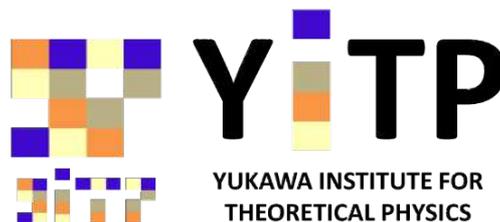


高エネルギー天体物理 High Energy Astrophysics

井岡 邦仁 (京大基研)

Kunihito Ioka (YITP, Kyoto U.)



重力波の初観測！

 Selected for a **Viewpoint** in *Physics*
PHYSICAL REVIEW LETTERS

week ending
12 FEBRUARY 2016

PRL 116, 061102 (2016)



Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21} . It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ . The source lies at a luminosity distance of 410_{-180}^{+160} Mpc corresponding to a redshift $z = 0.09_{-0.04}^{+0.03}$. In the source frame, the initial black hole masses are $36_{-4}^{+5} M_{\odot}$ and $29_{-4}^{+4} M_{\odot}$, and the final black hole mass is $62_{-4}^{+4} M_{\odot}$, with $3.0_{-0.5}^{+0.5} M_{\odot} c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

2月11日夜のビッグニュース！

Press Release

@YITP

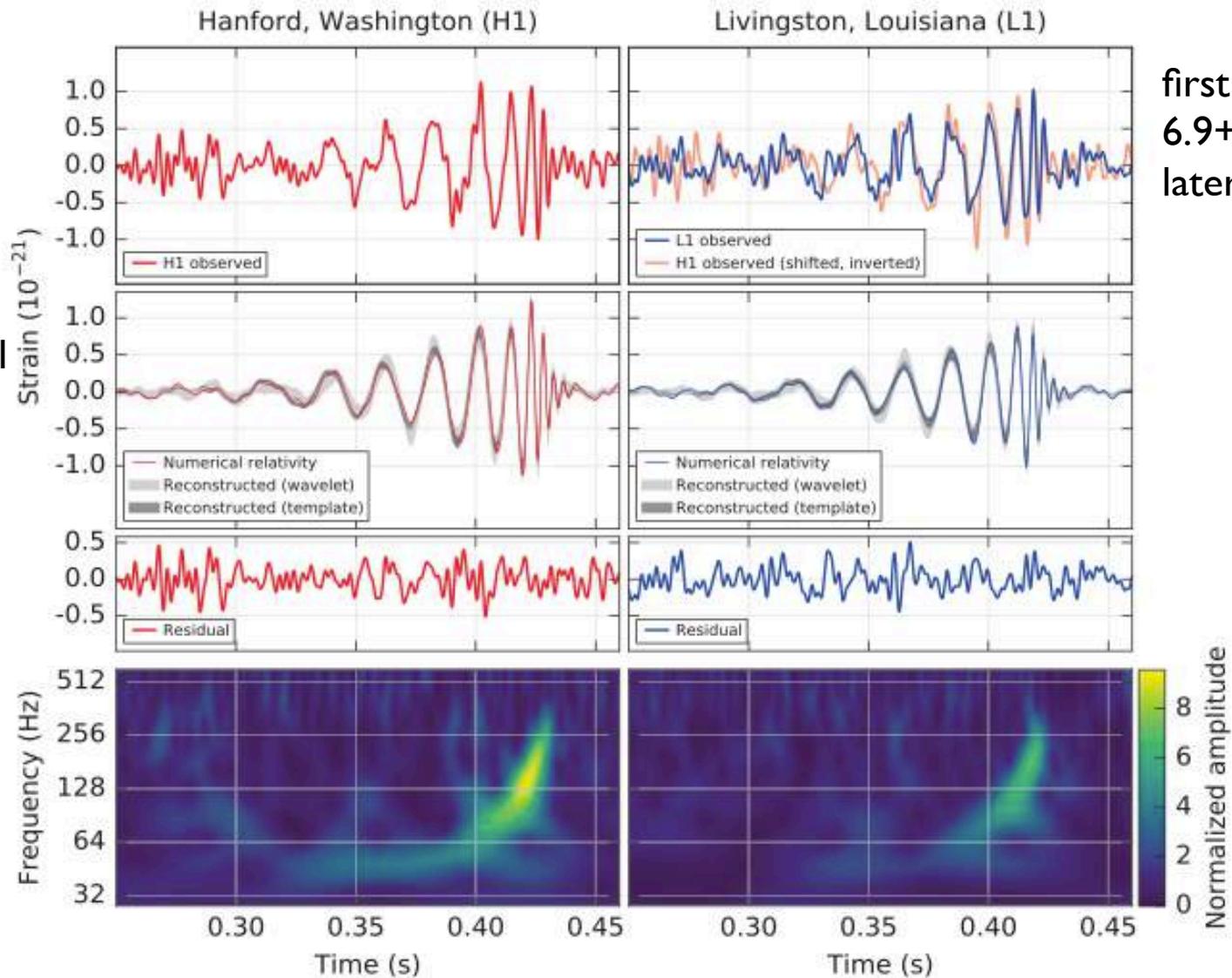
シャンペン
champagne



重力波波形

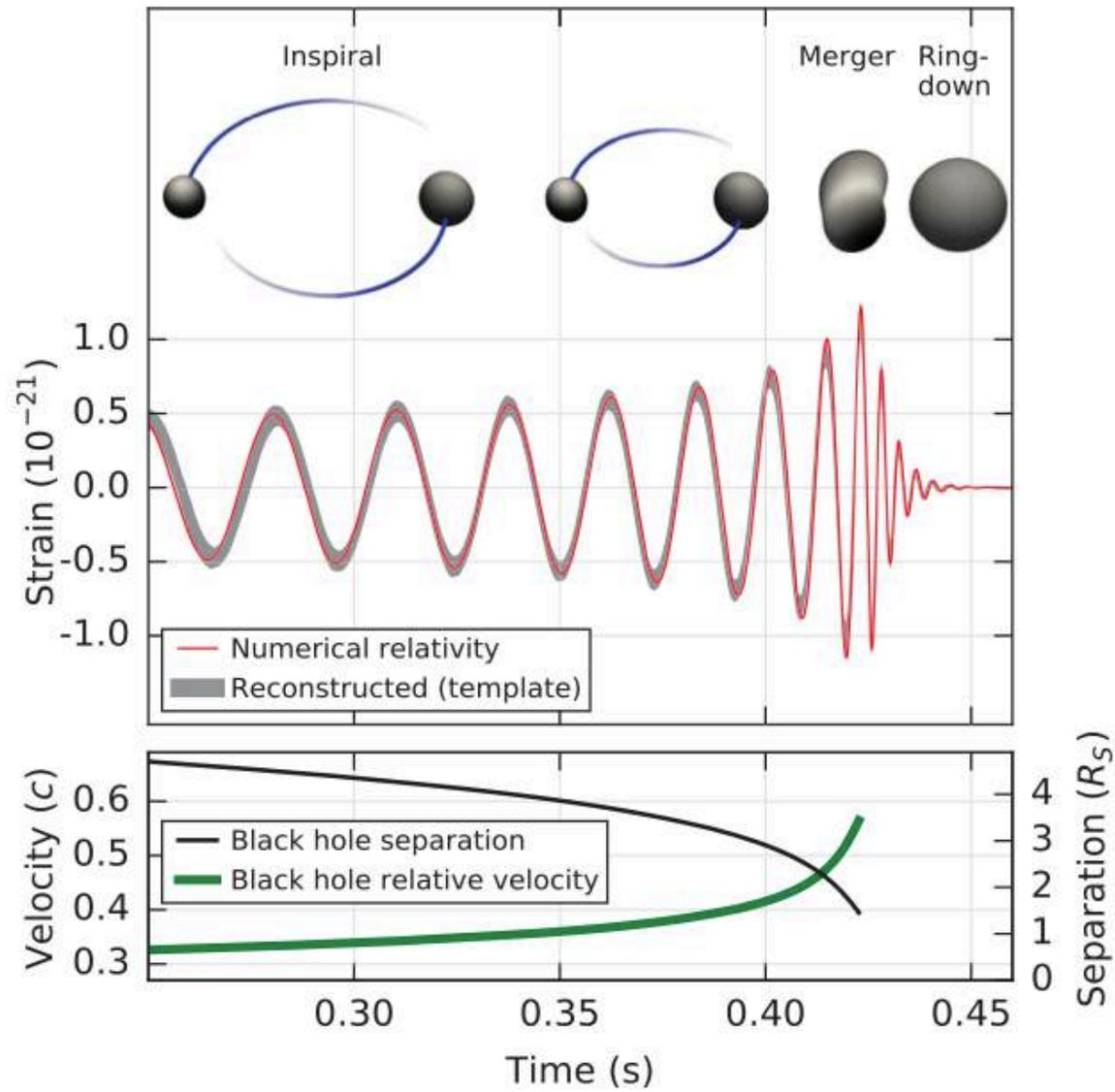
30-350Hz
bandpass
filter

Theoretical
wave form

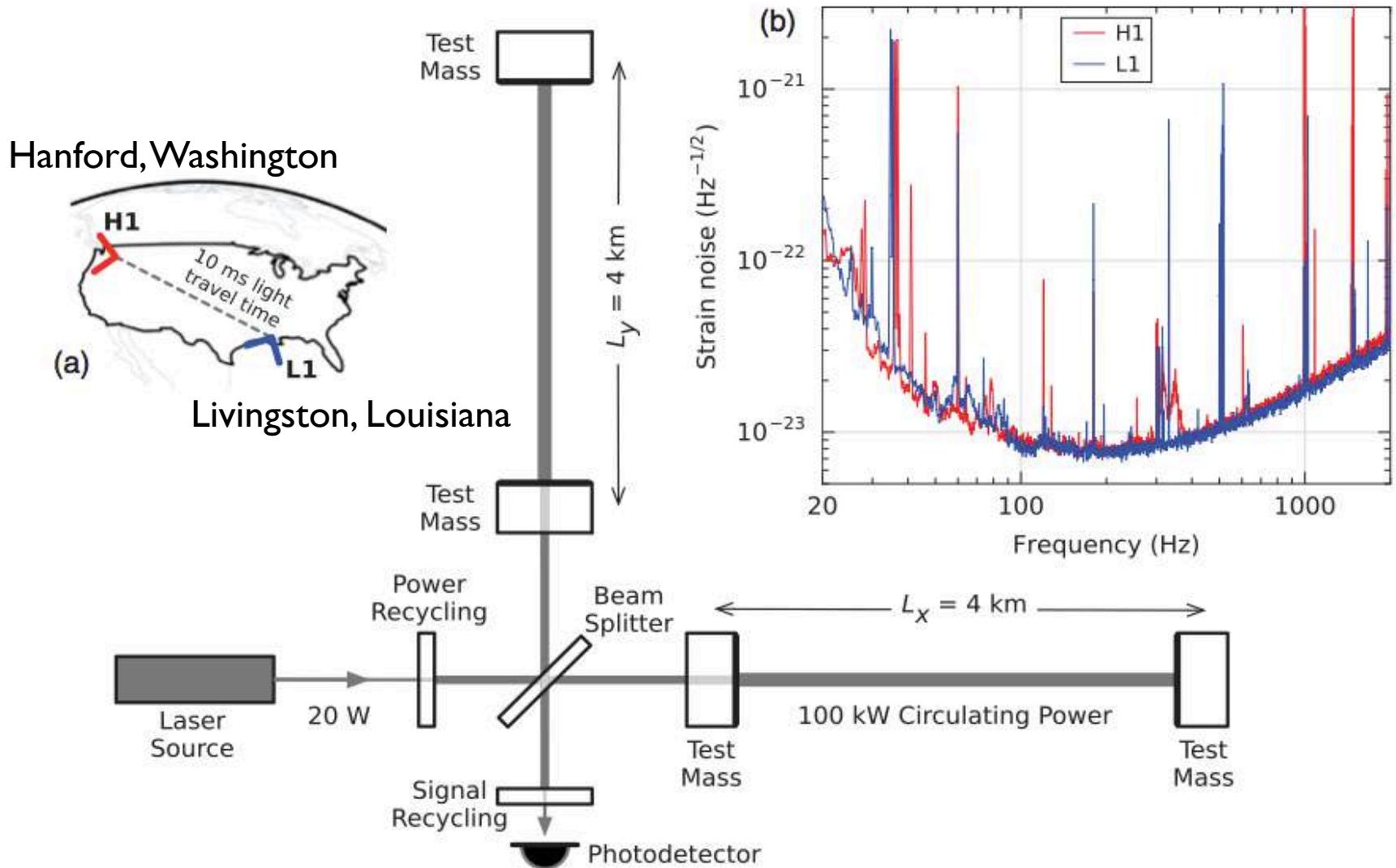


first at L1
6.9+0.5-0.4ms
later at H1

Inspiral, Merger, Ringdown



Advanced LIGO



ブラックホール連星

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G} \left[\frac{5}{96} \pi^{-8/3} f^{-11/3} \dot{f} \right]^{3/5},$$

speed of light. Estimating f and \dot{f} from the data in Fig. 1, we obtain a chirp mass of $\mathcal{M} \approx 30M_\odot$, implying that the total mass $M = m_1 + m_2$ is $\gtrsim 70M_\odot$ in the detector frame. This bounds the sum of the Schwarzschild radii of the binary components to $2GM/c^2 \gtrsim 210$ km. To reach an orbital frequency of 75 Hz (half the gravitational-wave frequency) the objects must have been very close and very compact; equal Newtonian point masses orbiting at this frequency would be only ≈ 350 km apart. A pair of neutron stars, while compact, would not have the required mass, while a black hole neutron star binary with the deduced chirp mass would have a very large total mass, and would thus merge at much lower frequency. This leaves black holes as the only known objects compact enough to reach an orbital frequency of 75 Hz without contact. Furthermore, the decay of the waveform after it peaks is consistent with the damped oscillations of a black hole relaxing to a final stationary Kerr configuration.

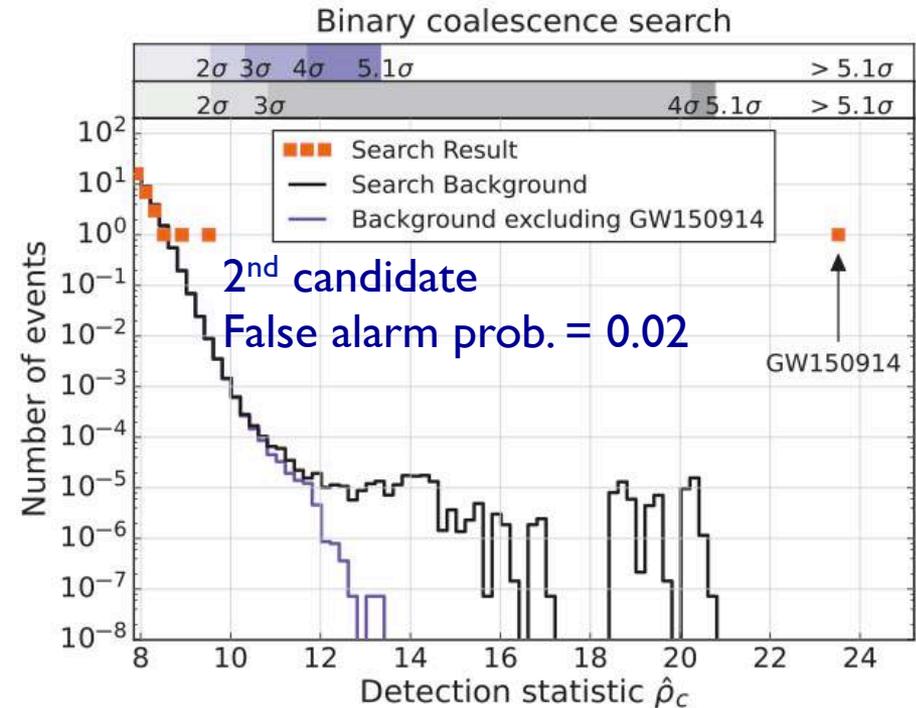
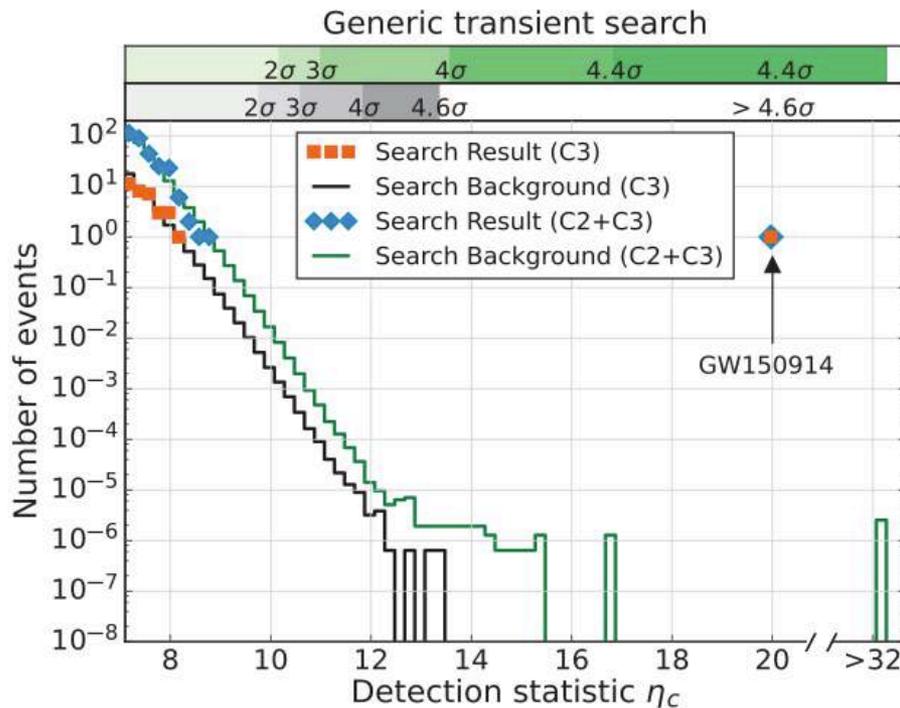
中性子星連星
ではない
BH-中性子星
ではない
⇒ BH
(後半の講義)

Significance

Analysis of 16 days (12 Sep – 20 Oct 2015)
Just before O1 (18 Sep – 12 Jan 2015)

**Within
3 min!**

SNR ~ 23.6, False alarm prob. < 2e-7
> 5.1 σ detection!



