連星中性子星合体とその周辺

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（東京大学ビックバン宇宙国際研究センター）

コンパクトオブジェクト分科会

タイトル	物理の「目」で見るコンパクト天体
座長団	北木 孝明(京都大学 D1), 大内 竜馬(京都大学 D1), 鈴木 遼(早稲田大学 D1), 津久井 崇史(総合研究大学院大学 M2), 財前 真理(東京大学 M2), 杉浦 健一(早稲田大学 M2), 津名大地(東京大学 M2)
紹介文	昨年、一大ニュースに全世界が泣いた。中性子星合体により放出された重力波の検出である。その後の追観測も見事な成功を納め、重元素の起源やガンマ線バーストの理論に制限を与えることに成功した。これはマルチメッセンジャー観測の時代が到来したことを象徴する出来事であった。 ブラックホールや中性子星、白色矮星などのコンパクト天体はそのコンパクト性ゆえに、ミクロ(量子力学、原子核物理など)からマクロ(電磁流体力学、相対性理論など)まで様々なスケールの物理が関与し、多彩な現象をもたらす。そのような現象として、超新星爆発、ジェット、ガンマ線バースト、重力波、降着円盤、高エネルギー粒子の生成、高速電波バーストなど具体例を挙げればきりがない。今や私たちは、これらの現象を電波からガンマ線まで多波長にわたる電磁波だけでなく、重力波やニュートリノといった多くの「目」によって「見る」ことができる。実際、Fermi、MAXI、Subaru、VLBI、LIGO、IceCubeなどの既存の観測機器に加え、最近新たにNICERやTomo-e Gozenによる観測が始まった。今後はJWSTやLSST、IXPE、CTAといった画期的な望遠鏡の稼働も予定されている。 このようなマルチメッセンジャーの時代に生きる私たちは、これまで以上に天体の多様な情報を得ることができるようになった。これらを駆使し、観測と理論の両側面からコンパクト天体現象を解明することが私たちの使命である。その足がかりとして本分科会で様々な講演を聞き、議論を重ねることでこれらの現象への理解を深め、私たち自身の「目」を鍛錬していくことが本分科会の目指す所である。またこの場を通して様々な人と交流し、今後の共同研究などへと発展すれば幸いである。

ある意味全世界が泣いた

- 一部の人々は本当に“泣いた”。
  長年の努力の結実
- 一部の人々は血の涙を流した。
  祭りフェイズ
- その他の野次馬はそれを羨ましそうに眺め、なんだか悔しくて泣いた。
  僕ココ

夜明け前

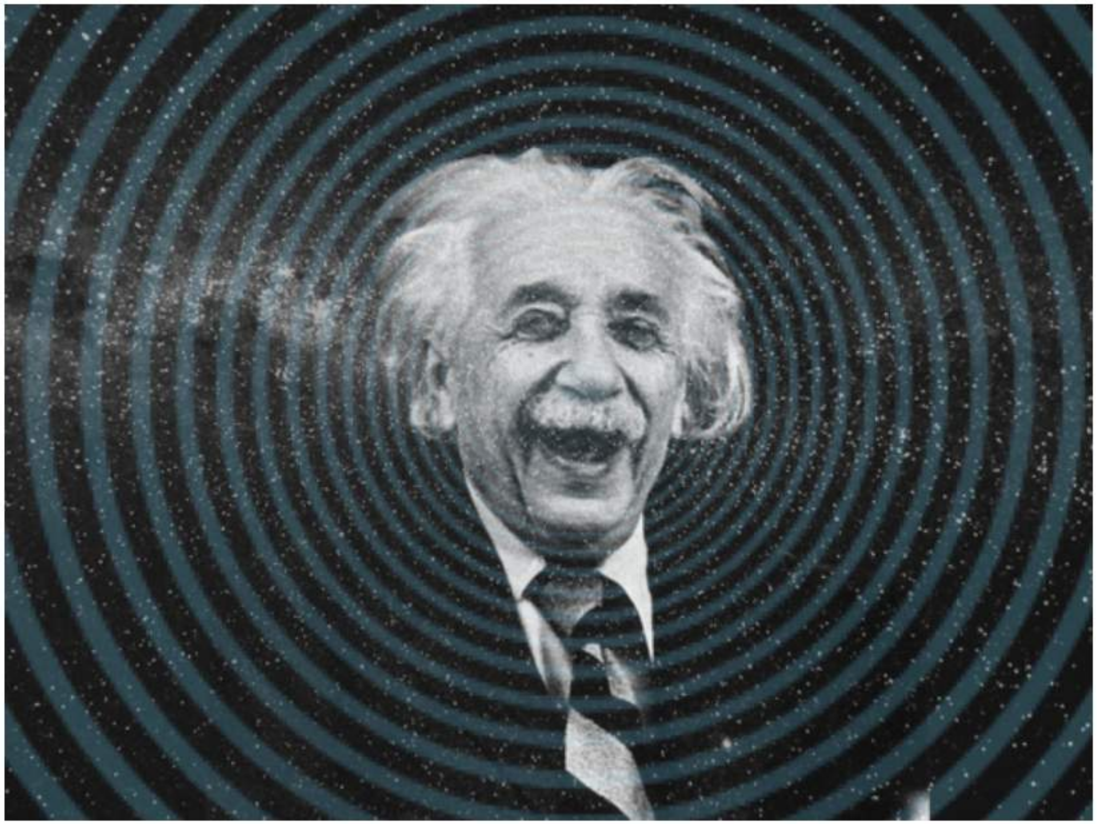
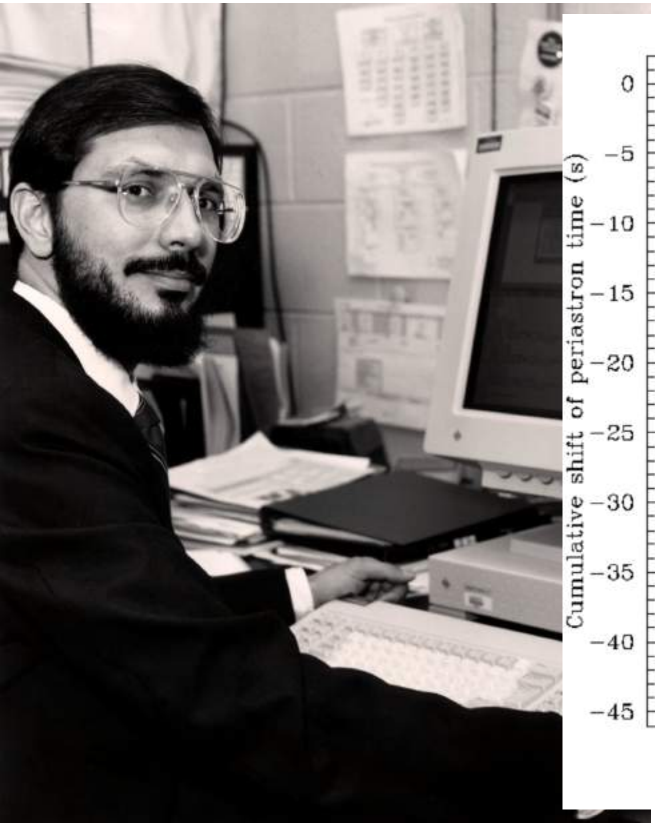
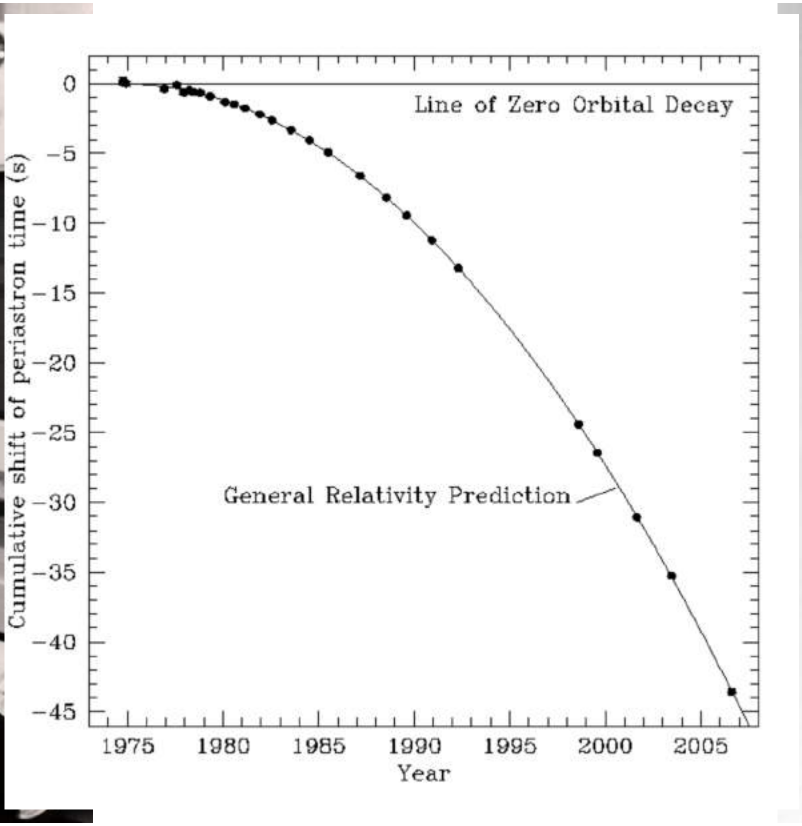


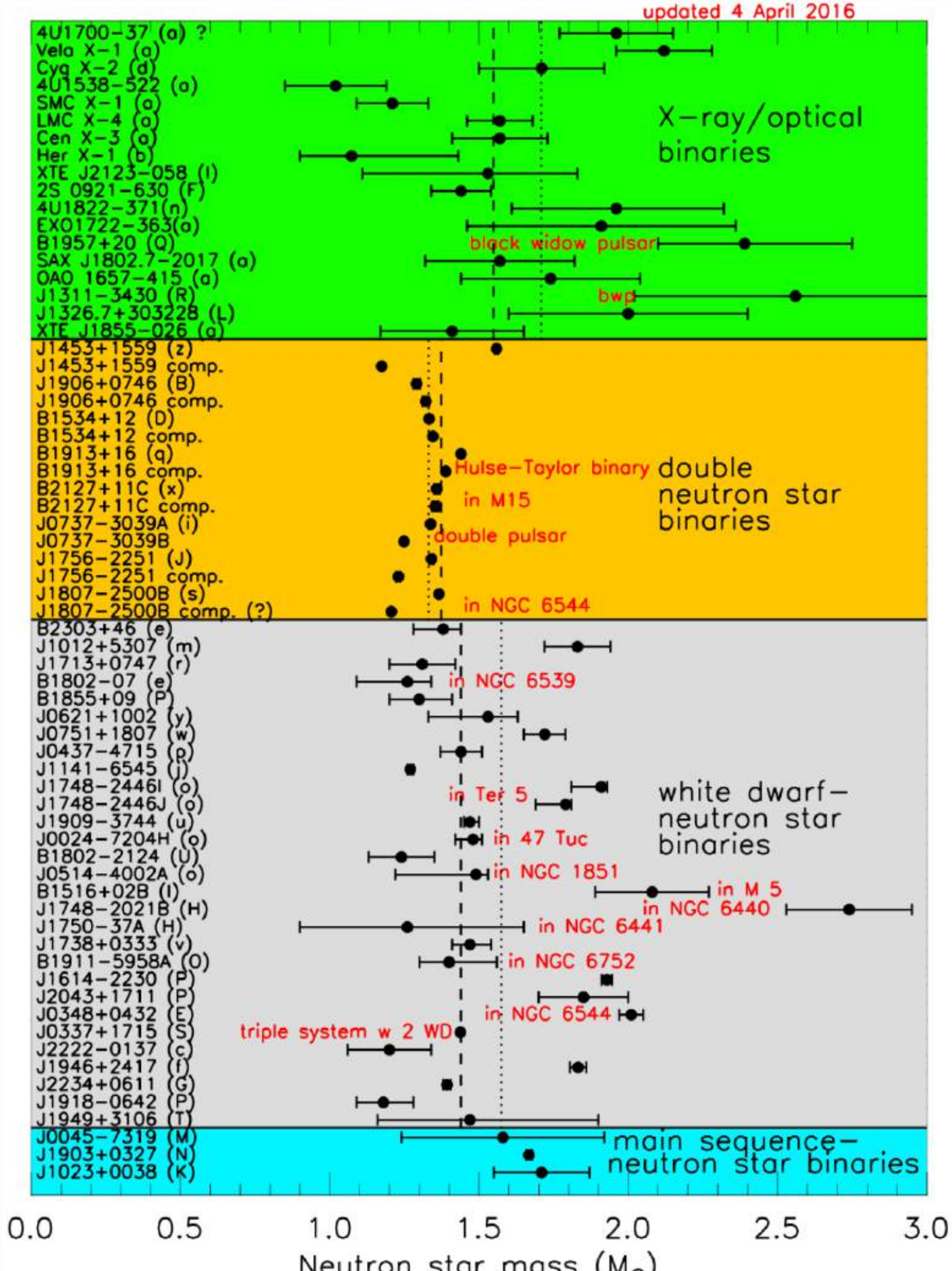
Photo: Ruth Orkin | Hulton Archive | Getty Images

Discovery of Hulse-Taylor binary (1974)

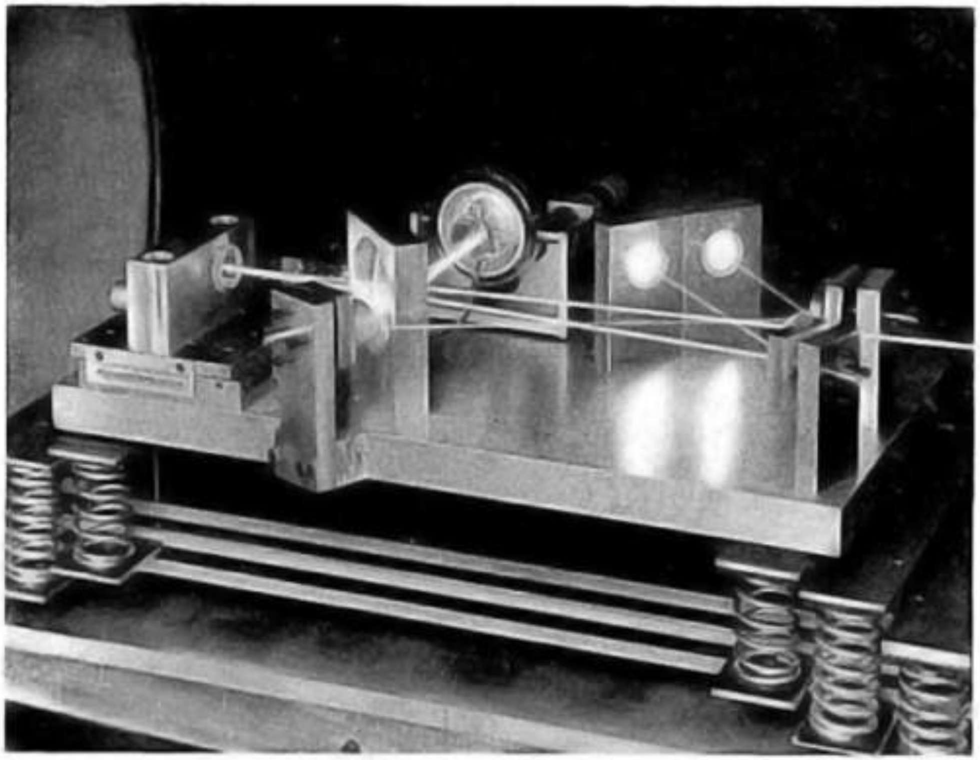




Graph from J.M. Weisberg, D.J. Nice, and J.H. Taylor


updated 4 April 2016
4U1700-37 (a) ?
Vela X-1 (a)
Cyg X-2 (d)
4U1538-522 (a)
SMC X-1 (a)
LMC X-4 (a)
Cen X-3 (a)
Her X-1 (b)
XTE J2123-058 (I)
2S 0921-630 (F)
4U1822-371(n)
EXO1722-363(a)
B1957+20 (Q)
SAX J1802.7-2017 (a)
OAO 1657-415 (a)
J1311-3430 (R)
J1326.7+303228 (L)
XTE J1855-026 (a)
X-ray/optical binaries
black widow pulsar
bwp
J1453+1559 (z)
J1453+1559 comp.
J1906+0746 (B)
J1906+0746 comp.
B1534+12 (D)
B1534+12 comp.
B1913+16 (q)
B1913+16 comp.
B2127+11C (x)
B2127+11C comp.
J0737-3039A (i)
J0737-3039B
J1756-2251 (J)
J1756-2251 comp.
J1807-2500B (s)
J1807-2500B comp. (?)
Hulse-Taylor binary
in M15
double pulsar
in NGC 6544
double neutron star binaries
B2303+46 (e)
J1012+5307 (m)
J1713+0747 (r)
B1802-07 (e)
B1855+09 (P)
J0621+1002 (y)
J0751+1807 (w)
J0437-4715 (p)
J1141-6545 (j)
J1748-2446I (o)
J1748-2446J (o)
J1909-3744 (u)
J0024-7204H (o)
B1802-2124 (U)
J0514-4002A (o)
B1516+02B (I)
J1748-2021B (H)
J1750-37A (H)
J1738+0333 (v)
B1911-5958A (O)
J1614-2230 (P)
J2043+1711 (P)
J0348+0432 (E)
J0337+1715 (S)
J2222-0137 (c)
J1946+2417 (f)
J2234+0611 (G)
J1918-0642 (P)
J1949+3106 (T)
in NGC 6539
in Ter 5
in 47 Tuc
in NGC 1851
in M 5
in NGC 6440
in NGC 6441
in NGC 6752
in NGC 6544
triple system w 2 WD
white dwarf-neutron star binaries
J0045-7319 (M)
J1903+0327 (N)
J1023+0038 (K)
main sequence-neutron star binaries
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Neutron star mass ($M_\odot$)

Joseph Weber and one of his gravitational wave detectors. SPECIAL COLLECTIONS AND UNIVERSITY ARCHIVES, UNIVERSITY OF MARYLAND LIBRARIES



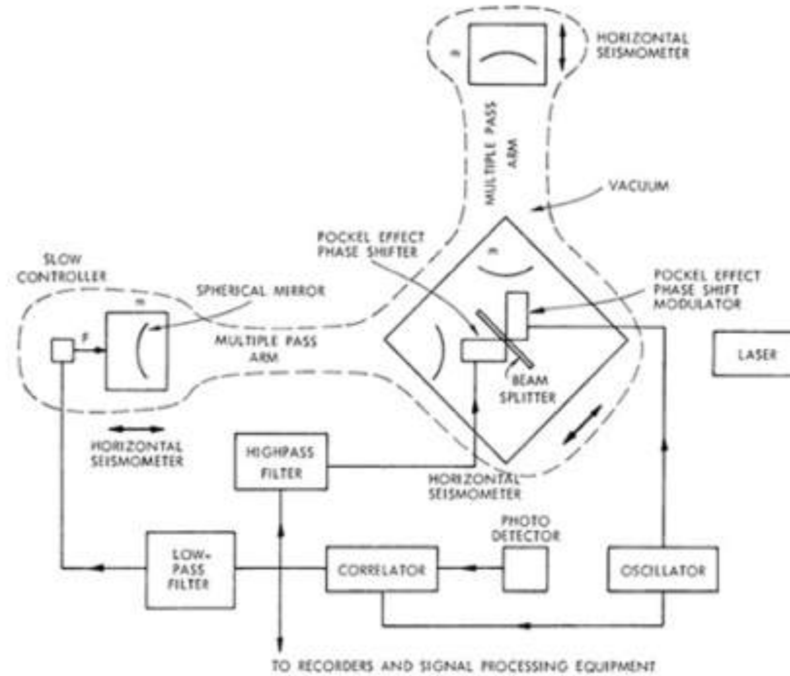
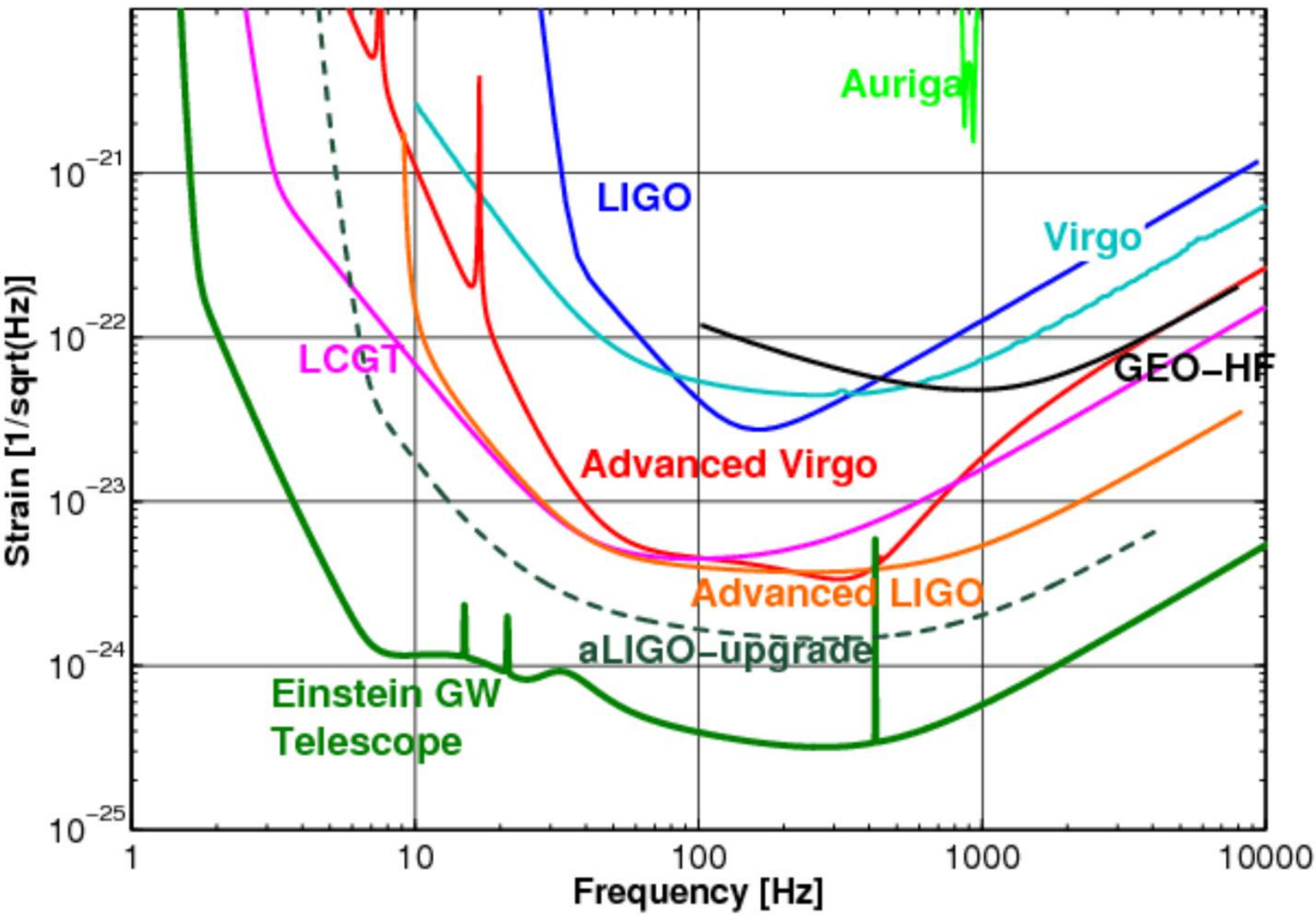


