ITER/BA成果報告会2019
核融合エネルギーフォーラム

重力波で見えてきた新しい宇宙の姿
低温重力波検出器KAGRAの現状と今後

国立天文台 重力波プロジェクト
麻生 洋一

Periodic Table

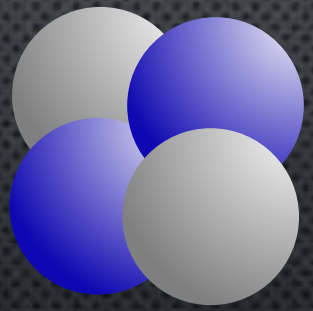
The Royal Society of Chemistry's interactive periodic table features history, alchemy, podcasts, videos, and data trends across the periodic table. Click the tabs at the top to explore each section. Use the buttons above to change your view of the periodic table and view Murray Robertson's stunning Visual Elements artwork. Click each element to read detailed information.

H 1																	He 2
Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
Cs 55	Ba 56	La 57	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
Fr 87	Ra 88	Ac 89	Rf 104	Db 105	Sg 106	Bh 107	Hs 108	Mt 109	Ds 110	Rg 111	Cn 112	Nh 113	Fl 114	Mc 115	Lv 116	Ts 117	Og 118

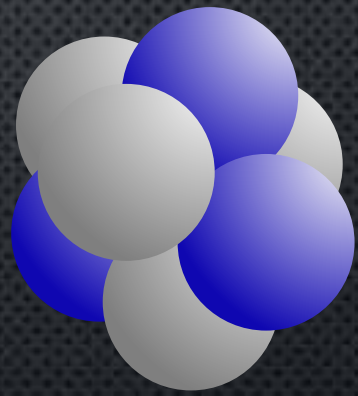
Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103