Source Parameters

TABLE I. Source parameters for GW150914. We report median values with 90% credible intervals that include statistical errors, and systematic errors from averaging the results of different waveform models. Masses are given in the source frame; to convert to the detector frame multiply by $(1+z)$ [90]. The source redshift assumes standard cosmology [91].

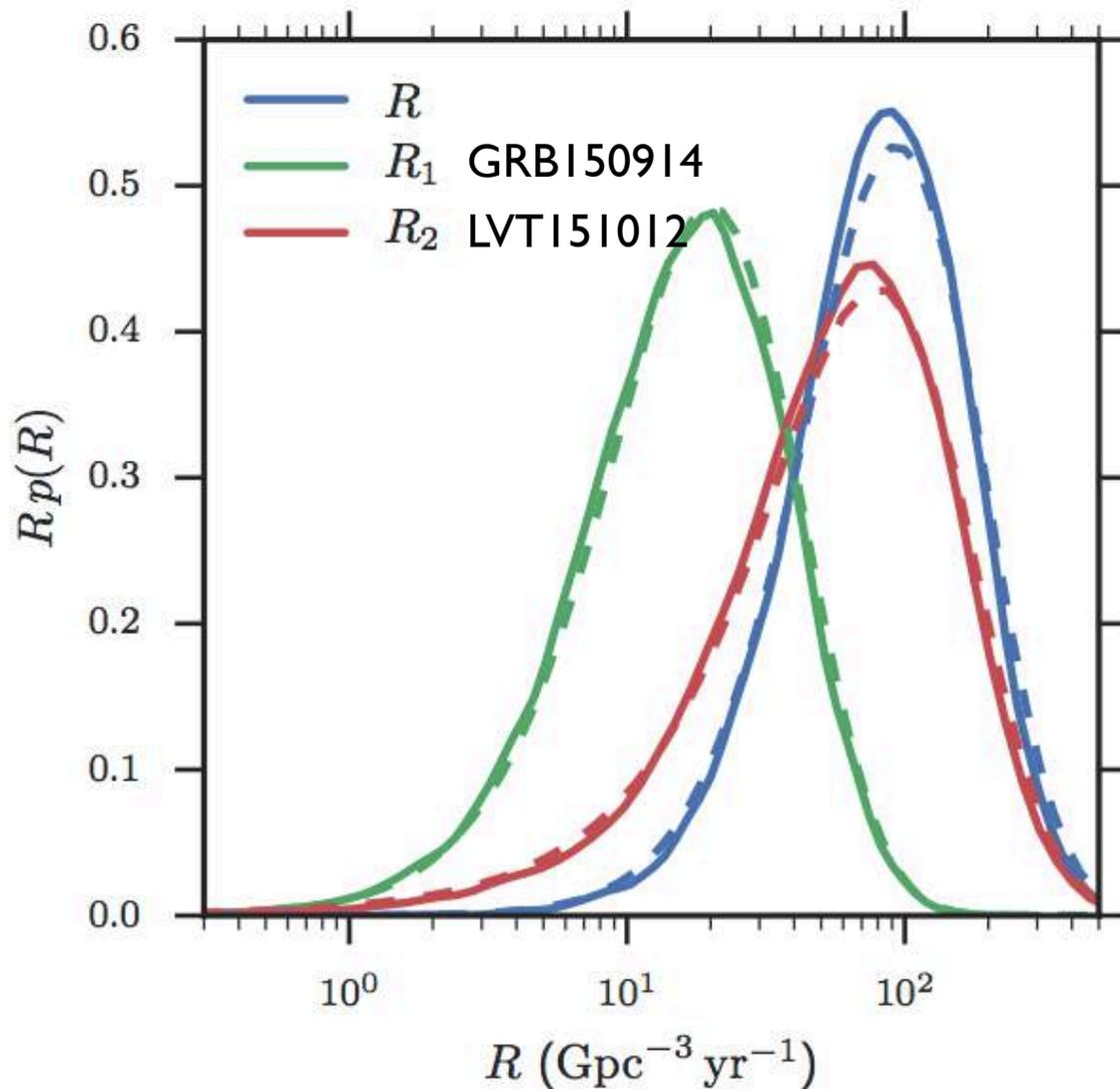
Primary black hole mass	$36_{-4}^{+5} M_{\odot}$
Secondary black hole mass	$29_{-4}^{+4} M_{\odot}$
Final black hole mass	$62_{-4}^{+4} M_{\odot}$
Final black hole spin	$0.67_{-0.07}^{+0.05}$
Luminosity distance	$410_{-180}^{+160} \text{ Mpc}$
Source redshift z	$0.09_{-0.04}^{+0.03}$

The Most Luminous in the Universe

- Total radiated mass
 $M \sim 3.0+0.5-0.5 M_{\odot}$
- Energy $E=Mc^2 \sim 6 \times 10^{54}$ erg
- **$L_{peak} \sim 3.6+0.5-0.4 \times 10^{56}$ erg/s**
 $\sim 200+30-20 M_{\odot}c^2/s$
 $\sim 10^{-3} c^5/G$
- **$> L_{Gamma-Ray Bursts} \sim 10^{50-54}$ erg/s**

太陽質量を ~ 0.01 秒で放出

Event Rate



$2-400 \text{ Gpc}^{-3} \text{yr}^{-1}$

我々の銀河の中の
合体BHの個数は?

銀河 $\sim 0.01 \text{ Mpc}^{-3}$

宇宙年齢 $\sim 10^{10} \text{ yr}$

$G=10^9, M=10^6$

$\Rightarrow 2,000-400,000$ 個

Low Metallicity

重元素量が多い \Rightarrow たくさんの吸収線
 \Rightarrow 放射を吸収 \Rightarrow 星の放射で wind
 \Rightarrow 星の質量が小さくなりすぎる

PopII?
 PopIII?

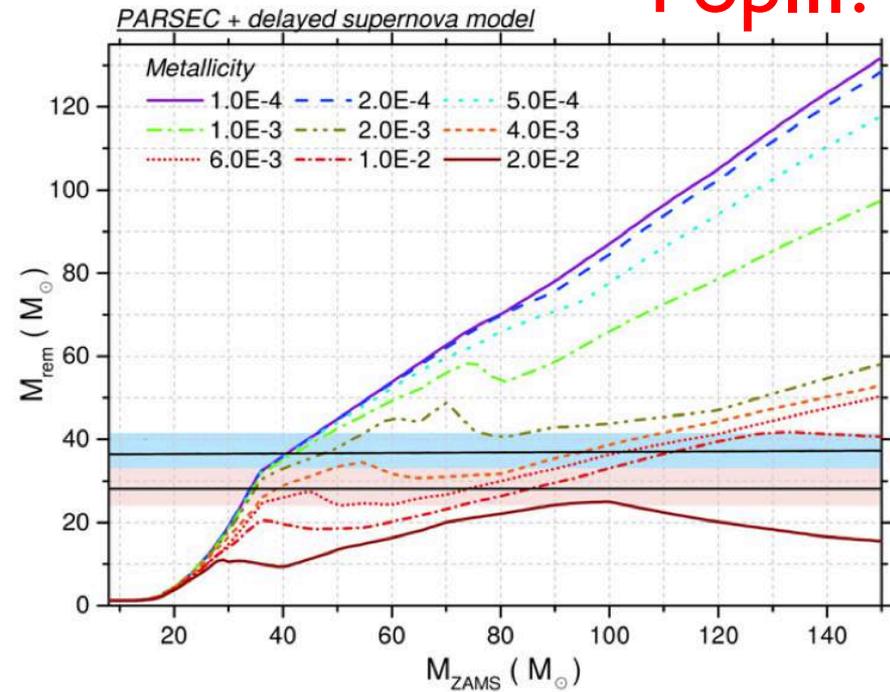
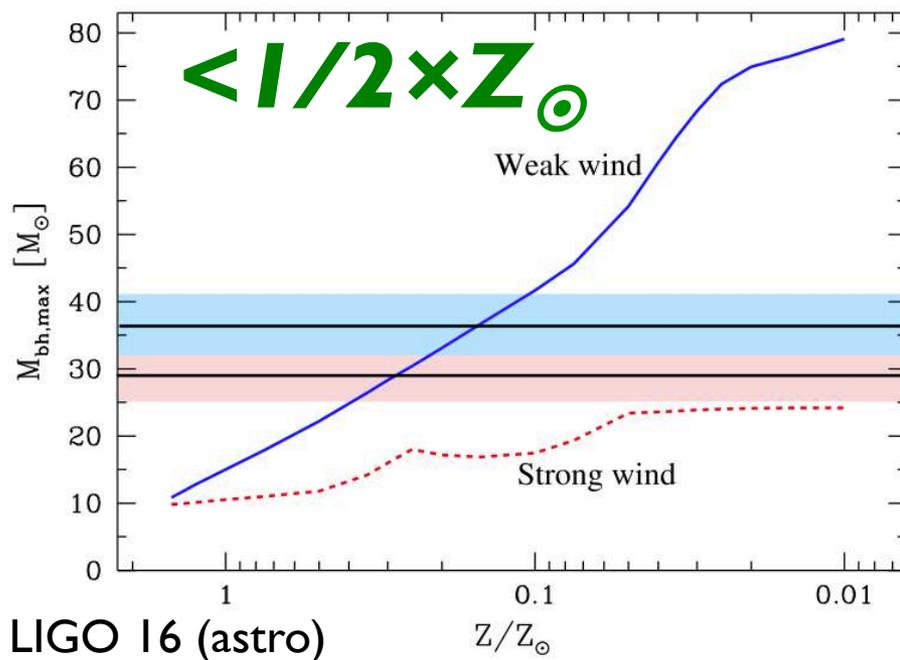
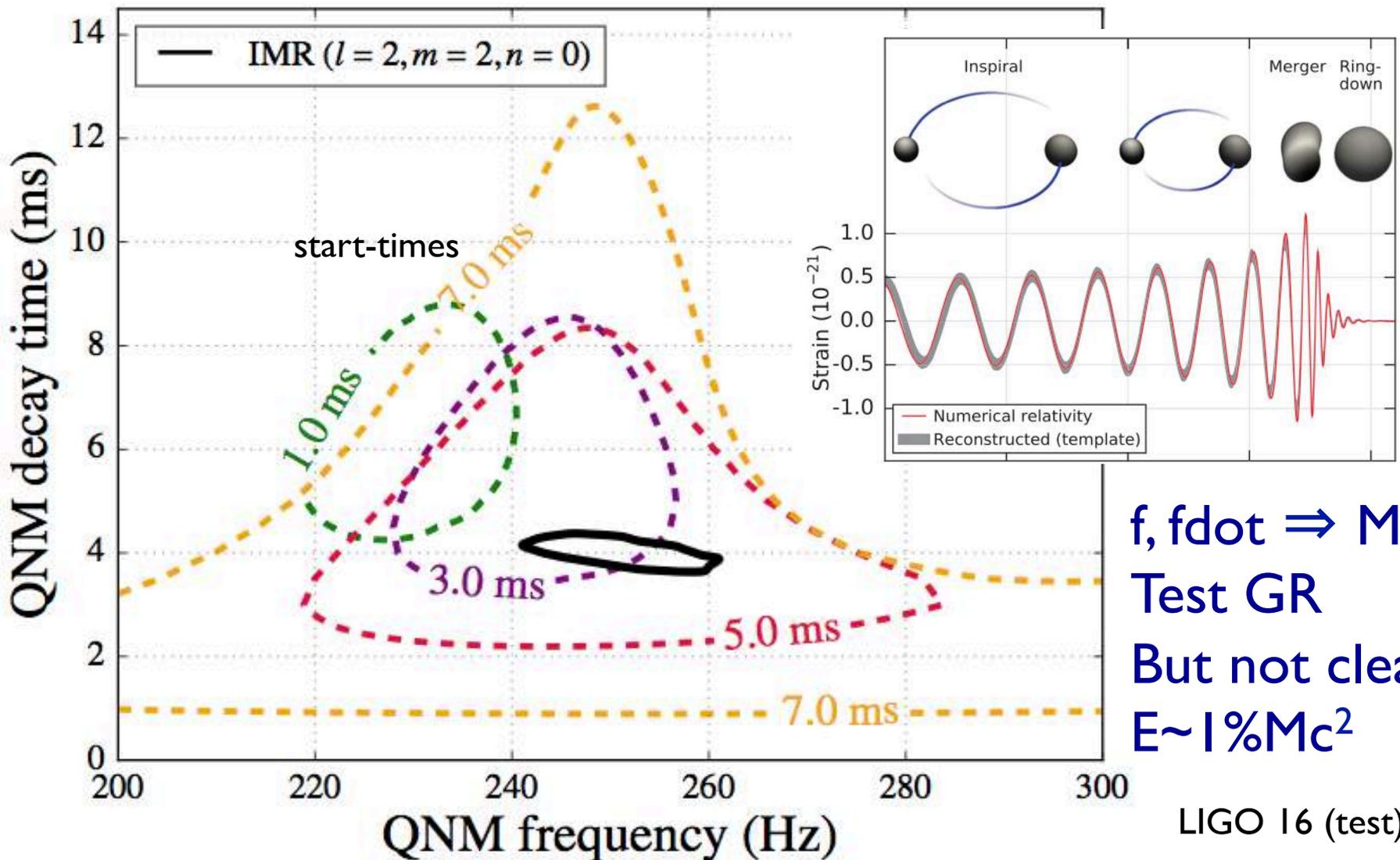


Figure 1. Left: dependence of maximum BH mass on metallicity Z , with $Z_{\odot} = 0.02$ for the old (strong) and new (weak) massive-star winds (Figure 3 from Belczynski et al. 2010a). Right: compact-remnant mass as a function of zero-age main-sequence (ZAMS; i.e., initial) progenitor mass for a set of different (absolute) metallicity values (Figure 6 from Spera et al. 2015). The masses for GW150914 are indicated by the horizontal bands.

Quasi-Normal Mode

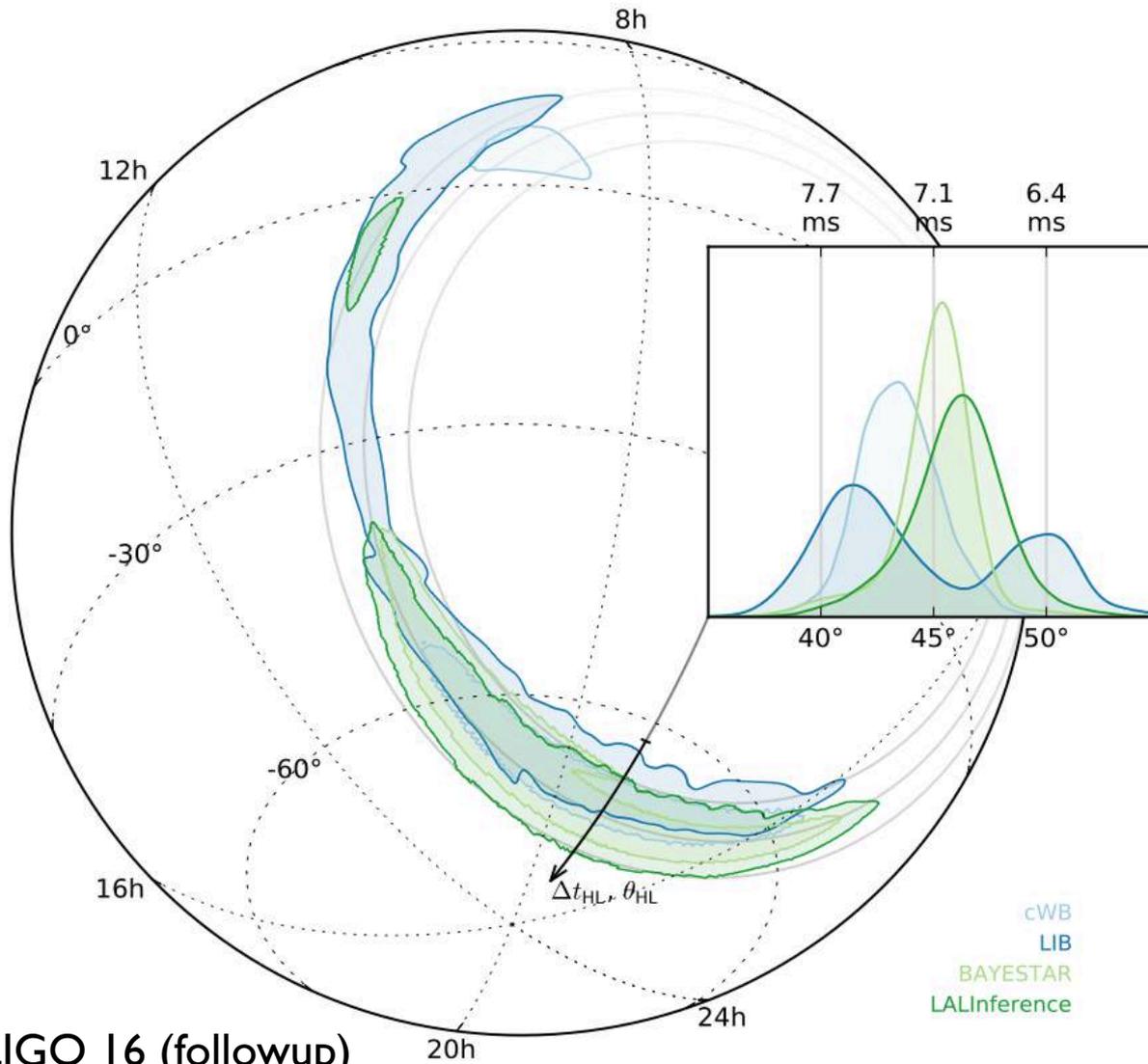


Speed of Graviton

振動数の異なる重力波がほぼ同じ速度

$$\frac{\Delta v}{c} \sim \frac{c/100\text{Hz}}{400\text{Mpc}} \sim 10^{-19}$$

Sky Position



~600 deg²

Bad localization

⇒ KAGRA,

LIGO-India

(IndIGO)