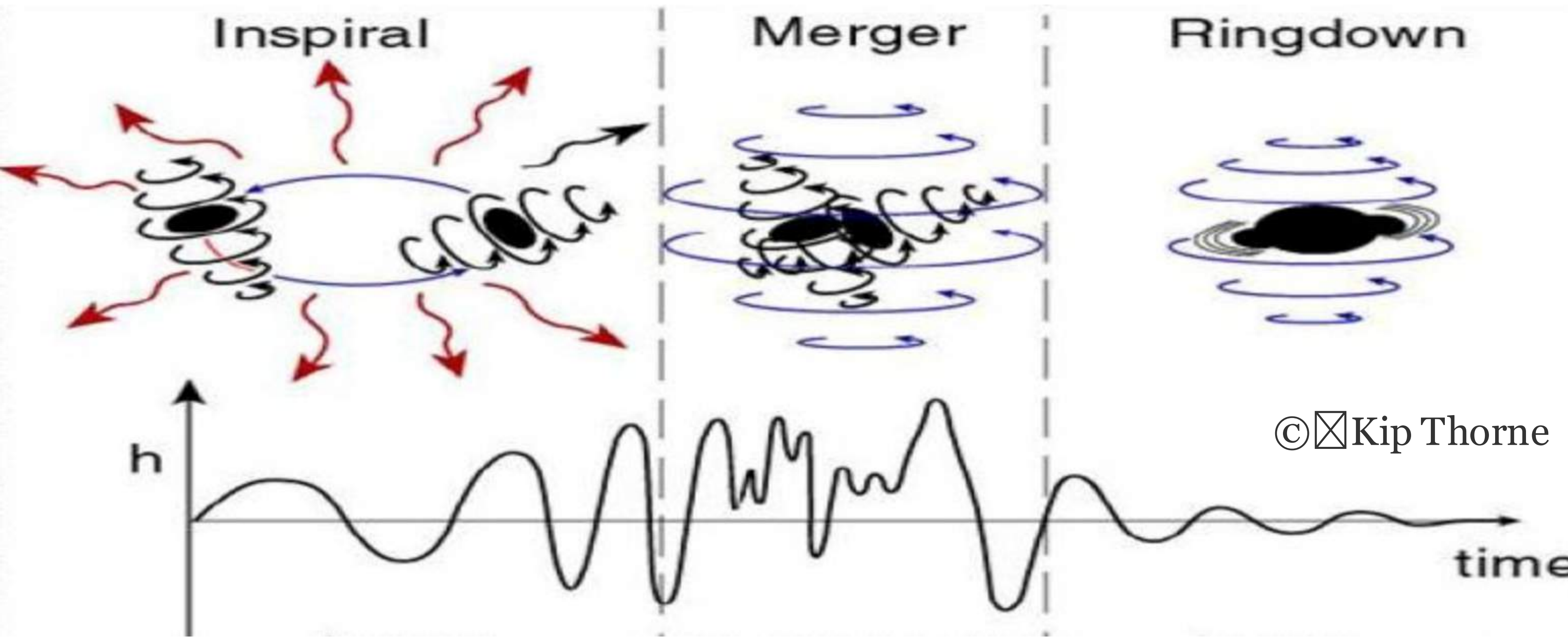
Fig. V-20. Proposed antenna.

(L) Bob Forward's first gravitational wave interferometer at Hughes Aircraft. (R) Rai Weiss' initial sketch of the components and operation of a laser interferometer like LIGO.



Auriga
LIGO
Virgo
LCGT
GEO−HF
Advanced Virgo
Advanced LIGO
aLIGO−upgrade
Einstein GW
Telescope
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
1
10
100
1000
10000
Strain [1/sqrt(Hz)]
Frequency [Hz]

コンパクト連星合体からの重力波



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ポストニュートン法の発展

The Last Three Minutes: Issues in Gravitational-Wave Measurements of Coalescing Compact Binaries

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(Received 24 August 1992)

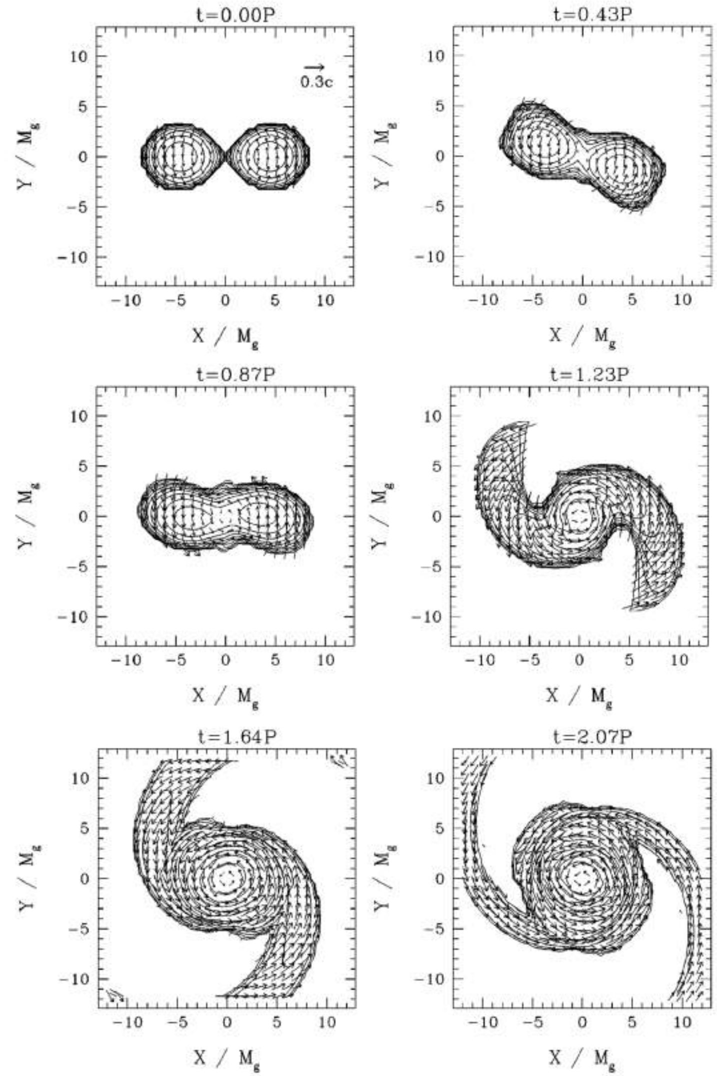
Gravitational-wave interferometers are expected to monitor the last three minutes of inspiral and final coalescence of neutron star and black hole binaries at distances approaching cosmological, where the event rate may be many per year. Because the binary's accumulated orbital phase can be measured to a fractional accuracy $\ll 10^{-3}$ and relativistic effects are large, the wave forms will be far more complex and carry more information than has been expected. Improved wave form modeling is needed as a foundation for extracting the waves' information, but is not necessary for wave detection.

$d\mathcal{N}_{\rm cyc}/d\ln f = (1/2\pi)(d\Phi/d\ln f)$, is

$$\frac{d\mathcal{N}_{\rm cyc}}{d\ln f} = \frac{5}{96\pi}\frac{1}{\mu M^{2/3}(\pi f)^{5/3}}\left\{1 + \left(\frac{743}{336} + \frac{11}{4}\frac{\mu}{M}\right)x - [4\pi + \text{S.O.}]x^{1.5} + [\text{S.S.}]x^2 + O(x^{2.5})\right\}.$$

数値相対論の発展

The BSSN formalism

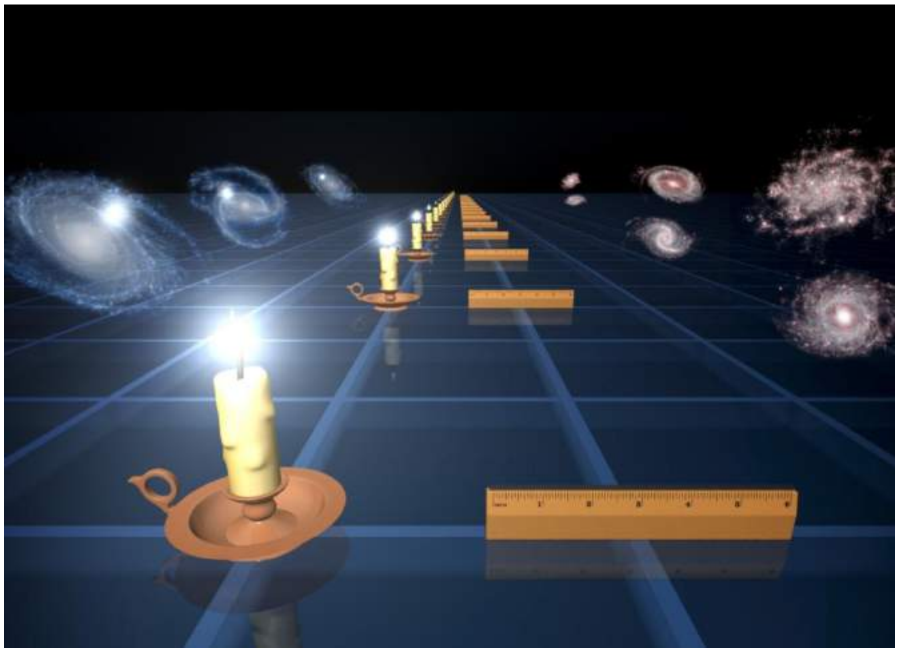


Shibata & Uryu 00

重力波宇宙物理学 with NSNS

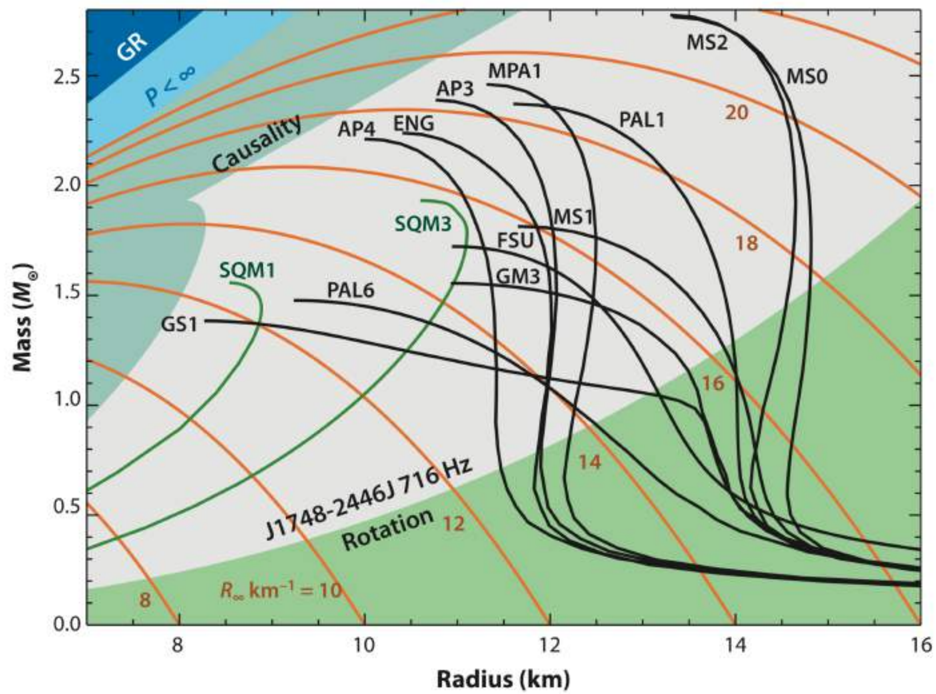
as a standard candle or *siren*

e.g. Krolak & Schutz 1987

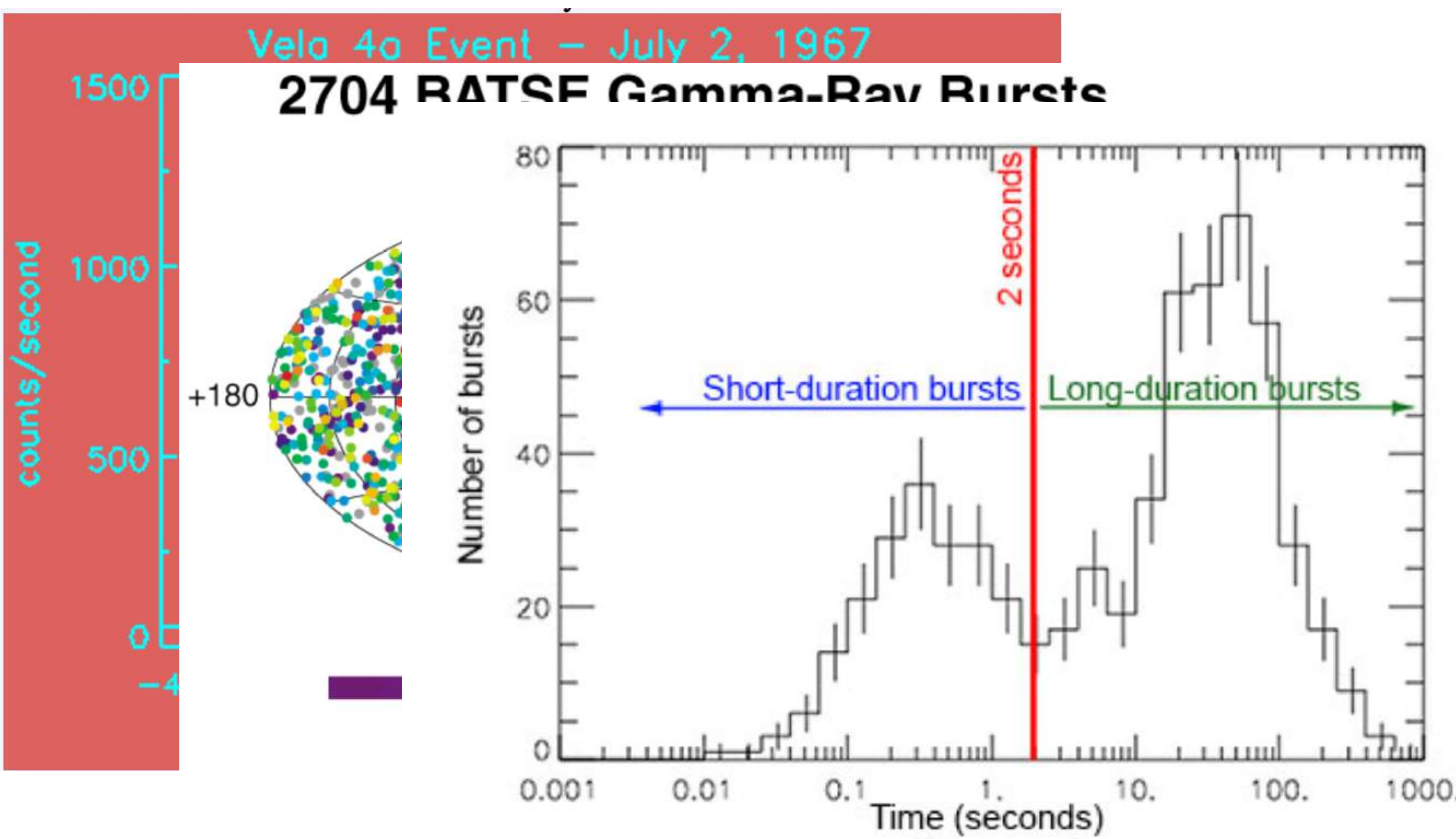


GW → NS EoS

e.g., Flanagan & Hinderer 08



Discovery of Gamma ray bursts



Pacynski 86; Goodman 86; Eichler et al. 89

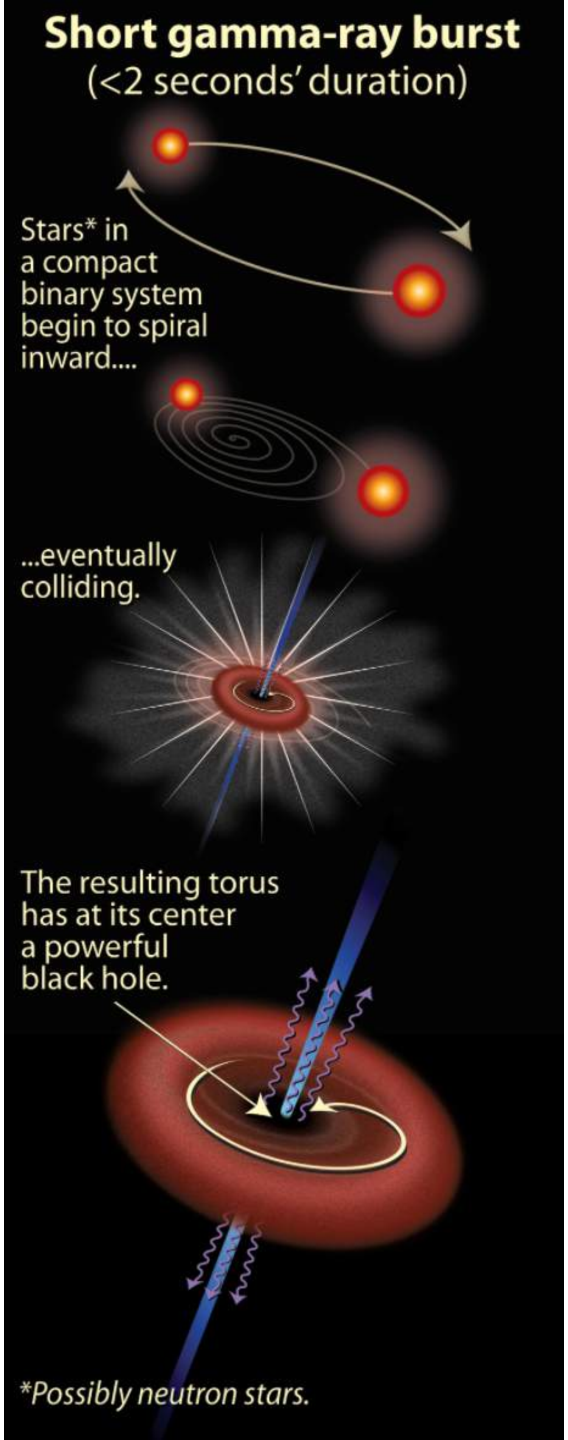
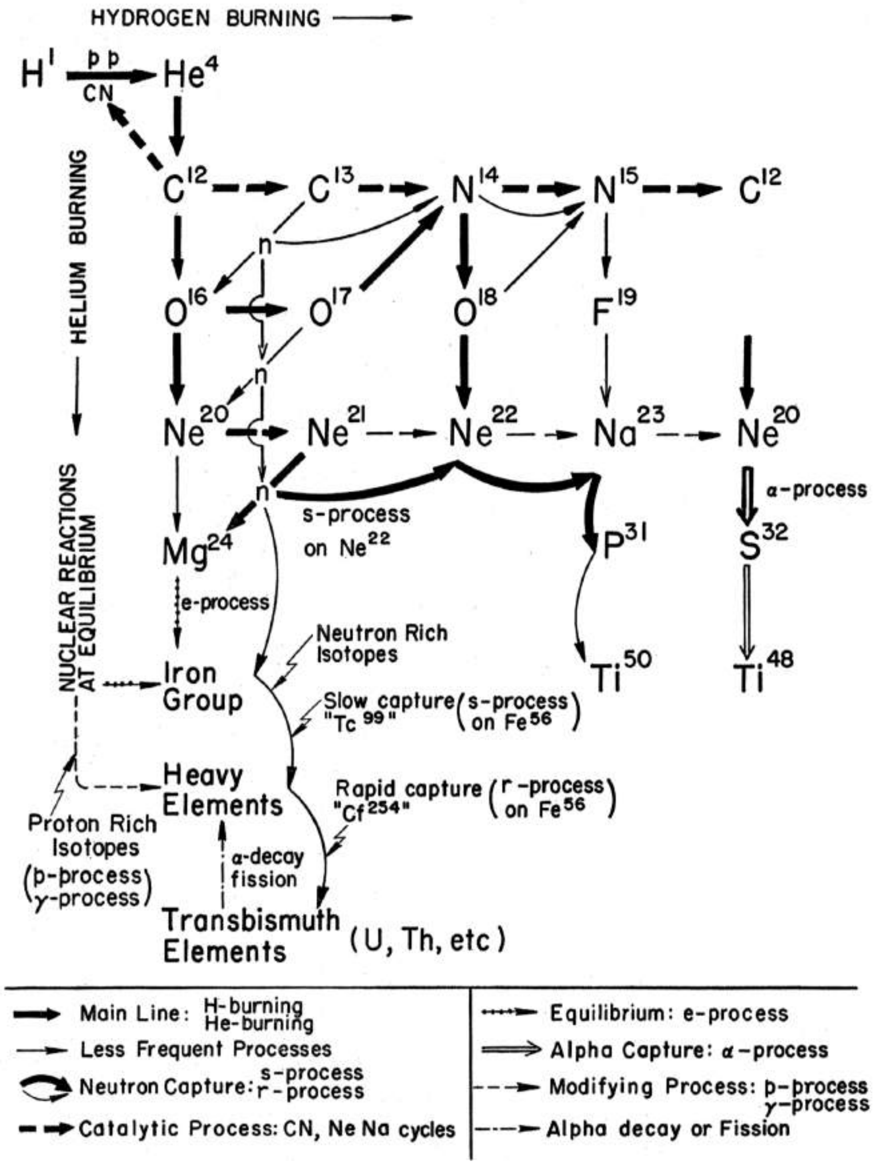


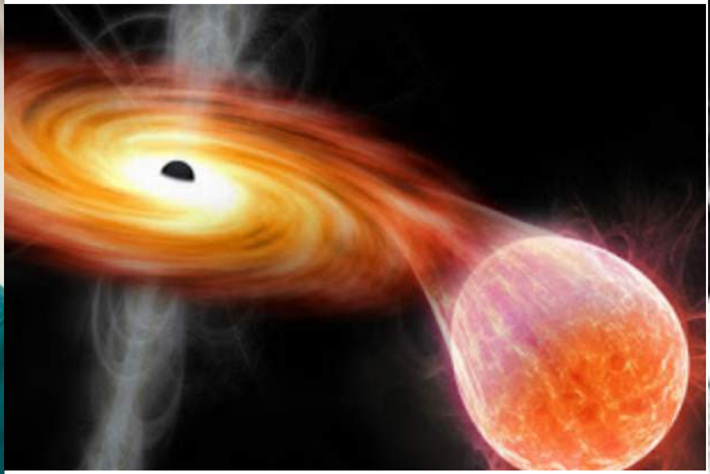
Image: R. P. MATTHEWS, PRINCETON UNIV.

