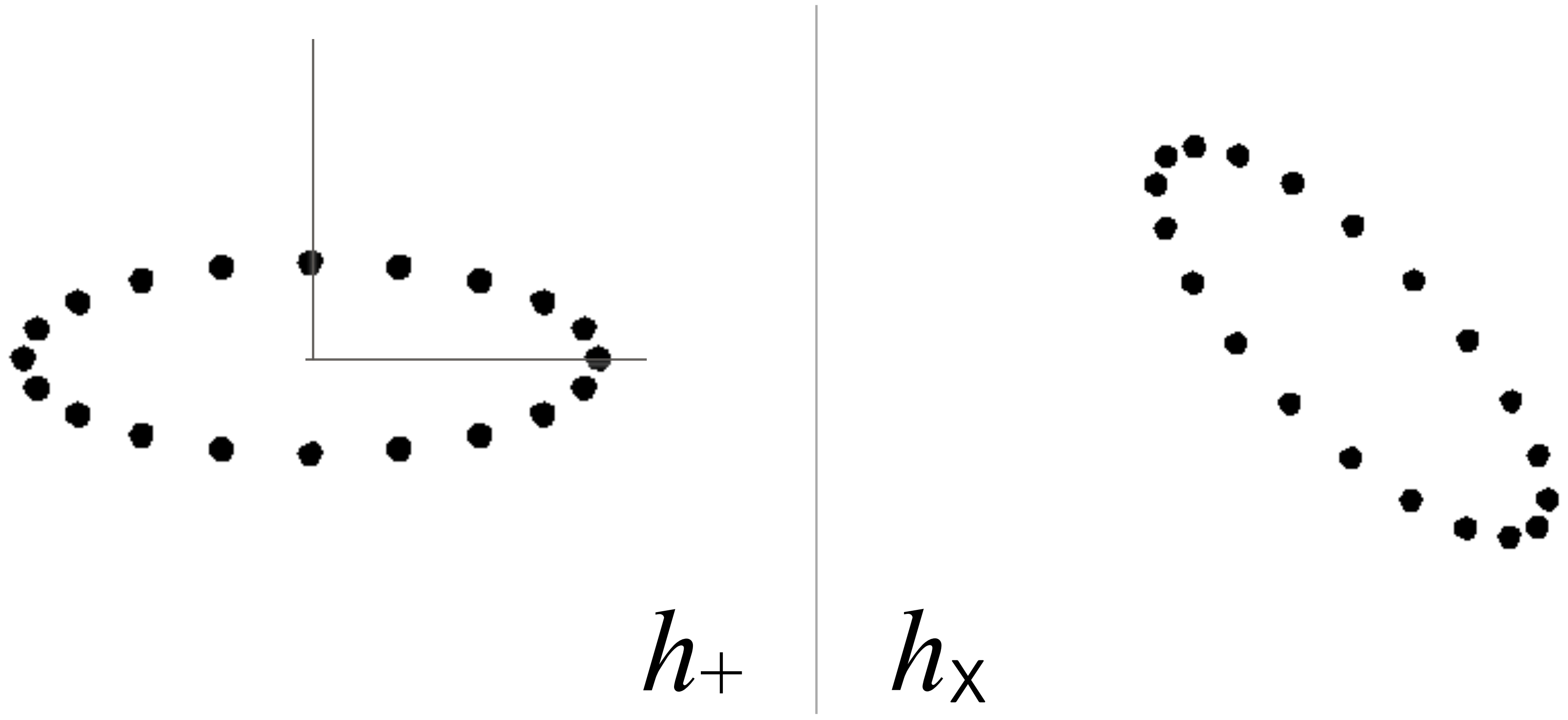
line element

$$ds^2 = -dt^2 + (1 + h_+)dx^2 + (1 - h_+)dy^2 + dz^2 + 2h_\times dxdy$$

lengths in x- & y-directions (plus polarization)

$$L_x = \int_{x_1}^{x_2} \sqrt{1 + h_+}dx \approx (1 + \frac{1}{2}h_+)L_{x0}; \qquad L_y = \int_{y_1}^{y_2} \sqrt{1 - h_+}dy \approx (1 - \frac{1}{2}h_+)L_{y0}$$



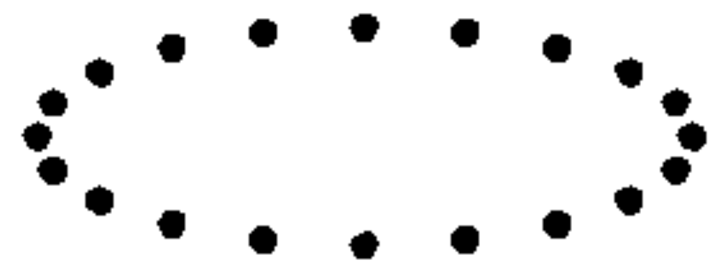


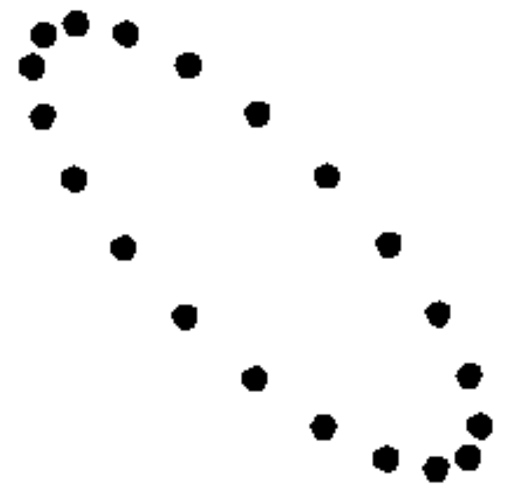
plus polarisation **cross polarisation**