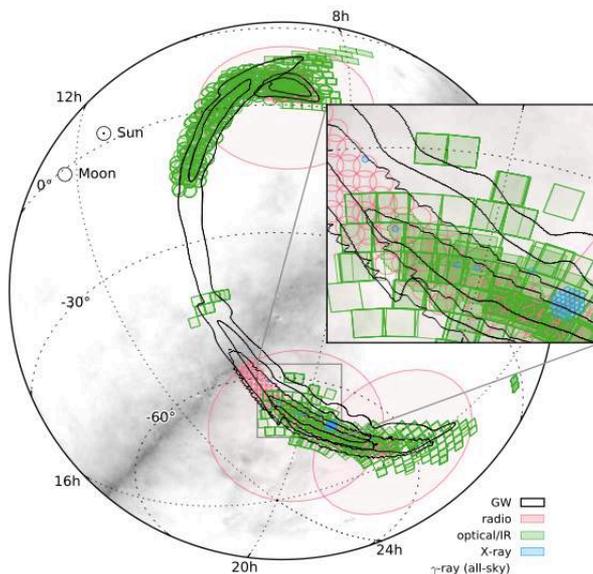
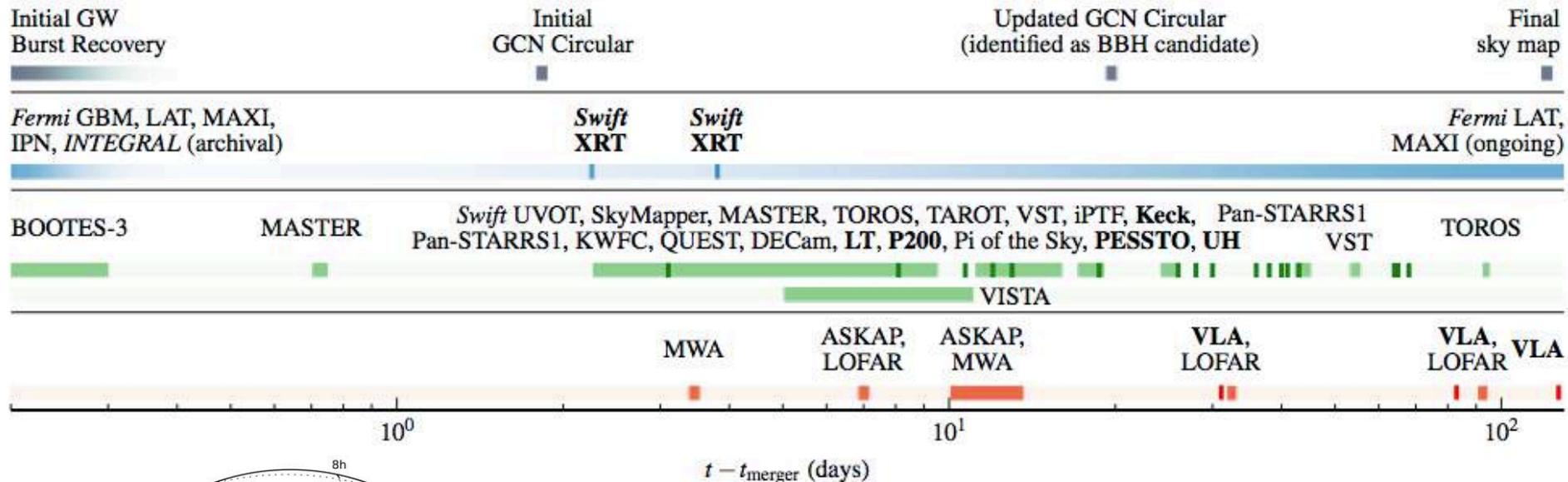
90%

Coherent WaveBurst

LALInference Burst

BAYESTAR algorithm

Follow-up Observations

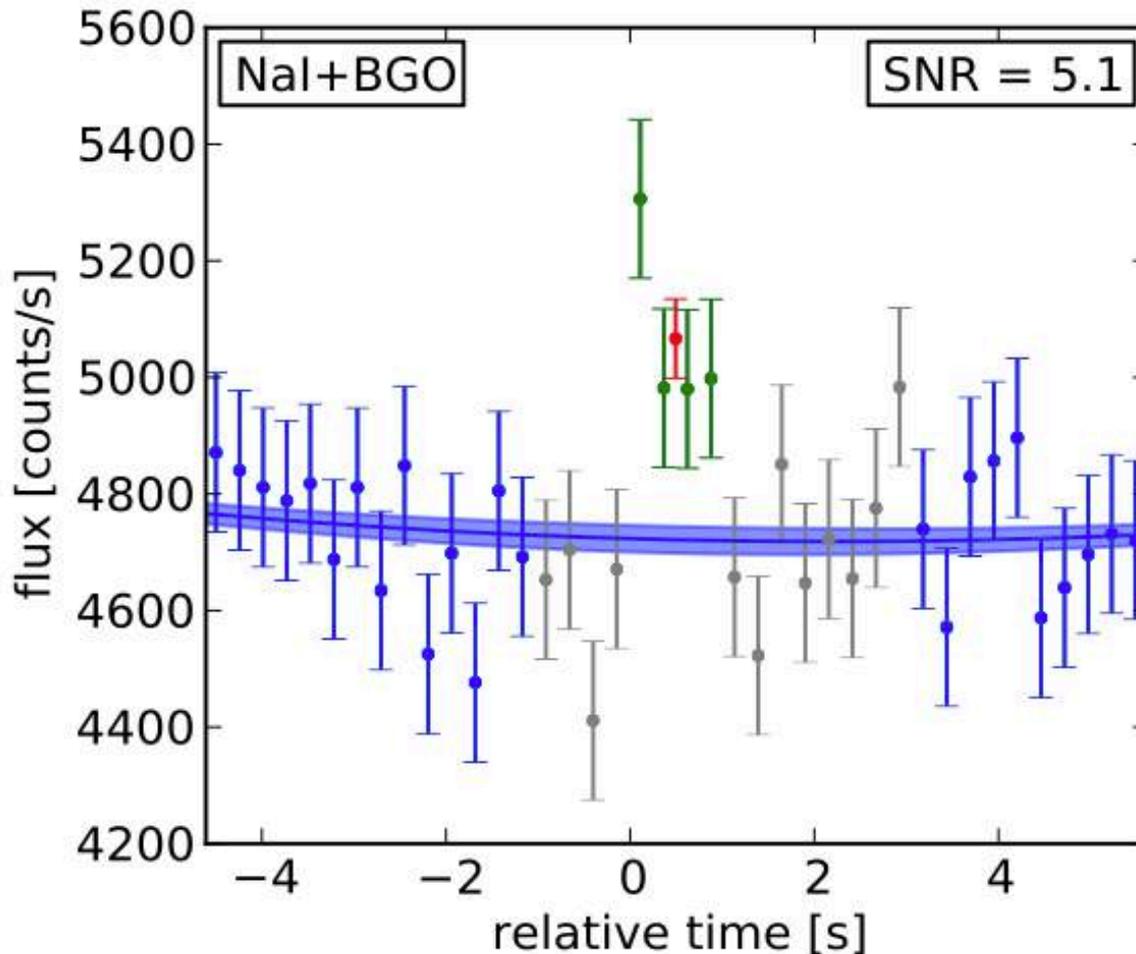


**Many,
multi-wavelength
follow-ups**

LIGO 16 (followup)

Fermi γ -ray Burst Monitor

GBM detectors at 150914 09:50:45.797 +1.024s



>50keV

0.4s after GW

$T \sim 1$ sec

False alarm ~ 0.0022

$L \sim 1.8^{+1.5}_{-1.0} e^{49} \text{erg/s}$

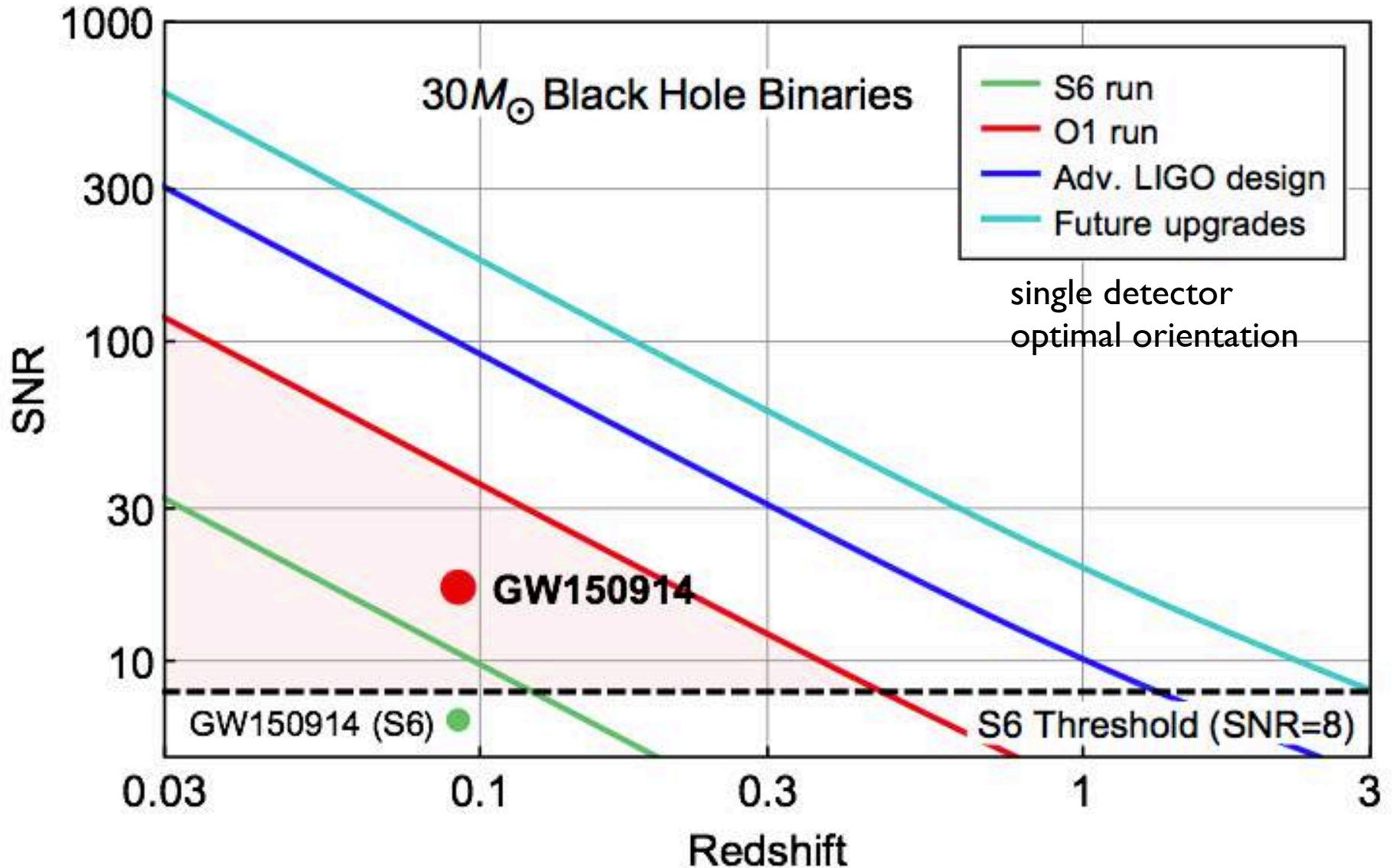
Short GRB!?

信じられない!!

今回のすごい点

- 重力波の初の直接観測
- 連星ブラックホールの発見
- 最大光度天体の発見
- Quasi-normal mode が見えかけ
- PopIII かもしれない
- Short GRB なら倍すごい

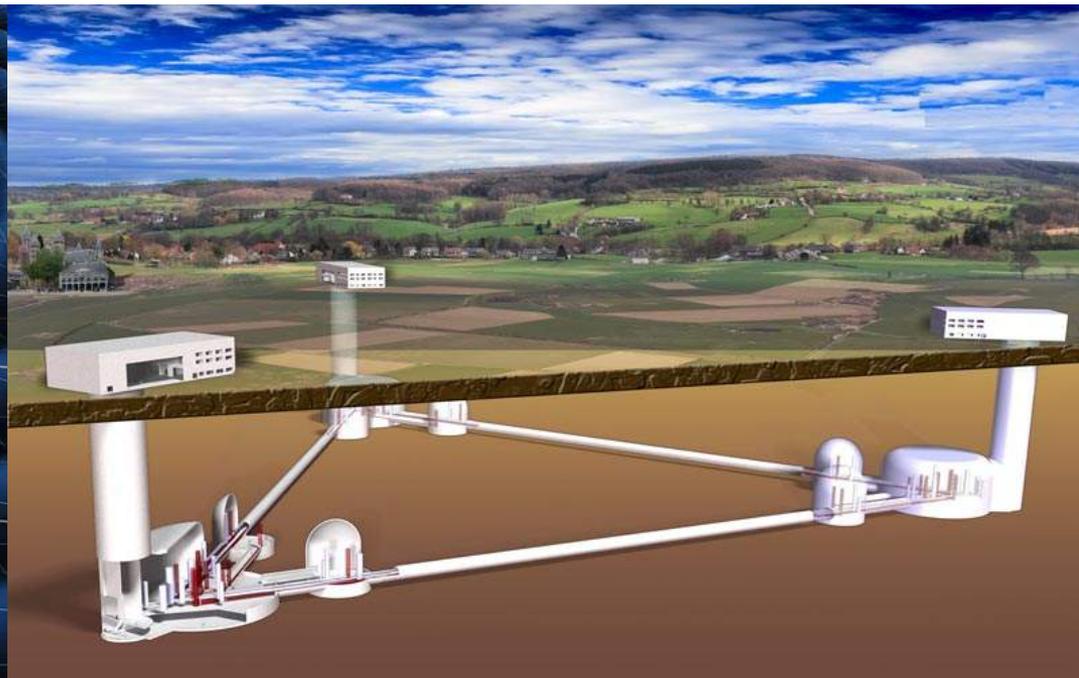
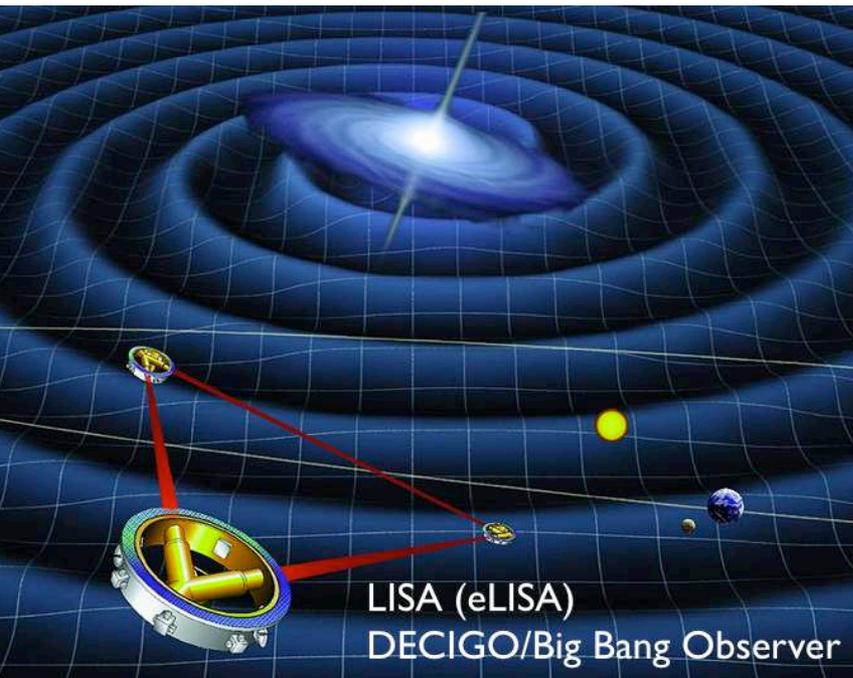
Future Prospects