B2FH & Cameron 57



NSBH mergers are plausible!

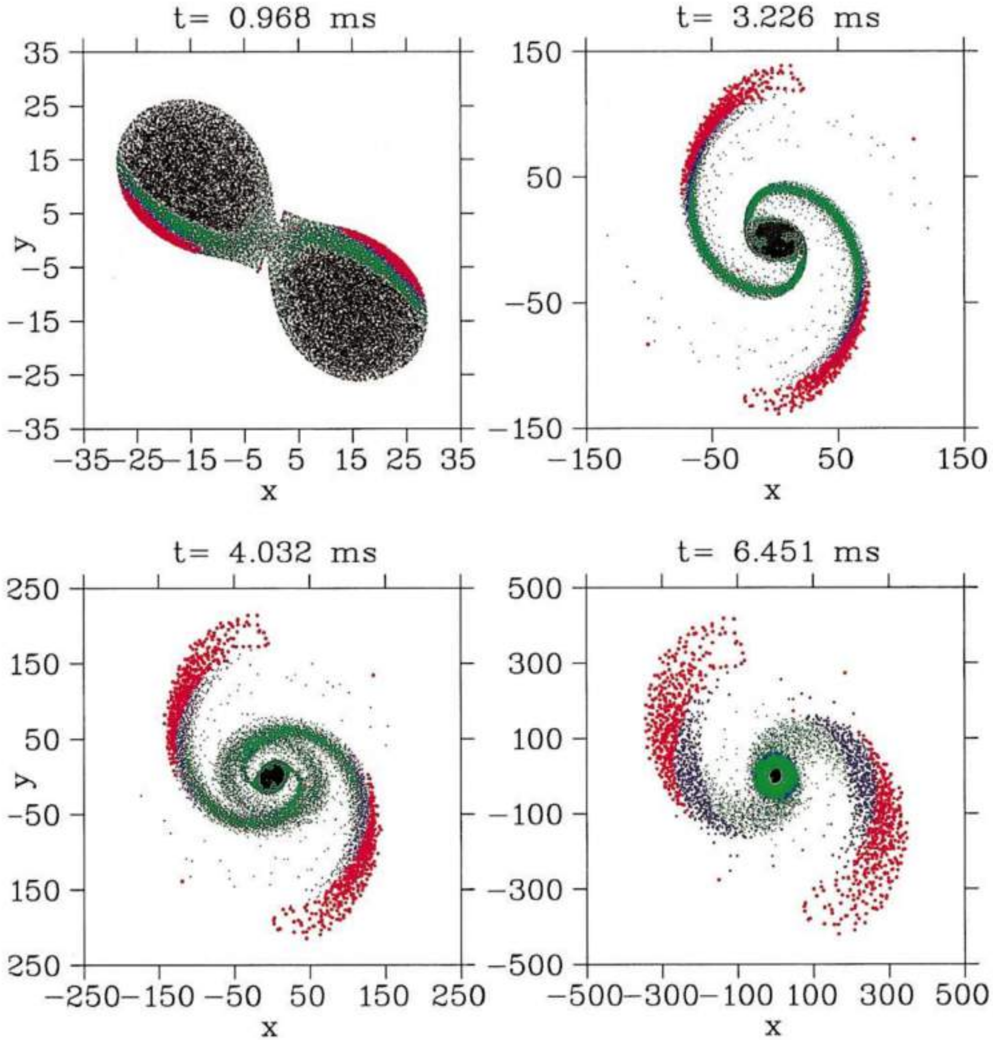
Lattimer & Schramm 74



NSNS will also work!

Symbalisty & Schramm 82; Eichler et al.89

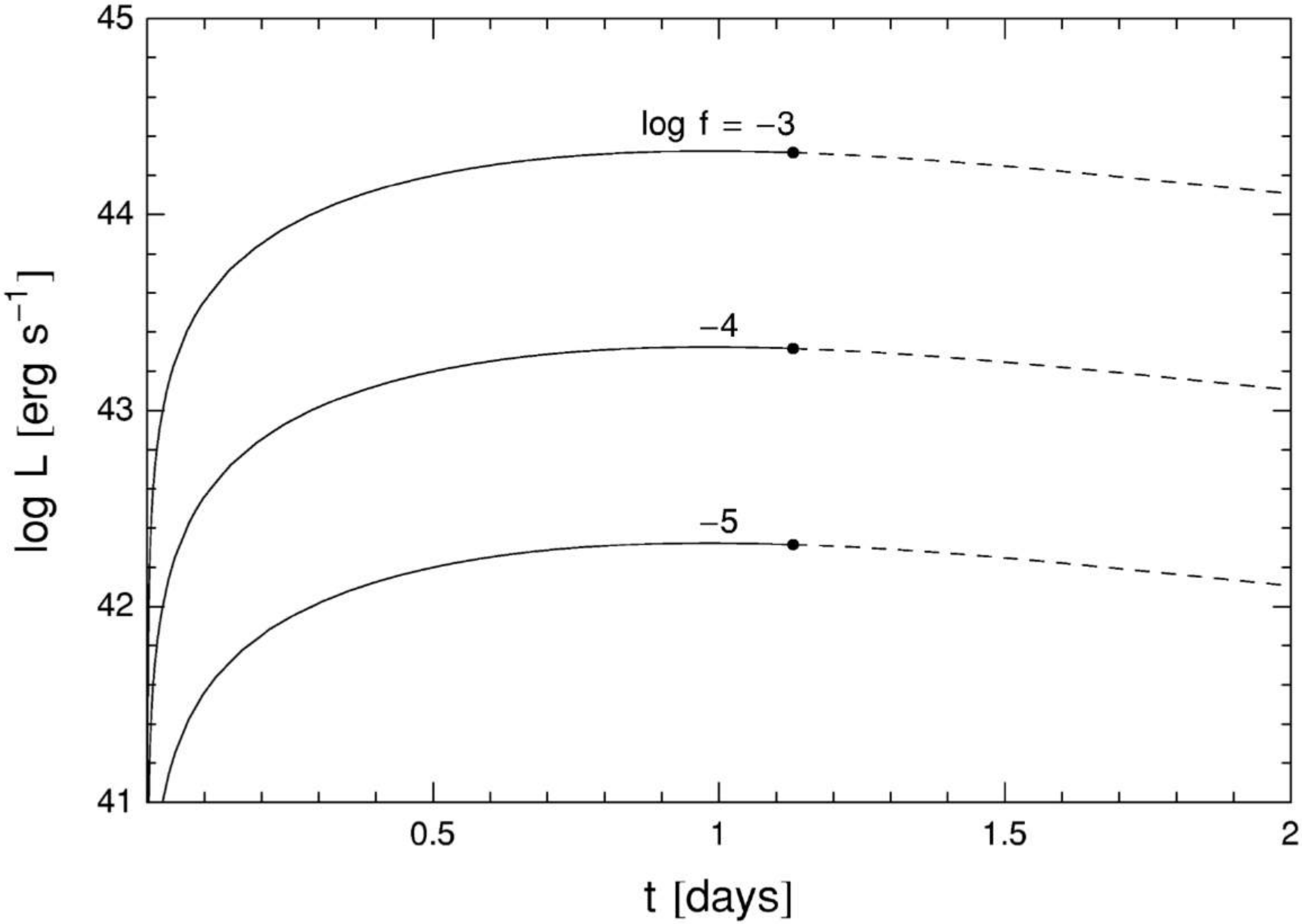
Some demonstrations with numerical simulations



e.g.,
Davies et al. 94;
Ruffert et al. 97;
Rosswog et al. 99

Li-Paczinski novae

Li & Paczinski 98



夜明け間近（～2010以降）

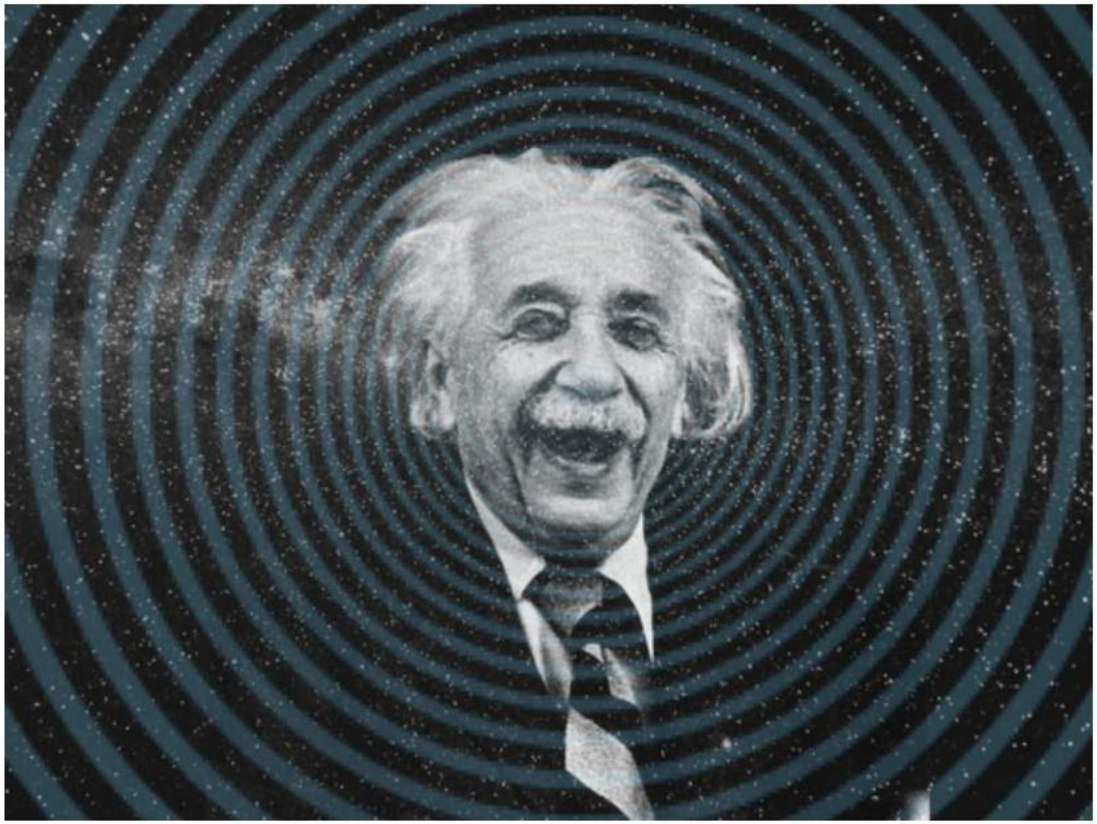
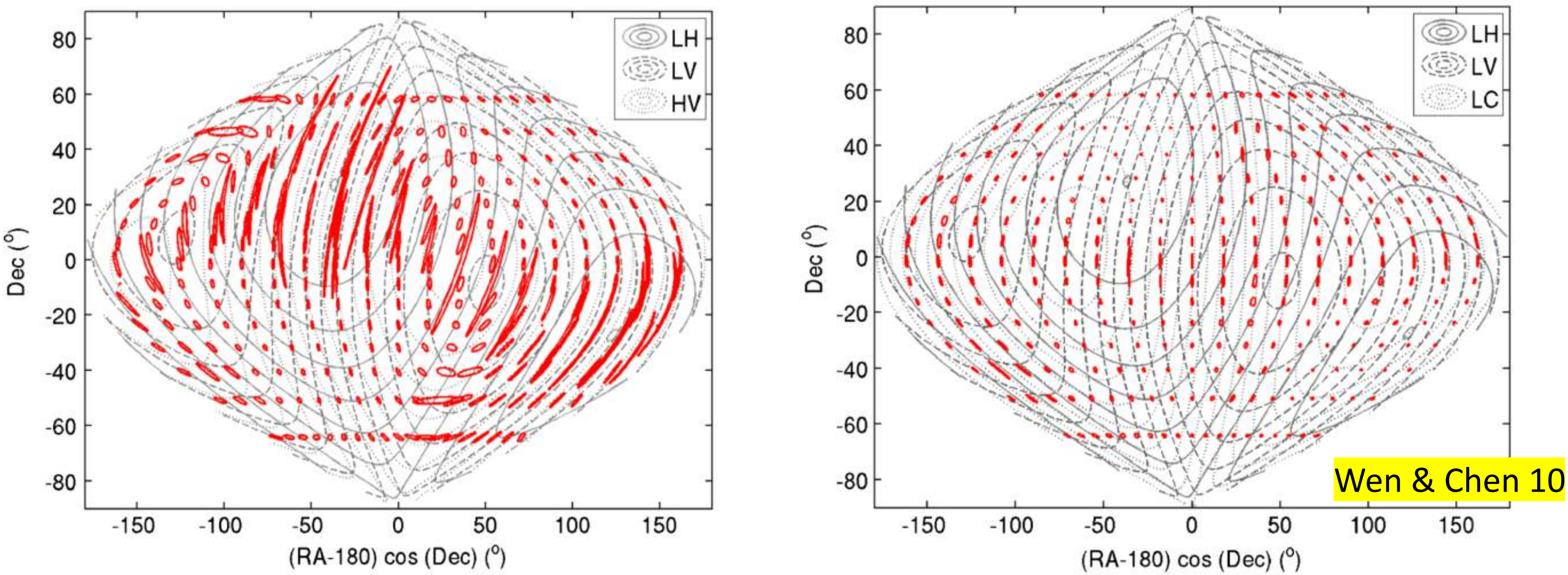


Photo: Ruth Orkin | Hulton Archive | Getty Images

advLIGO、
もうすぐ
動くってよ

重力波干渉計は目(耳)が悪い

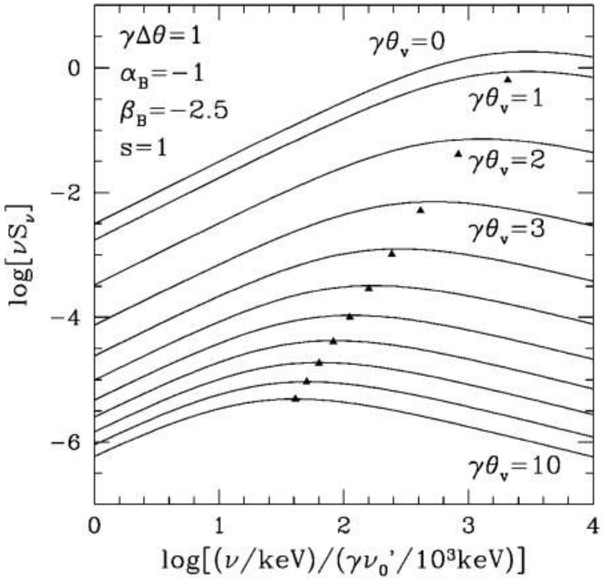


Wen & Chen 10

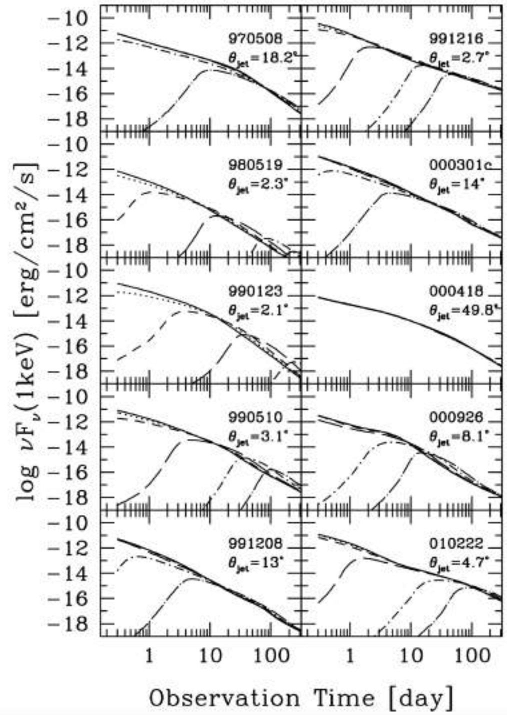
母銀河決まらない→ 重力波宇宙物理学できない … e.g. Schutz 1986