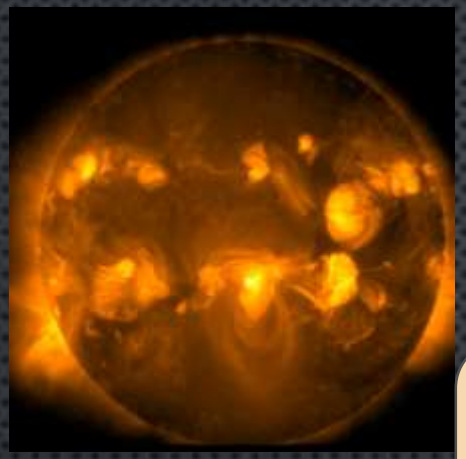
H

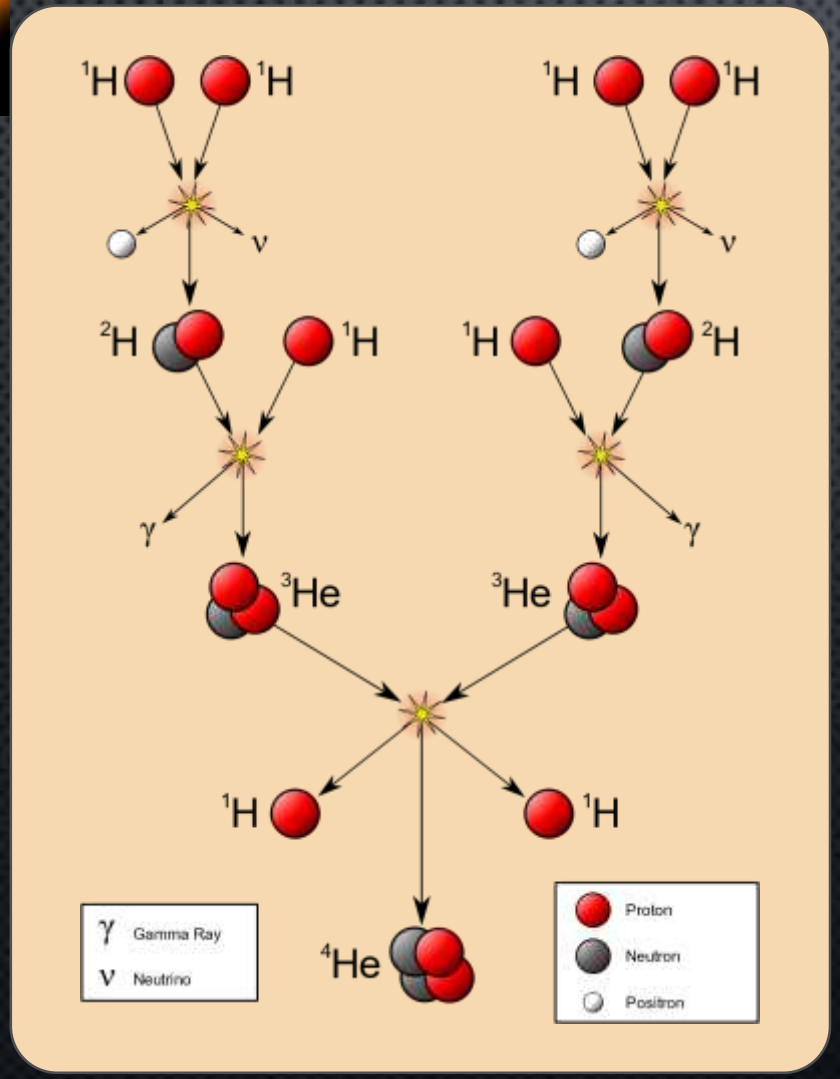
He

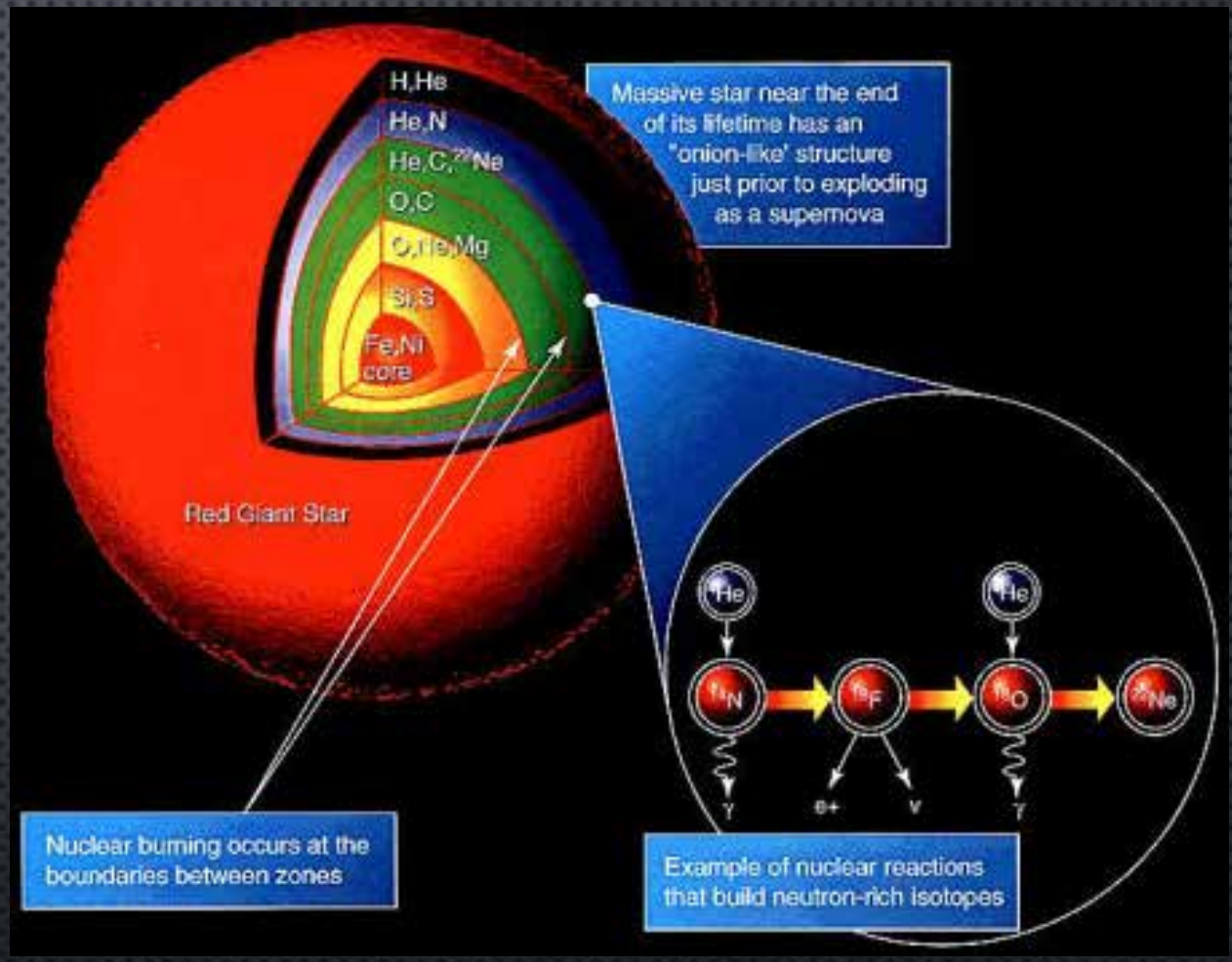


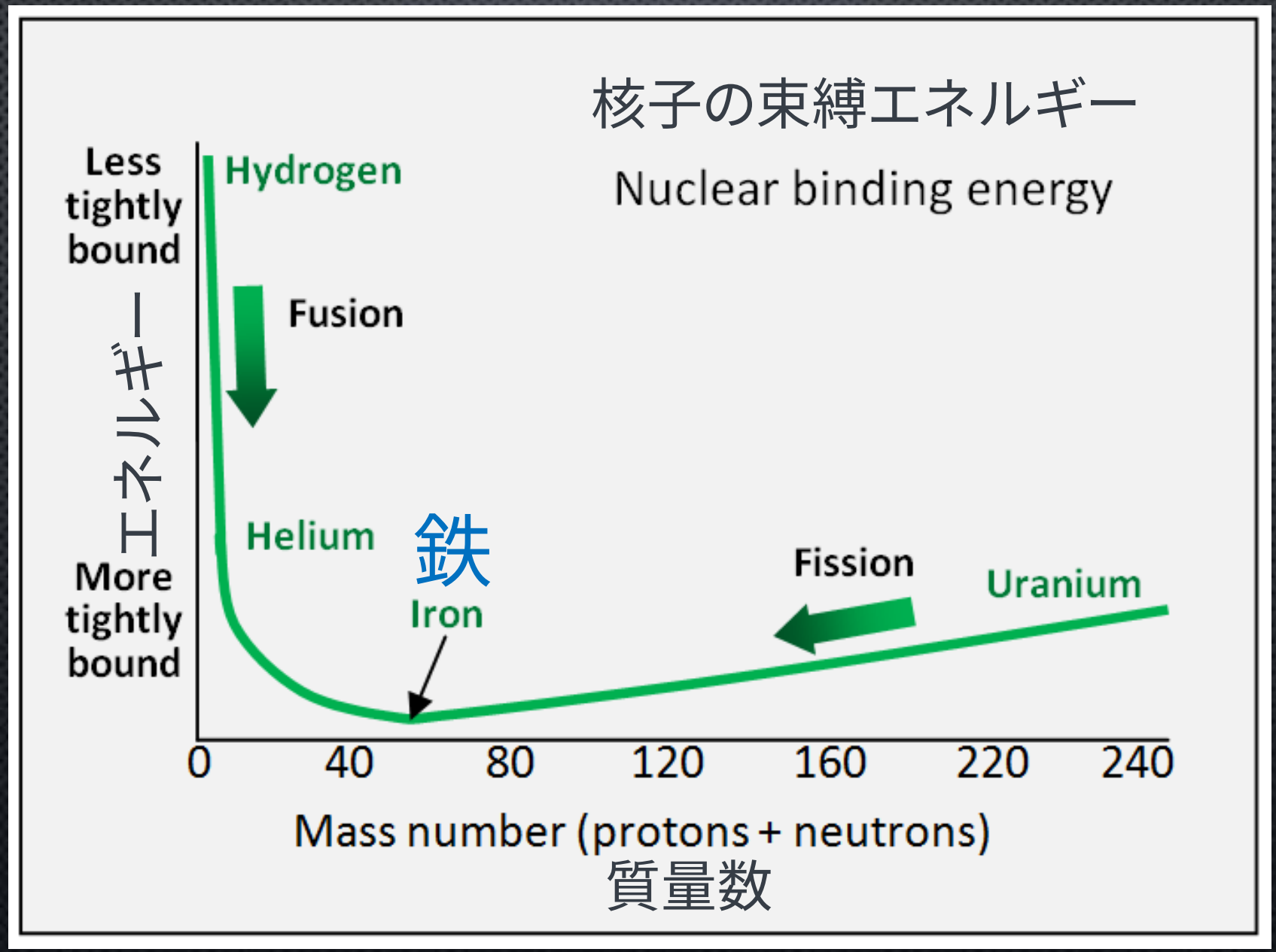
Li

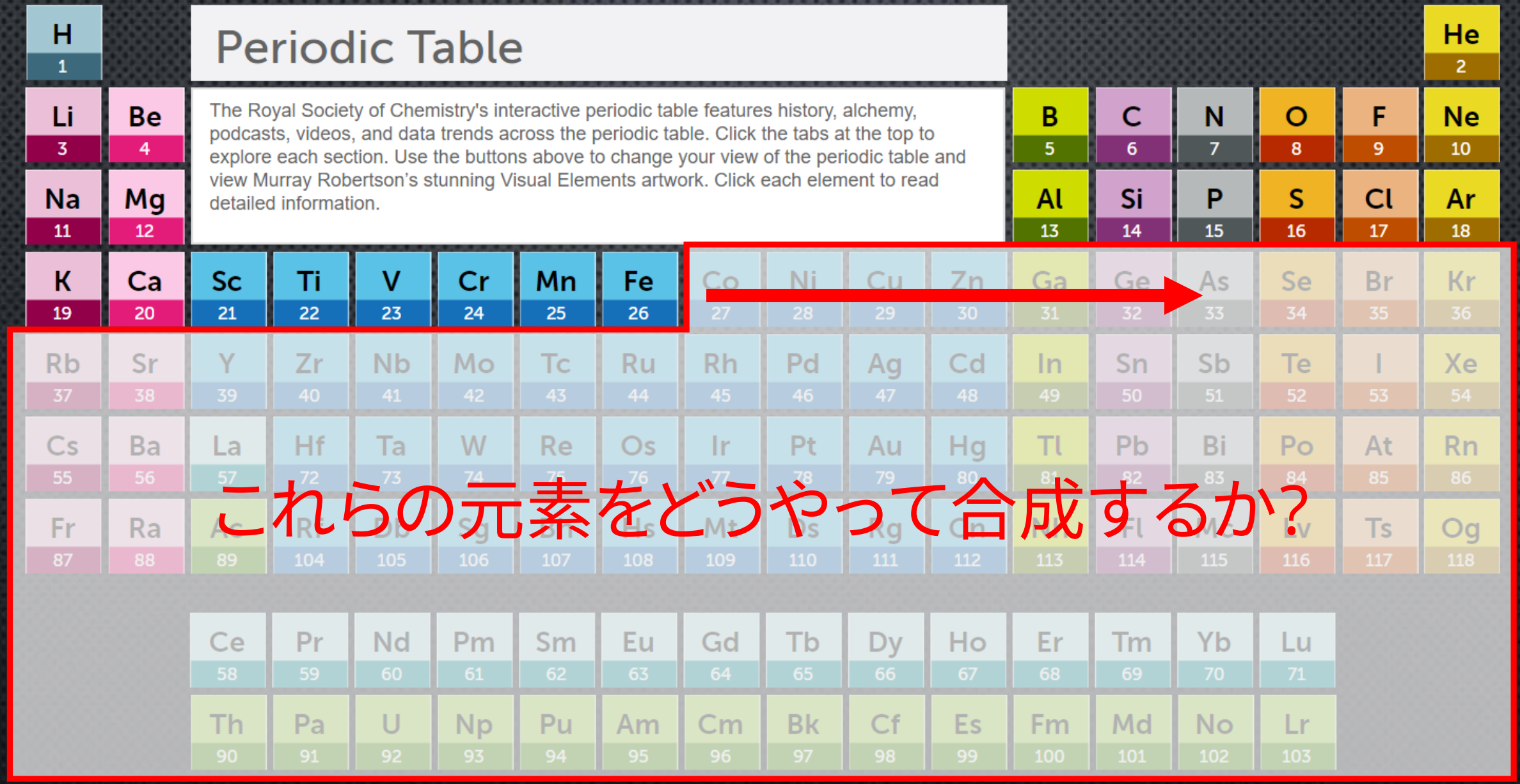





^1H ^1H
ν
^2H ^1H
γ
^3He
^1H ^1H
ν
^1H ^2H
γ
^3He
^1H ^1H
^4He
γ Gamma Ray
ν Neutrino
Proton
Neutron
Positron


H,He
He,N
He,C,^{22}Ne
O,C
O,Ne,Mg
Si,S
Fe,Ni core
Red Giant Star
Massive star near the end of its lifetime has an "onion-like' structure just prior to exploding as a supernova
Nuclear burning occurs at the boundaries between zones
^4He
^{13}N
^{18}F
^{18}O
^{22}Ne
γ
$\beta+$
ν
γ
Example of nuclear reactions that build neutron-rich isotopes


核子の束縛エネルギー
Nuclear binding energy
Less tightly bound
エネルギー
More tightly bound
Hydrogen
Fusion
Helium
鉄
Iron
Fission
Uranium
0
40
80
120
160
220
240
Mass number (protons + neutrons)
質量数