究極重力波望遠鏡

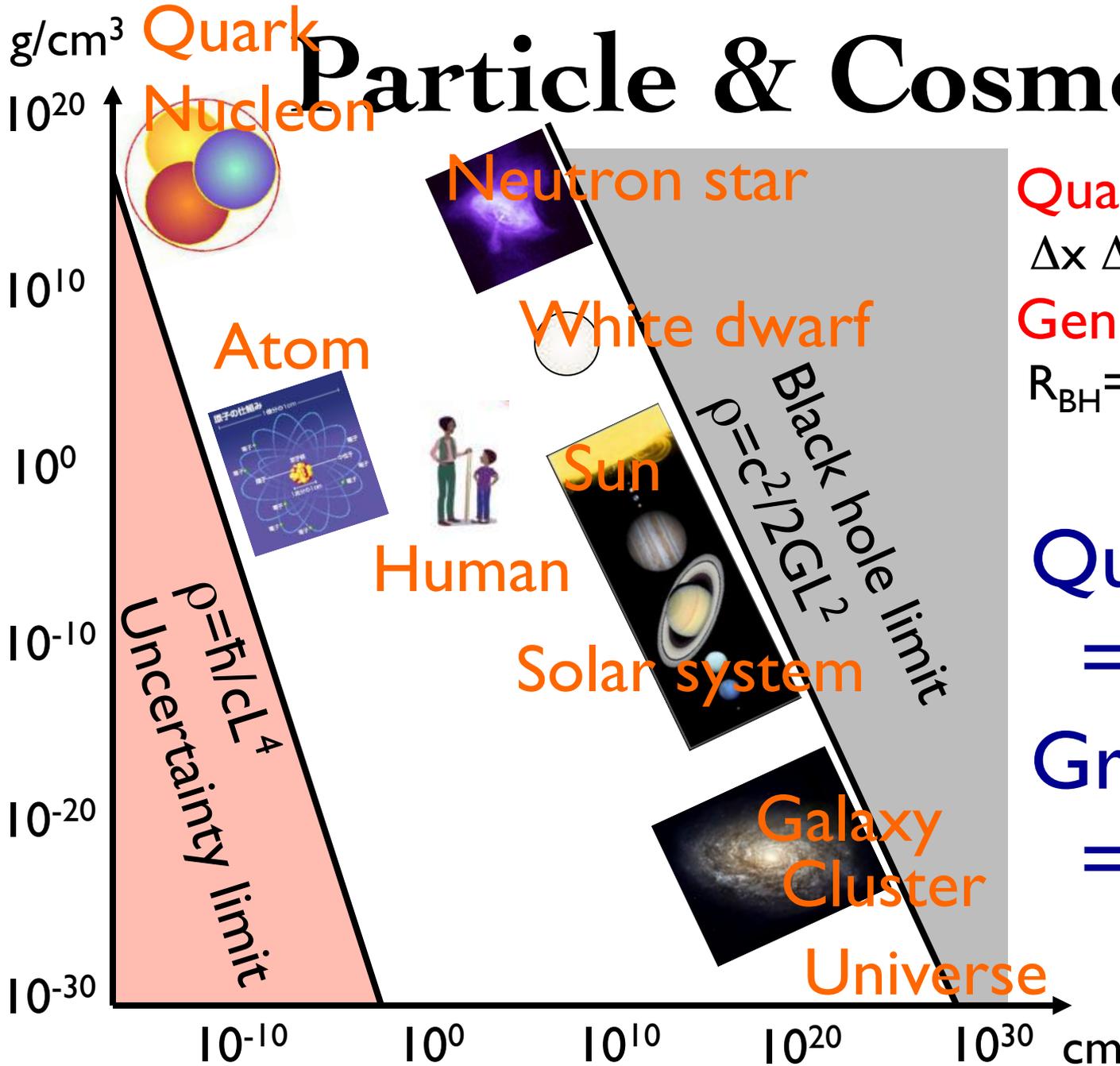
eLISA, DECIGO

Einstein Telescope



宇宙最初のブラックホール
から全ての歴史を明らかに

Particle & Cosmos



Quantum mechanics

$$\Delta x \Delta p \geq \hbar$$

General relativity

$$R_{\text{BH}} = 2GM/c^2$$

Quantum “ \hbar ”

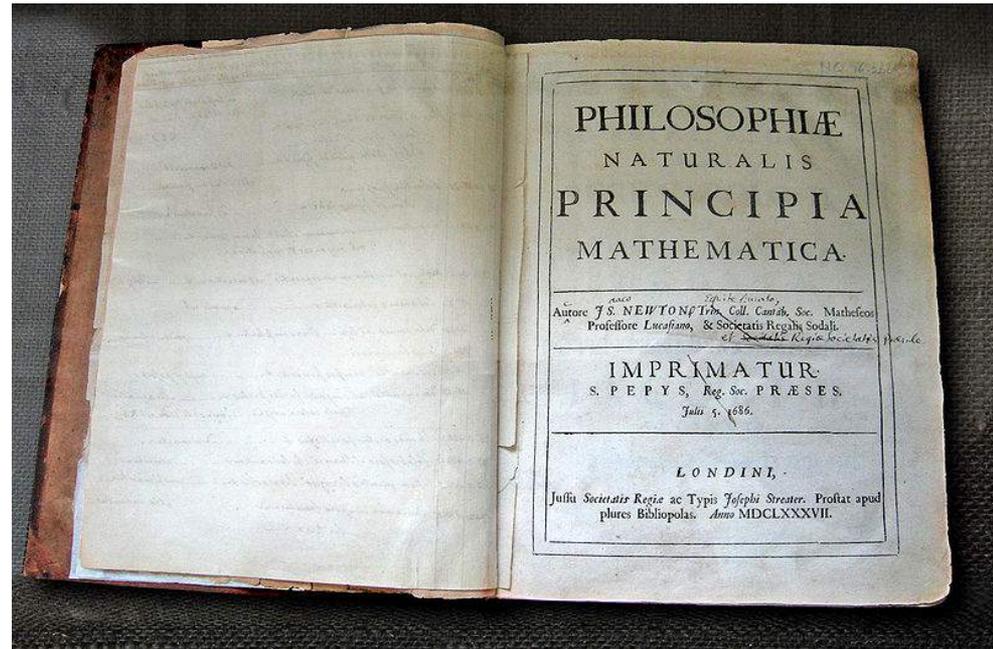
⇒ Particle

Gravity “G”

⇒ Universe

Newton Gravity

- 1678年 Newton “*Principia*”
- Philosophiae naturalis principia mathematica
Latin title
- **Theory of Gravity**
in mathematics
- \Rightarrow Planet motion
- Classical dynamics
- Beginning of Physics



General Relativity

- Albert Einstein
(1879-1955)
- Theory of spacetime geometry for gravity
- Einstein eq. (1915)

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- Establish classical gravity

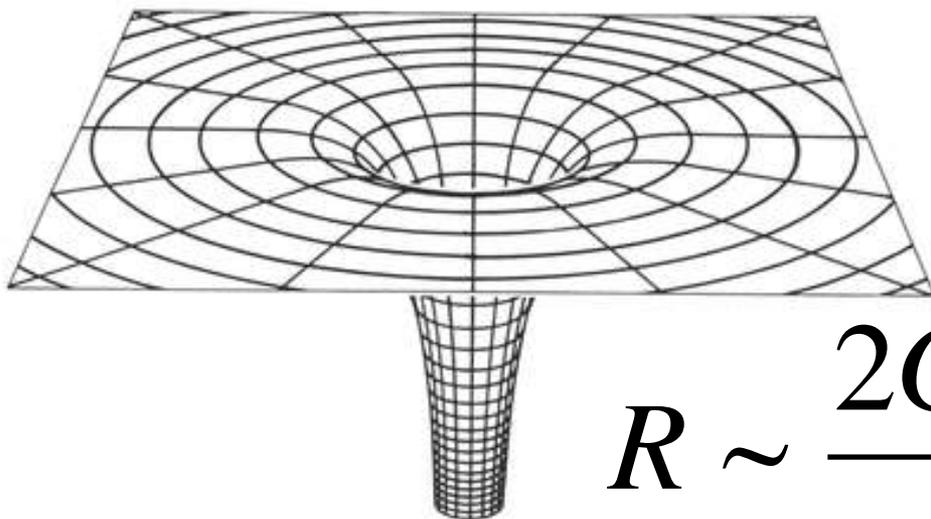


⇒ Beginning of modern cosmophysics

Amazing Predictions

Black Hole

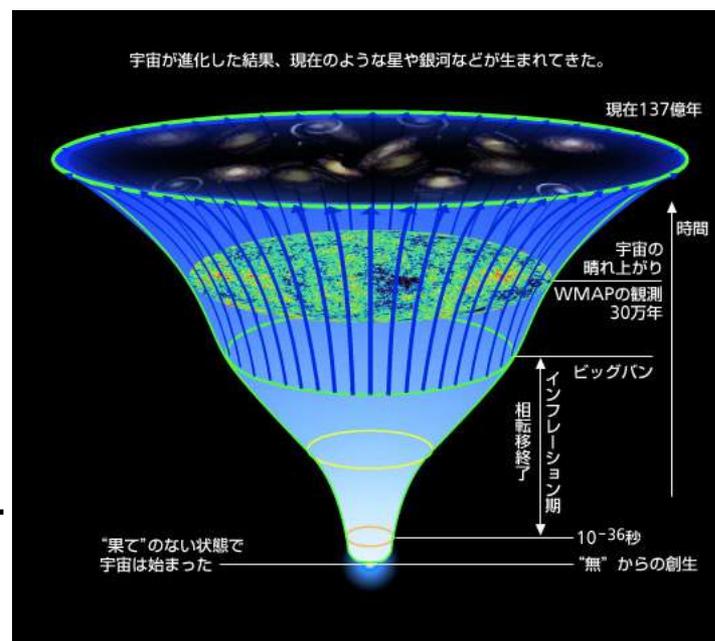
Expanding Universe



$$R \sim \frac{2GM}{c^2}$$

Final fate of stellar evolution

Astrophysics



Big Bang

Cosmology

Evolution to Black Hole

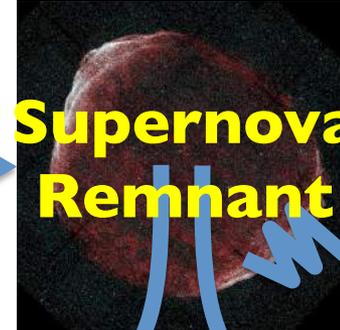
Gravity
Quantum



Star

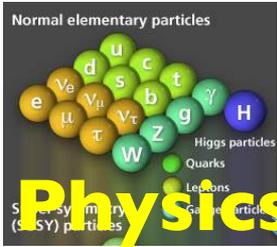


**Supernova
GRB**



**Supernova
Remnant**

W. A. Fowler

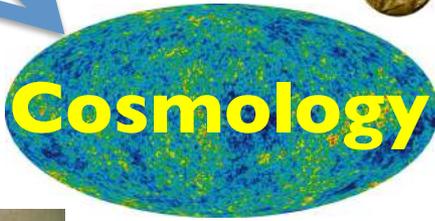


Physics

**Chandrasekhar
Bethe**

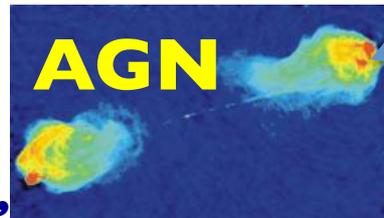


**Davis
Koshiba**



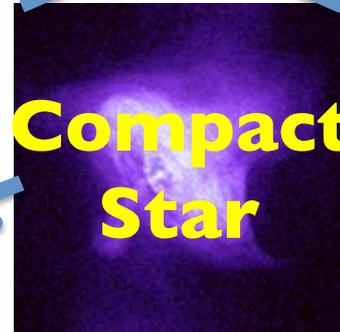
Cosmology

**Penzias, Wilson
Perlmutter, Riess,
Schmidt**



AGN

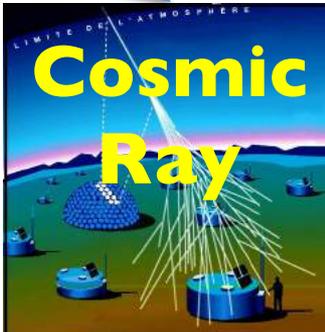
Active galactic nuclei
Massive black hole
at the center of galaxy



**Compact
Star**

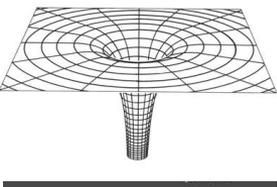
Black Hole
Neutron Star
White Dwarf

**Giacconi
Hewish
Hulse, Taylor**



**Cosmic
Ray**

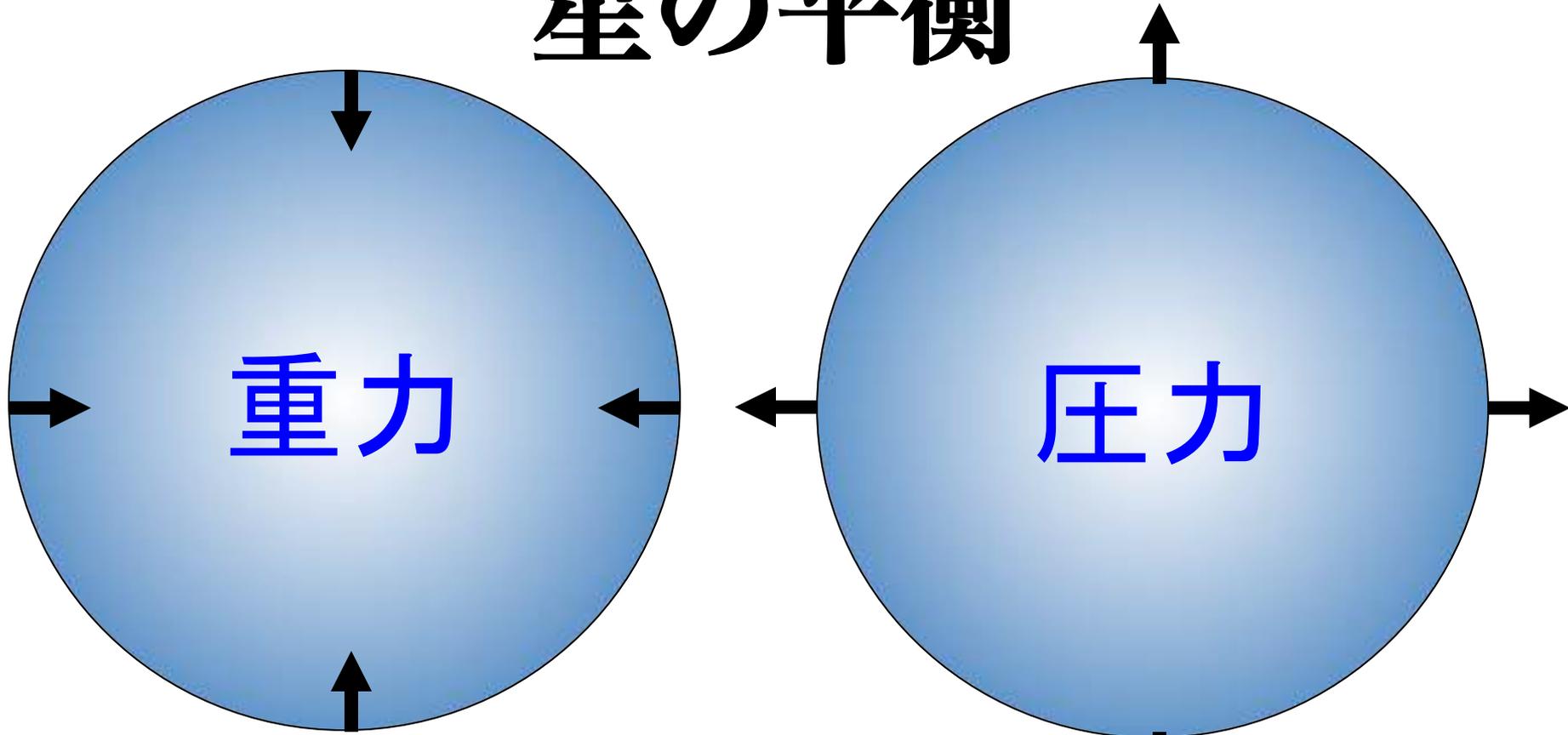
**Hess
Anderson
Yukawa
Powell
Kajita**



Computer

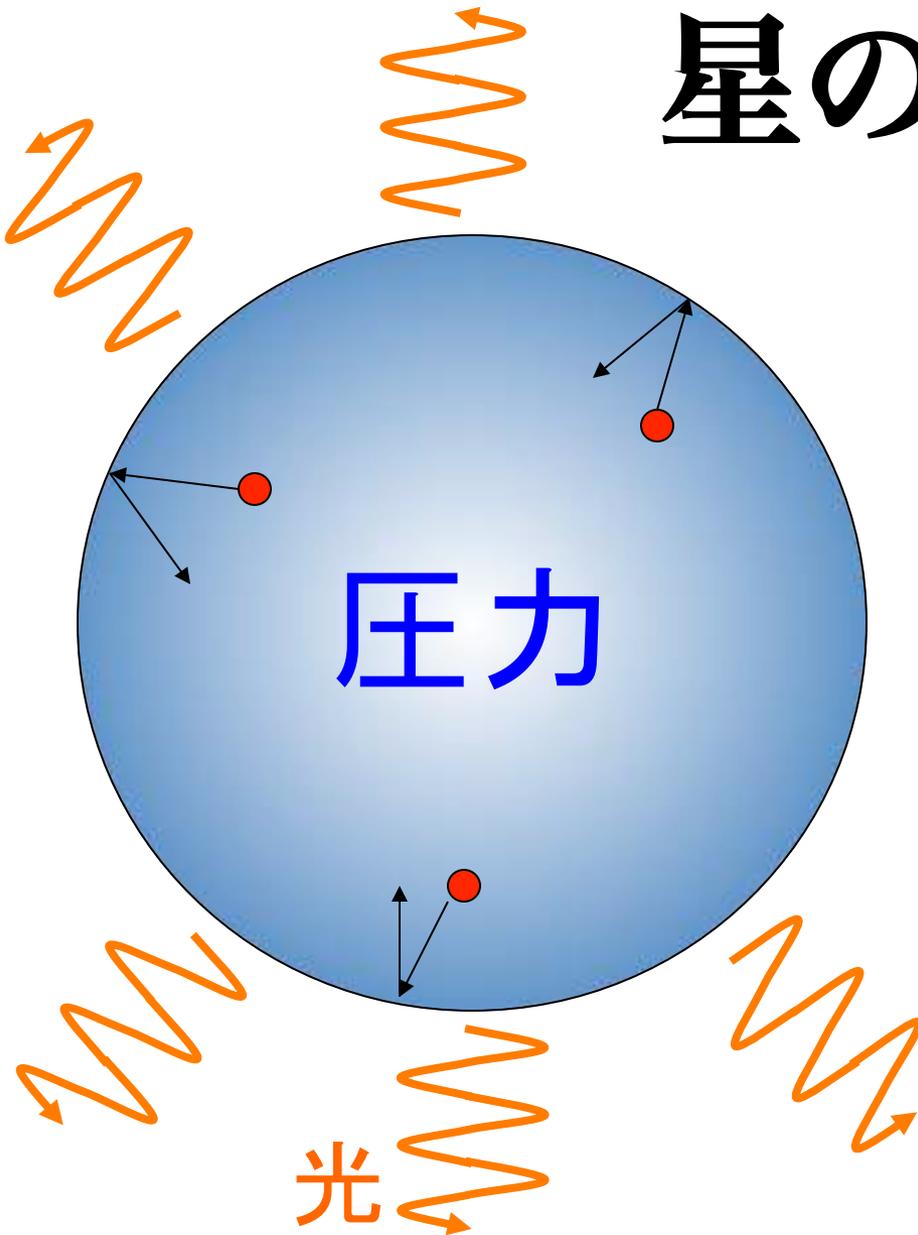
High Energy Universe

星の平衡



太陽などの圧力は**ガス圧**（例えば風船）
中性子星、白色矮星は**別の圧力**で支えている
釣り合っている限り**ブラックホールにならない**

星の冷却



ガスの熱運動(温度)
⇒ 圧力

表面から光が出て
エネルギーを失う
(温度が下がる)
⇒ 圧力が減る
⇒ 重力で潰れる

逆になぜ太陽は
潰れないか？

太陽のエネルギー源は？

- 太陽の光度 $L_{\odot} \sim 4 \times 10^{33} \text{erg/s}$ ($= 4 \times 10^{26} \text{J/s}$)
- 太陽の質量 $M_{\odot} \sim 2 \times 10^{33} \text{g}$ ($= 2 \times 10^{30} \text{kg}$)
- 太陽の半径 $R_{\odot} \sim 7 \times 10^{10} \text{cm}$ ($= 7 \times 10^8 \text{m}$)
- 単位質量当たり $\sim 2 \text{erg/s/g}$ ($= 2 \times 10^{-4} \text{W/kg}$)