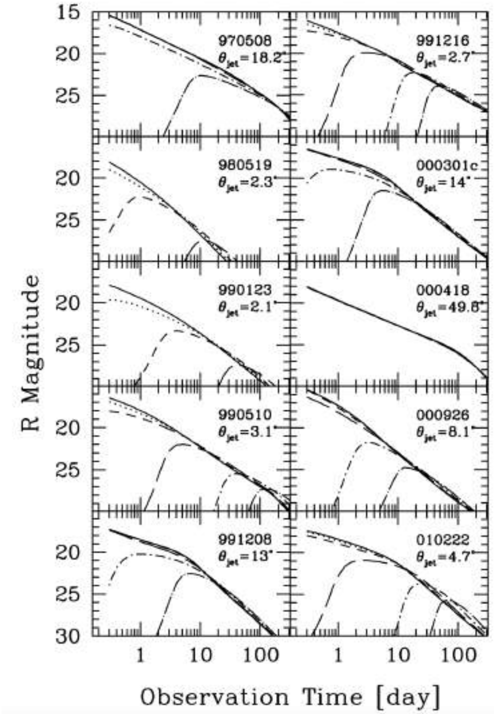
電磁波カウンターパートどげんかせんといかん、という機運の高まり

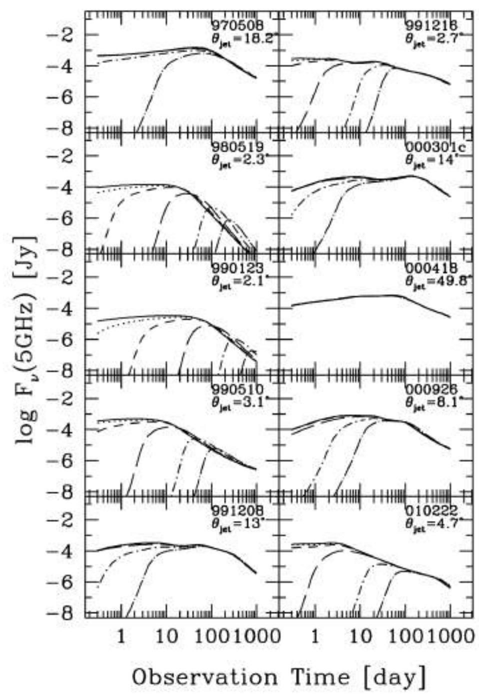
しかし横から見ると(off axis)
GRBは暗いし遅い



Ioka & Nakamura 01



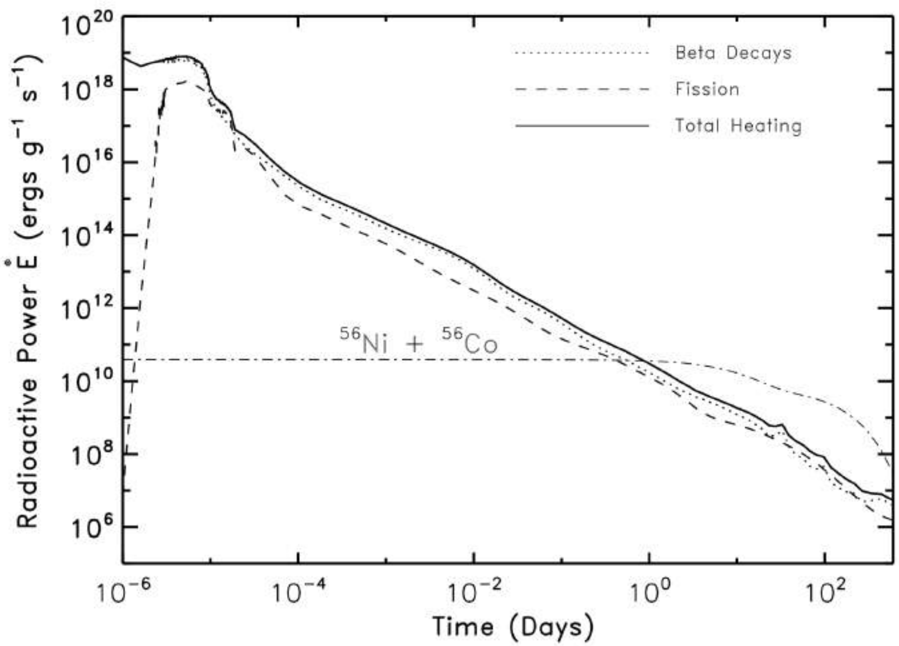


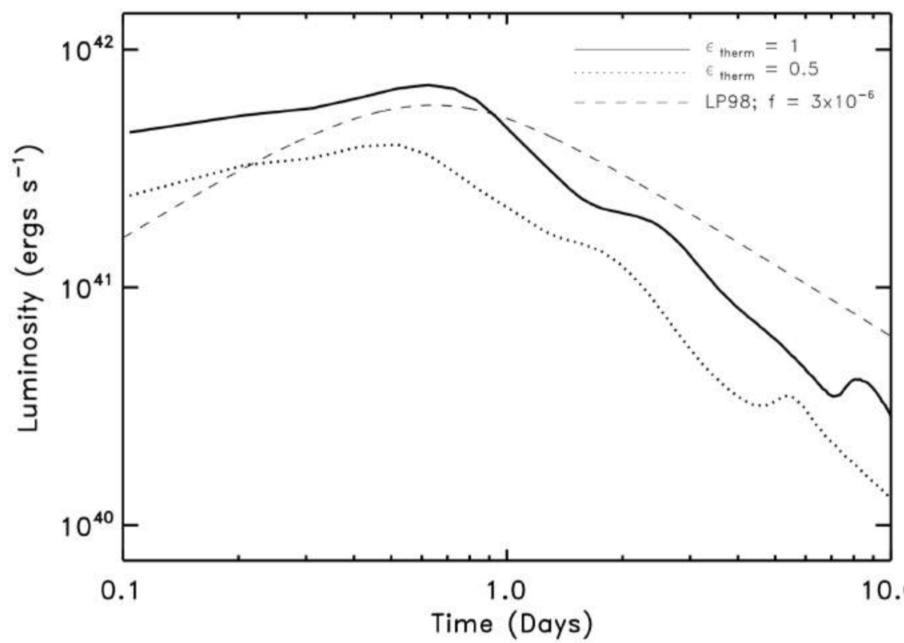


Totani & Panaitecu 02

“Kilo”novae

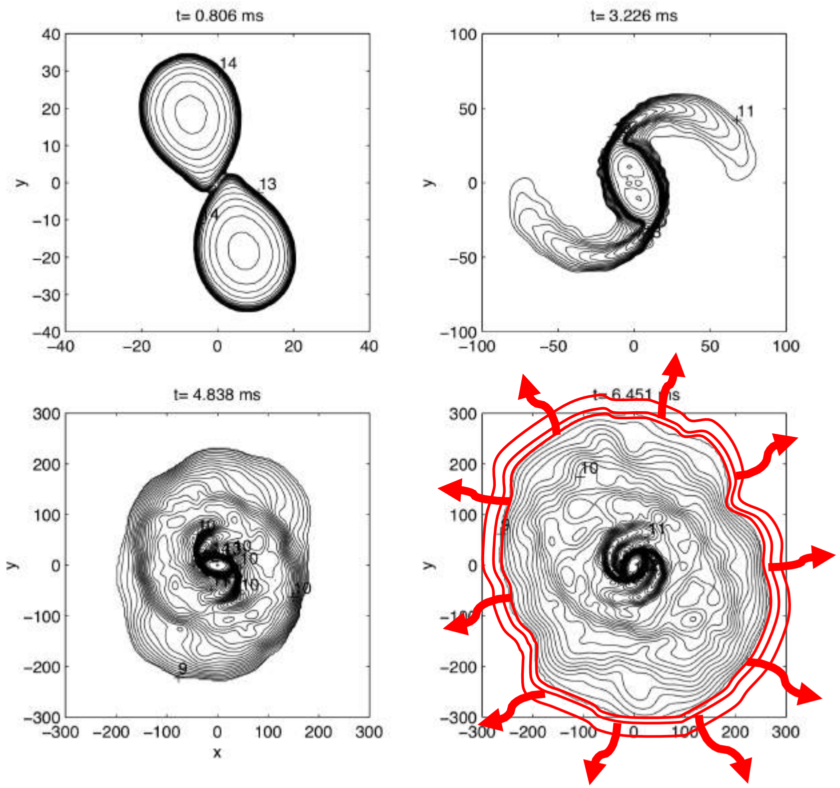
Metzger et al. 10

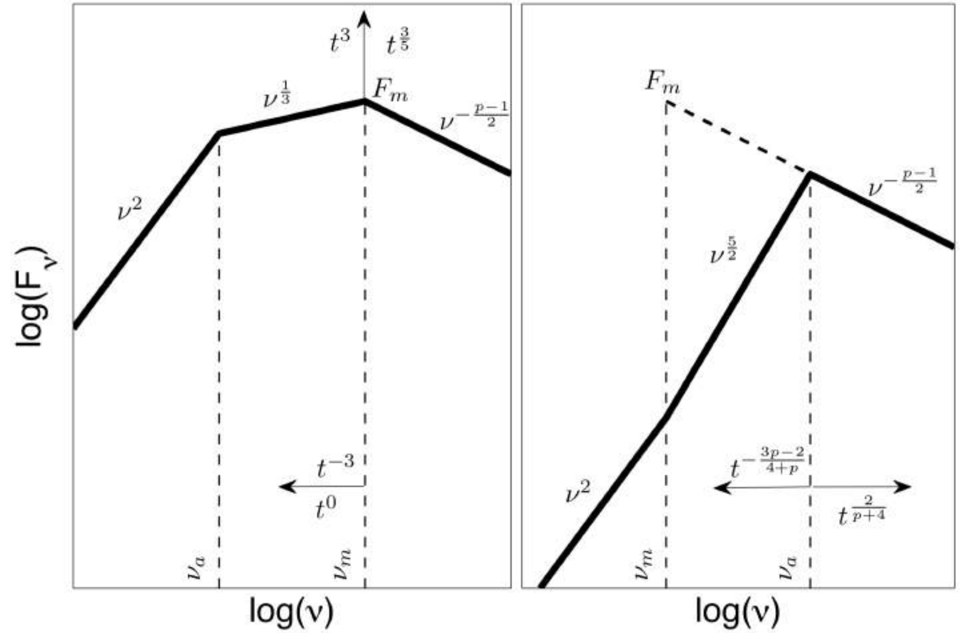




R-process element形成、崩壊に伴う
heating rateをはじめて“真面目に”計算

A Newly Proposed Radio Counterpart



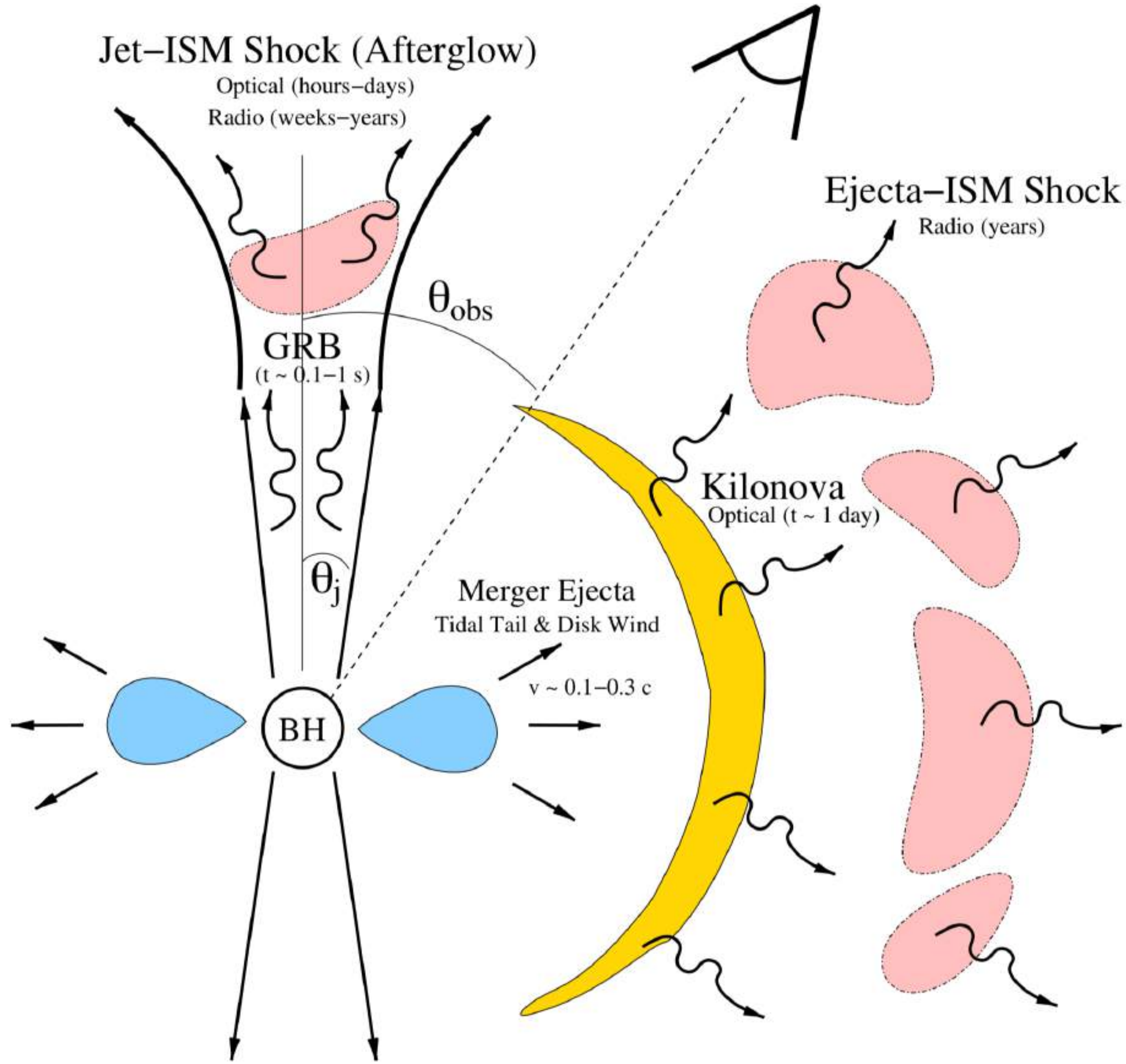


Nakar & Piran 11

Table 1 | Observing radio flares

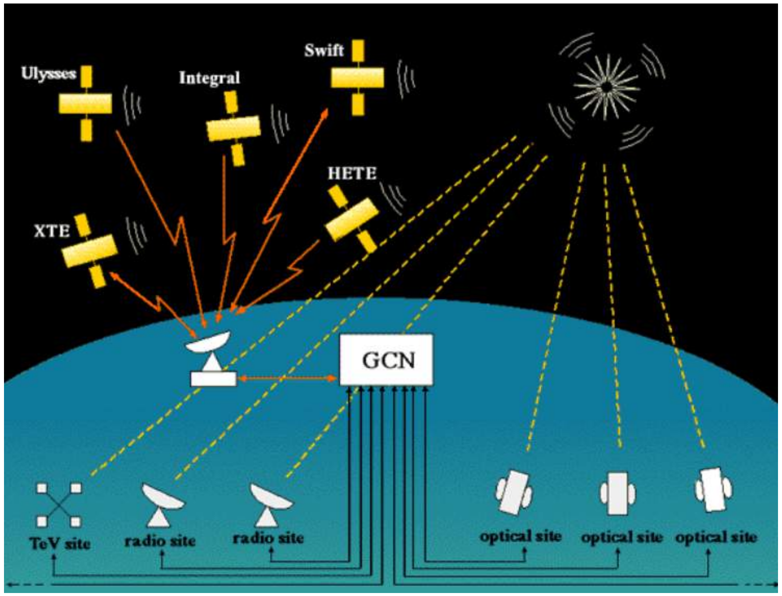
Radio facility	Observing frequency (GHz)	Field of view (deg^2)	One-hour r.m.s.* (μJy)	One-hour detection horizon†			Ten-hour detection horizon‡
				$\beta_i \approx 1$, $E_{49} = 1$, $n_0 = 1$	$\beta_i \approx 1$, $E_{49} = 10$, $n_0 = 1$	$\beta_i = 0.2$, $E_{49} = 10$, $n_0 = 1$, $p = 2.5$	$\beta_i \approx 1$, $E_{49} = 1$, $n_0 = 10^{-3}$, $p = 2$
EVLA	1.4	0.25	7	1 Gpc	3.3 Gpc	370 Mpc	140 Mpc
ASKAP	1.4	30	30	500 Mpc	1.6 Gpc	180 Mpc	70 Mpc
MeerKAT	1.4	1.5	35	500 Mpc	1.6 Gpc	165 Mpc	65 Mpc
Apertif	1.4	8	50	400 Mpc	1.25 Gpc	140 Mpc	50 Mpc
LOFAR	0.15	20	1,000	35 Mpc	90 Mpc	70 Mpc	20 Mpc

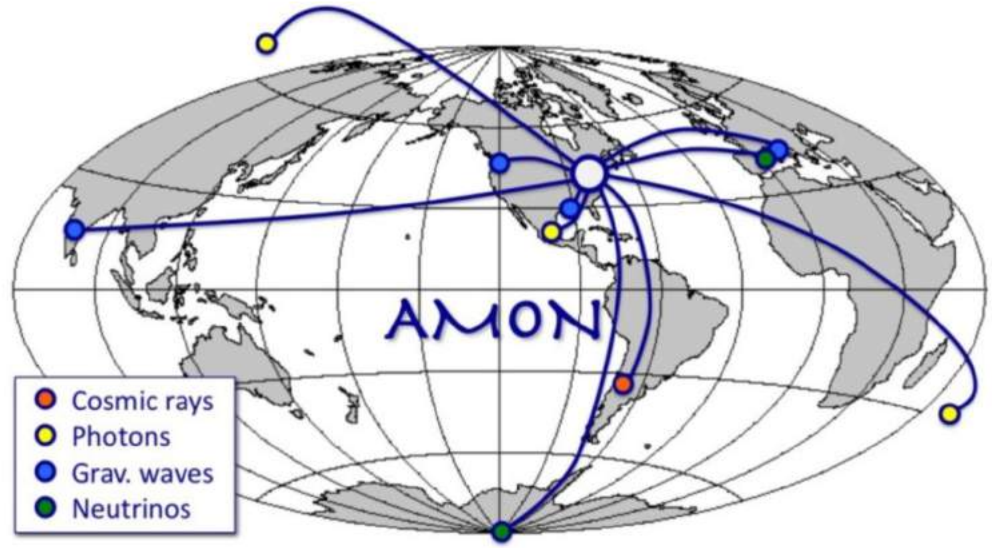
Scenario for the EM counterparts 5 years ago