Periodic Table
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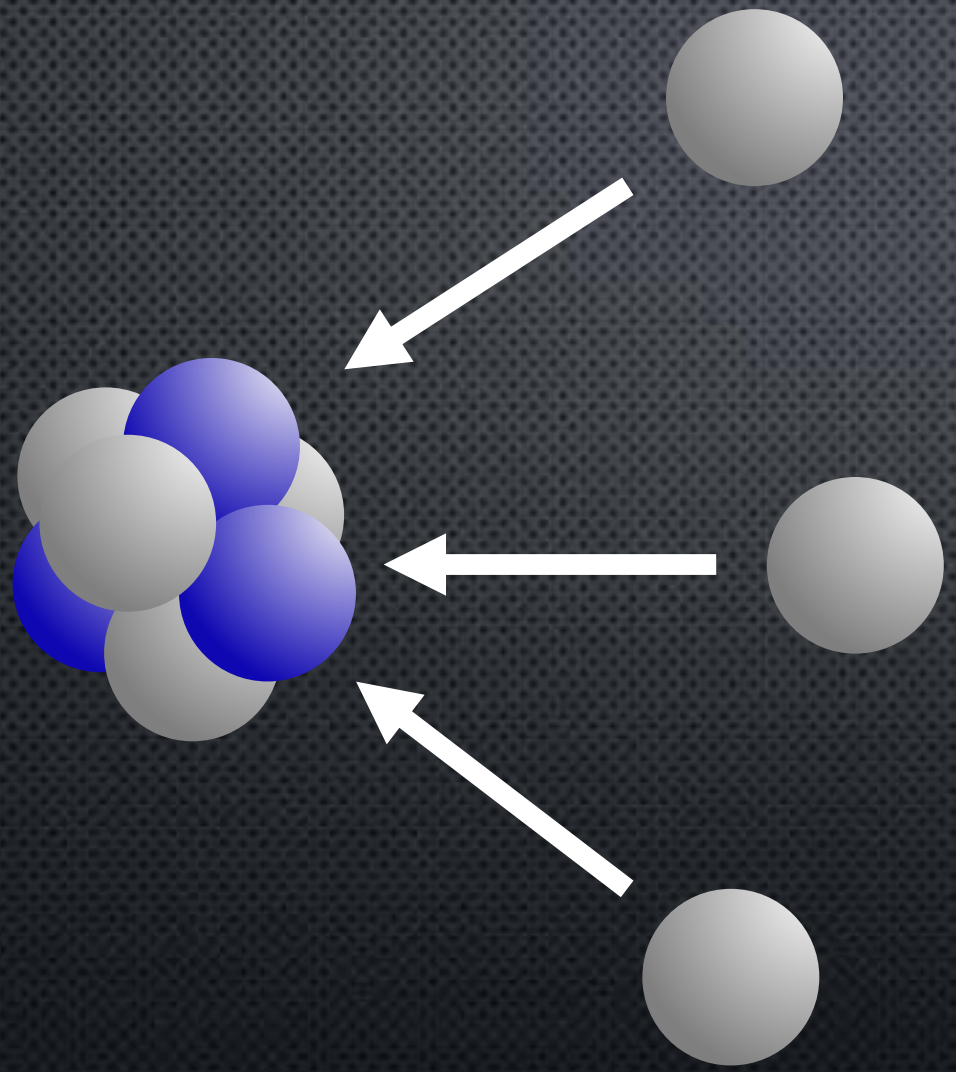
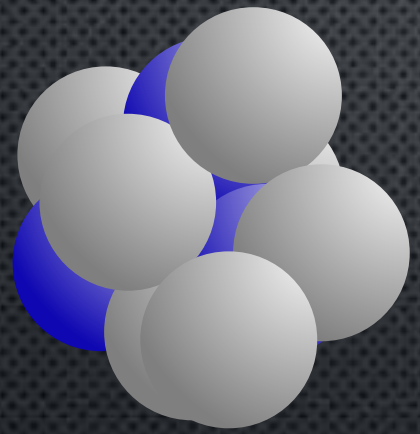
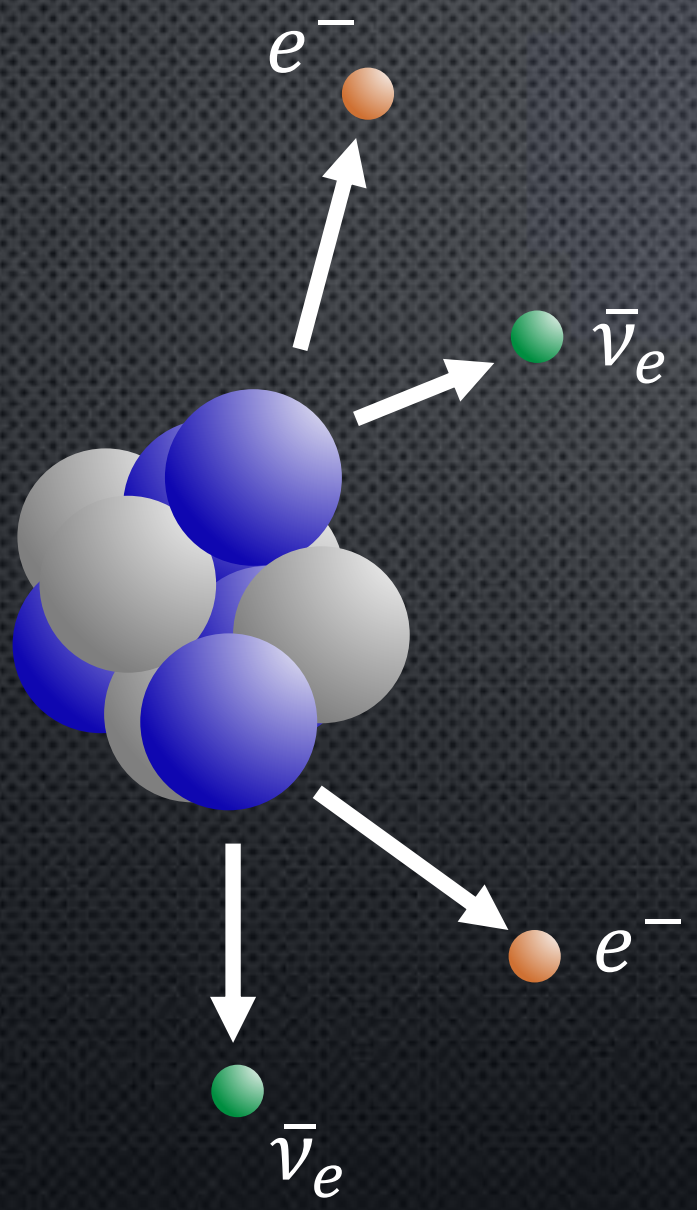
これらの元素をどうやって合成するか?