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

λ : 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)

Regge-Wheeler gauge

linear $l = 2$ perturbation onto spherically symmetric star

$$\begin{aligned} ds^2 = & - e^{2\Phi(r)} \left[1 + H(r) Y_{20}(\theta,\varphi)\right] dt^2 \\ & + e^{2\Lambda(r)} \left[1 - H(r) Y_{20}(\theta,\varphi)\right] dr^2 \\ & + r^2 \left[1 - K(r) Y_{20}(\theta,\varphi)\right] (d\theta^2 + \sin^2(\theta) d\varphi^2) \end{aligned}$$

$$K'(r) = H'(r) + 2H(r)\Phi'(r)$$

$$f = \frac{d\epsilon}{dp}$$

$$\left(-\frac{6e^{2\Lambda}}{r^2} - 2(\Phi')^2 + 2\Phi'' + \frac{3}{r}\Lambda' + \frac{7}{r}\Phi' - 2\Phi'\Lambda' + \frac{f}{r}(\Phi' + \Lambda')\right) H + \left(\frac{2}{r} + \Phi' - \Lambda'\right) H' + H'' = 0$$

$$\begin{aligned} \frac{dH}{dr} &= \beta \\ \frac{d\beta}{dr} &= 2\left(1 - 2\frac{m_r}{r}\right)^{-1} H \left\{-2\pi\left[5\epsilon + 9p + f(\epsilon + p)\right] \right. \\ & \quad \left. + \frac{3}{r^2} + 2\left(1 - 2\frac{m_r}{r}\right)^{-1} \left(\frac{m_r}{r^2} + 4\pi r p\right)^2\right\} \\ & \quad + \frac{2\beta}{r}\left(1 - 2\frac{m_r}{r}\right)^{-1} \left\{-1 + \frac{m_r}{r} + 2\pi r^2(\epsilon - p)\right\} \end{aligned}$$

Tidal love number

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

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

$$\begin{aligned} k_2 \quad = \quad & \frac{8C^5}{5}(1-2C)^2[2+2C(y-1)-y] \\ & \times \Big\{ 2C[6-3y+3C(5y-8)] \\ & \quad +4C^3[13-11y+C(3y-2)+2C^2(1+y)] \\ & \quad +3(1-2C)^2[2-y+2C(y-1)]\ln(1-2C) \Big\}^{-1} \end{aligned}$$

$$y = \frac{R\beta(R)}{H(R)} \qquad C = \frac{M}{R}$$

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

Systematic Parameter Errors in Inspiraling Neutron Star Binaries

Marc Favata*

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

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

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

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

6PN

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

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

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

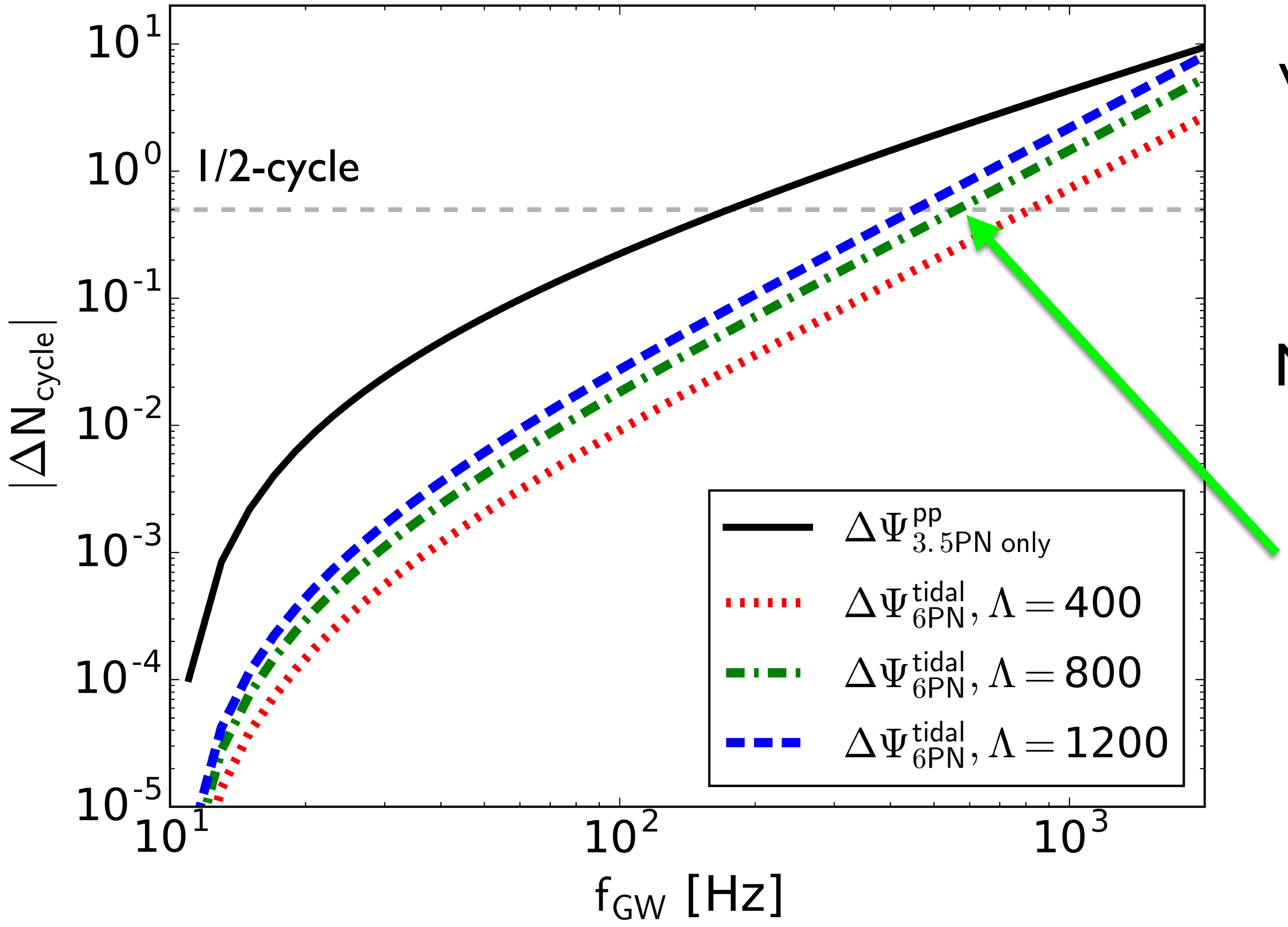
$$x = (\omega M)^{2/3} \Rightarrow \left(\omega \frac{GM}{c^3}\right)^{2/3}$$