- **重力エネルギー説**

ヘルムホルツ(19世紀半ば)

$$E_G = -\frac{GM_{\odot}}{R_{\odot}} = -2 \times 10^{15} \text{ erg/g}$$

太陽の寿命

$$\frac{2 \times 10^{15} \text{ erg/g}}{2 \text{ erg/s/g}} = 10^{15} \text{ s} \sim 3 \times 10^7 \text{ year}$$

- 隕石の放射線年代測定
隕石の年齢はおよそ**45.5億年**
- Darwin「種の起源」 **3000万年では短すぎる**
- 化学エネルギーは?
水素原子の結合エネルギーは13.6 eV.
1gの水素には水素原子が $\sim 6 \times 10^{23}$ 個.
つまり, $\sim 10^{13}$ erg/g < 重力エネルギー.
足りない!

$$E=mc^2$$

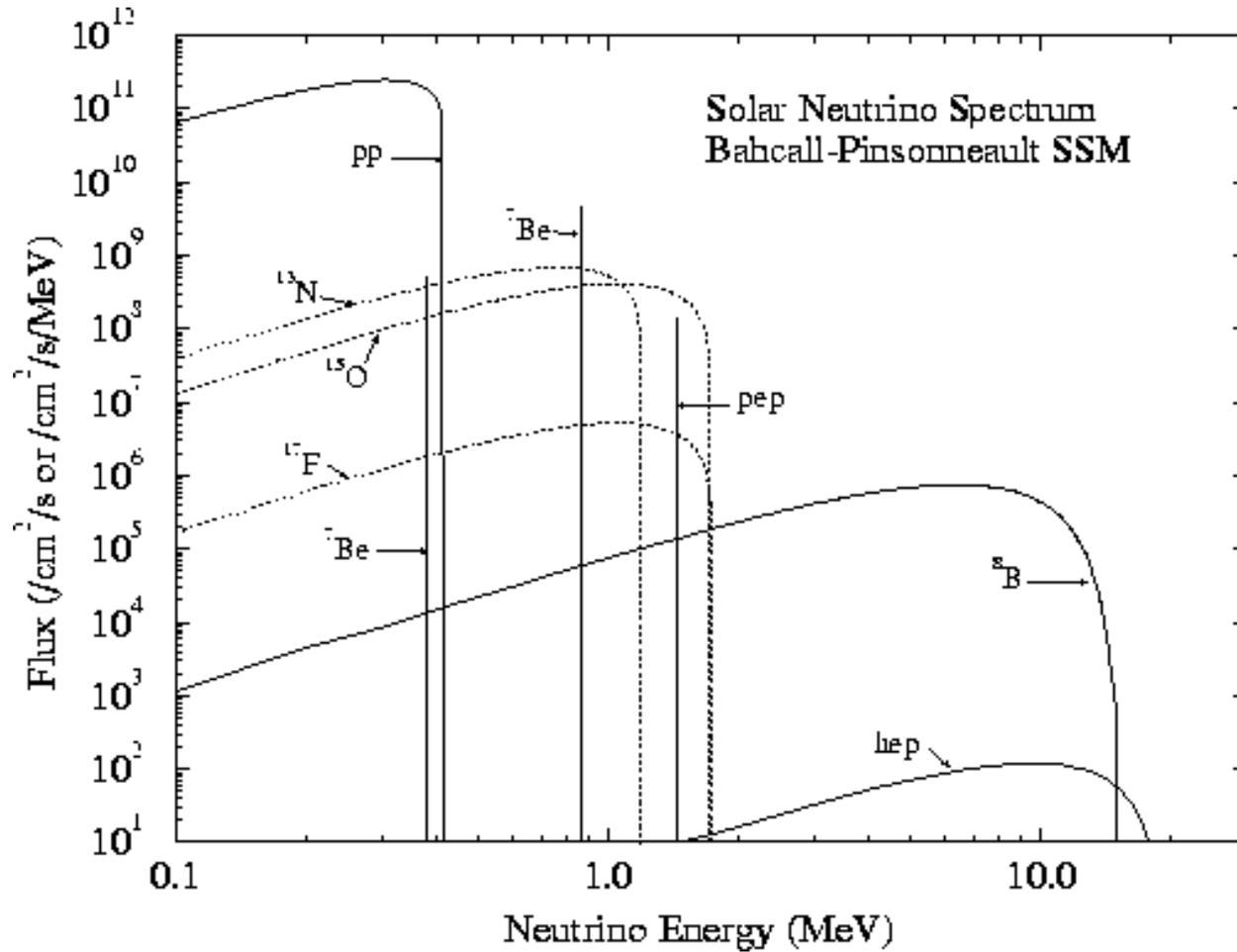
- Eddington (1920) 静止エネルギーは?

$$\frac{E}{M} = c^2 = 9 \times 10^{20} \text{ erg/g}$$

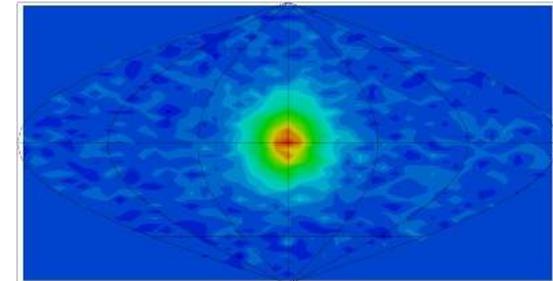
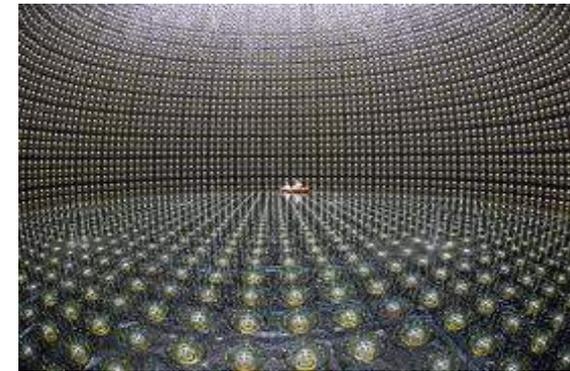
- ~10兆年輝ける!
- しかしどうやって静止エネルギーを輻射に変換するのか不明だった.
- 1930年代 核反応ではないか?
- 1938年 ワシントンで天体物理学者と物理学者を Gamov が招集



太陽ニュートリノ



核反応 $\Rightarrow \nu$
Super Kamiokande
ニュートリノ振動



Davisが初めて測定. 予想の1/3!!



オーダー評価

- 宇宙では何桁にも渡るスケールが出てくる
- 桁(オーダー)を見積もる力が必要
- Enrico Fermi (1901-1954) が良く質問した
 - シカゴにいるピアノ調律師の数は?
 - 日本に電柱は何本あるか?
 - 台風と地震どちらのエネルギーが大きい?
 - 人間のエネルギー発生率は?
- Fermi推定, Fermi問題とも言われる.
- 実生活でも役立つ

人間は何Wか？

人間は何Wか？

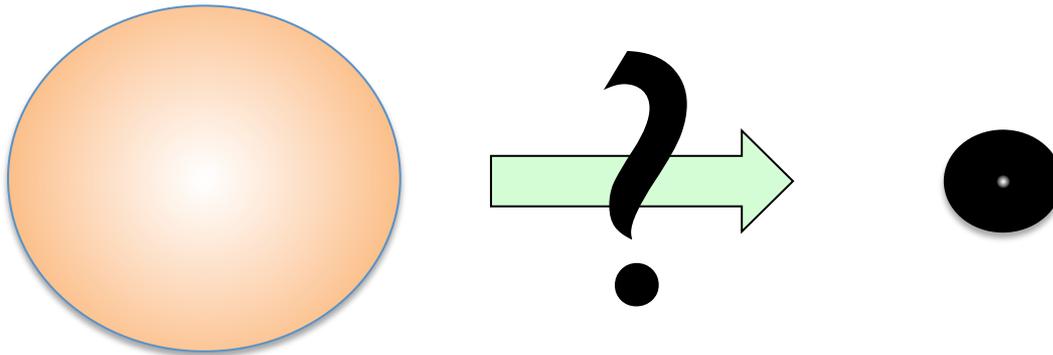
- 1日に $2000\text{kcal}=2000\text{k} \times 4.2 \text{ J}=8 \times 10^6 \text{ J}$
- $1 \text{ 日}=24\text{h} \times 60\text{m} \times 60\text{s}=86400\text{sec} \sim 10^5\text{sec}$
- これは $\sim 100\text{W}$
- 体重を50kgとすると $\sim 2\text{W/kg}$
- このエネルギー発生率は太陽の ~ 1 万倍!
- 部屋に10人いれば $\sim 1\text{kW}$ ~ヒーター並

核燃料は有限

- 重い星ほど中心温度が高く, 短寿命

$$t_{\text{age}} \sim 10^{10} \text{ yr} \left(\frac{M}{M_{\odot}} \right)^{-2.5}$$

- 寿命後潰れてブラックホールになる?



量子力学

- 波 = 粒子
- 1925年 Heisenbergの行列力学
- 1925年 Pauliの排他律
- 1926年 Schrödingerの波動力学
- 1927年 Heisenberg 不確定性原理

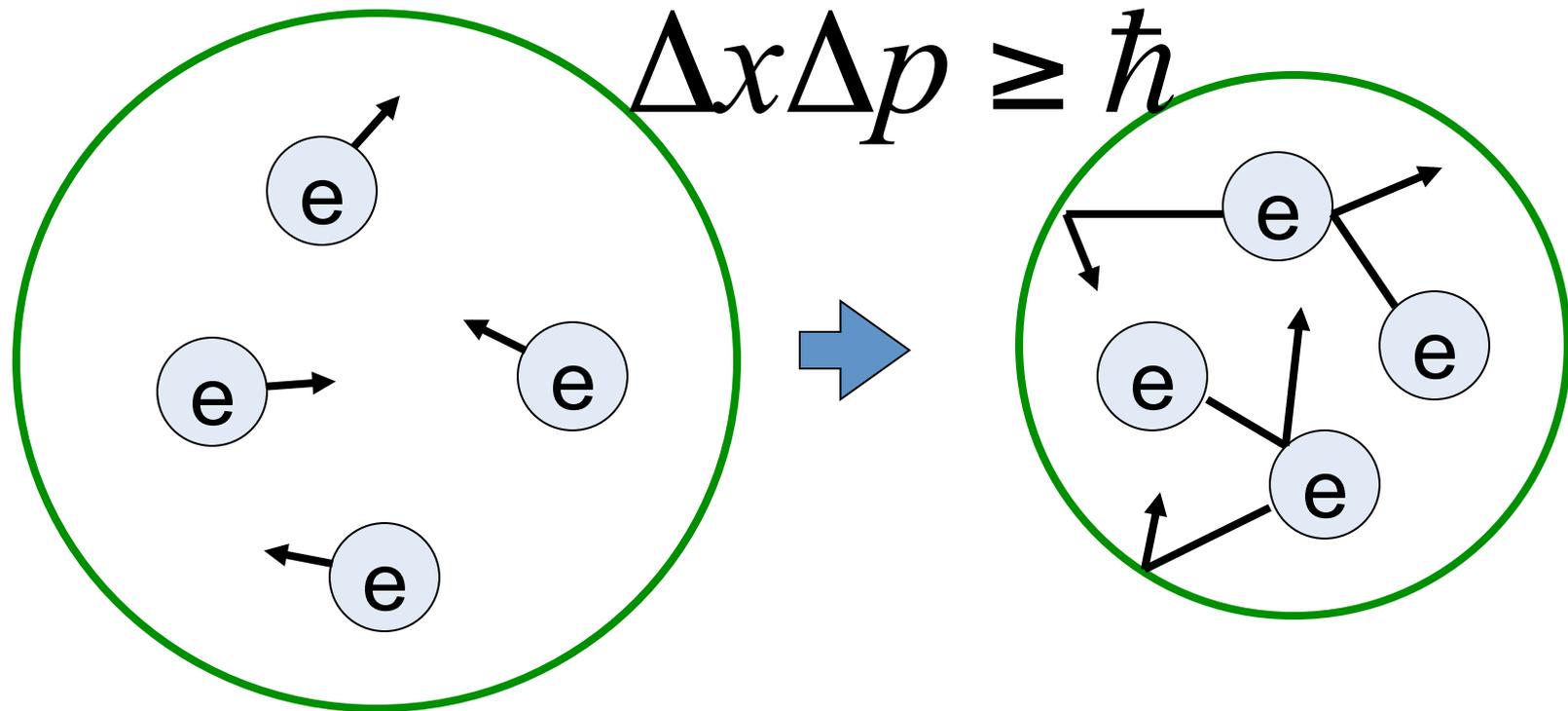
$$\Delta x \Delta p \geq \hbar$$



縮退圧

ガス圧⇒縮退圧で支える

Pauliの排他律＋不確定性原理の帰結



せまいところへ閉じ込めるほど圧力が上がる

白色矮星



Adams (1925)
Redshift in Sirius B
の観測で確実に



縮退圧で重力を支える
温度0でも存在

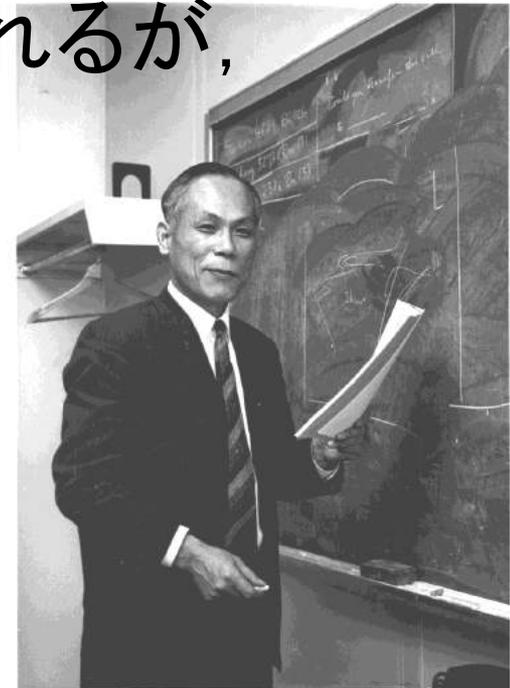
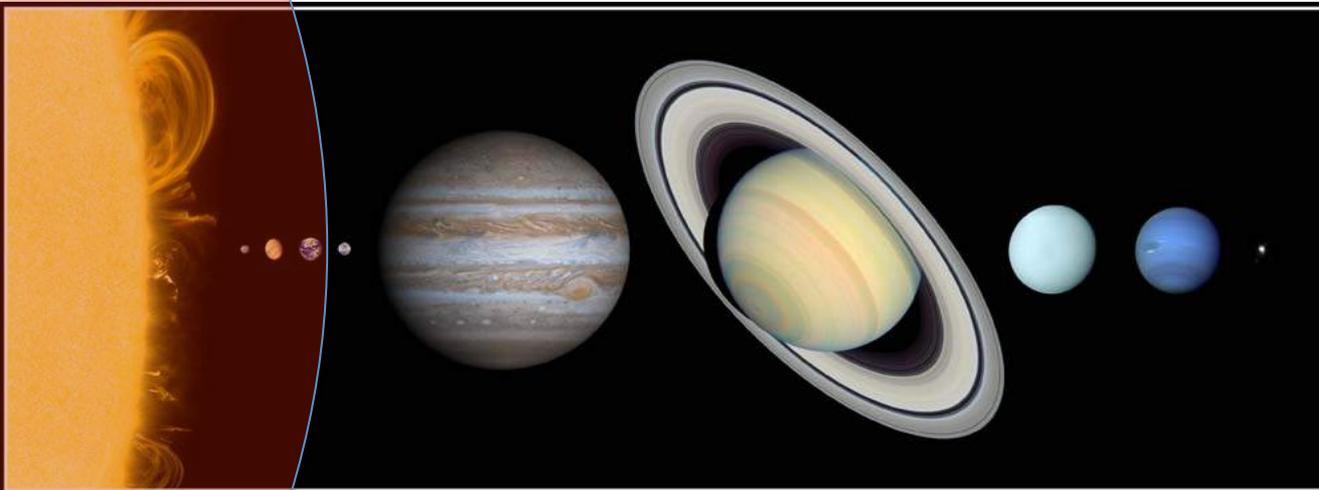
ガス圧で重力を支える