重い原子核

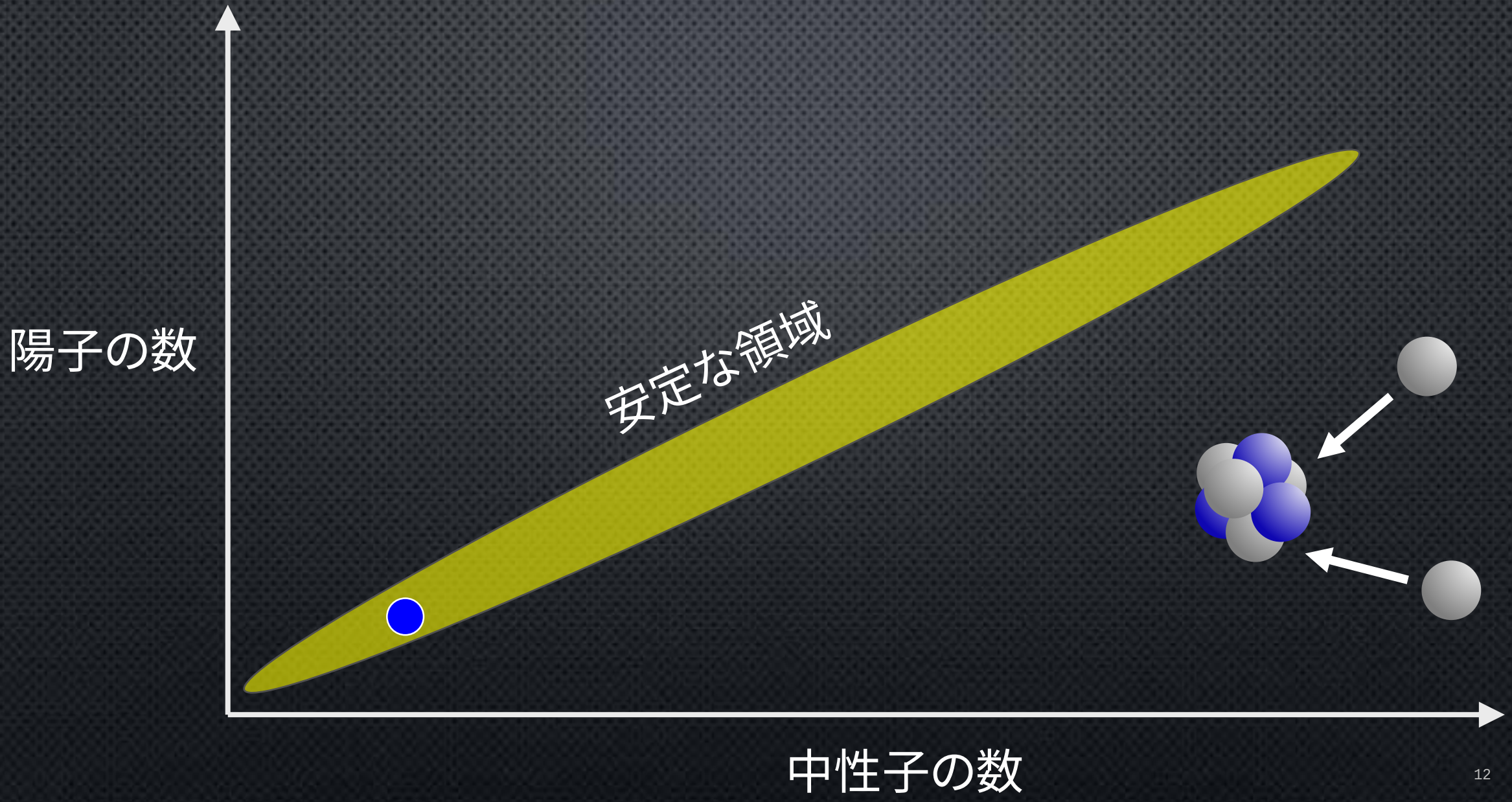
電気的な反発が強い







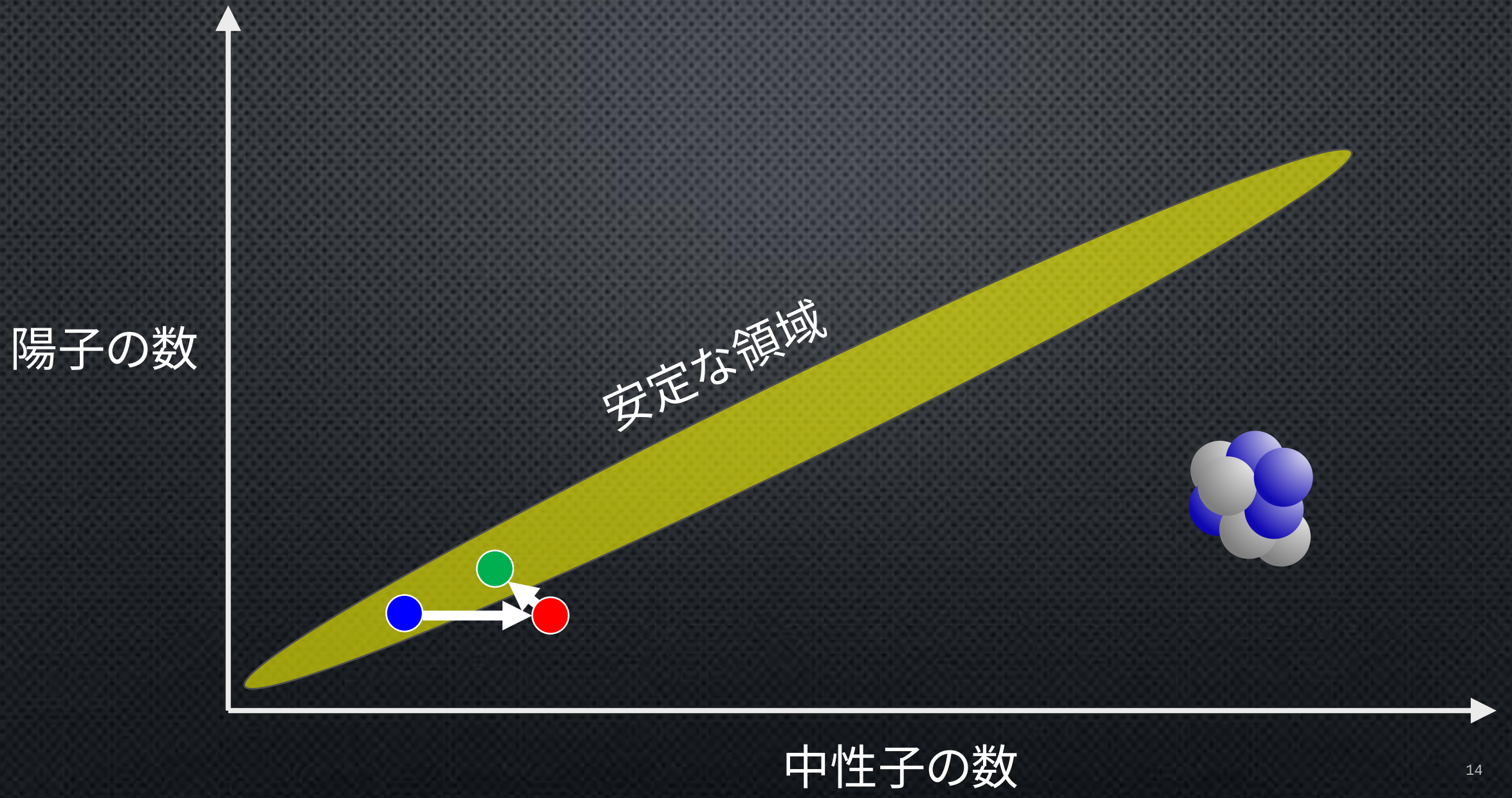
β 崩壊

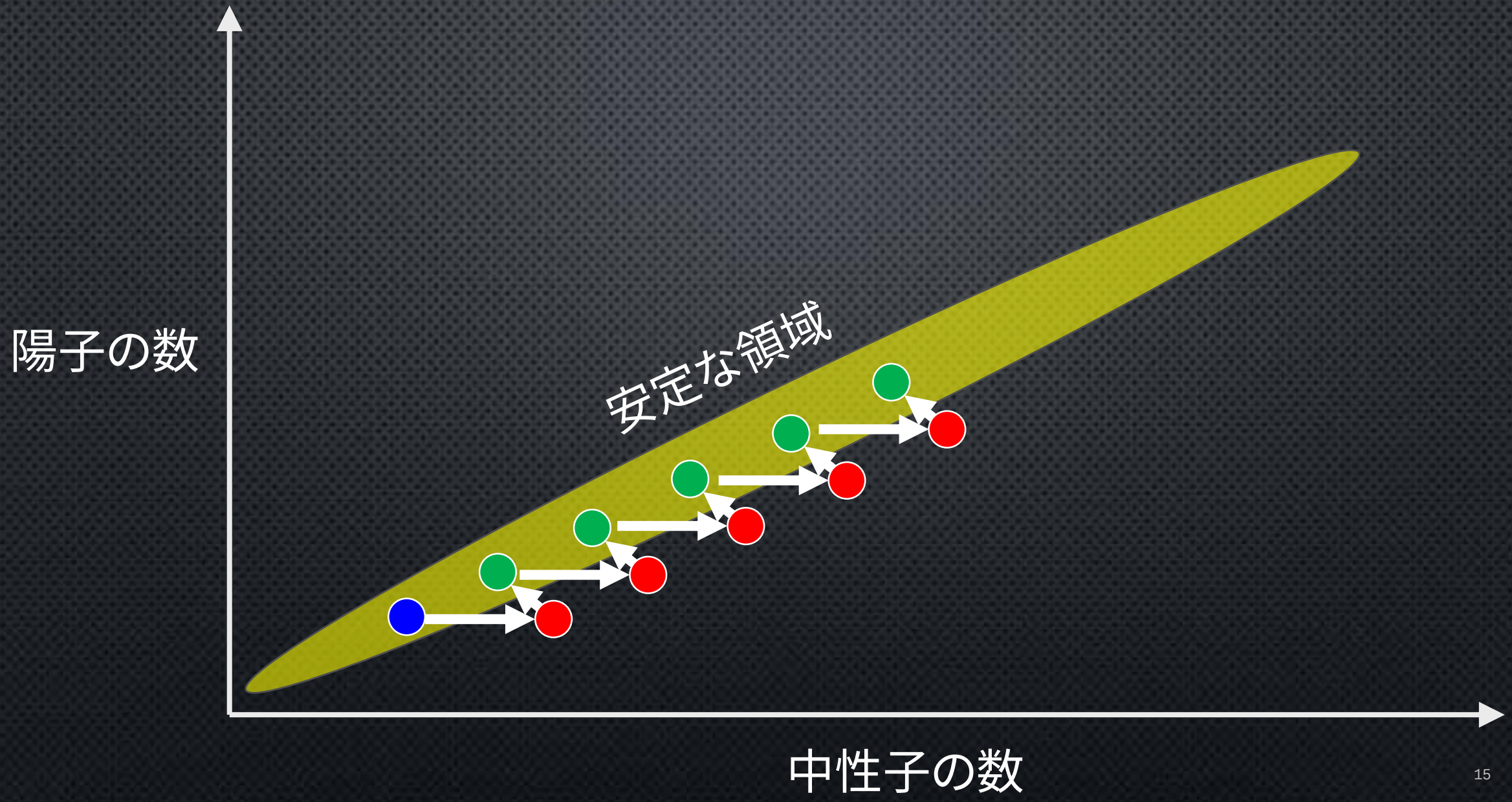

陽子の数
安定な領域
中性子の数

陽子の数

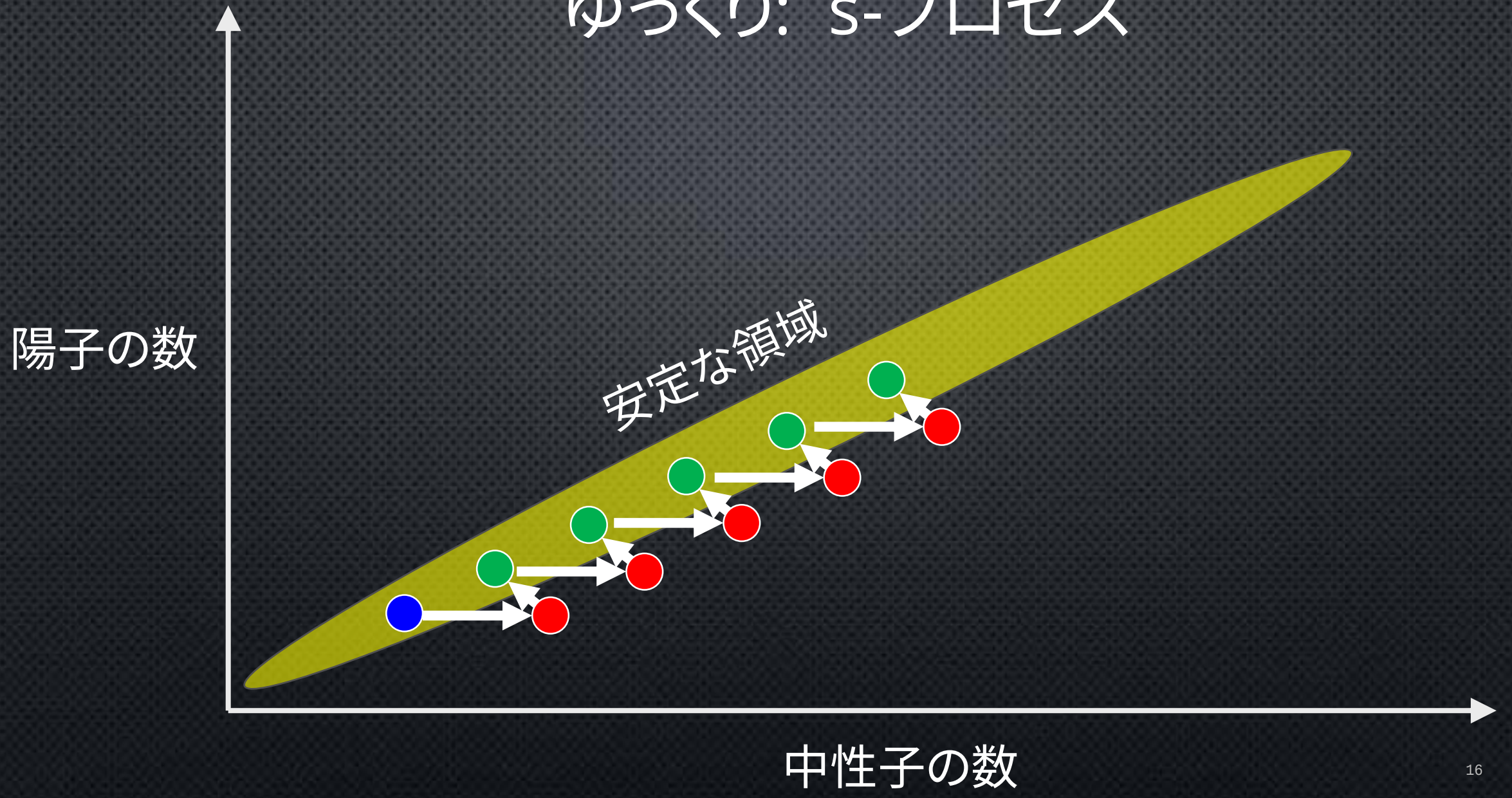
安定な領域

中性子の数


陽子の数
安定な領域
中性子の数

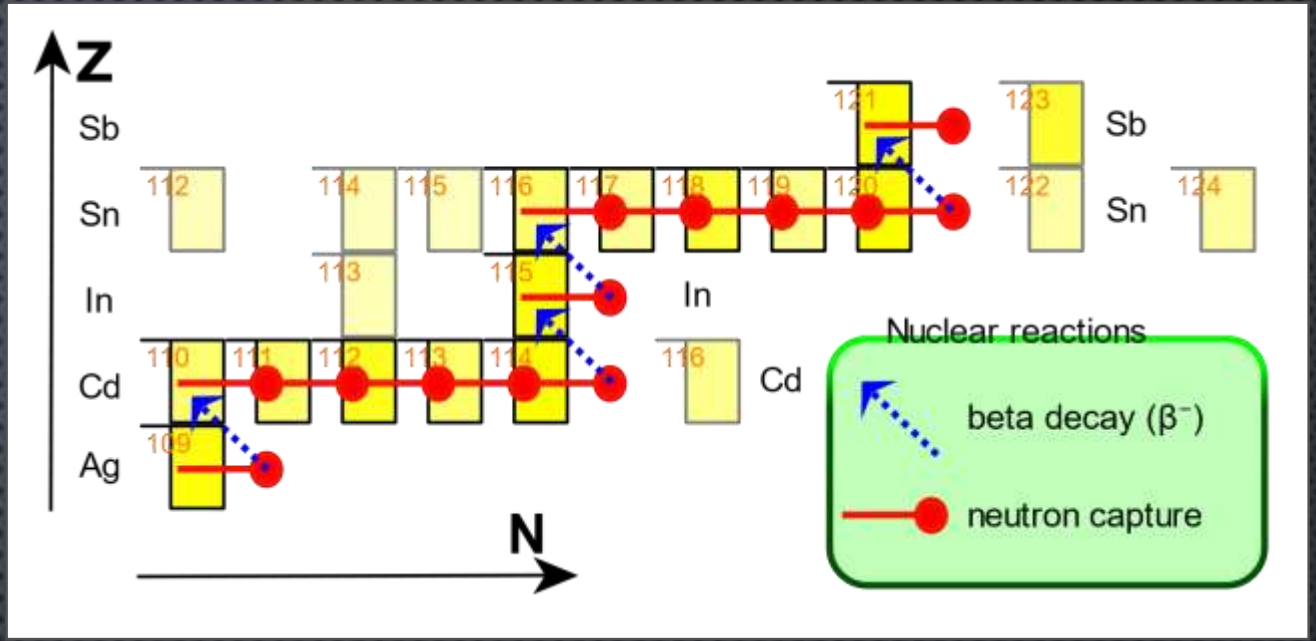

陽子の数
安定な領域
中性子の数