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

dimensionless

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

accumulated GW phase

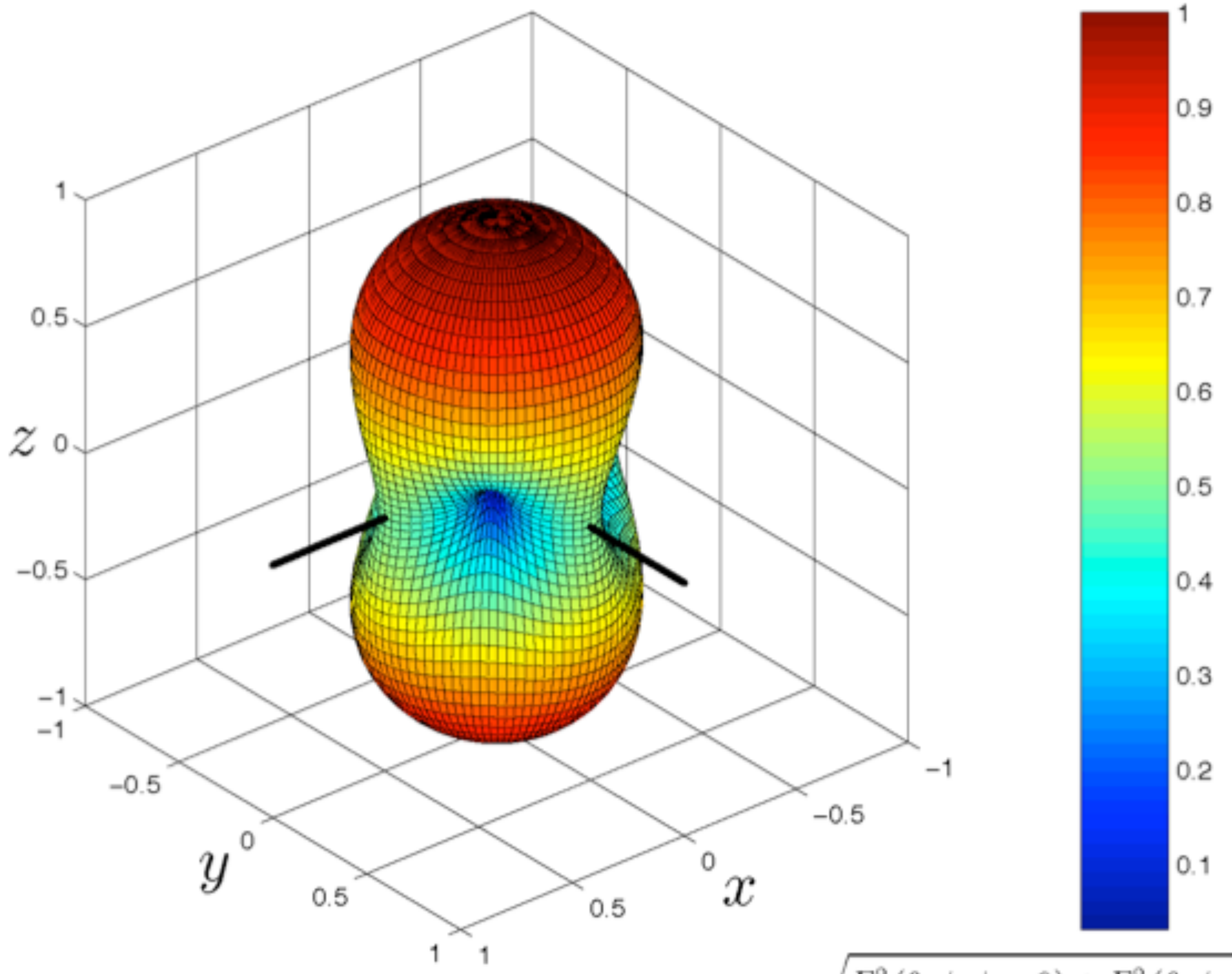


waveform model:
TaylorF2(SPA)