白色矮星の半径~地球半径~太陽半径/100

白色矮星の密度 ~1トン/cm³(角砂糖が1t)

巨星

- 太陽は白色矮星になる
- 白色矮星コア+外層 \Rightarrow 巨星になる
- 林フェイズにより大きさが制限されるが、
- 50億年後、地球は飲み込まれる



NASA G-68-10,414

林忠四郎

相対論的縮退

- ではすべての星は白色矮星になるか? No!
- 白色矮星には**最大質量**が存在する
- 質量が大きくなると粒子が**相対論的**に

- 縮退エネルギー

- 非相対論的 $E_F \sim \frac{p^2}{m} \propto \frac{1}{R^2}$

$$p \sim \frac{\hbar}{R/N^{1/3}}$$

- 相対論的 $E_F \sim pc \propto \frac{1}{R}$

- 重力エネルギー $E_G = -\frac{GMm_p}{R}$

チャンドラセカール質量

重さ

重い星の死

Chandrasekhar (1931)
1983年 Nobel賞

縮退エネルギー

$$E_F \sim \hbar n^{1/3} c$$

重力エネルギー

$$E_G \sim -\frac{GMm_p}{R} \sim -\frac{GNm_p^2}{R}$$

太陽の死

縮退圧
> 重力

半径

$$E = E_F + E_G \sim \frac{\hbar c N^{1/3}}{R} - \frac{GNm_p^2}{R}$$

全エネルギー

$$N_{\max} \sim \left(\frac{\hbar c}{Gm_p^2} \right)^{3/2} \sim 2 \times 10^{57}$$

最大粒子数

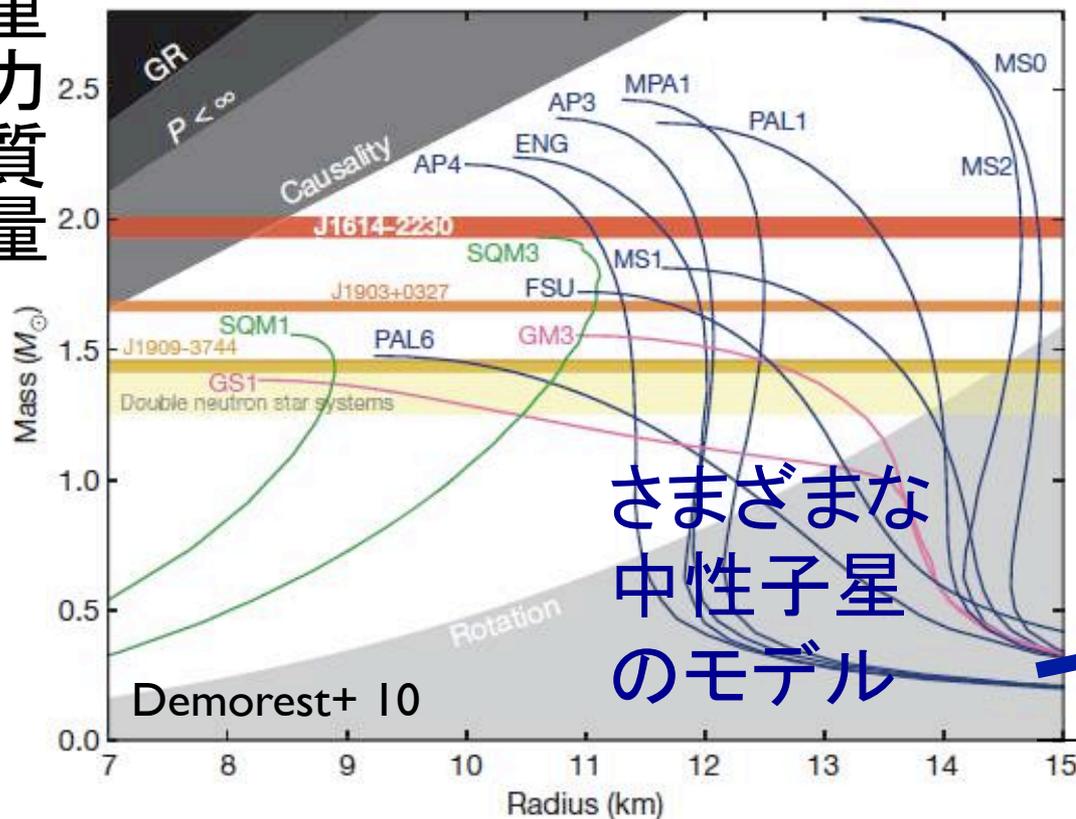
$$M_{\max} \sim N_{\max} m_p \sim 4 \times 10^{33} \text{ g}$$

最大質量



中性子星

重力質量



さまざまな
中性子星
のモデル

安定な
白色矮星

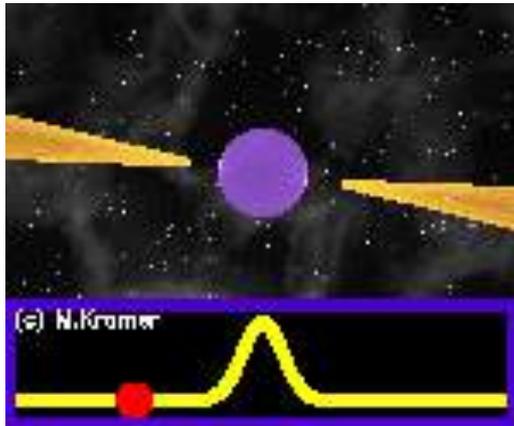
半径 R
 $\sim 10^3 - 10^4 \text{ km}$

白色矮星: 電子の縮退圧
中性子星: 中性子の縮退圧
同様に最大質量あり

Chadwick 1932 中性子の発見
1935 Nobel賞 

Baade & Zwicky 1934
中性子星の予言

パルサー

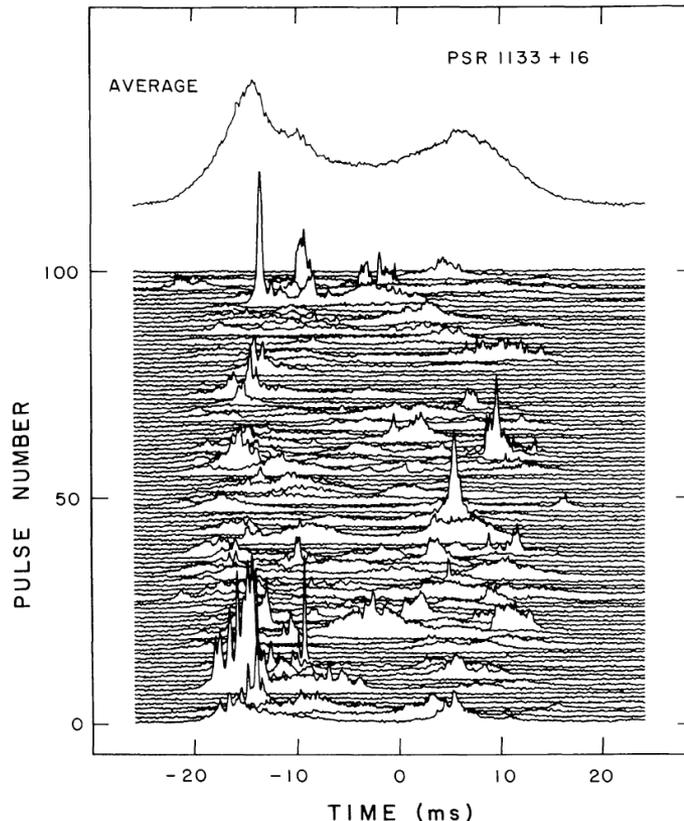


Bell (大学院生), Hewish 1967
 1974年Nobel賞 (Hewishのみ)
 (同年 Ryle 電波干渉)



規則的な電波源

宇宙人 (Little green man) 説もあった
 700回転/秒のものもある
 ⇒ 密度が異常に高い天体



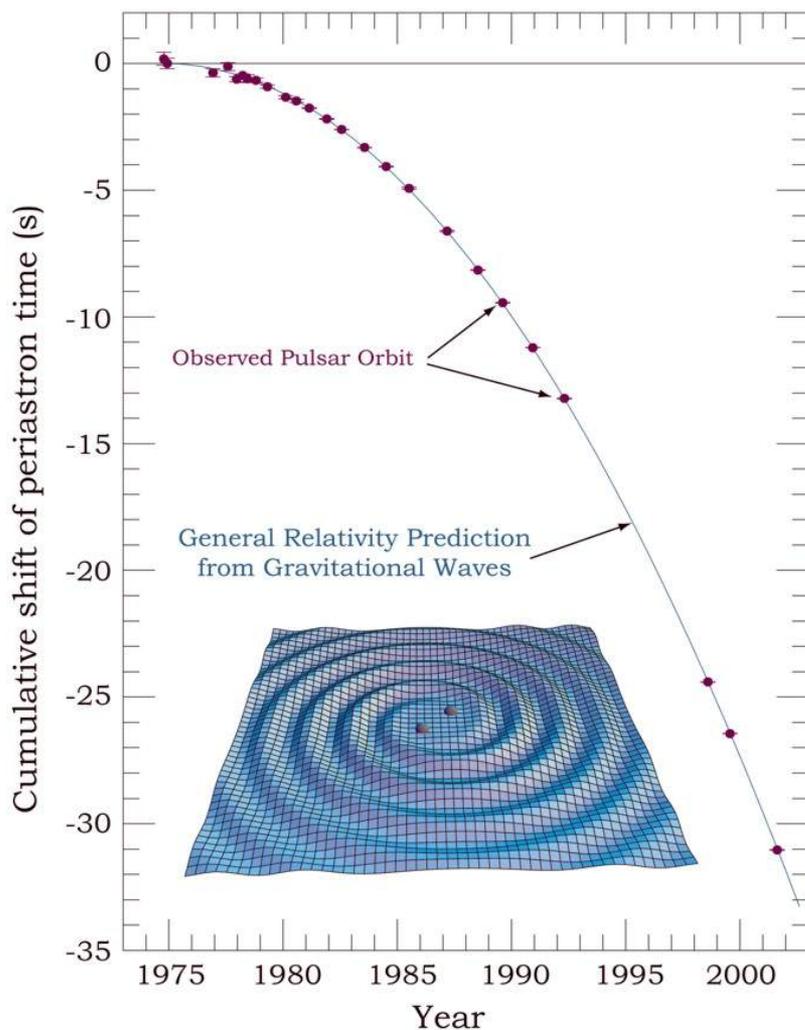
$$\frac{GM}{R^2} > R\Omega^2 \quad (\text{重力} > \text{遠心力})$$

$$\bar{\rho} > \frac{3\Omega^2}{4\pi G} \sim 5 \times 10^{13} \text{ g cm}^{-3}$$

原子核の密度 $\sim 3 \times 10^{14} \text{ g cm}^{-3}$
 ⇒ 中性子星 ($e+p \rightarrow n+\nu$)

Fig. 1. A sequence of 100 pulses from PSR1133+16 recorded at 600 MHz. An average of 500 pulses is shown at the top.

重力波の間接観測



重力波は間接的には存在が証明されていた

連星パルサーPSR B1509-58
重力波放出によって公転周期が変化



Hulse
Taylor
1993 Nobel賞



星の進化

中心で核融合

水素→ヘリウム→炭素→…→鉄
星の進化は主に**質量**で決まる

$M < 0.08 M_{\text{太陽}}$	水素が燃えない → 褐色矮星
$0.08 M_{\text{太陽}} < M < 0.45 M_{\text{太陽}}$	ヘリウムが燃えない →ヘリウムの白色矮星
$0.45 M_{\text{太陽}} < M < 8 M_{\text{太陽}}$	炭素が燃えない → 炭素の白色矮星
$8 M_{\text{太陽}} < M < 13 M_{\text{太陽}}$	Ne、Mgまで進む。電子捕獲後 超新星爆発して中性子星？
$13 M_{\text{太陽}} < M$	鉄まで進み重力崩壊。 外層が飛べば中性子星？ 失敗すればブラックホール

(境目の質量はよく分かっていない)