ゆっくり: s-プロセス



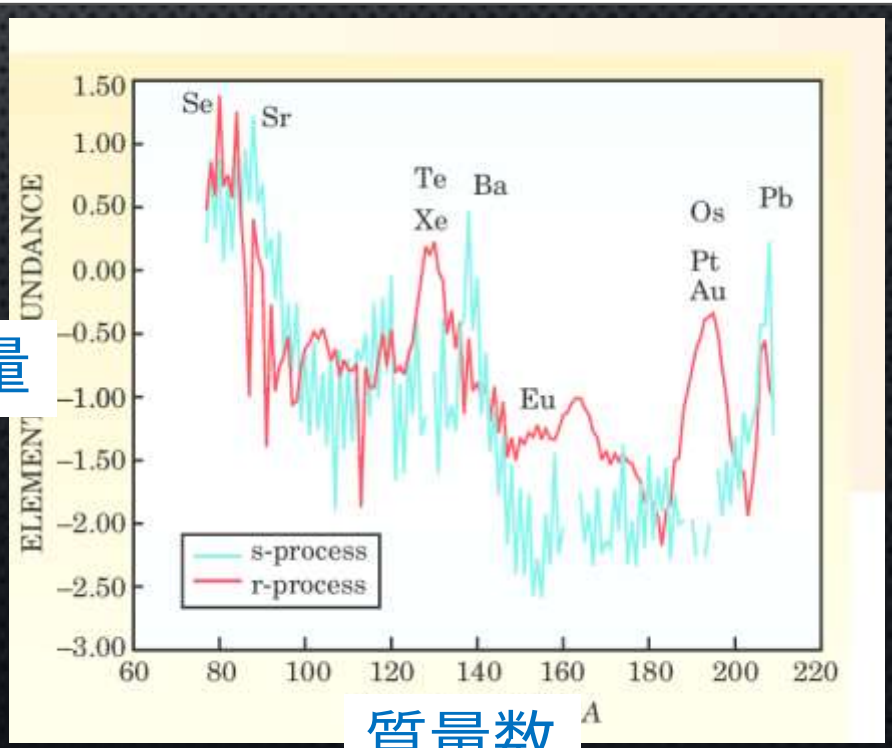
s-プロセス

- ゆっくり中性子を捕獲
- 古い星で起こる



r-プロセス

- 高速な中性子捕獲
- どこで起こるのか?



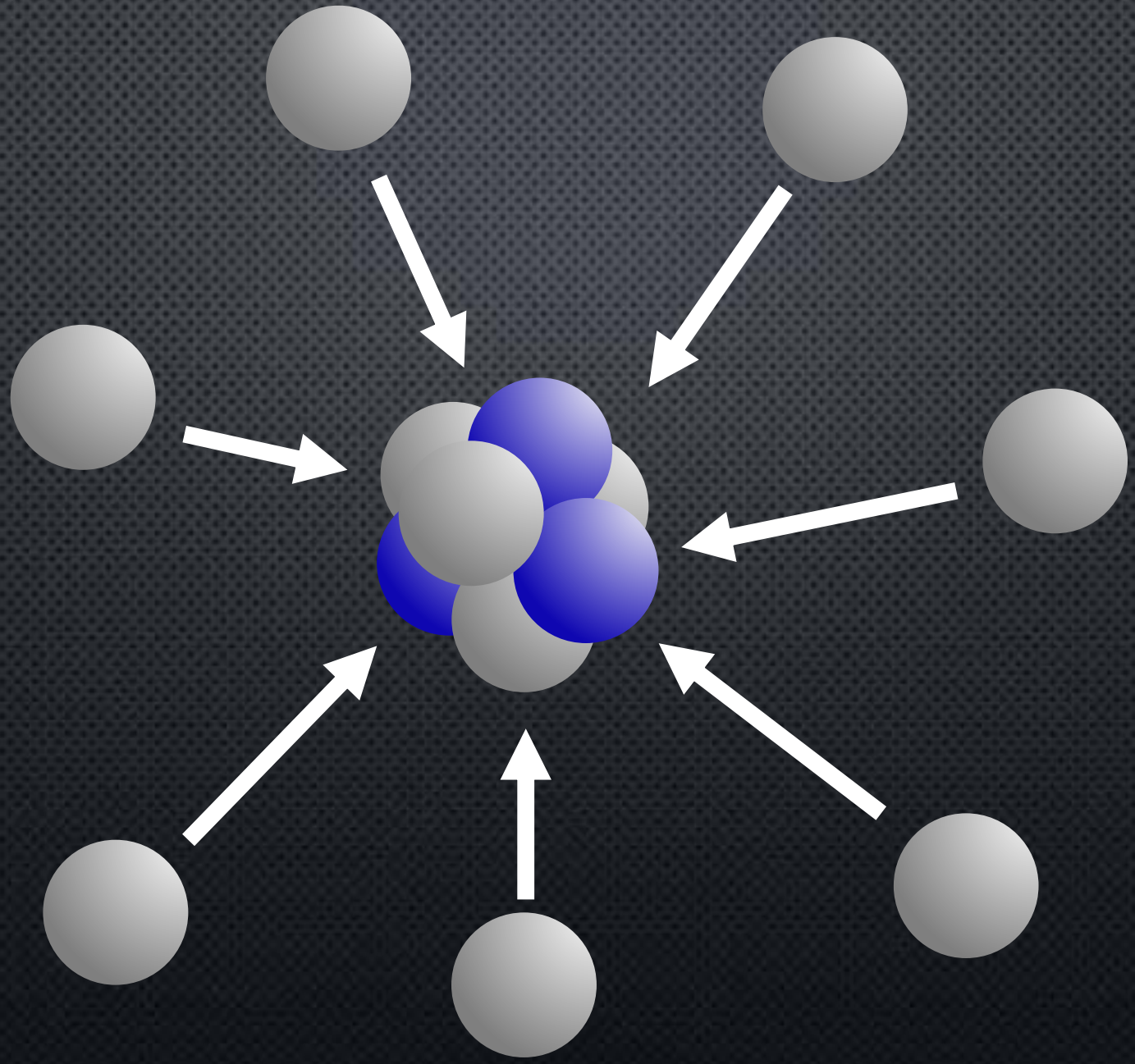
By Szaaman - https://commons.wikimedia.org/wiki/File:Gold_bullion_1.jpg, Public Domain, https://commons.wikimedia.org/w/index.php?curid=35565318