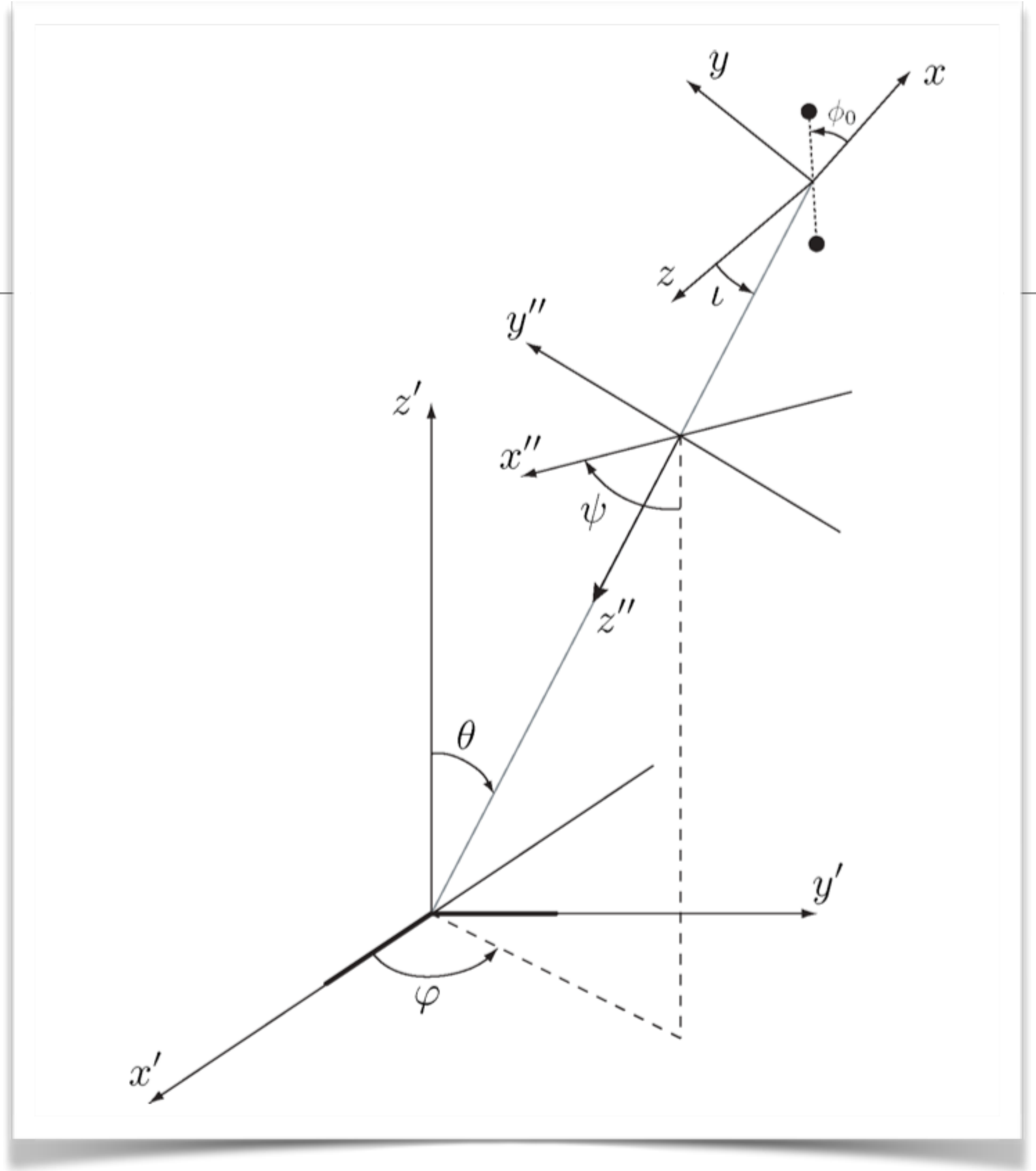
Mch=1.188M$_\odot$
M1=M2=1.365M$_\odot$

~600 Hz

Magnitude of strain



$\sqrt{F_+^2(\theta,\phi,\psi=0)+F_\times^2(\theta,\phi,\psi=0)}$



with $\iota = \psi = 0$

Selected for a Viewpoint in *Physics*
PRL **119,** 161101 (2017) 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.