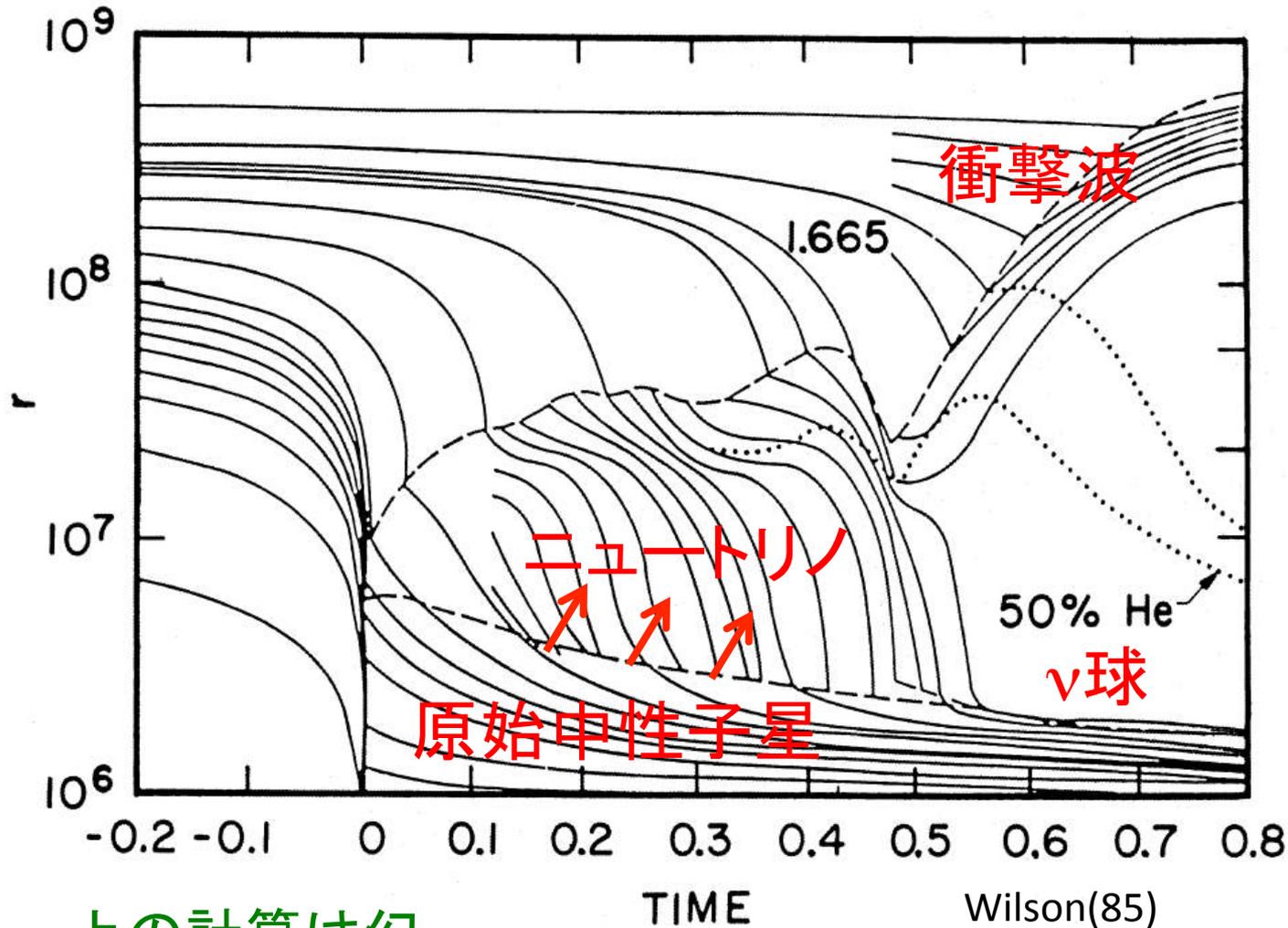
超新星1987A



爆発後

爆発前

超新星爆発



電子捕獲
鉄の光分解
⇒不安定化
⇒重力崩壊

核密度で
急に硬くなる

$$E_{\text{重力}} = \frac{GM^2}{R}$$

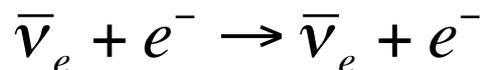
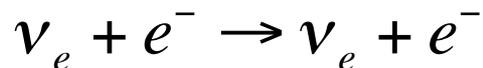
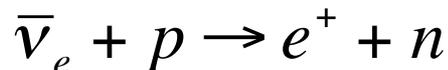
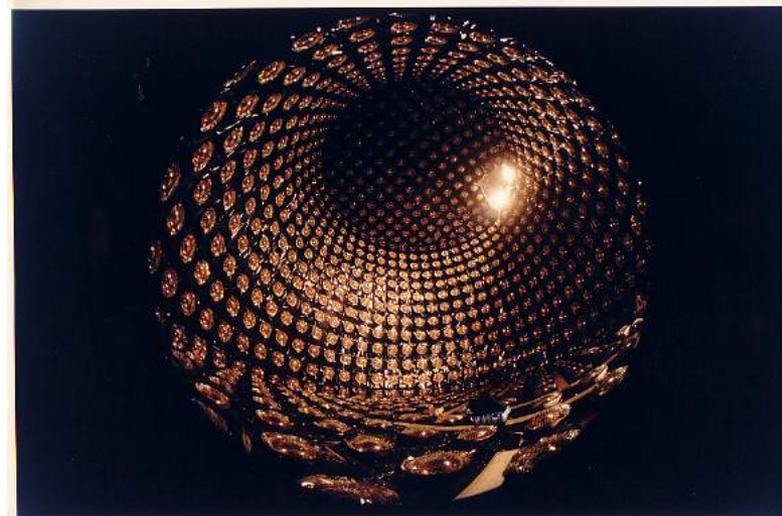
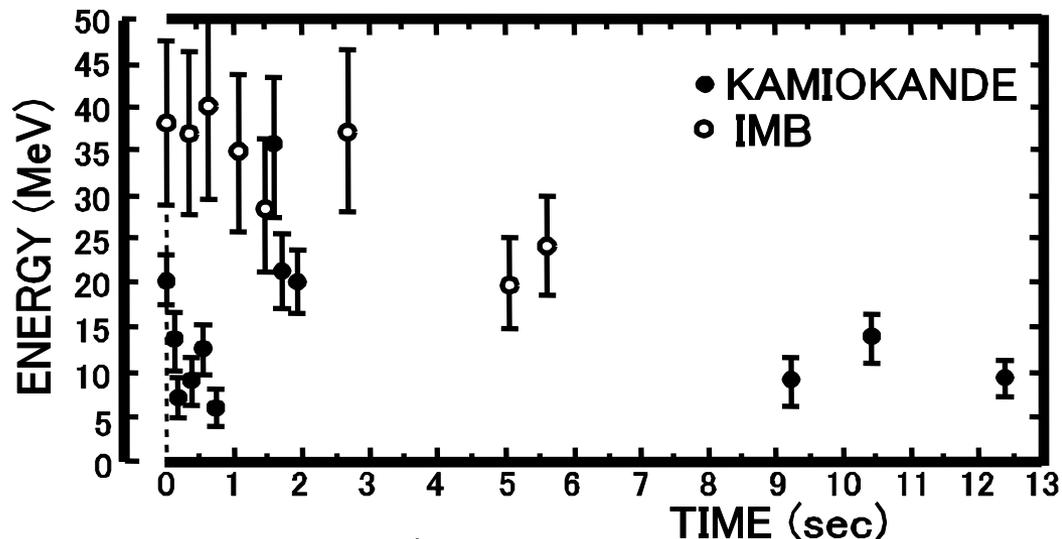
$$\sim 10^{53} \text{ erg}$$

~99%はν

上の計算は幻

まだ数値計算で完全な超新星爆発を起こせない

超新星ニュートリノ



Reines
1956 ν 発見
1995 Nobel賞
Davis
Koshiba
2002 Nobel賞



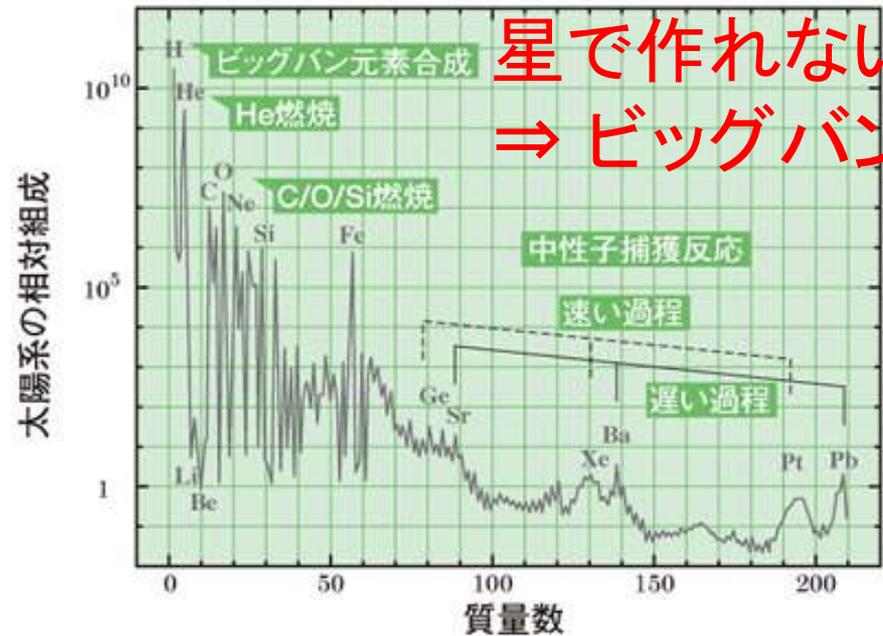
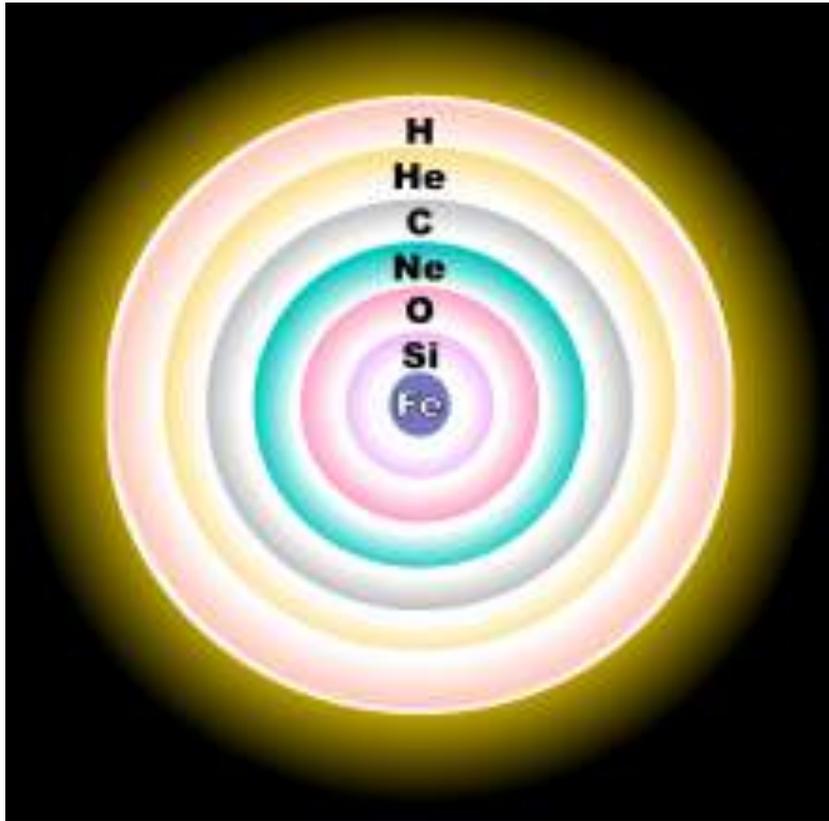
~3000tの水, チェレンコフ光

13秒間でKamiokandeが11事象, IMBが8事象.

⇒ 球対称だと $\sim(3 \pm 1) \times 10^{53} \text{erg}$ ~中性子星の重力エネルギー

元素の起源

逆にHeをすべて
星で作れない
⇒ ビッグバン



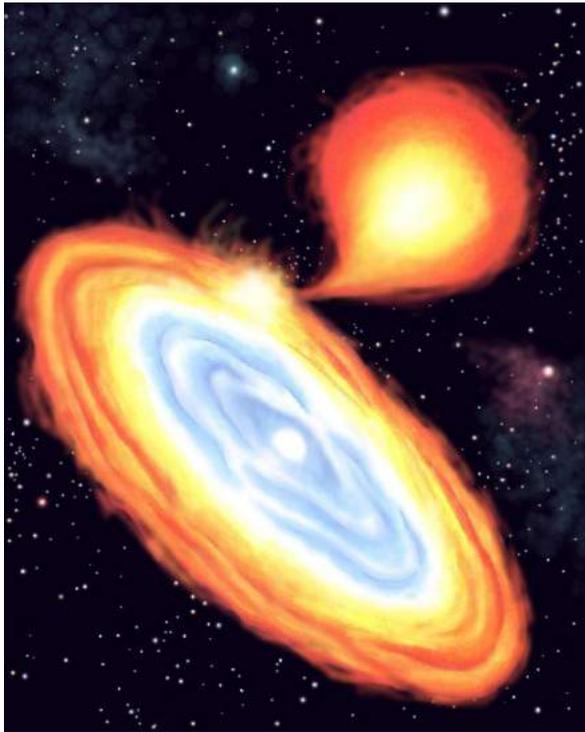
核融合で生まれた重元素は
超新星爆発によって宇宙に。
地球や我々の体の源。



W.A. Fowler
1957 review 著作
1983 Nobel賞
shared w/ Chandra



X線連星



重力エネルギーを開放して光る

$$L = \frac{GM}{R} \frac{dM}{dt} \sim 10^{38} \frac{dM/dt}{10^{17} \text{ g/s}} \text{ erg/s}$$

温度は

$$T \sim \left(\frac{L}{4\pi R^2 \sigma_{SB}} \right)^{1/4} \quad (\text{量子力学})$$

$$\sim 2 \times 10^7 \left(\frac{L}{10^{38} \text{ erg/s}} \right)^{1/4} \left(\frac{10^6 \text{ cm}}{R} \right)^{1/2} \text{ K}$$

ちょうどX線ぐらい



Giacconi
1962 Cyg X-1発見
2002 Nobel賞



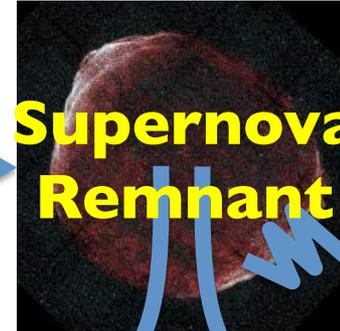
Evolution to Black Hole



Star



Supernova GRB

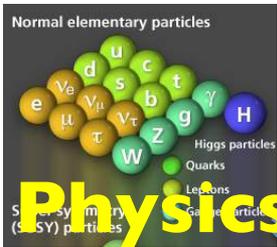


Supernova Remnant

W. A. Fowler



Gravity
Quantum

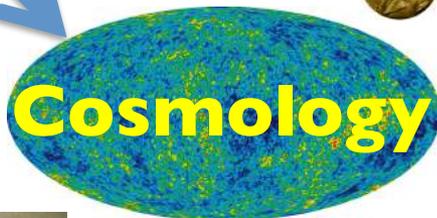


Physics

**Chandrasekhar
Bethe**

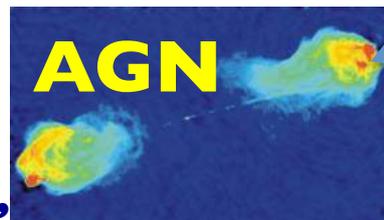


**Davis
Koshiba**



Cosmology

**Penzias, Wilson
Perlmutter, Riess,
Schmidt**



AGN

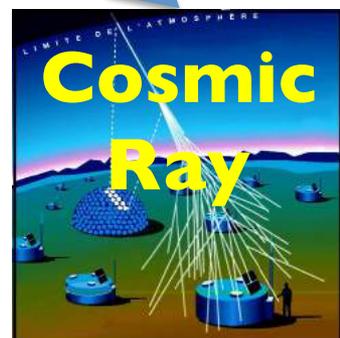
Active galactic nuclei
Massive black hole
at the center of galaxy



Compact Star

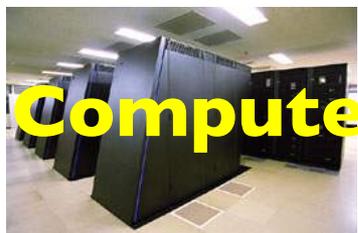
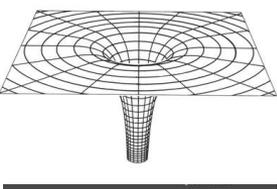
Black Hole
Neutron Star
White Dwarf

**Giacconi
Hewish
Hulse, Taylor**



Cosmic Ray

**Hess
Anderson
Yukawa
Powell
Kajita**

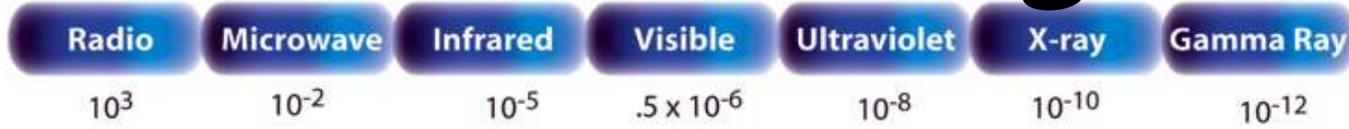


Computer

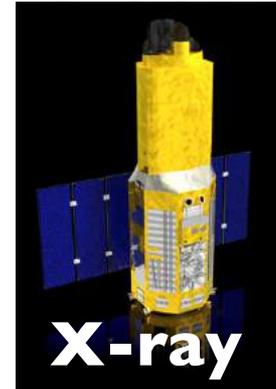
High Energy Universe

Multi-Wavelength

Wavelength
(meters)

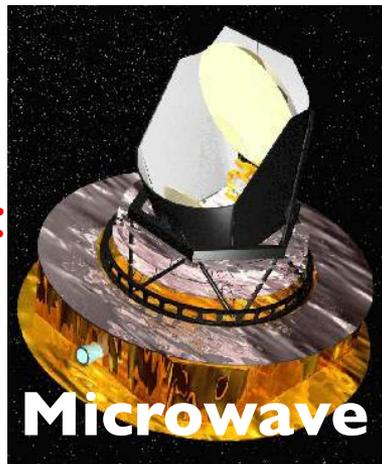


About the size of...



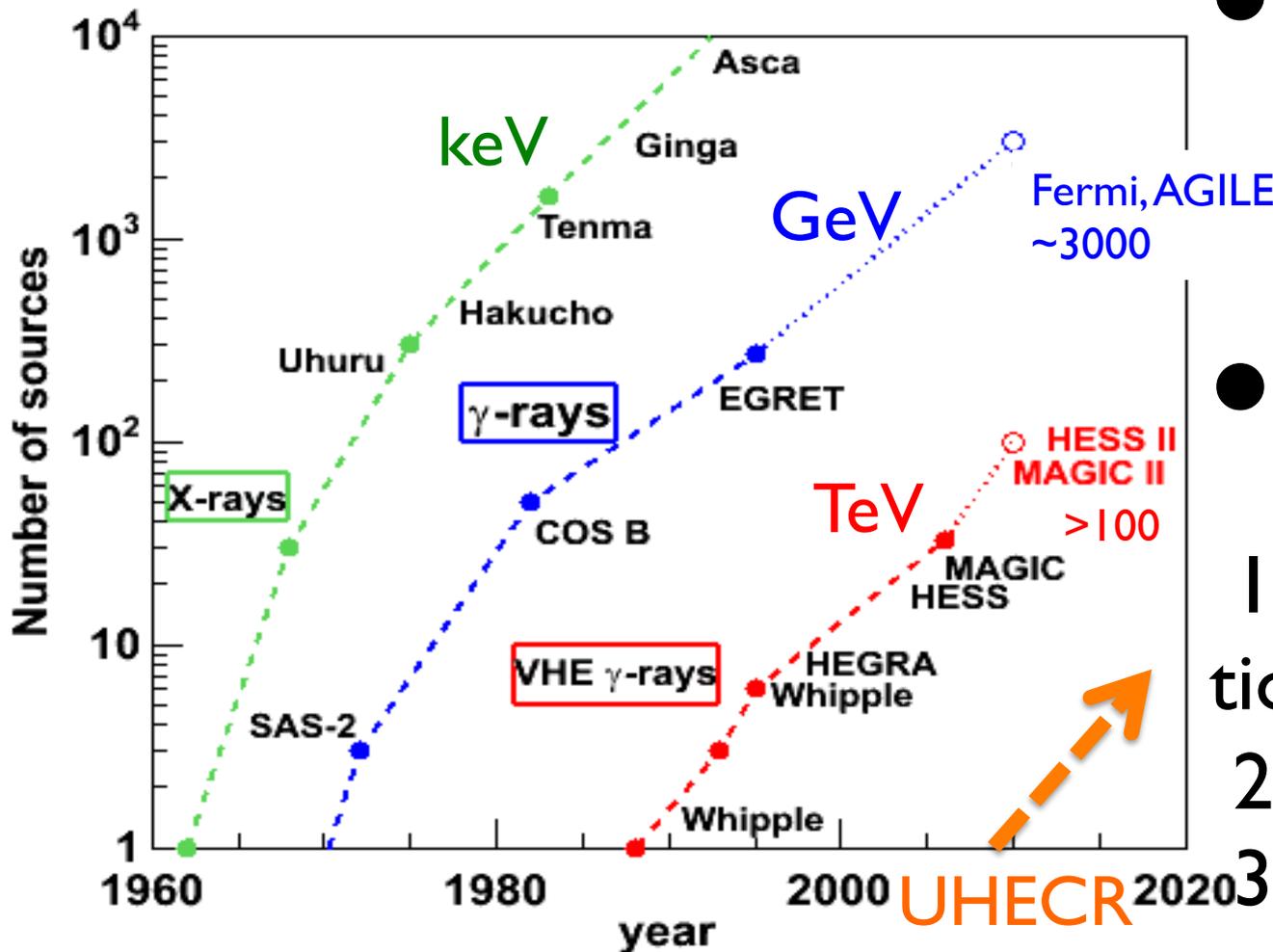
TeV = 10^{12} eV
 GeV = 10^9 eV

20th century observations:
 In particular,
 X- γ -VHE γ



Explosive Discoveries

Kifune Plot



- # of sources are increasing exponentially

High Energy Universe

1. Origin & Evolution (CR, Jet, ...)
2. \Leftrightarrow Cosmology
3. \Leftrightarrow Fund. Physics

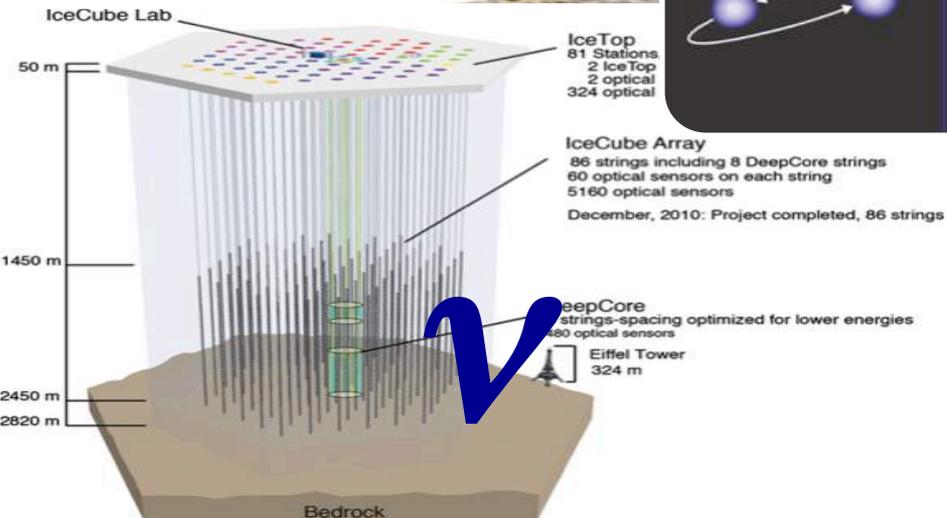
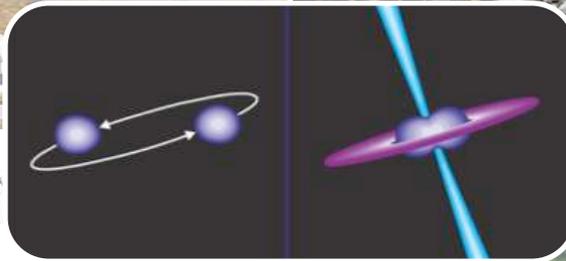
UHECR
 ν , GW