金

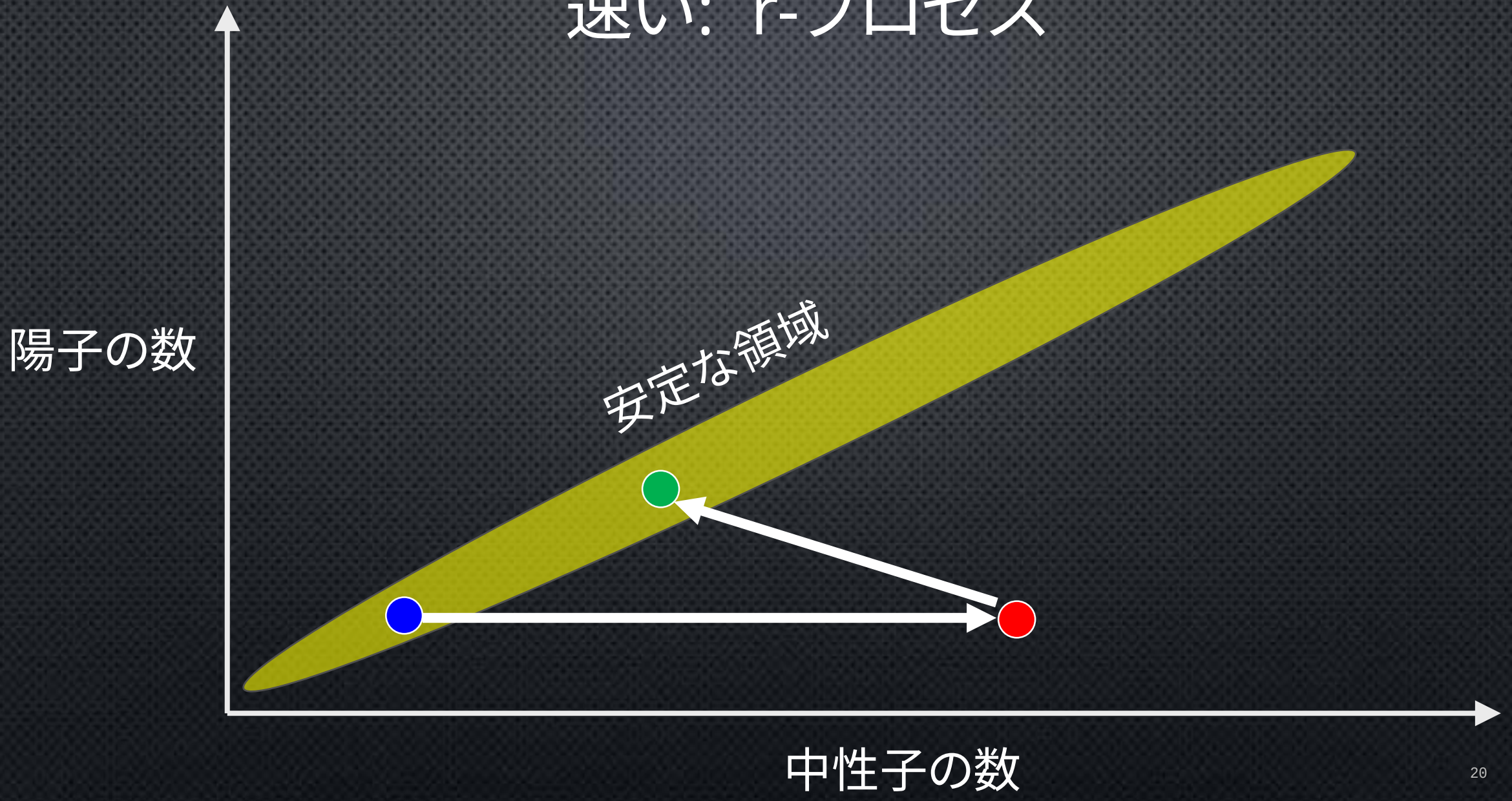
ウラン

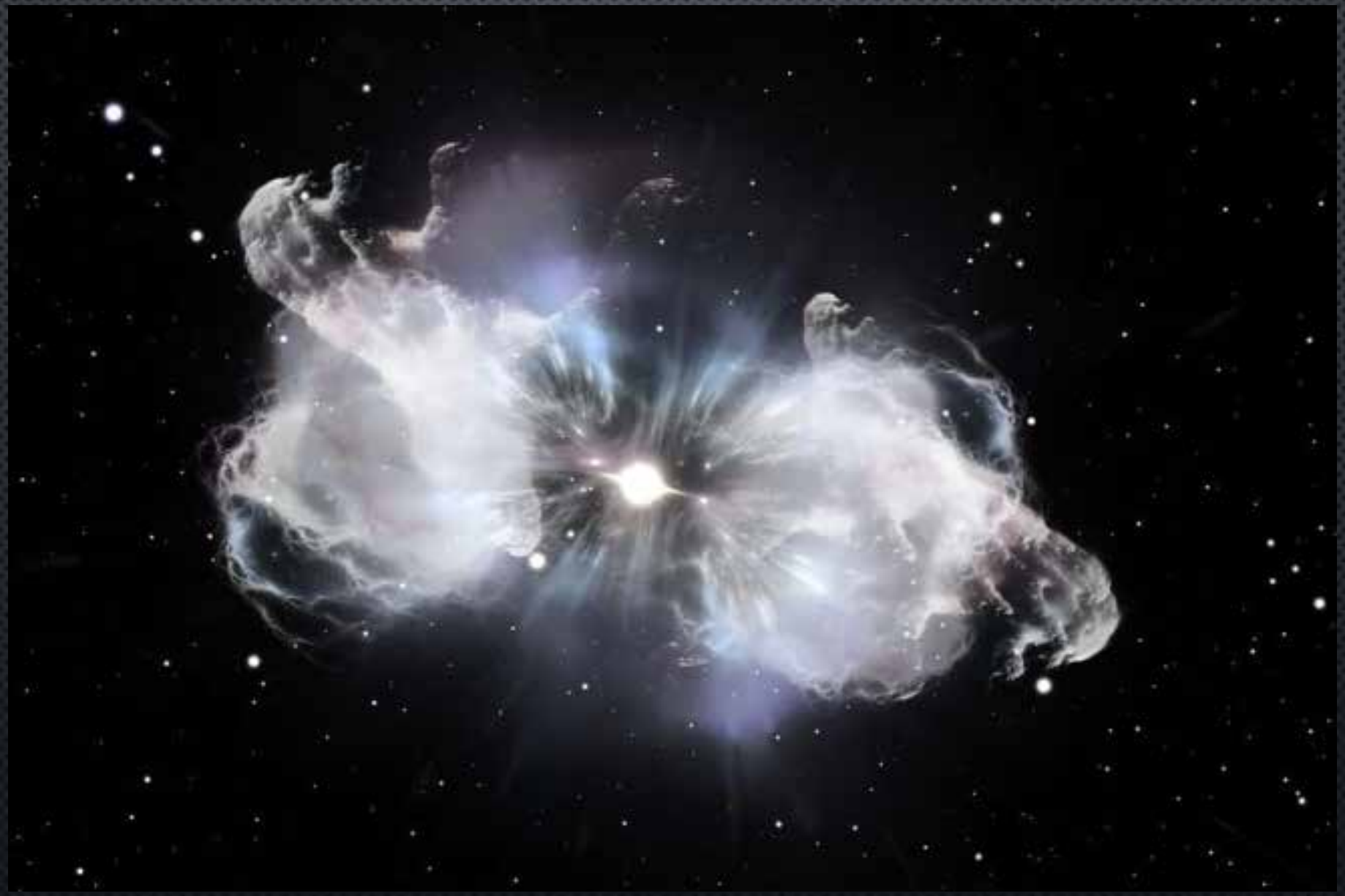
プラチナ

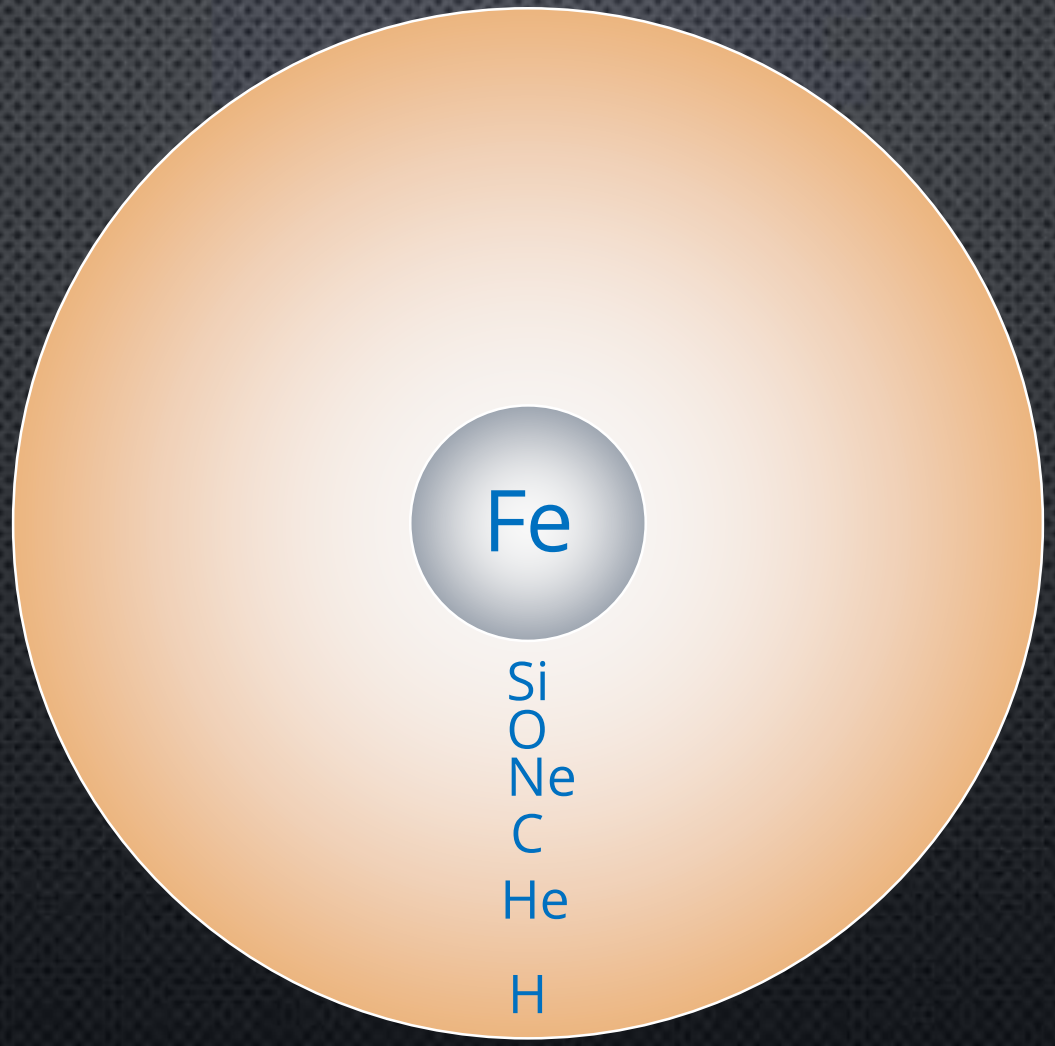
By Rob Lavinsky, iRocks.com – CC-BY-SA-3.0, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=10465065