Metzger & Berger 12

急ピッチで進んだ観測体制の整備

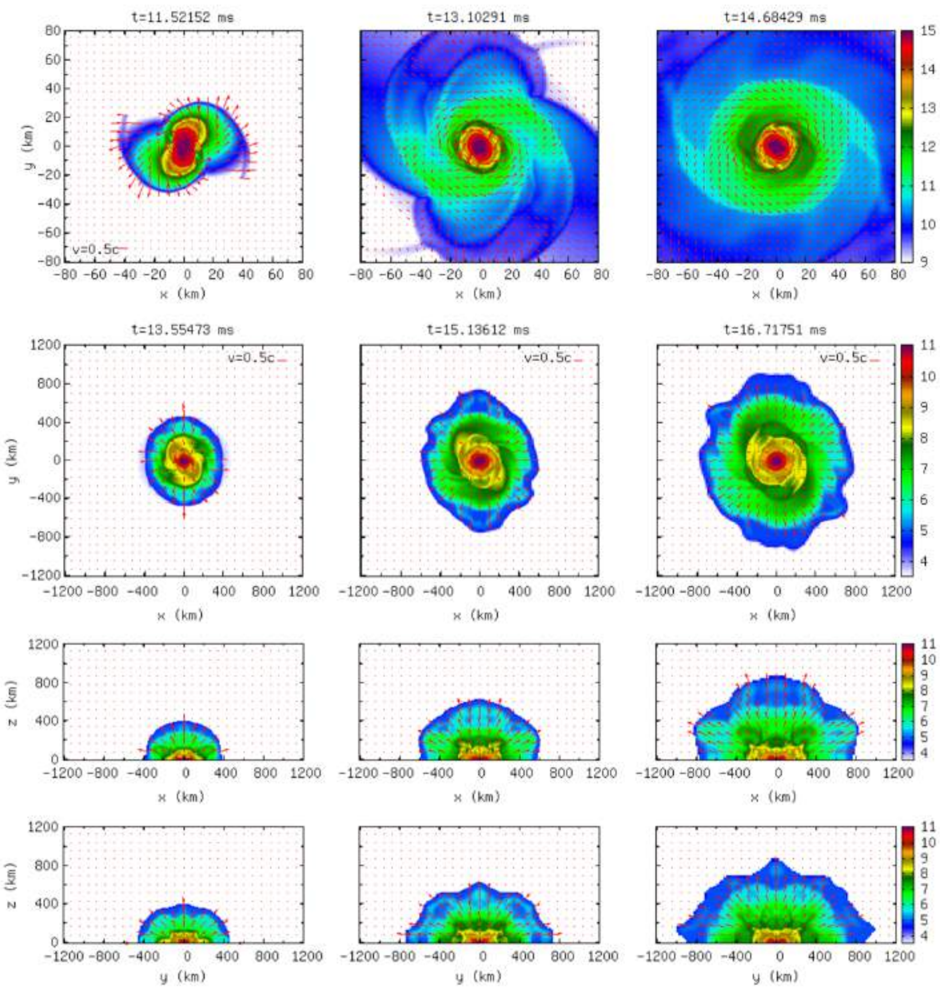




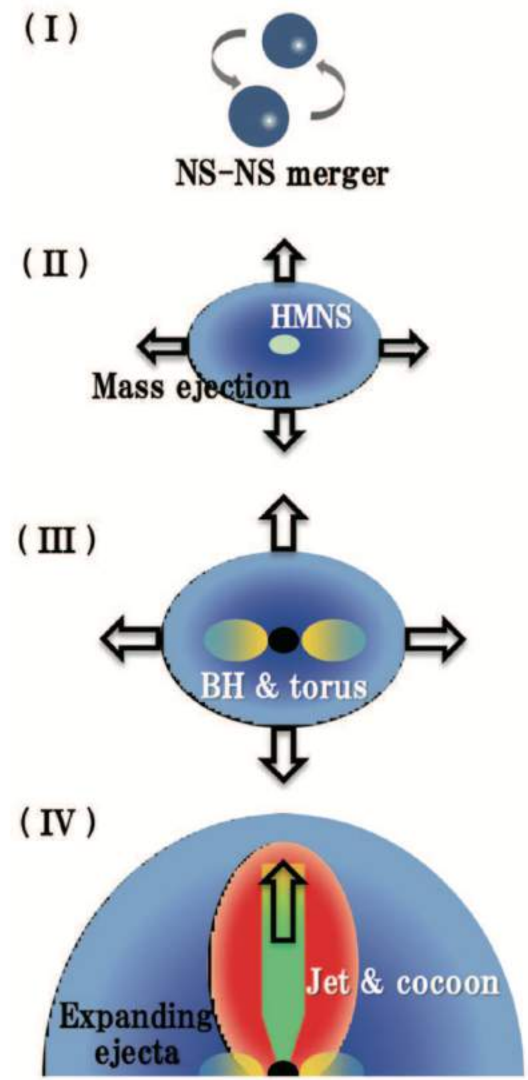
日本の重力波追跡観測網J-GEM（提供：J-GEM）

上にも結構飛ぶんじゃね？

Nagakura et al. 14

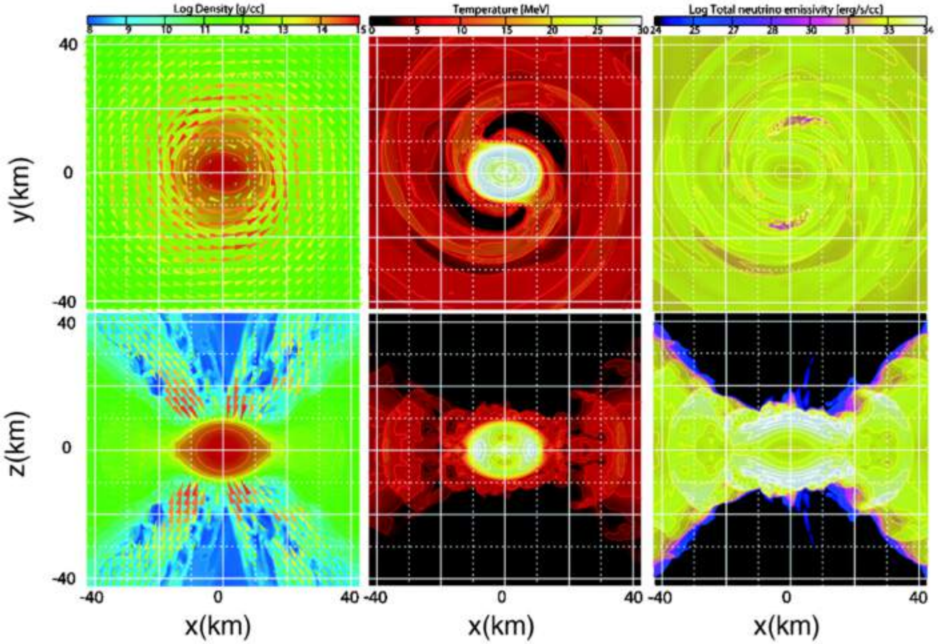


Hotokezaka et al. 13

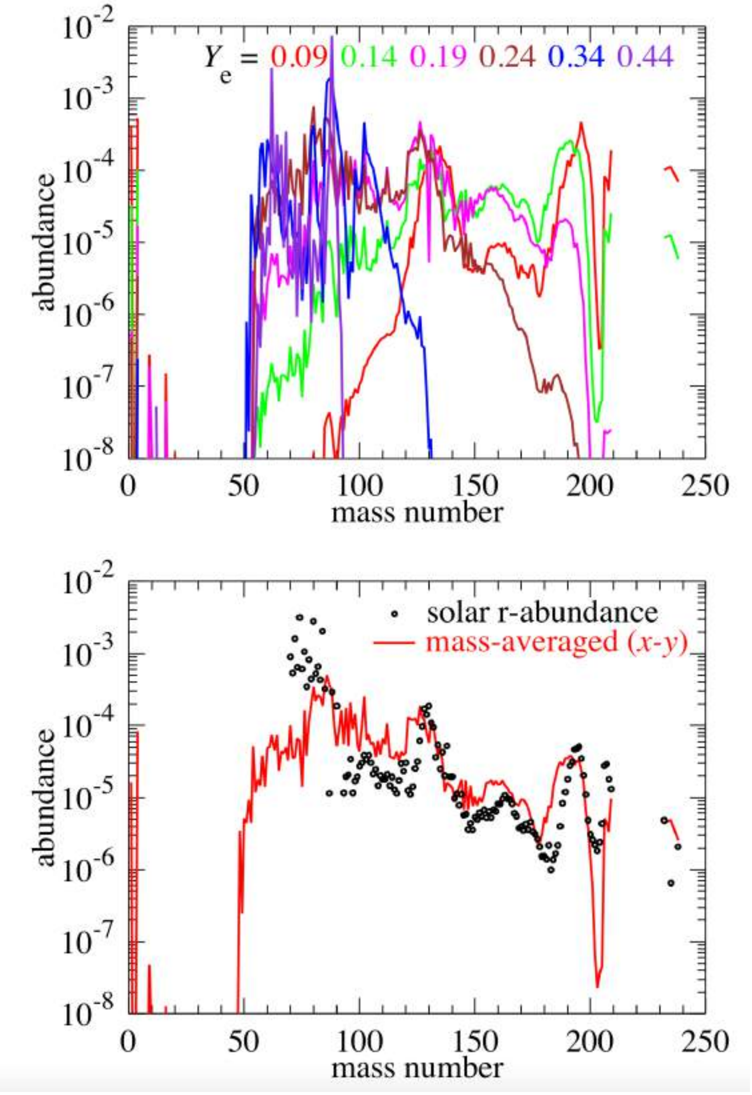


R-process元素、合うんじゃね？

ニュートリノ入りfull GR計算

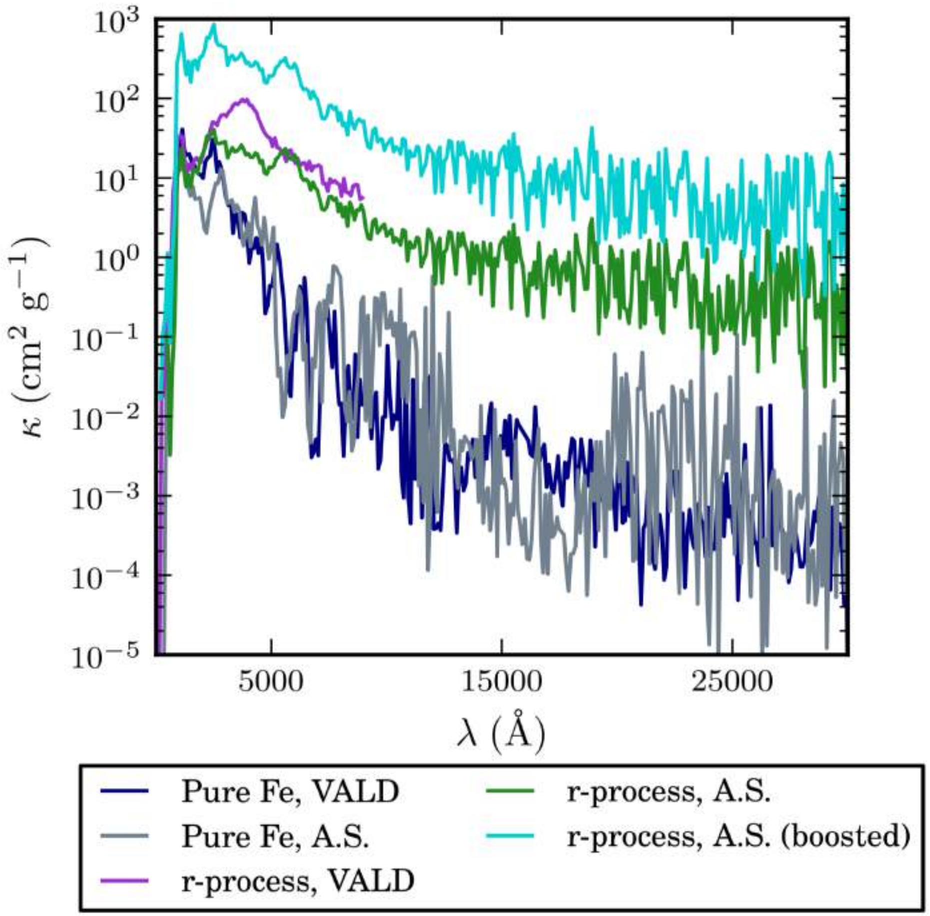


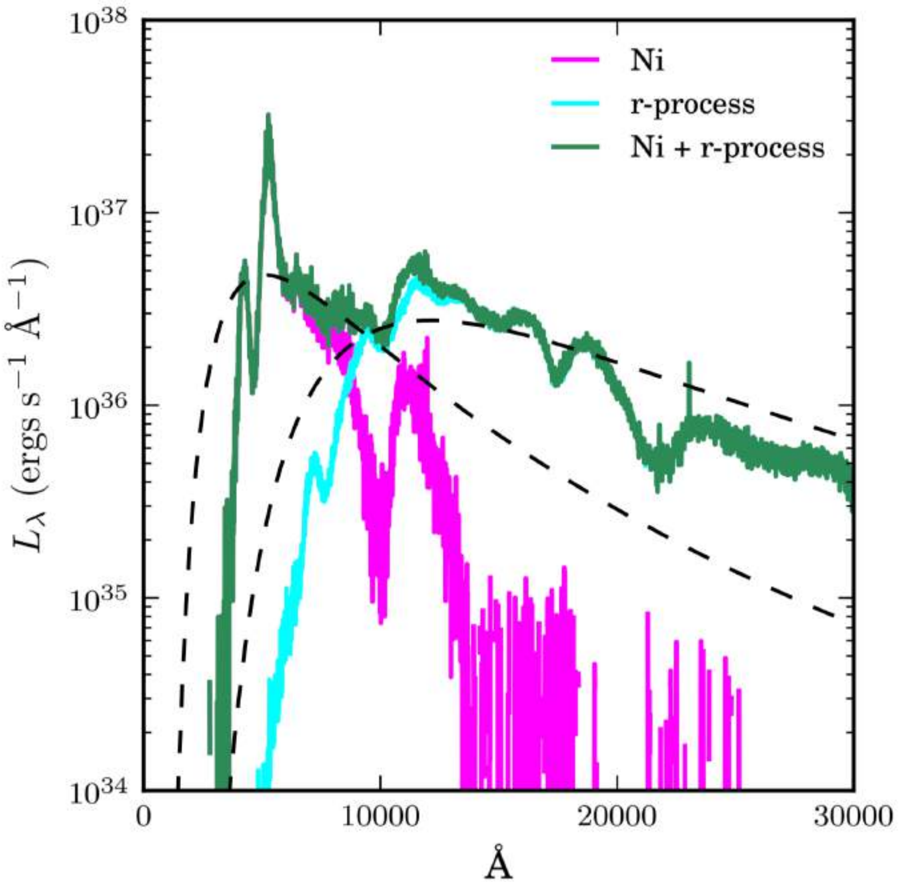
Sekiguchi et al. 11



Wanajyo et al. 14

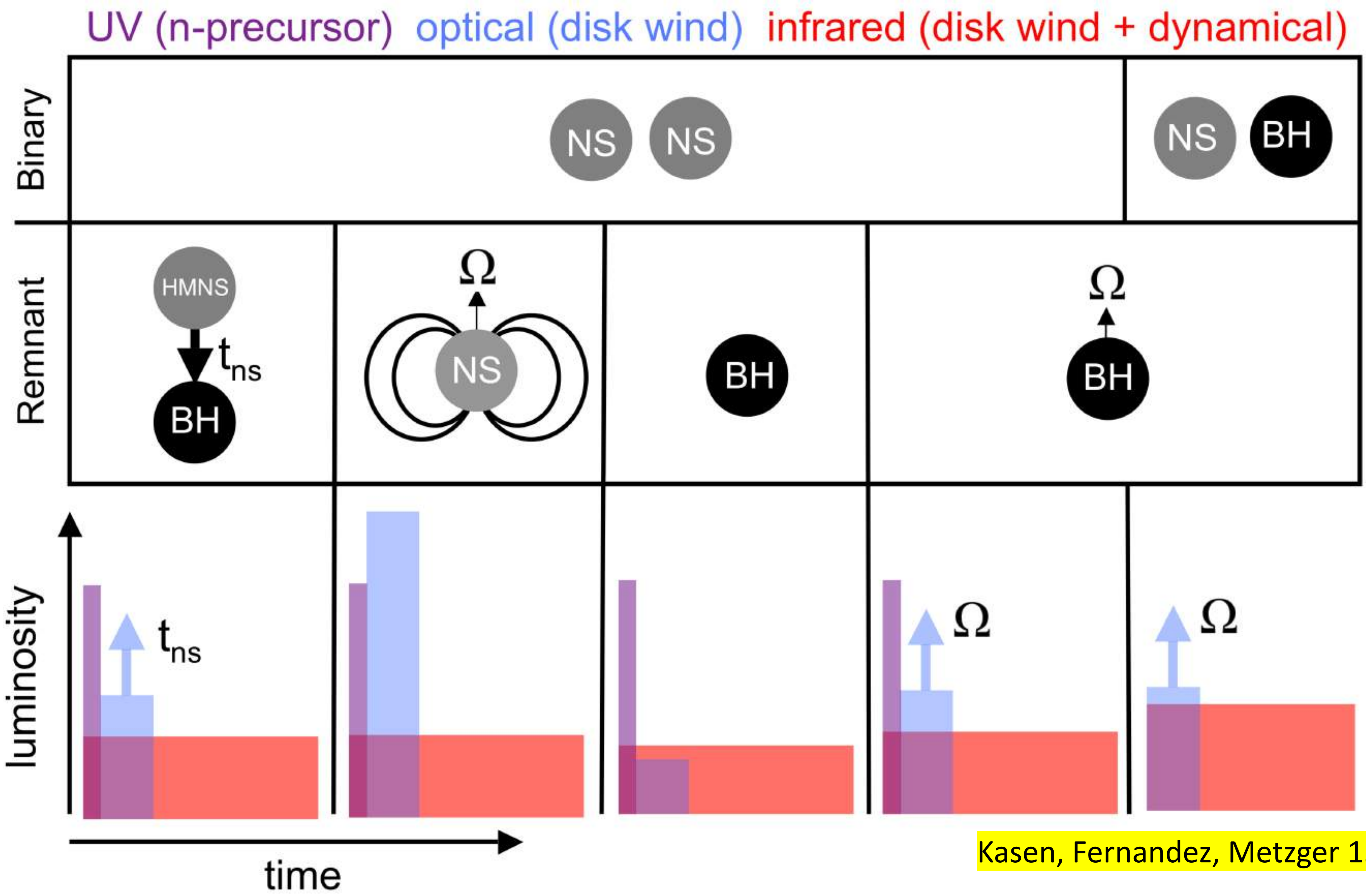
Kilo/macronova、赤いんじゃね？





Tanaka & Hotokezaka 13, Barnes & Kasen 13

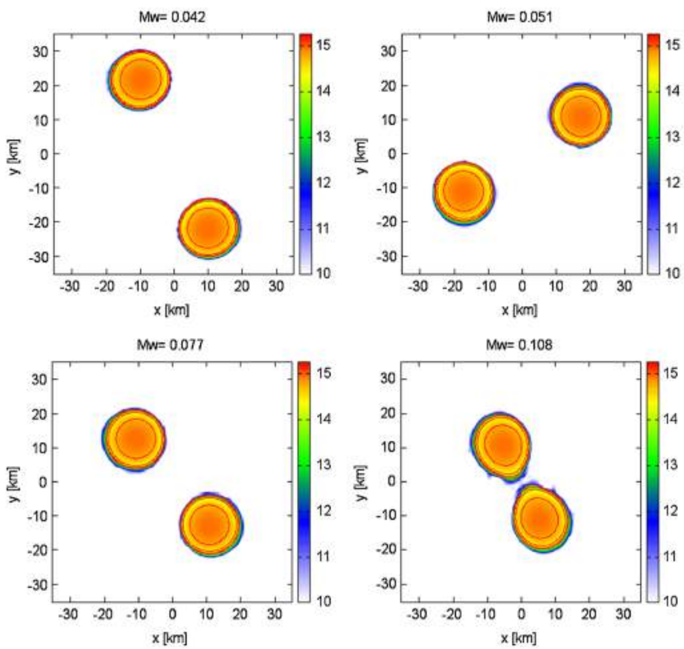
Kilo/macronovaとRemnantの関係

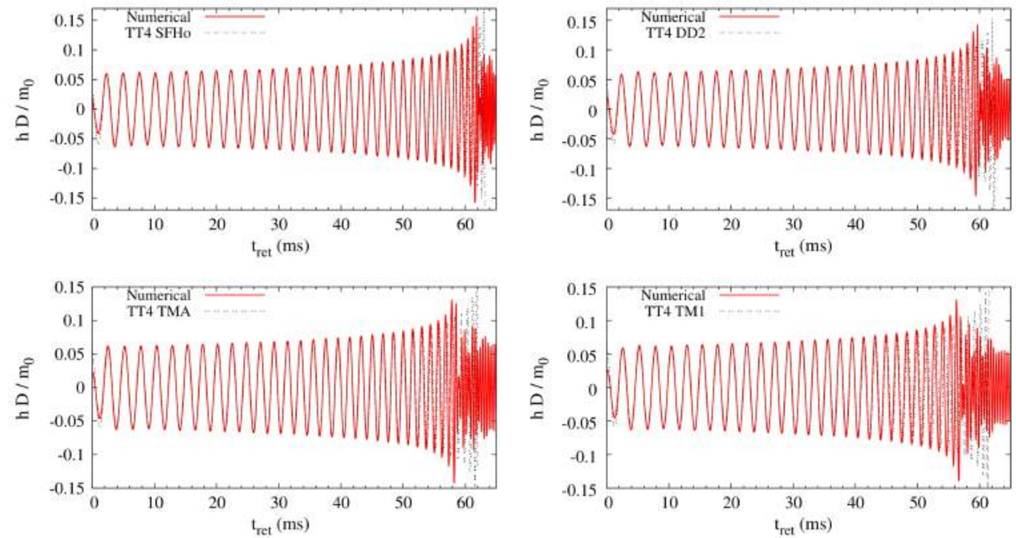


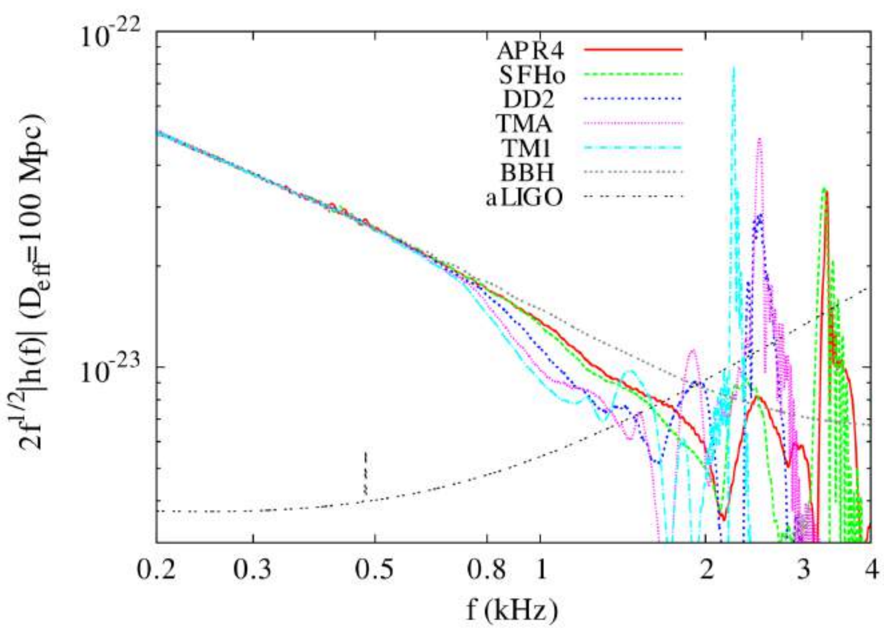
Kasen, Fernandez, Metzger 15

Tidal deformation、測れるんじゃね？

Full GR 計算







Biotti et al. 10
Hokezaka et al. 13, 15

夜明け

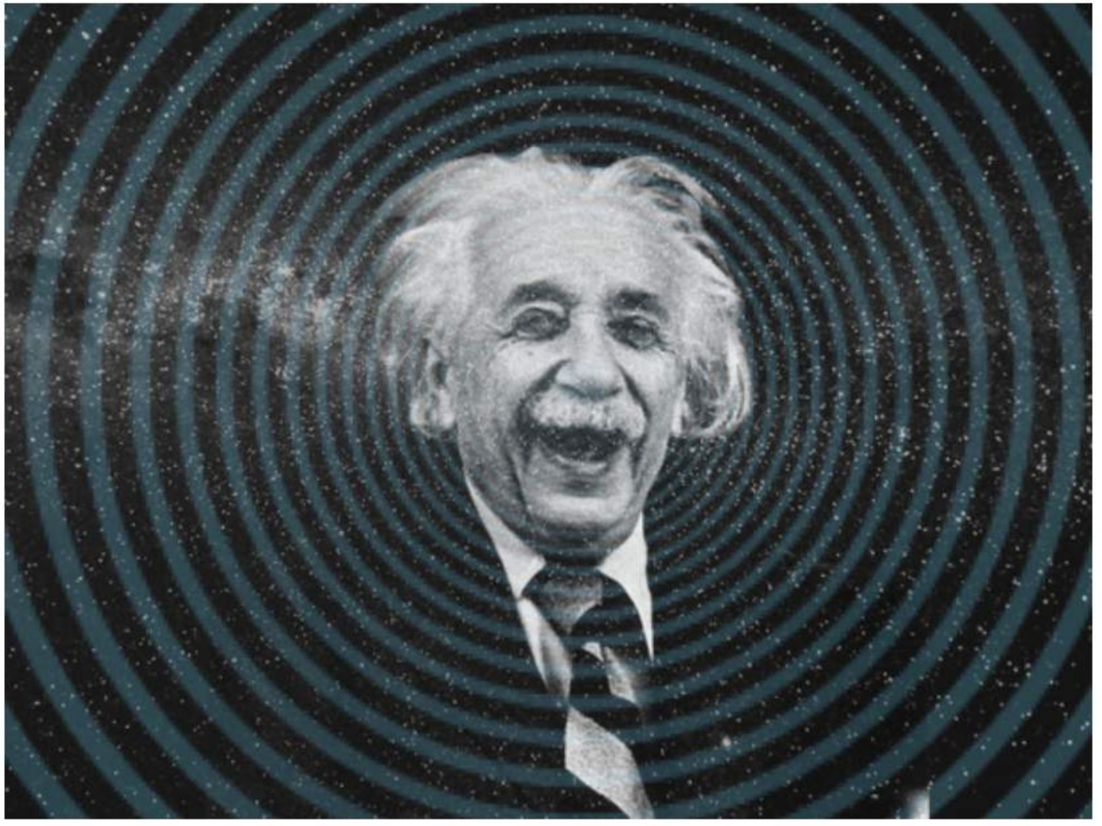
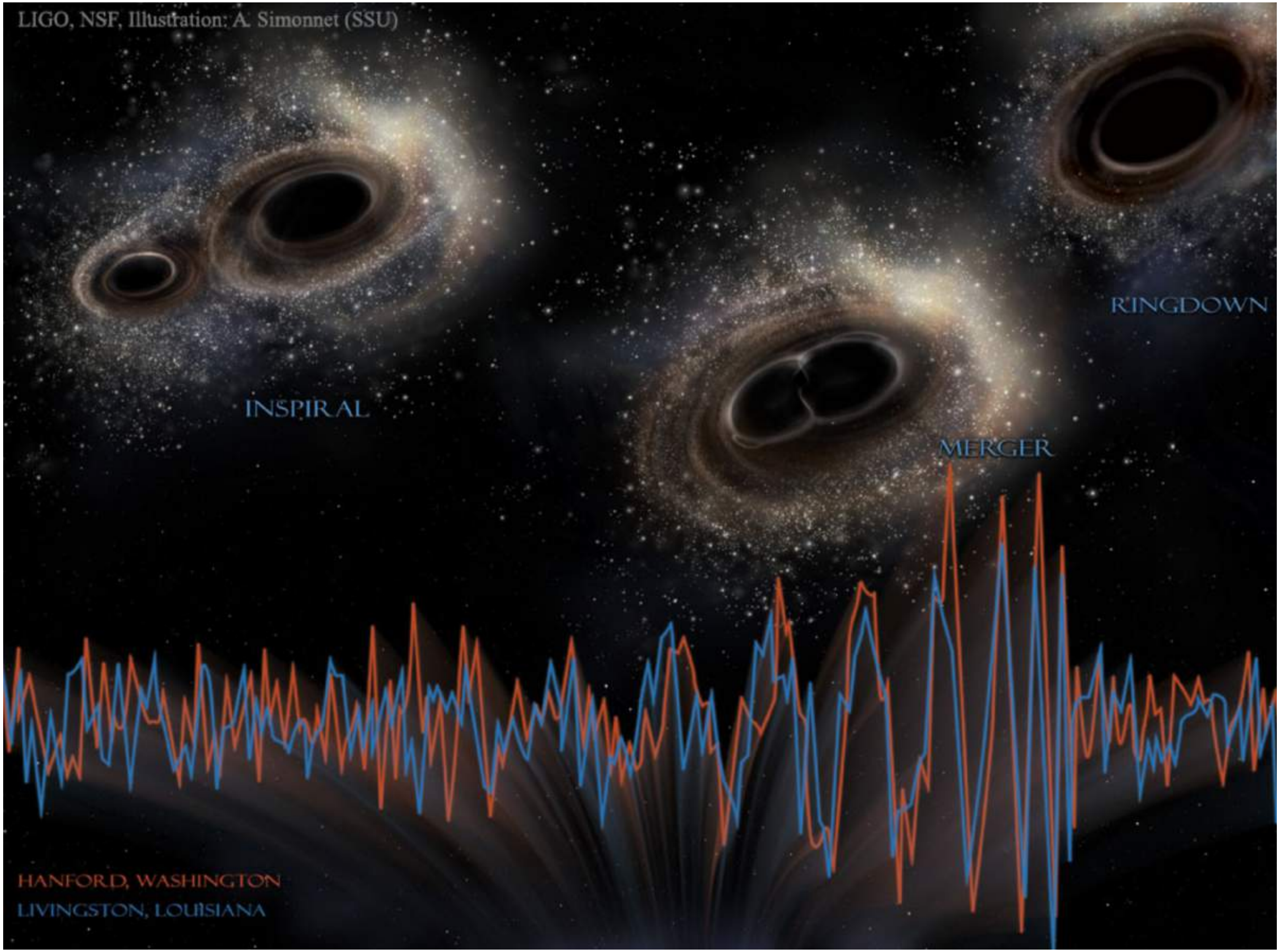
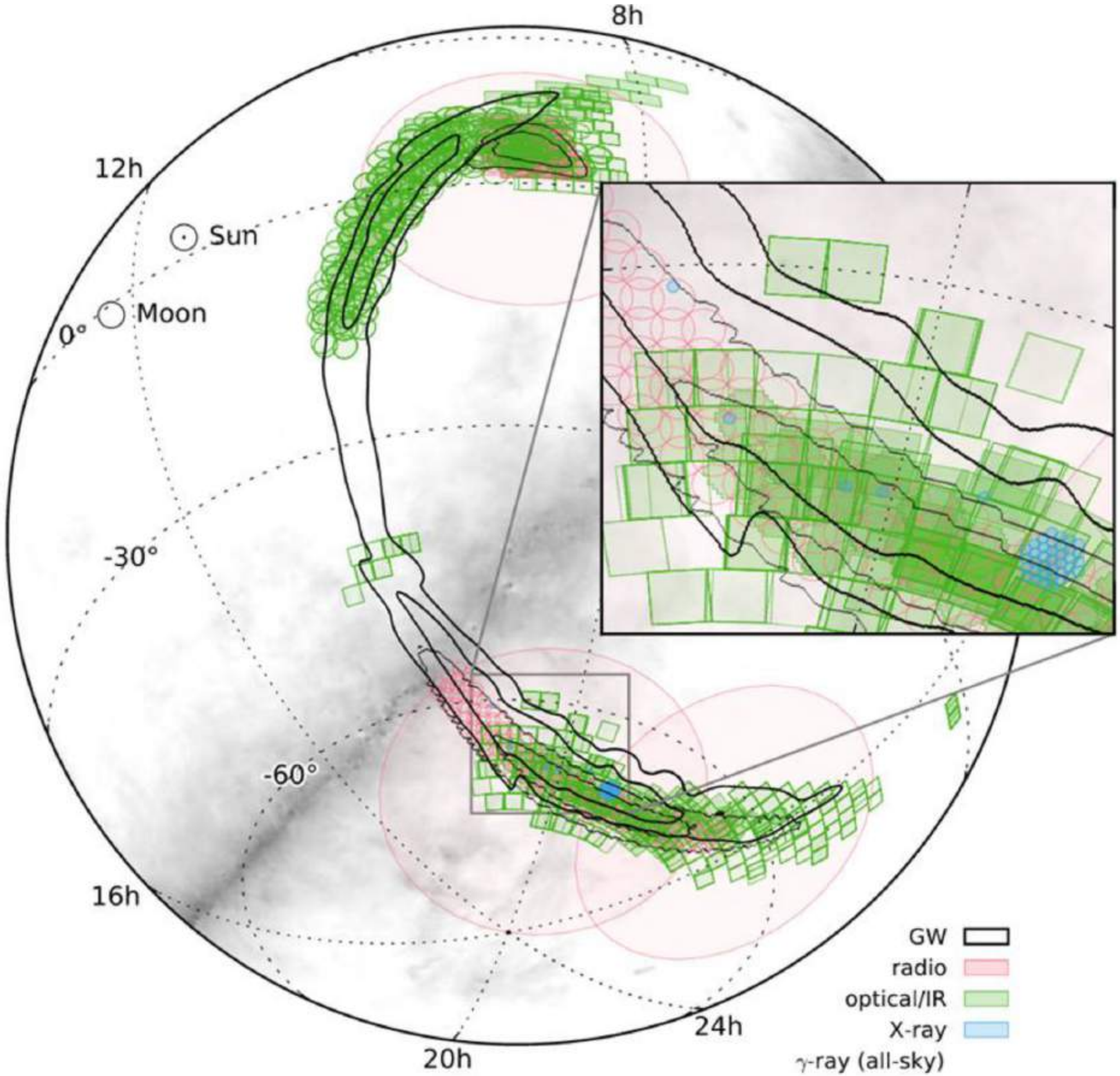


Photo: Ruth Orkin | Hulton Archive | Getty Images