Multi-Messenger

Photon



Cosmic Ray



Gravitational Wave

21st Century: Multi-Messenger Era

詳しくは

KEK物理学シリーズ

3

宇宙物理学



高エネルギー加速器研究機構 [監修]

[著]
小玉英雄
井岡邦仁
郡 和範

- KEK素粒子原子核研究所に創設された宇宙物理学理論グループの現在のメンバーが総力を結集して書いた宇宙物理学の教科書。
- 素粒子宇宙論、高エネルギー天体物理、宇宙線の全般についてその基礎から最前線の研究までカバーする。
- 1章：宇宙の姿
- 2章：星の構造・進化
- 3章：超新星爆発とガンマ線バースト
- 4章：中性子星、ブラックホール
- 5章：高エネルギー宇宙線・ γ ・ ν や重力波
- 6章：宇宙マイクロ波背景放射(CMB)
- 7章：宇宙初期における元素合成
- 8章：ダークマター、バリオン数生成
- 9章：インフレーション

Thank

You

Test General Relativity

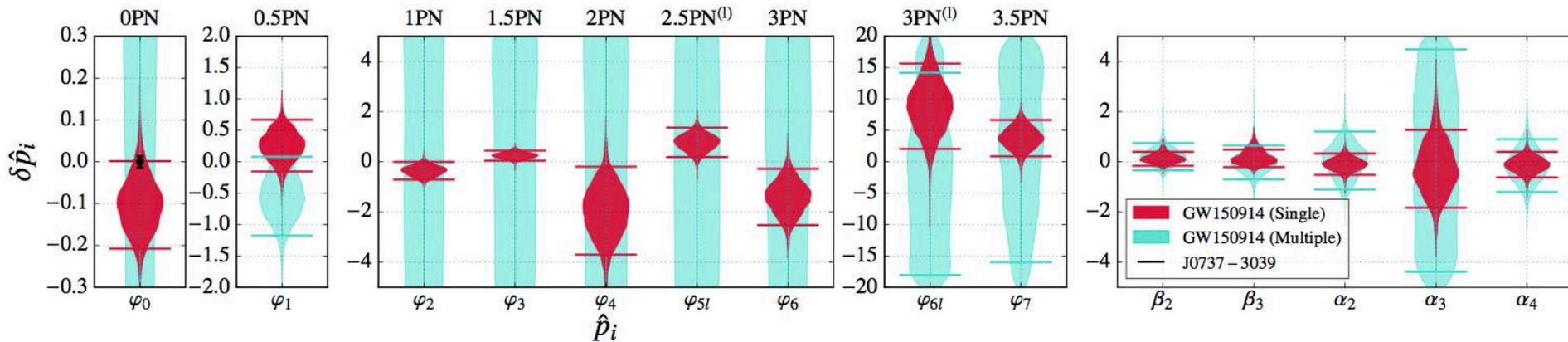


FIG. 7. *Violin* plot summarizing the posterior probability density distributions for all the parameters in the gIMR model. From left to right: the plot shows increasingly high-frequency regimes as outlined in the text and Fig. 5; the leftmost posteriors, labeled from 0PN to 3.5PN, are for the early-inspiral PN regime; the β_i and α_i parameters correspond to the intermediate and merger-ringdown regimes. Note that the constraints get tighter in the merger and ringdown regimes. In red, we show posterior probability distributions for the single-parameter analysis while in cyan we show the posterior distribution for the multiple-parameter analysis. The black error bar at 0PN show the bound inferred from the double pulsar; higher PN orders are not shown as their constraints are far weaker than GW150914’s measurement and they would appear in the plot as vertical black lines covering the entire y -axis. Summary statistics are reported in Table I. The 2.5PN term reported in the figure refers to the logarithmic term $\delta\hat{\varphi}_{5l}$. Because of their very different scale compared to the rest of the parameters, the 0PN and 0.5PN order posterior distributions from GW150914 and the double-pulsar limits at 0PN order are shown on separate panels. The error bars indicate the symmetric 90% credible regions reported in Table I. Due to correlations among parameters, the posterior distribution obtained from the multiple-parameter analyses in the early-inspiral regimes are informative only for the 0.5PN coefficient.

High- z BH-BH?

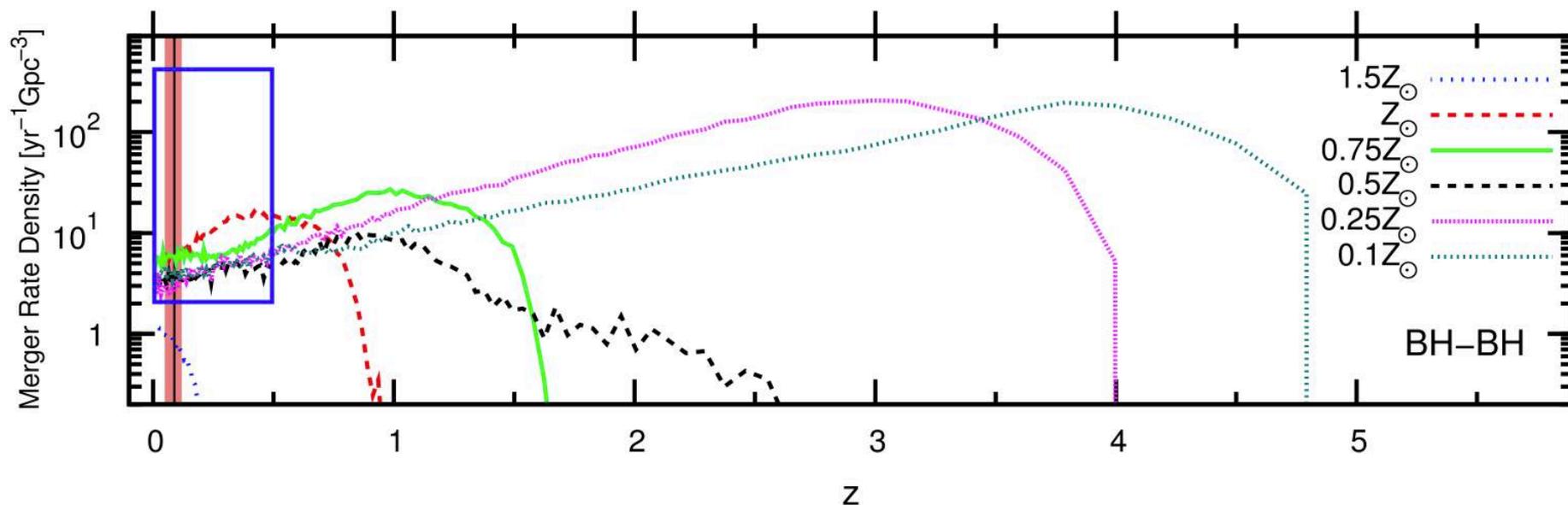
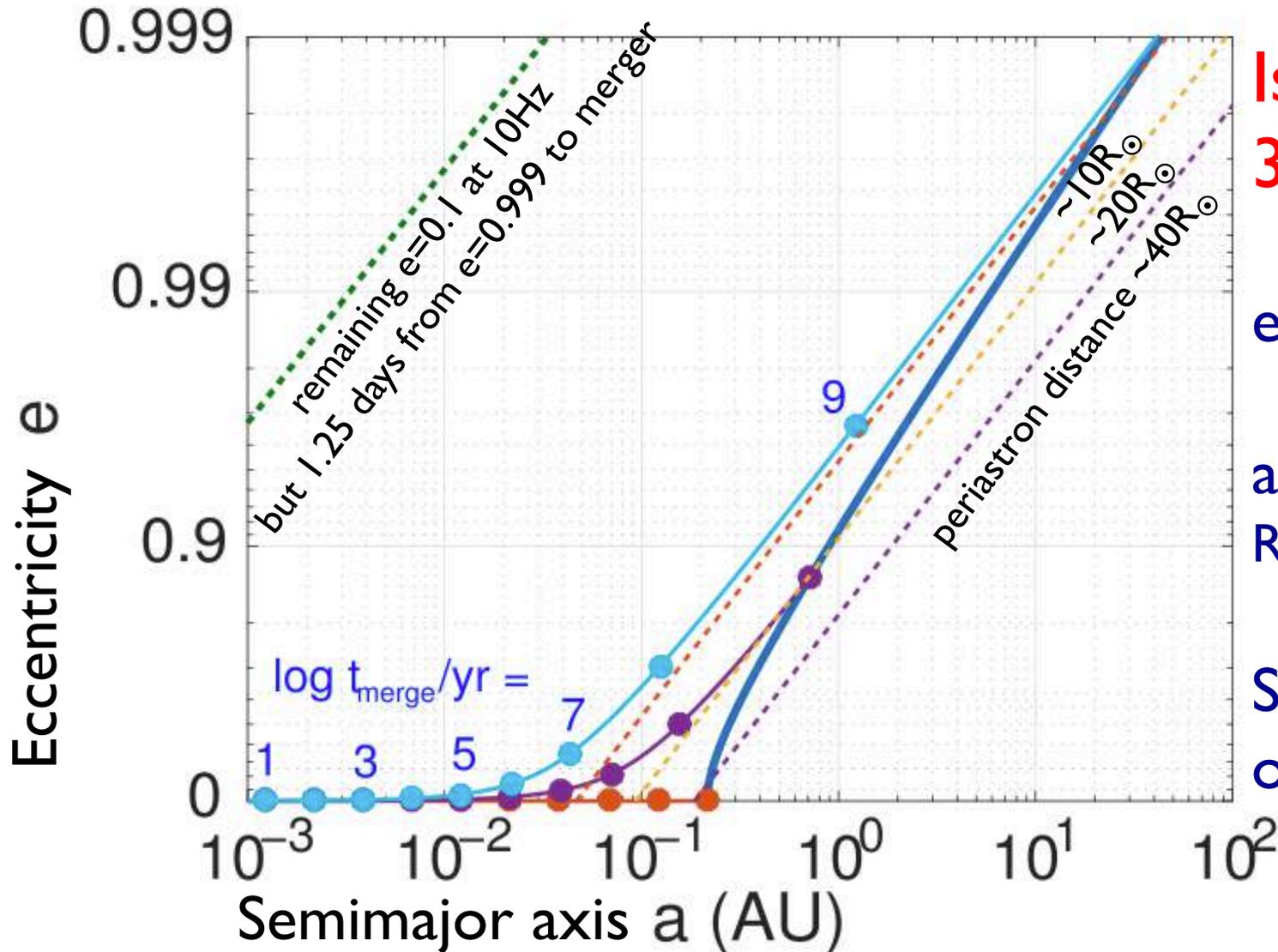


Figure 2. Predictions of BBH merger rate in the comoving frame ($\text{Gpc}^{-3} \text{yr}^{-1}$) from isolated binary evolution as a function of redshift for different metallicity values (adopted from Figure 4 in Dominik et al. 2013). At a given redshift, the total merger rate is the sum over metallicity. The redshift range of GW150914 is indicated by the vertical band; the range of the BBH rate estimates and the redshift out to which a system like GW150914 could have been detected in this observing period are indicated by an open blue rectangular box.

LIGO 16 (astro)
Dominik+ 13

Initial a & e



Isolated or
3-body?

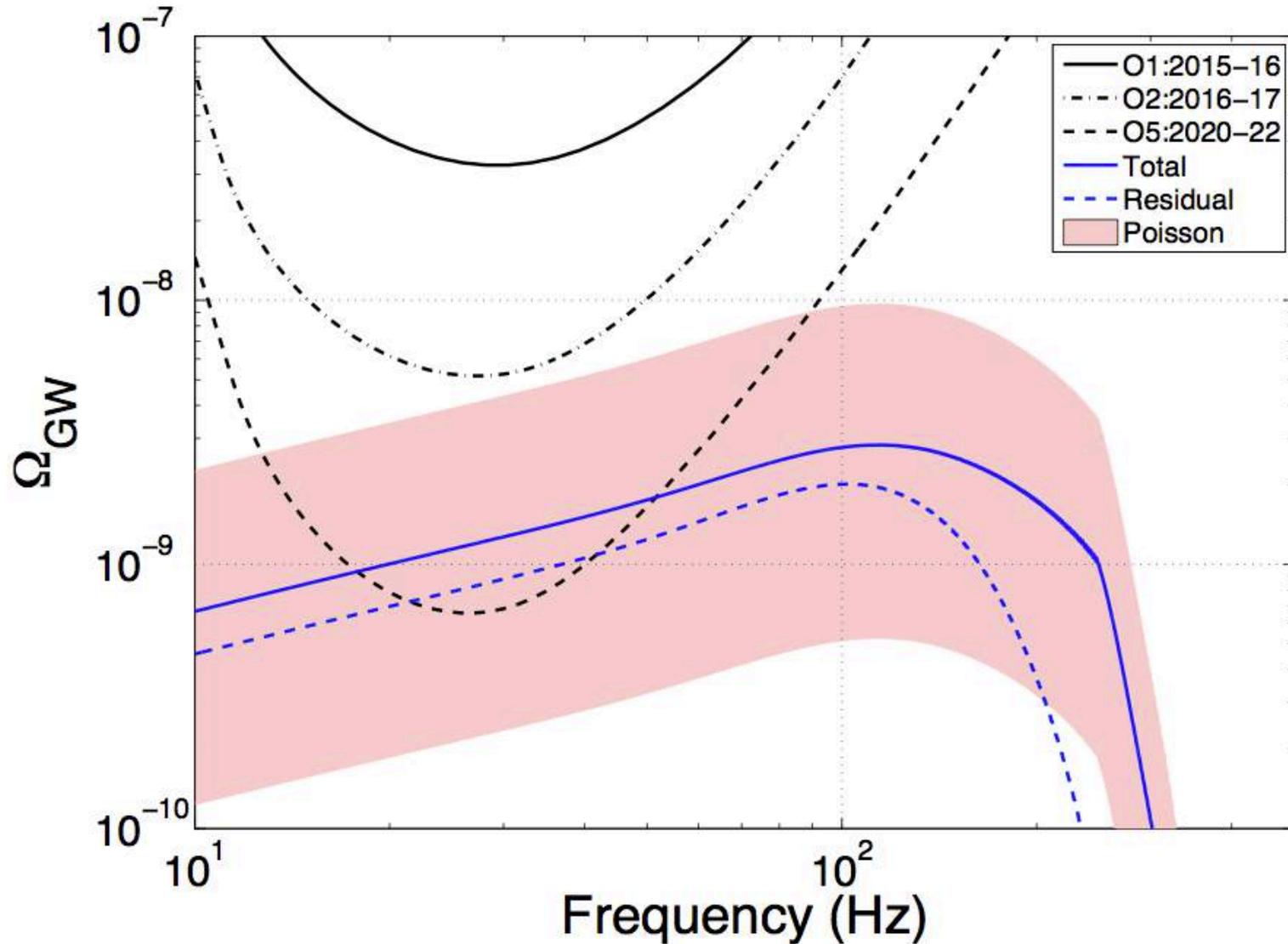
e may be small

$a \Leftrightarrow$ giant?

Rotation, PopIII?

Spins aligned
or misaligned?

Stochastic Background



重力波

電荷が加速度運動⇒電磁波：真空中を光速で進む横波

質量が加速度運動⇒重力波：真空中を光速で進む横波

1918年に一般相対性理論にもとづいてアインシュタインが予言

NS-NSやNS-BH連星の合体は重力波の強力な源



重力波を放出するとエネルギーを失う。重力エネルギーは $E = -GM^2/r$ なので、距離が縮まって合体