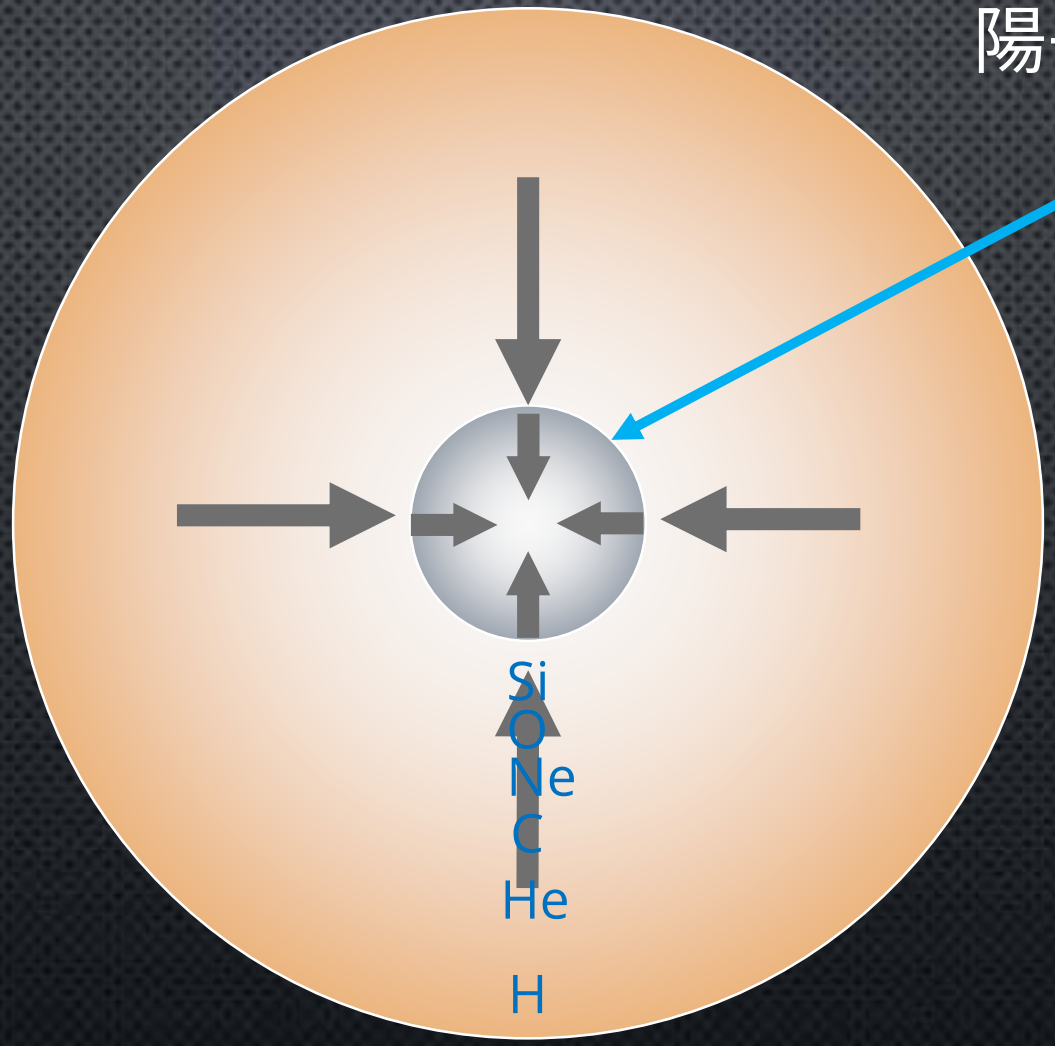
速い: r-プロセス

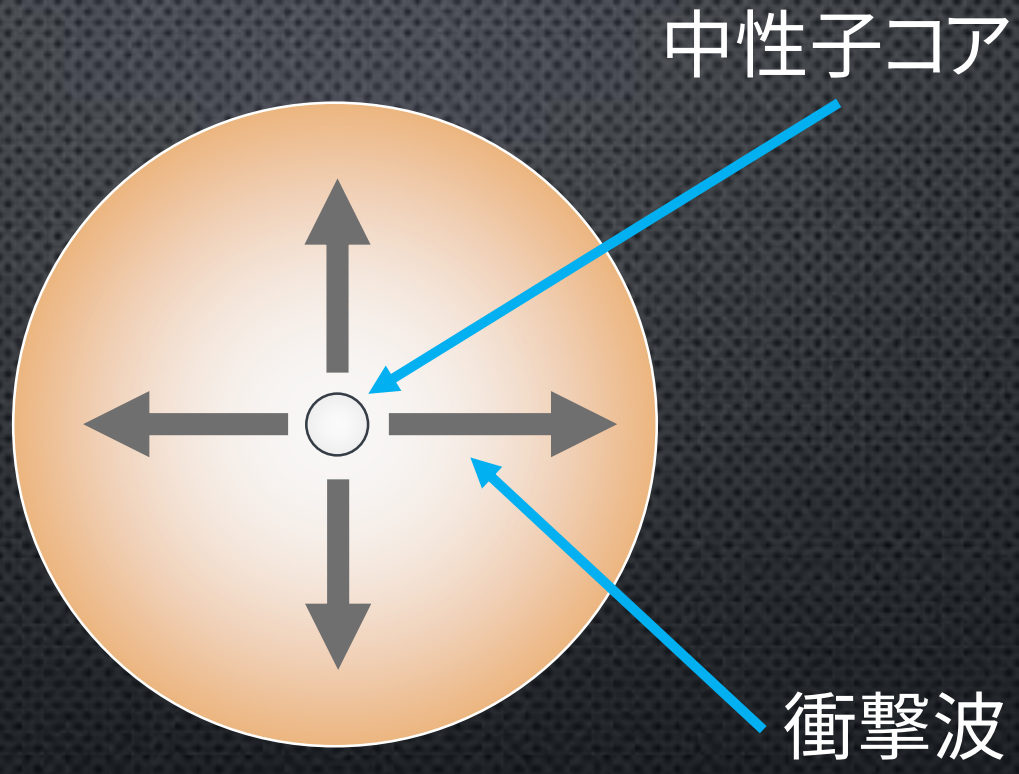




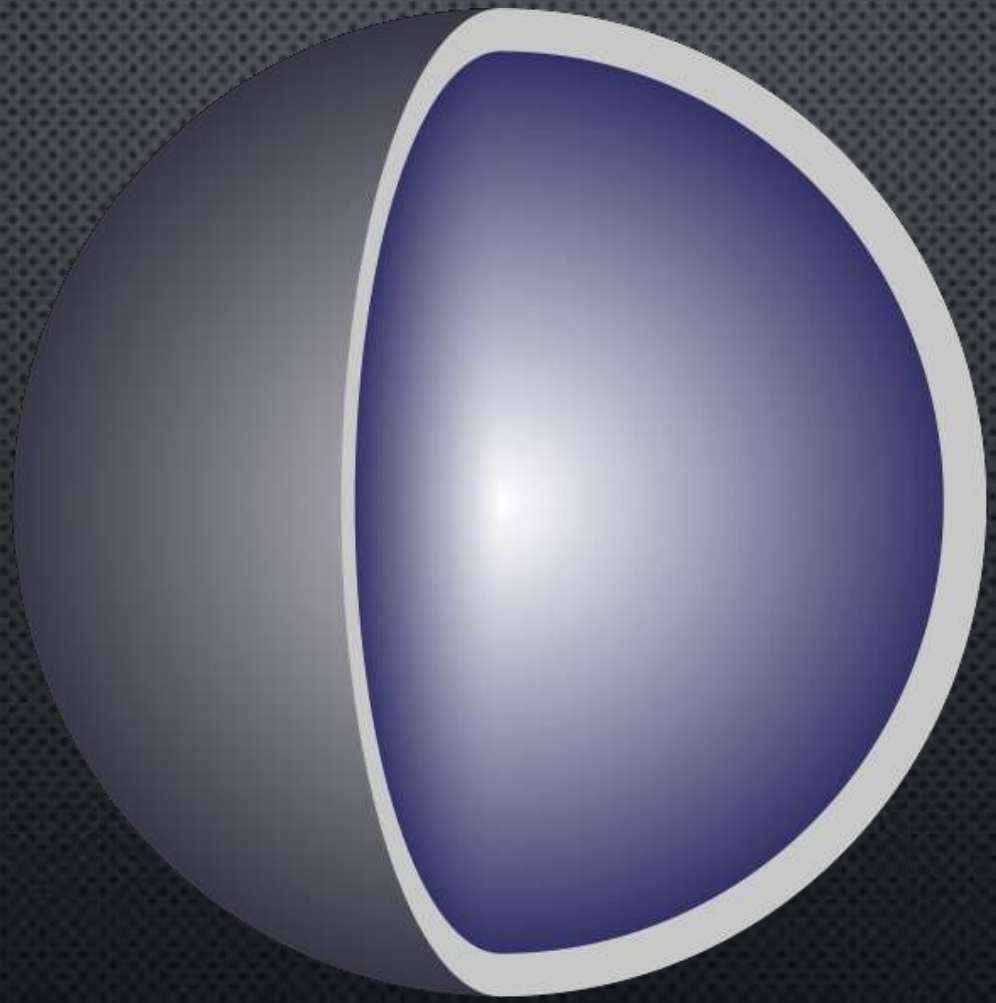