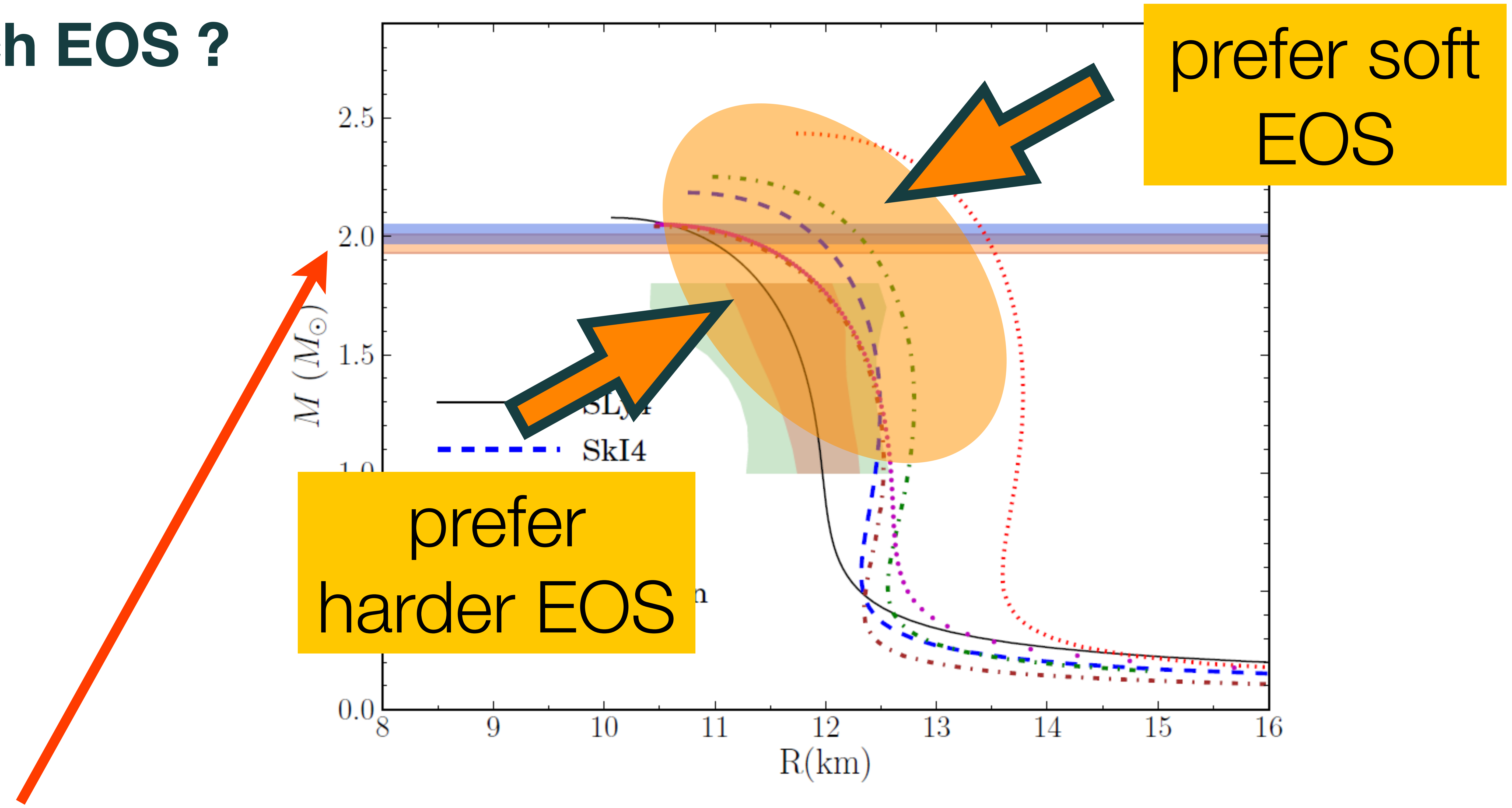
	Low-spin priors ($\lvert\chi\rvert \leq 0.05$)	High-spin priors ($\lvert\chi\rvert \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	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

Mass & radius of neutron star

Tidal deformability of NS from GW

Q) Which EOS ?



Neutron Star-White Dwarf Binaries

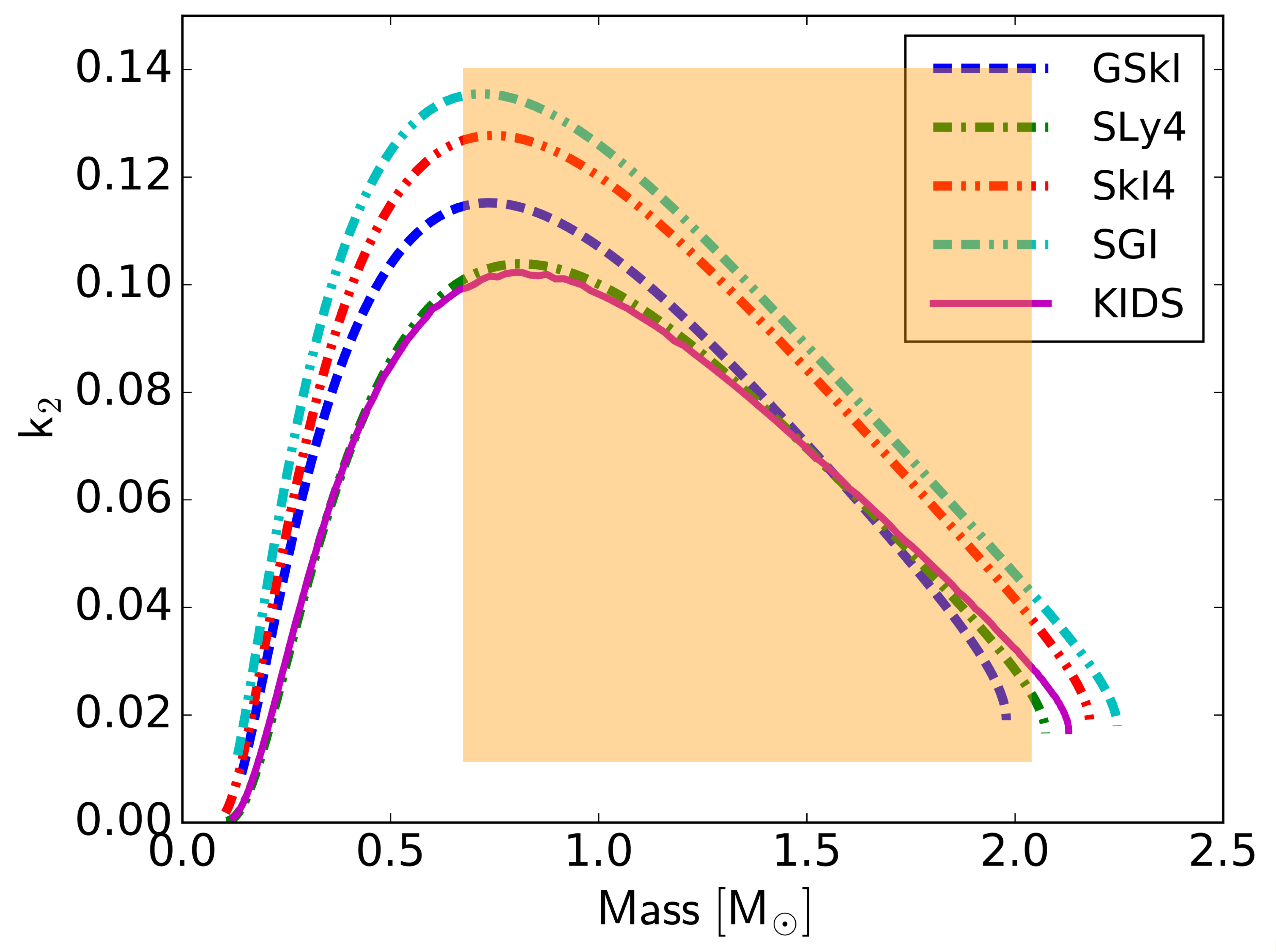
1.97 solar mass NS : Nature 467 (2010) 1081