チュンチュンチュン

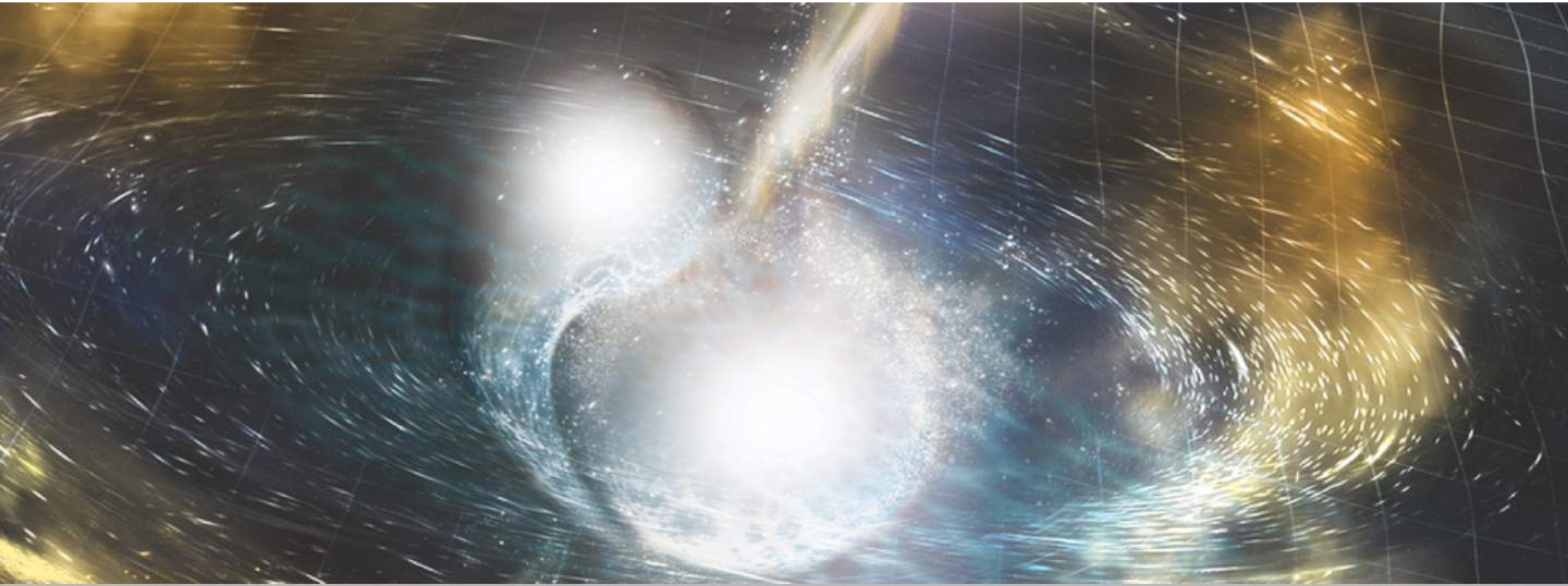

LIGO, NSF, Illustration: A. Simonnet (SSU)
INSPIRAL
MERGER
RINGDOWN
HANFORD, WASHINGTON
LIVINGSTON, LOUISIANA

チュンチュンチュン

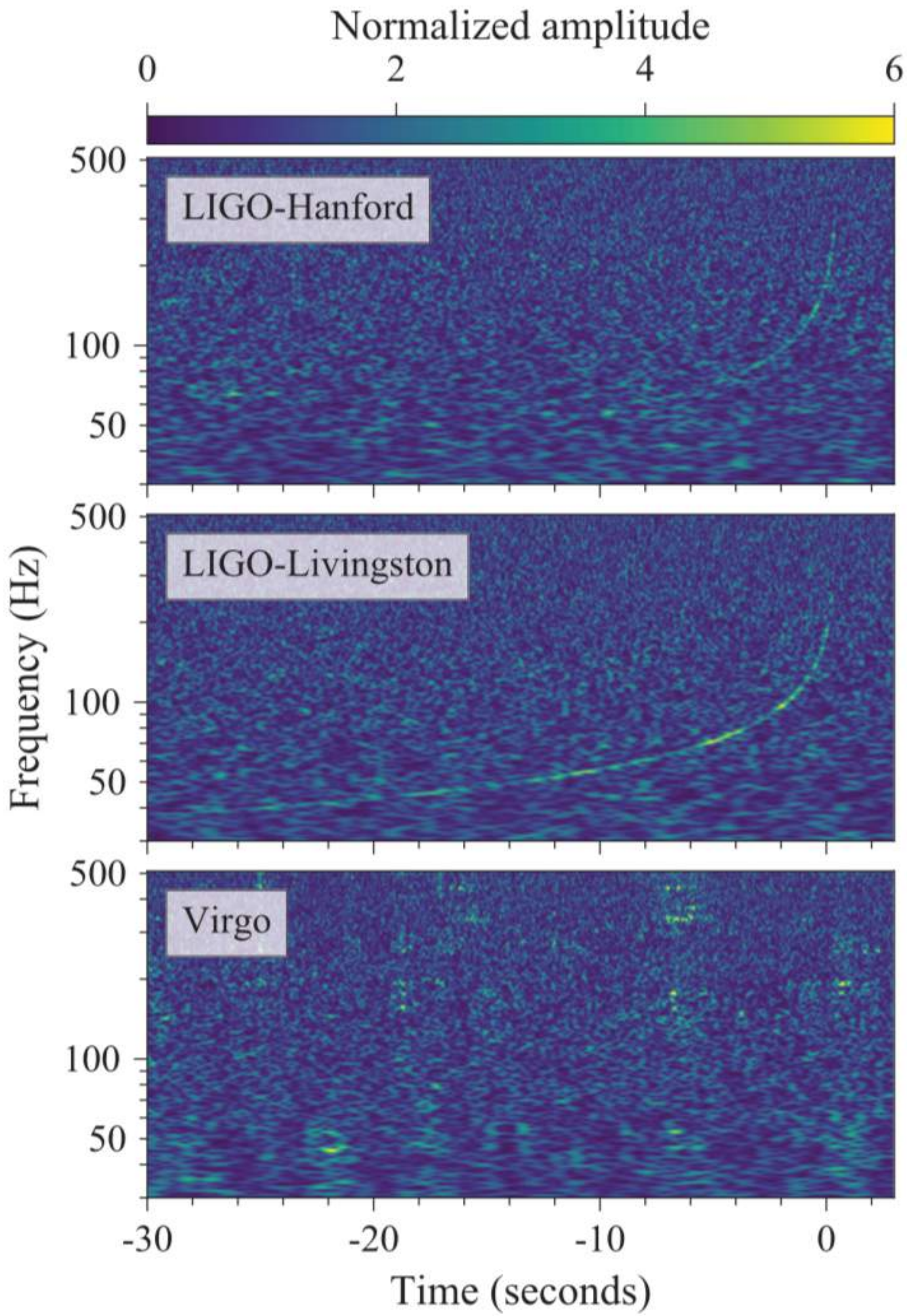


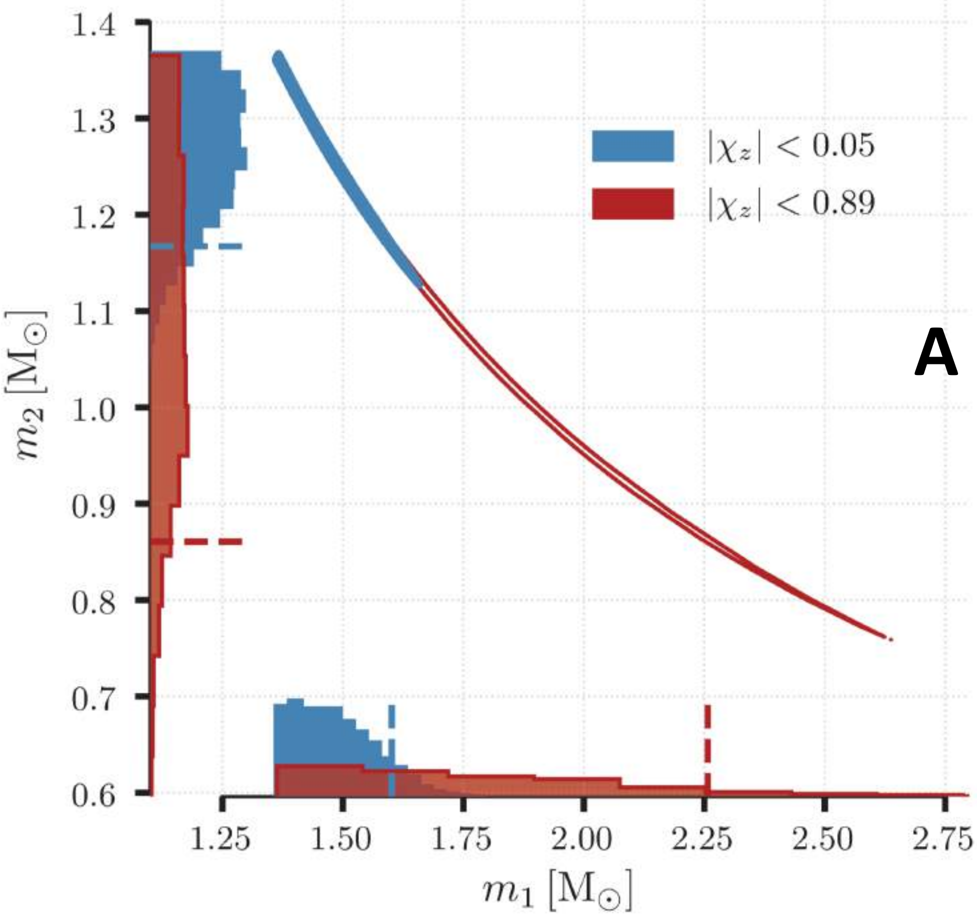
8h
12h
Sun
Moon
0°
-30°
-60°
16h
20h
24h
GW
radio
optical/IR
X-ray
γ-ray (all-sky)

コケコッコー！！！



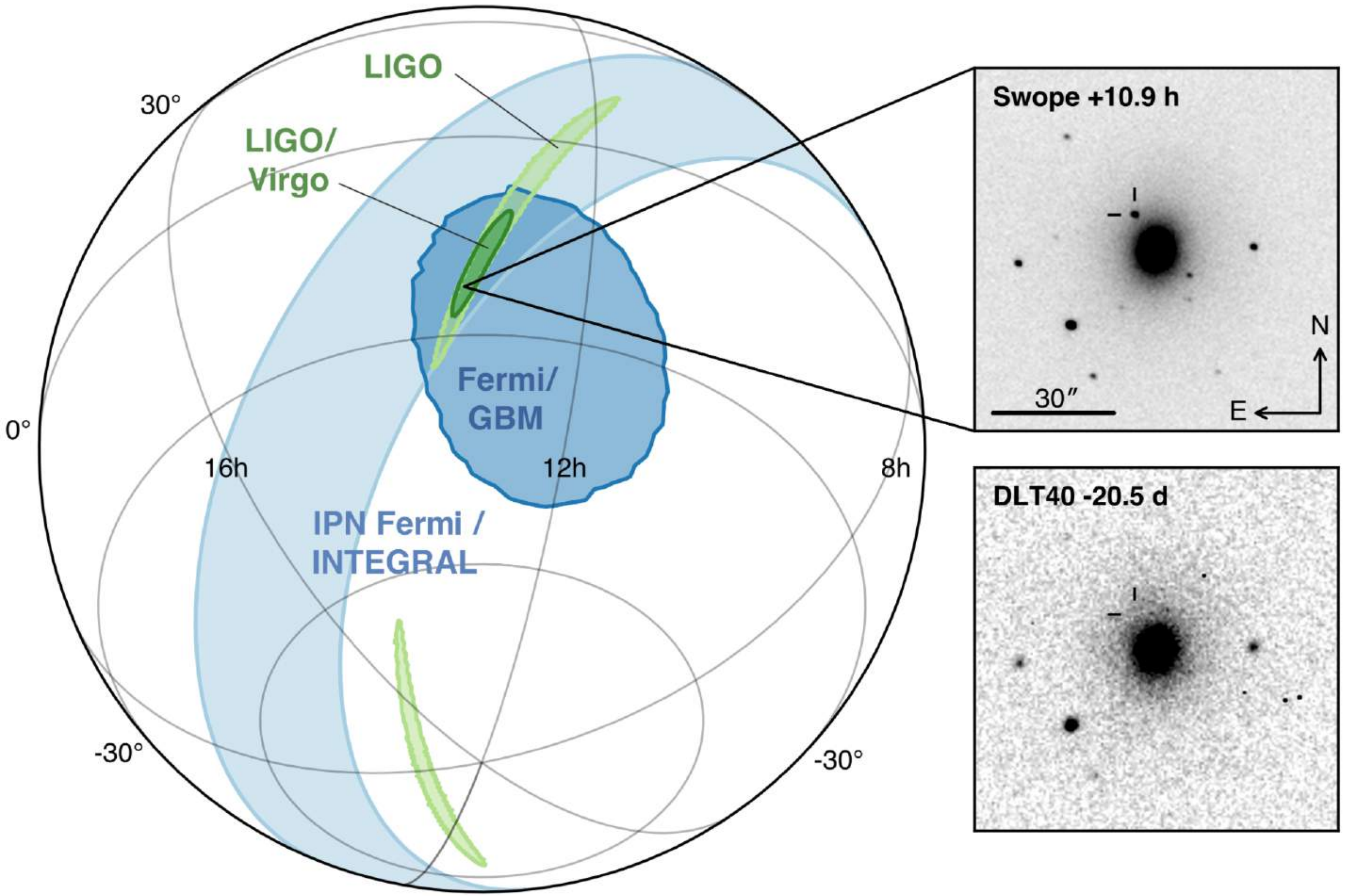
Cataclysmic Collision Artist's illustration of two merging neutron stars. The rippling space-time grid represents gravitational waves that travel out from the collision, while the narrow beams show the bursts of gamma rays that are shot out just seconds after the gravitational waves. Swirling clouds of material ejected from the merging stars are also depicted. The clouds glow with visible and other wavelengths of light. Image credit: NSF/LIGO/Sonoma State University/A. Simonnet


Normalized amplitude
0
2
4
6
LIGO-Hanford
LIGO-Livingston
Virgo
Frequency (Hz)
500
100
50
Time (seconds)
-30
-20
-10
0