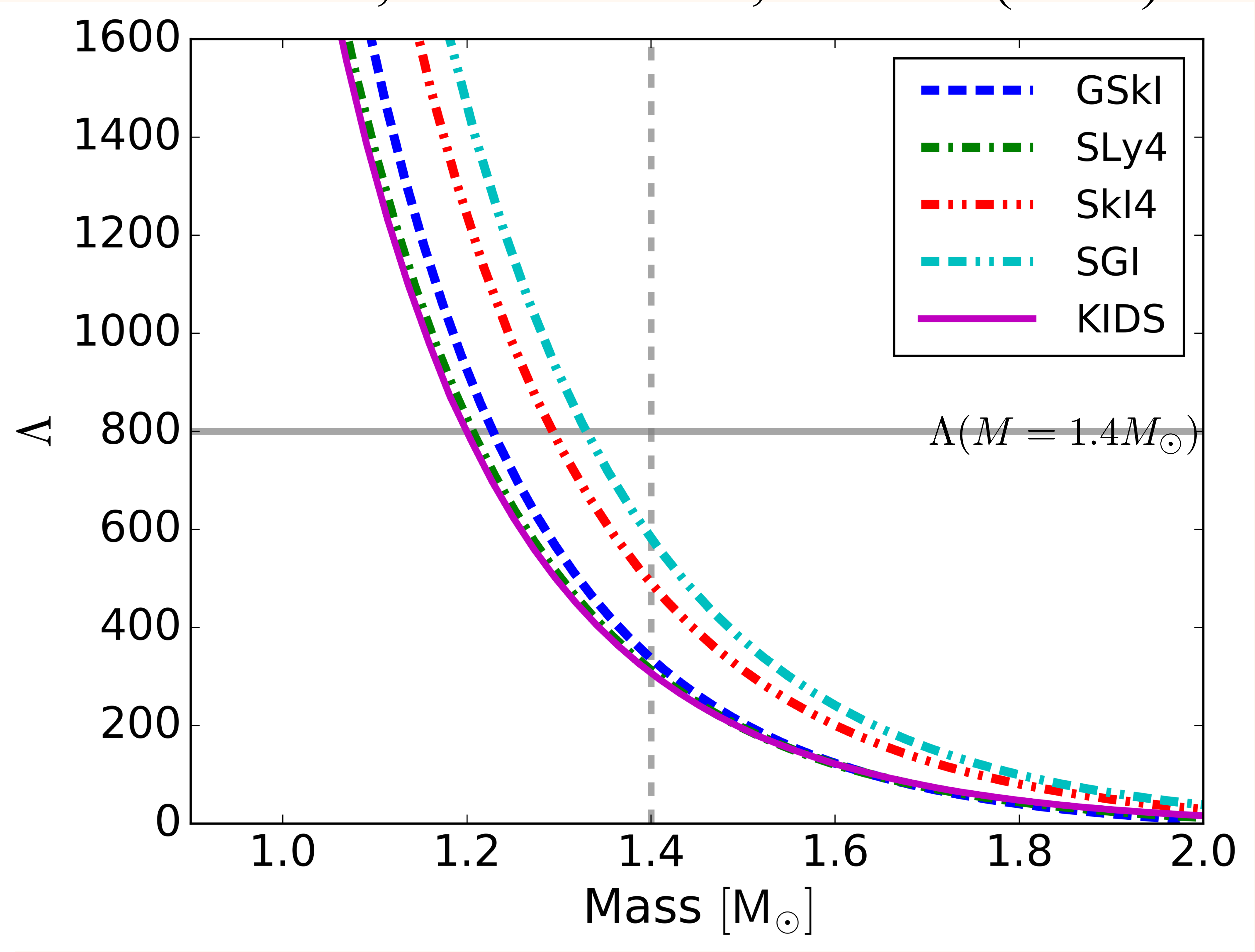
2.01 solar mass NS : Science 340 (2013) 6131

Tidal deformability

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

Kim, et al. PRC 98, 065805 (2018)





GW170817

$$M_{\mathrm{chirp}} = 1.188 M_\odot$$

$$\Lambda_{1.4M_\odot}^{\mathrm{low\ spin}} < 800 \qquad \Lambda_{1.4M_\odot}^{\mathrm{high\ spin}} < 1400$$