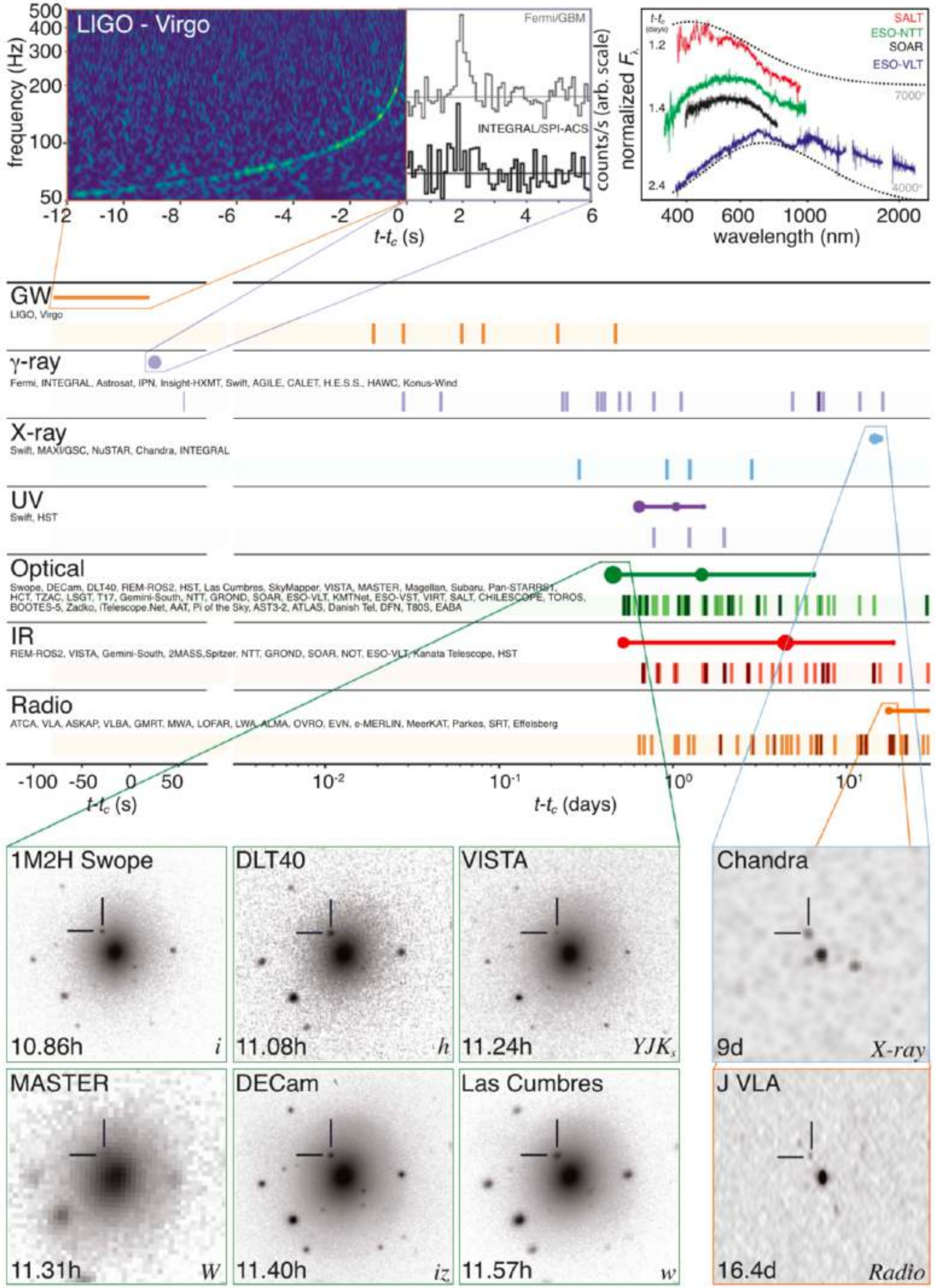


A NSNS merger at ~40 Mpc!!

	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	$\leq 28°$	$\leq 28°$

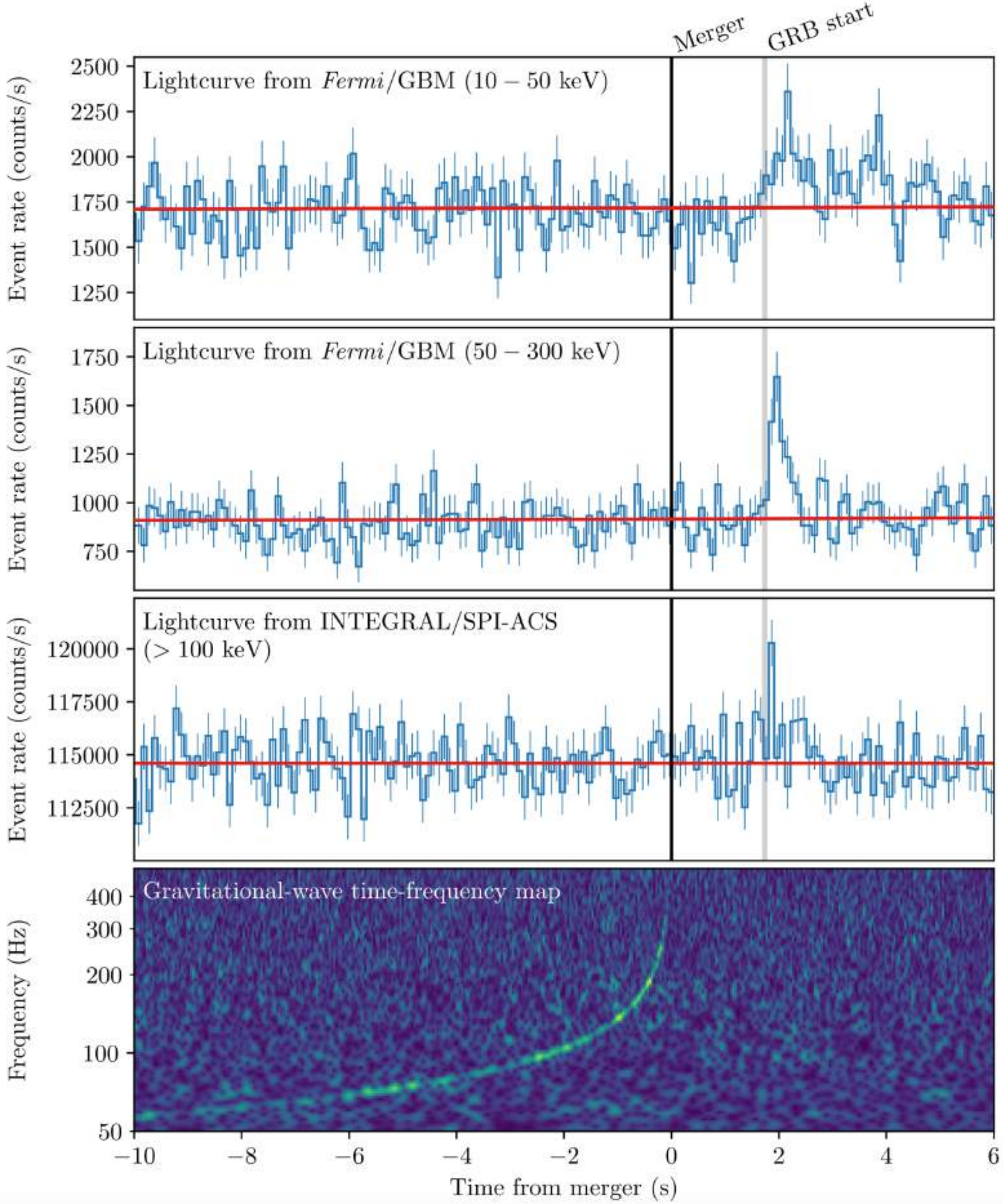


LIGO
LIGO/
Virgo
30°
0°
-30°
-30°
16h
12h
8h
Fermi/
GBM
IPN Fermi /
INTEGRAL
Swope +10.9 h
N
E
30″
DLT40 -20.5 d

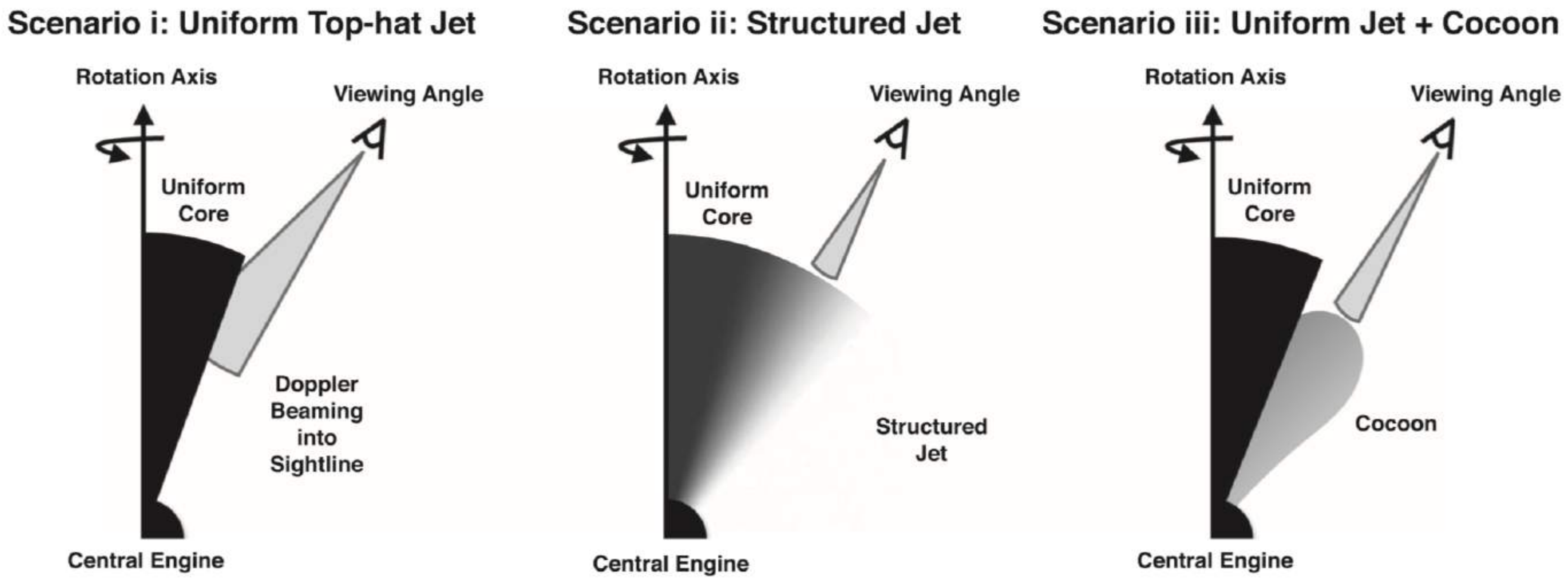


LIGO - Virgo
frequency (Hz)
500
400
300
200
100
50
-12
-10
-8
-6
-4
-2
0
2
4
6
t-t_c (s)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
normalized F_λ
t-t_c (days)
1.2
1.4
2.4
SALT
ESO-NTT
SOAR
ESO-VLT
7000°
4000°
400
600
1000
2000
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
-100
-50
0
50
t-t_c (s)
10^-2
10^-1
10^0
10^1
t-t_c (days)
1M2H Swope
10.86h
i
DLT40
11.08h
h
VISTA
11.24h
YJK_s
Chandra
9d
X-ray
MASTER
11.31h
W
DECam
11.40h
iz
Las Cumbres
11.57h
w
J VLA
16.4d
Radio

GRB 170817A



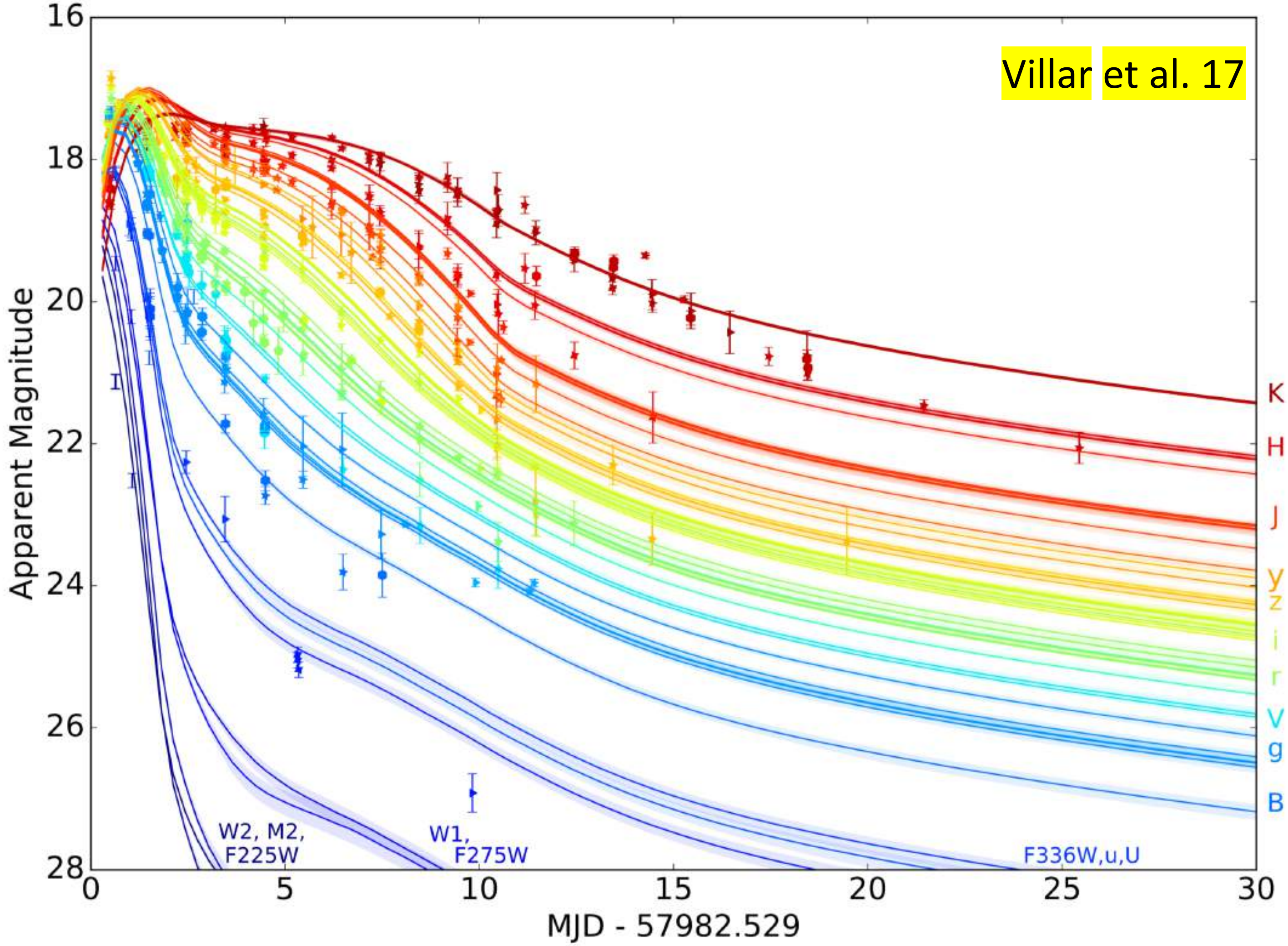
Merger
GRB start
Lightcurve from Fermi/GBM (10 – 50 keV)
Lightcurve from Fermi/GBM (50 – 300 keV)
Lightcurve from INTEGRAL/SPI-ACS
(> 100 keV)
Gravitational-wave time-frequency map
Event rate (counts/s)
Frequency (Hz)
Time from merger (s)
2500
2250
2000
1750
1500
1250
1000
750
120000
117500
115000
112500
400
300
200
100
50
−10
−8
−6
−4
−2
0
2
4
6

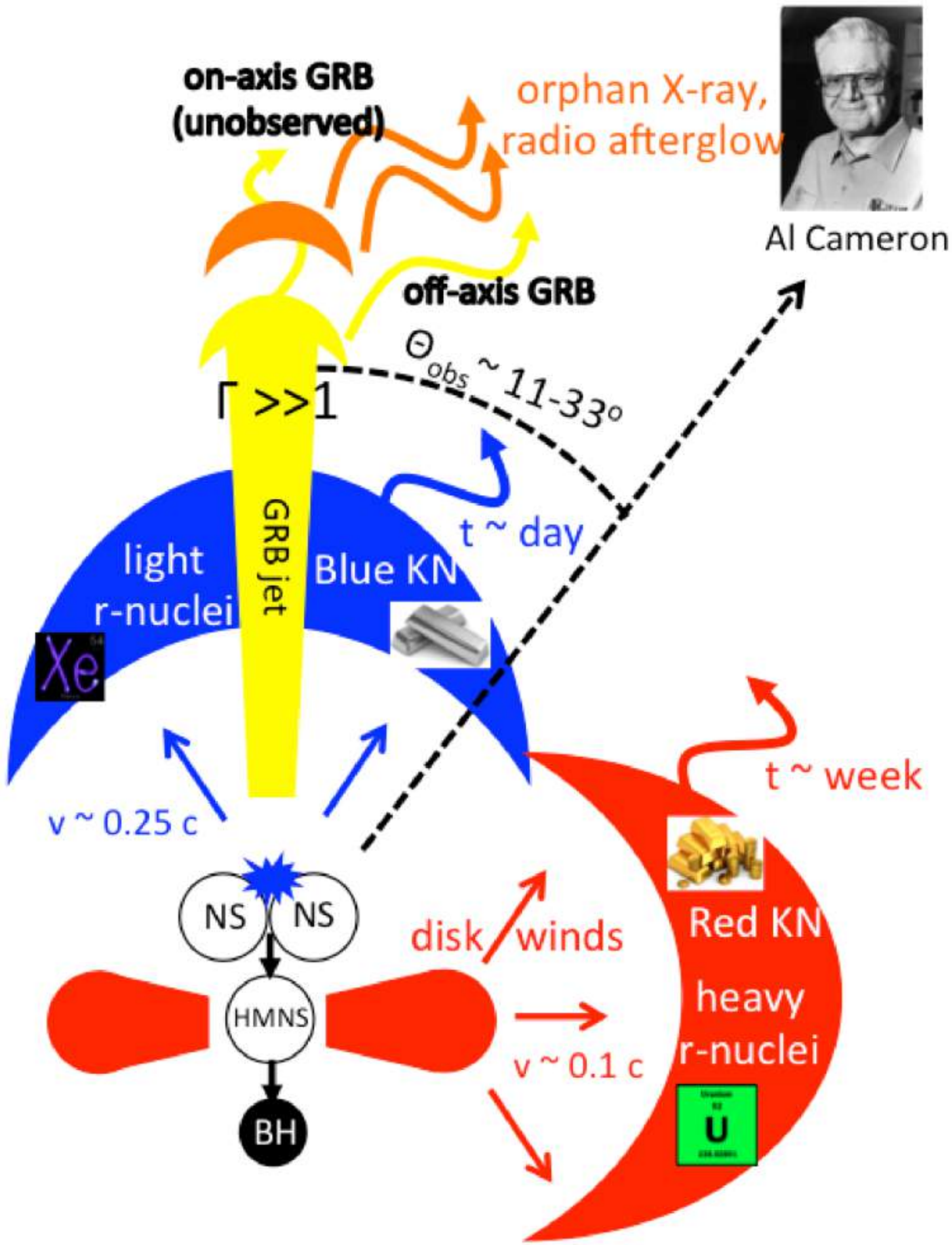


LIGO Scientific Collaboration and Virgo Collaboration, Fermi Gamma-ray Burst Monitor, and INTEGRAL

The kilo/macro nova

Arcavi et al. 2017; Chornock et al. 2017; Coulter et al. 2017; Cowperthwaite et al. 2017; D´ıazetal. 2017;Drout et al. 2017; Evansetal. 2017; Kasliwal et al. 2017; Kilpatrick et al. 2017; McCully et al. 2017; Nicholl et al. 2017; Pian et al. 2017; Shappee et al. 2017; Smartt et al. 2017; Soares-Santos et al. 2017; Tanvir et al. 2017; Tominaga et al. 2018; Utsumi et al. 2017; Valenti et al. 2017 …