Prospects of the Observing Runs

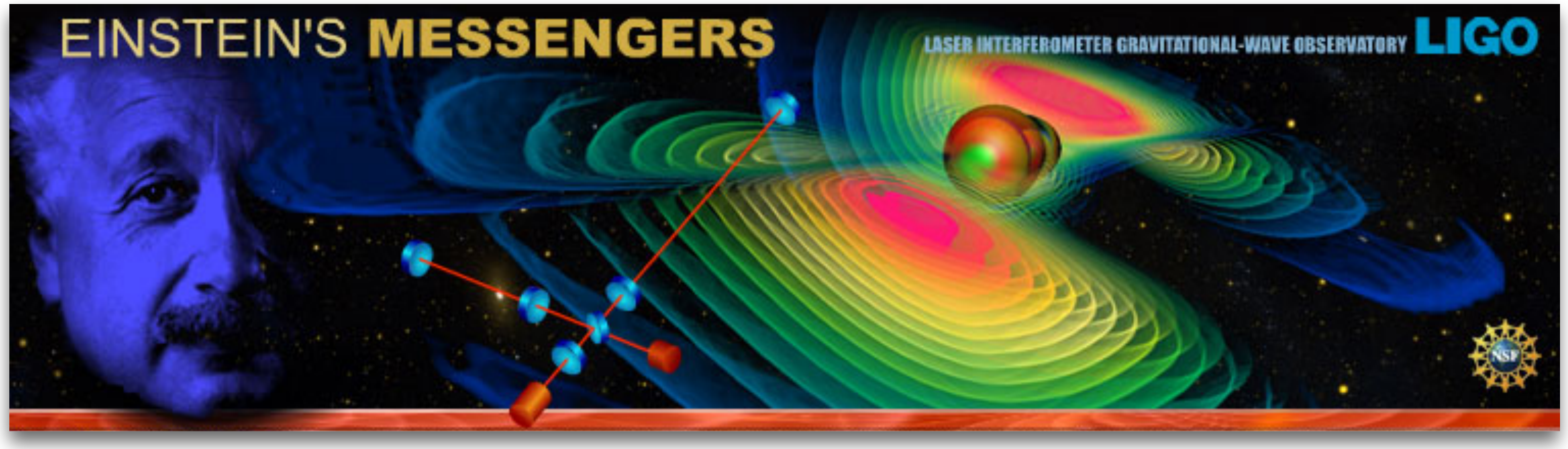
"Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA",
arXiv:1304.0670v4, LIGO-P1200087-v45, Living Rev. Relativity, 21, 3 (2018)

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

LIGO

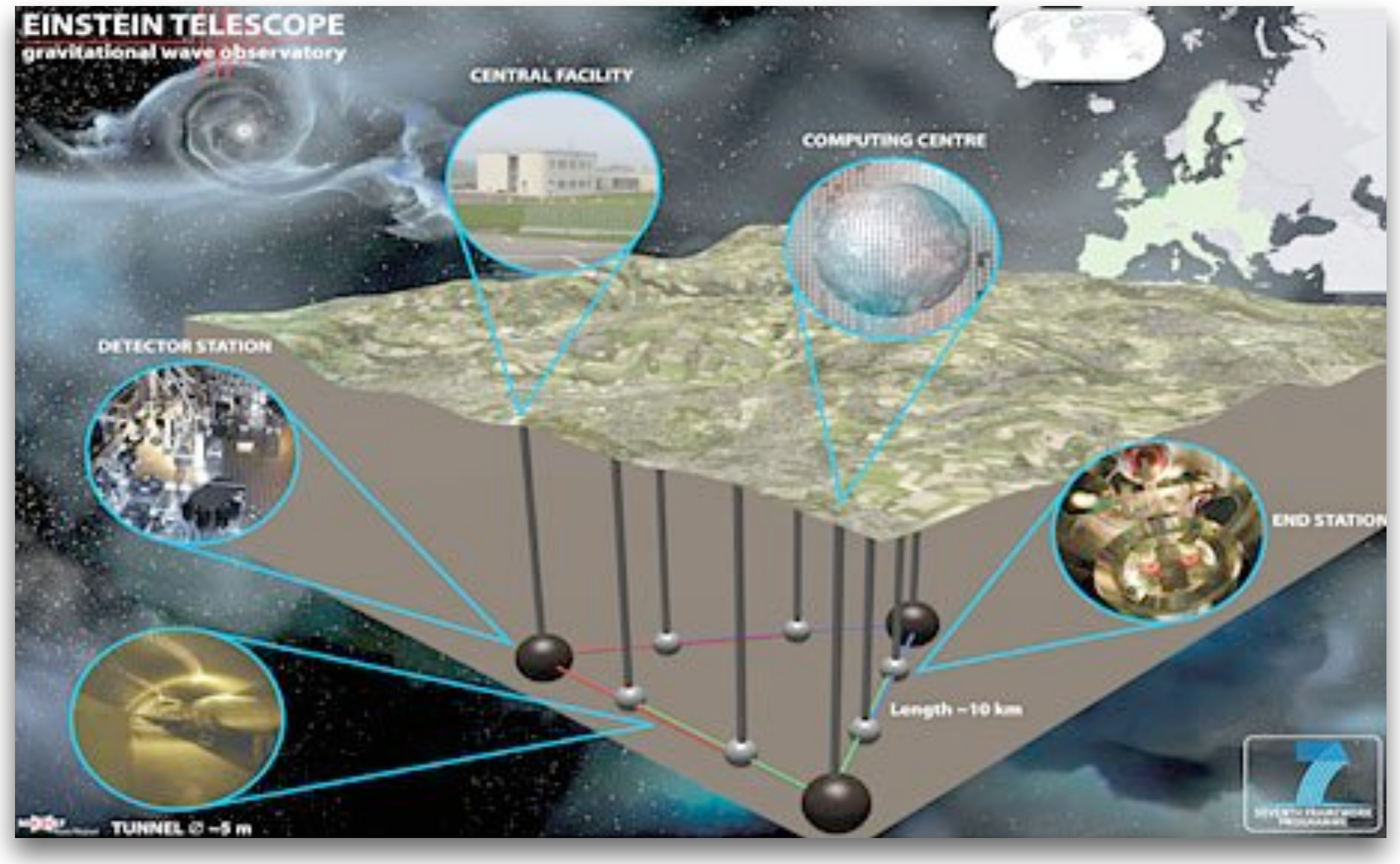
- First detection of gravitational-waves
- First detection of black hole binary
- First observation of heavy black holes
- New possibilities: grativational-wave astronomy
- Neutron stars, black holes, supernovae, gamma-ray bursts, …
- … …



Future Gravitational-Wave Observatories

Einstein Telescope

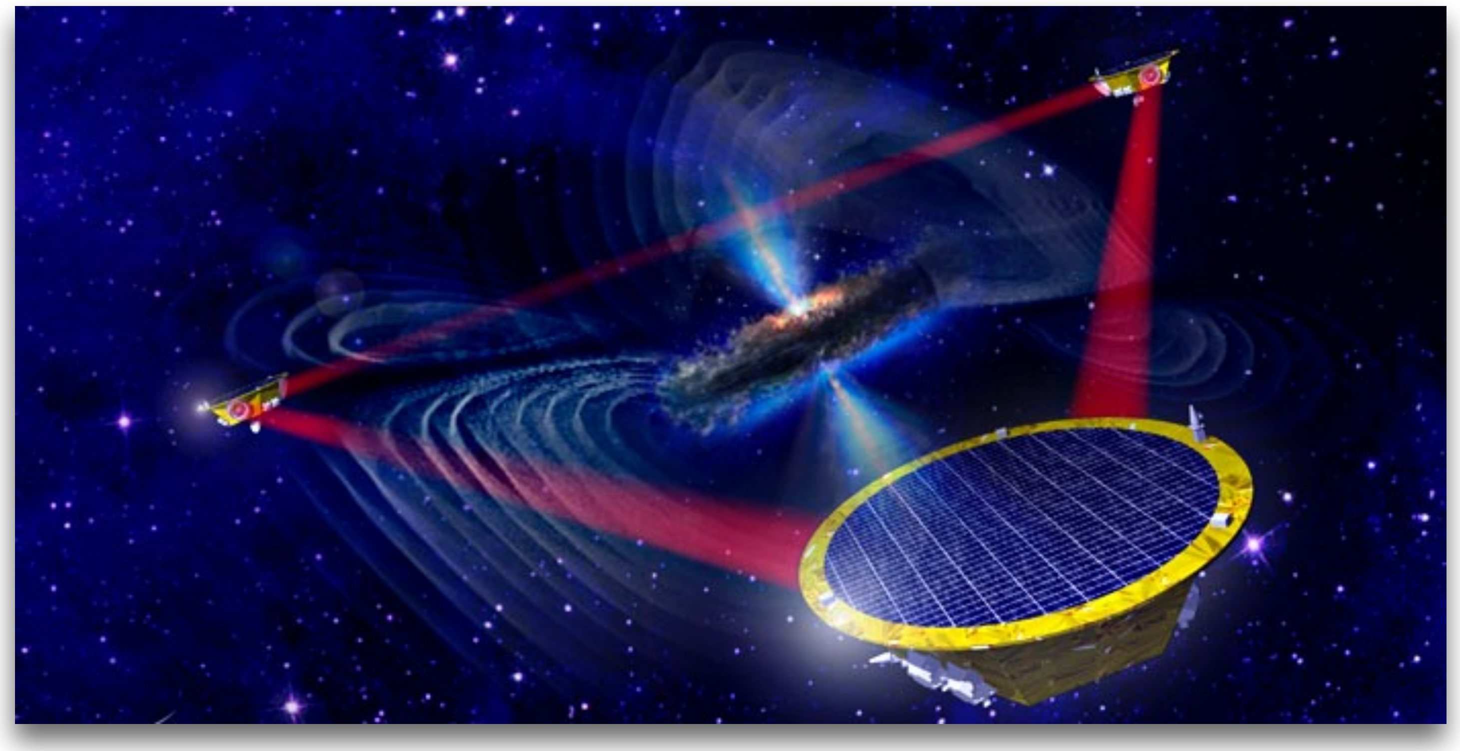
ESA / 2030? (designing stage)



10 km

eLISA

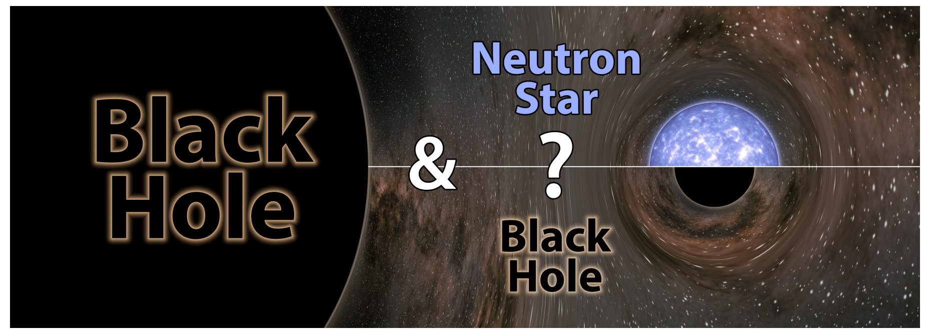
2034



10^6 km

Prospect

- **GW** from NS mergers
  - GW190425 : (1.4 $M_{\odot}$ + 2.1 $M_{\odot}$) NS-NS merger (500 Mly, 153 Mpc)
  - GW190426 : (?? $M_{\odot}$ + ?? $M_{\odot}$) NS-BH merger candidate (1.2 Gly, 368 Mpc)
  - GW190814 : (2.6 $M_{\odot}$ + 23 $M_{\odot}$) NS/BH-BH merger (700 Mly, 240 Mpc)



- **BUD²-McGill Collaboration**
  - DJBUU (new transport code) for RAON
  - Dense Matter & Neutron Star EOS