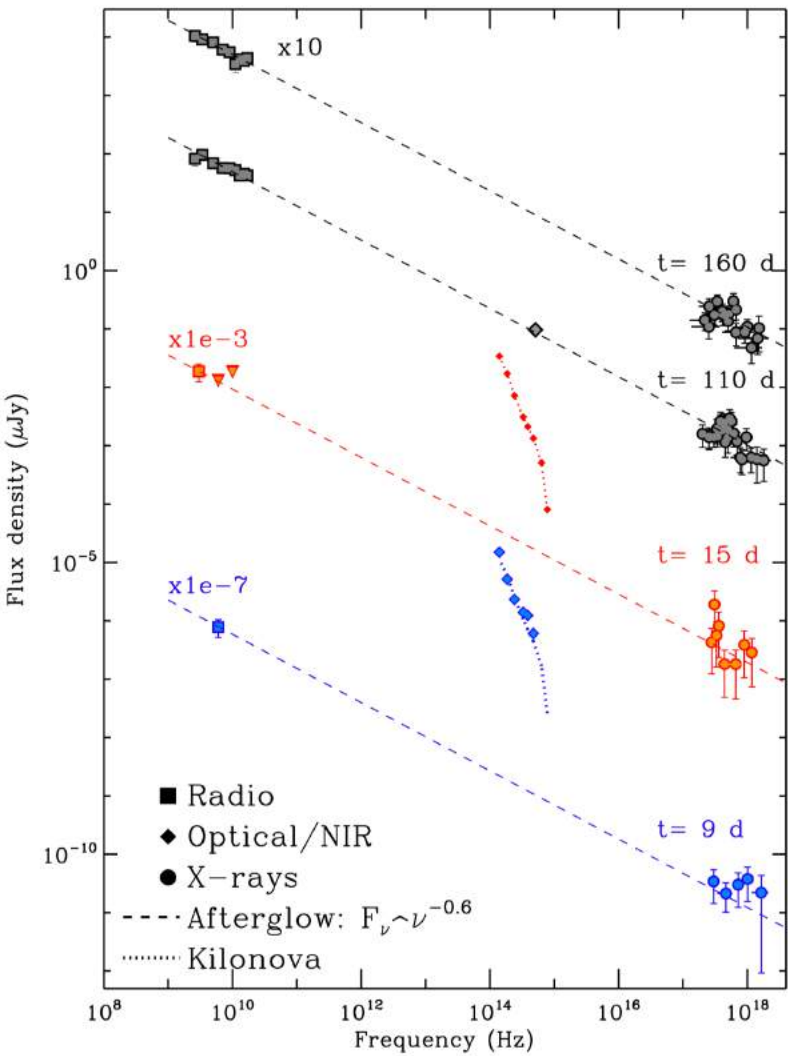


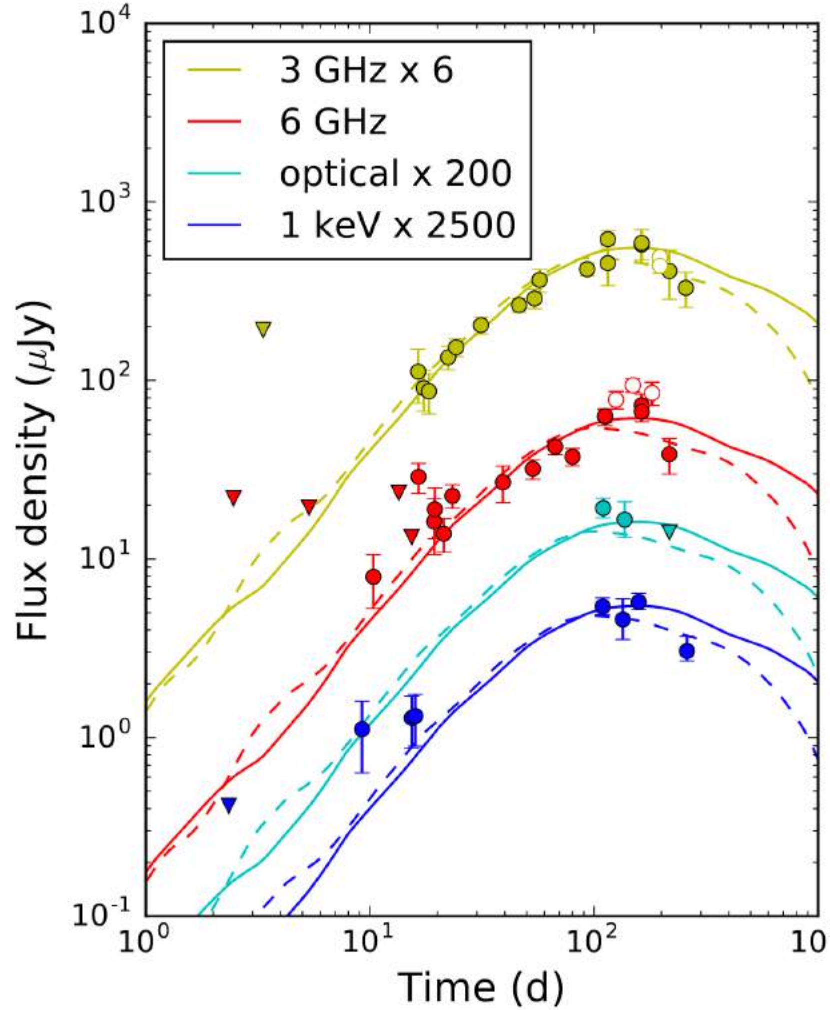

on-axis GRB (unobserved)
orphan X-ray, radio afterglow
Al Cameron
off-axis GRB
Θobs ~ 11-33°
Γ >>1
GRB jet
light r-nuclei
Blue KN
t ~ day
Xe
v ~ 0.25 c
t ~ week
NS
NS
HMNS
BH
disk winds
Red KN
heavy r-nuclei
v ~ 0.1 c
U

Metzger 17

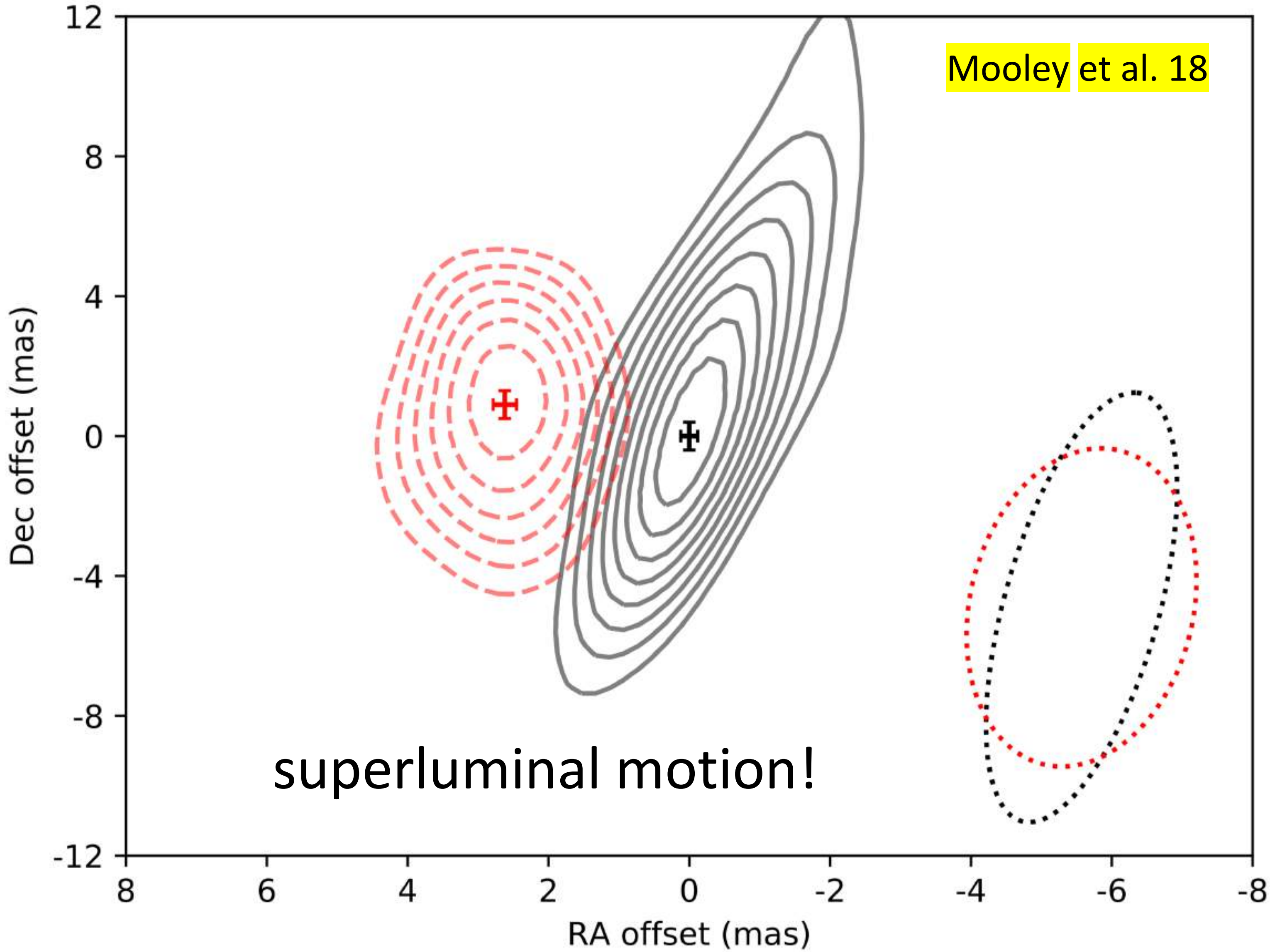
EM afterglow of GW170817

Haggard et al. 2017; Margutti et al. 2017; Troja et al. 2017; Alexander et al. 2017; Hallinan et al. 2017; Kim et al. 2017

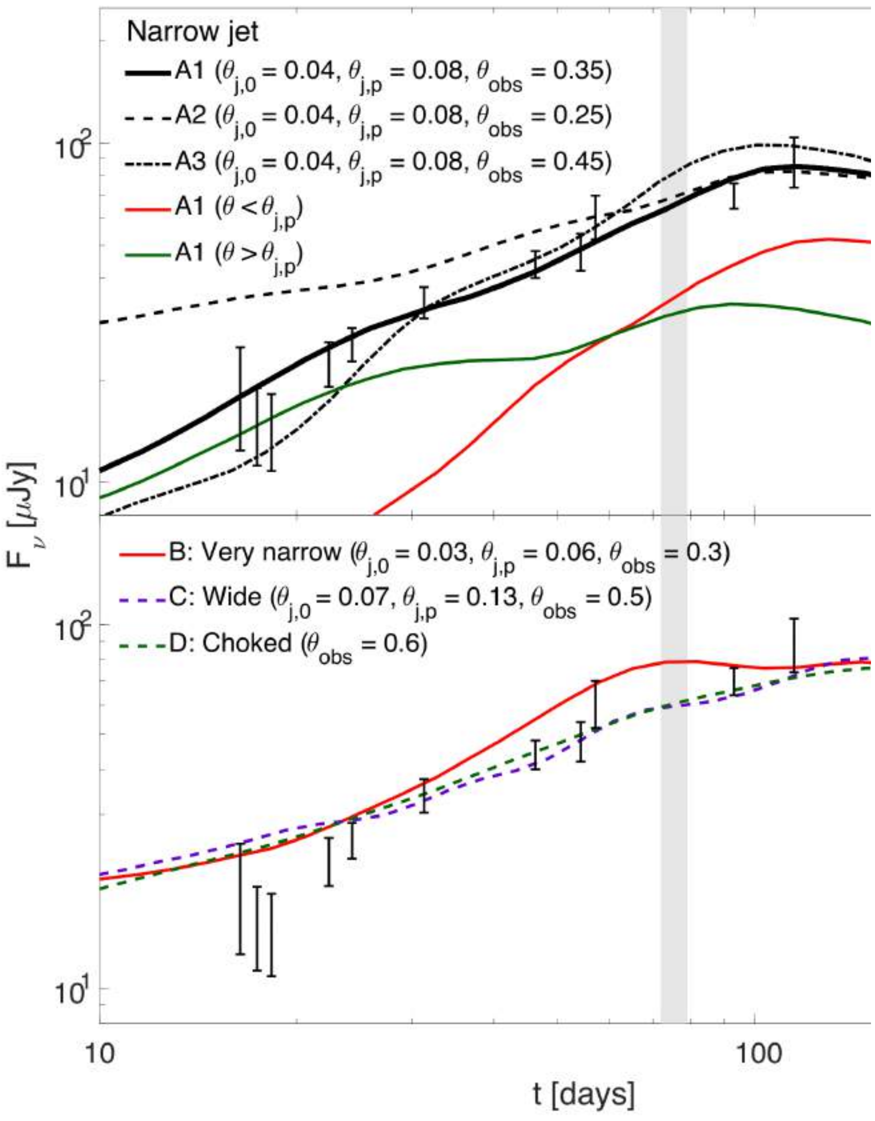


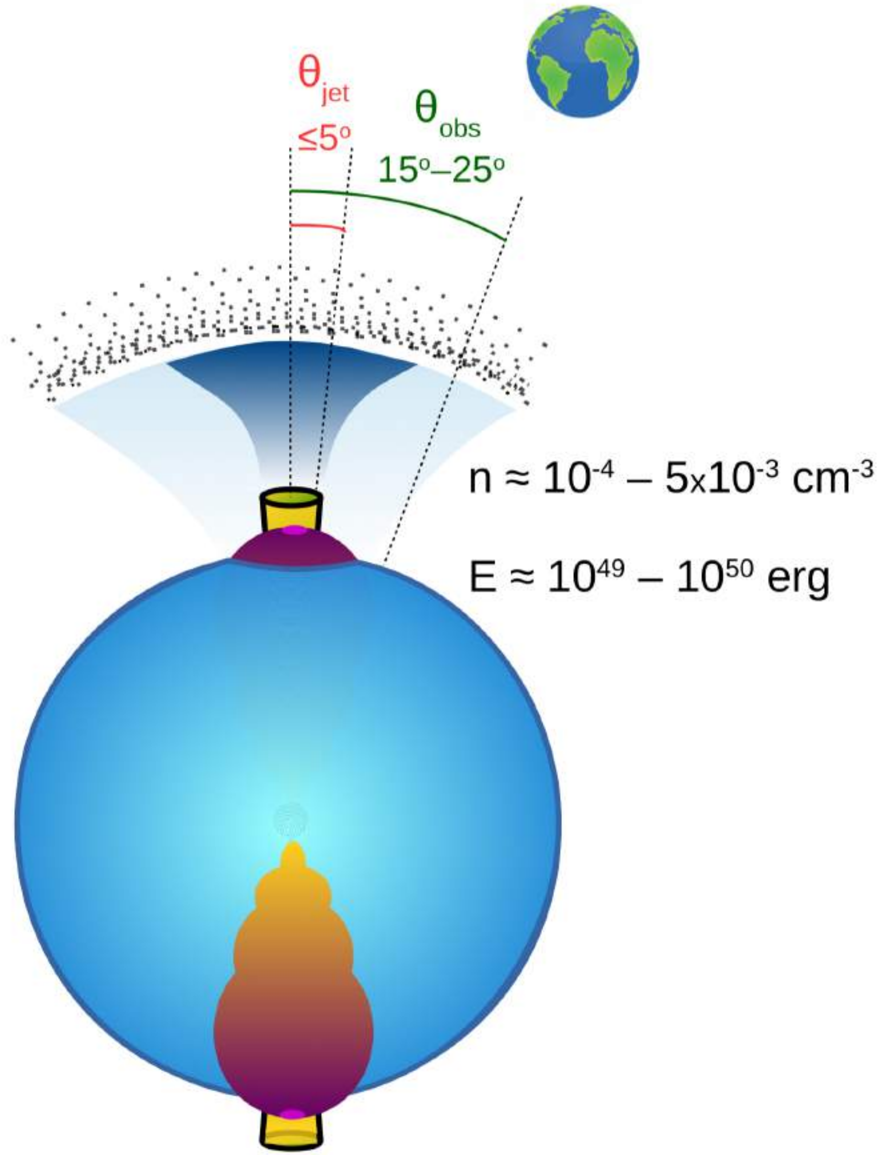


The VLBI image

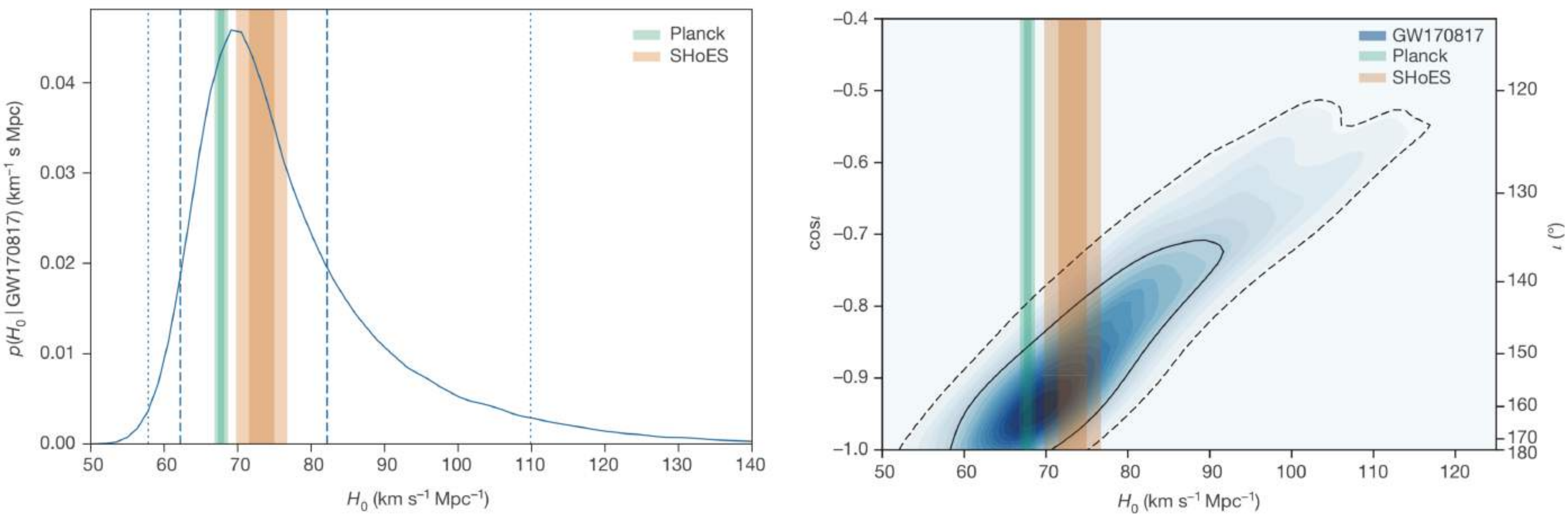


Mooley et al. 18





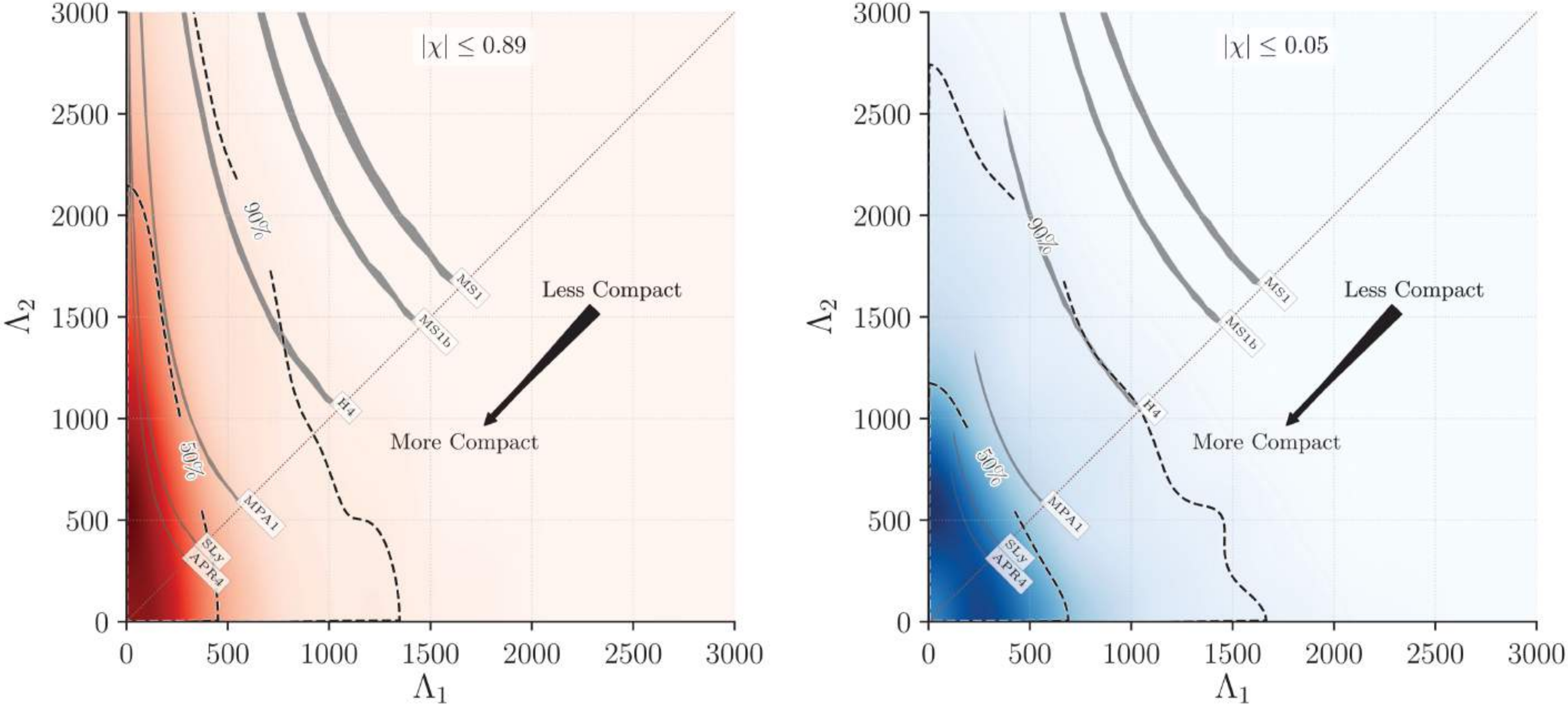
Standard SirenとHubble Tension



Inclination angleの不定性を減らすことが重要 → jetの観測と組み合わせることが重要

Hotokezaka et al. 18

Tidal deformability



“比較的小さい” 中性子星を作るEoSが良い感じだが、まだ制限はゆるい。

陽は昇る

まとめ

- GW170817に全世界が泣いた
  - ✓~30 yr前くらいに大枠の予言は出揃っていた
    (今思えば)簡単で重要な仕事、概念創出phase
  - ✓~5yr前くらいからの急ピッチの進展はしかしすごい
    (比較的)難しくて重要な仕事、問題・ルールの整備phase
  - ✓~ms後からこれまで、怒涛の~1yr
    "答え合わせ"、徒競走 & マラソンphase

とはいえOpen Question

- NSNS merger = sGRB？
- どうやって相対論的なジェットを出すのか？
- 本当にr-process elementできてるのか？
- それがsolar abundanceを説明するか？
- NSNS merger → HMNS、どうなるのか？
- NSBH merger、どうなるのか？
- いつ、どこで、どうやってcompact binaryができたのか？（特にBHBH、NSBH）

- ~100発/yrの時代が来る→ 数の力で寄り切れる？