Fe
Si
O
Ne
C
He
H

電子捕獲
陽子 → 中性子

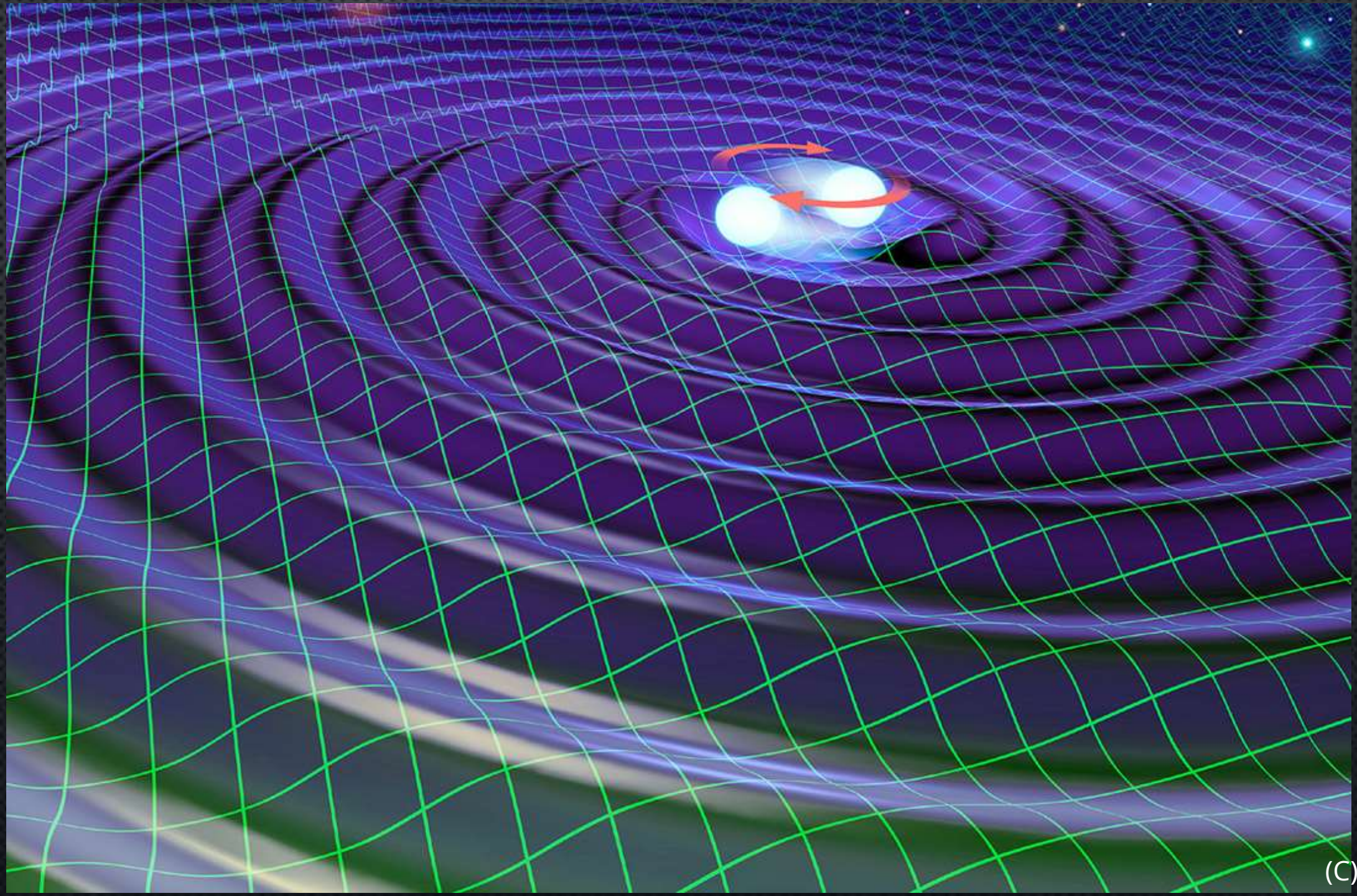


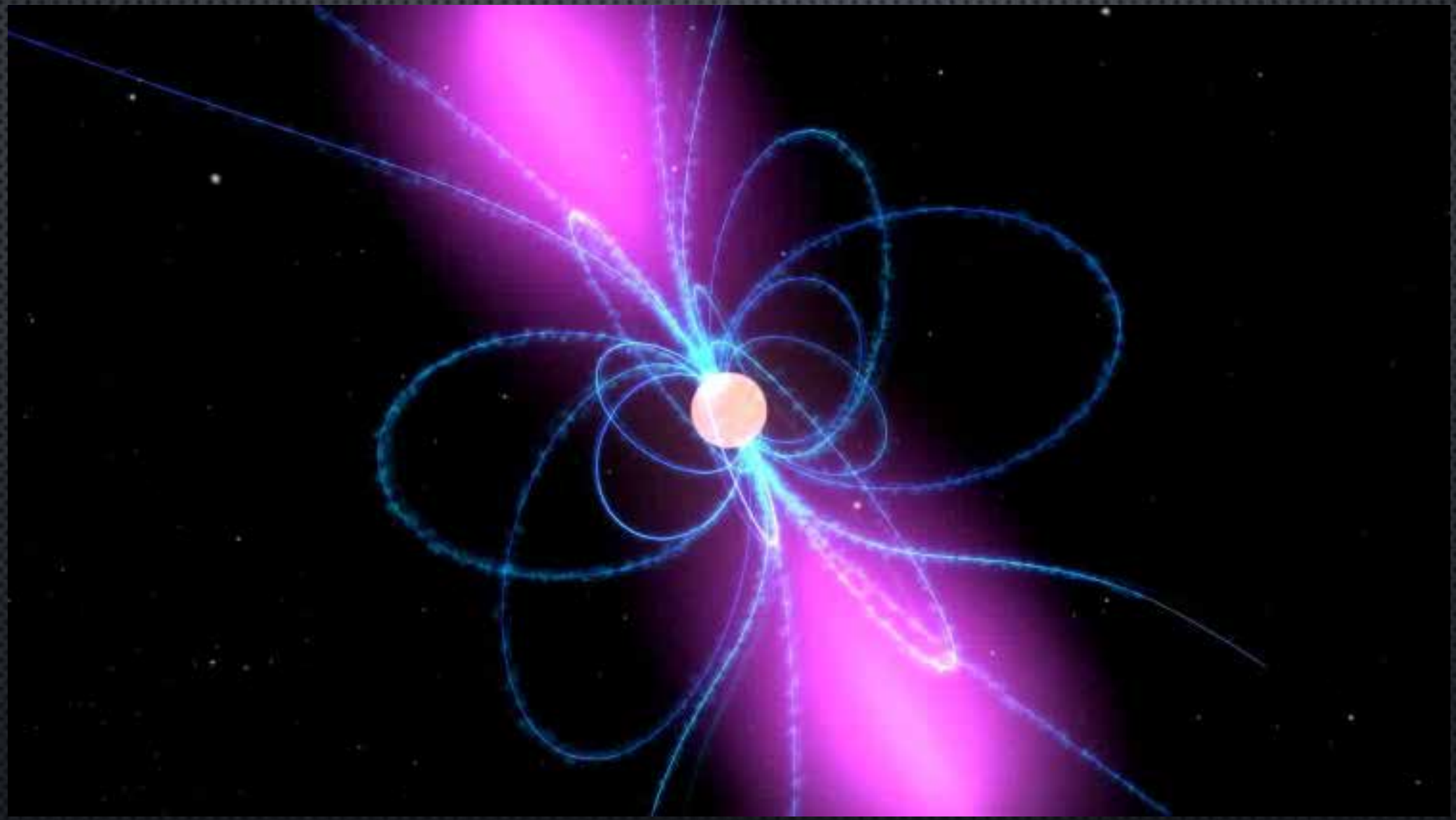

中性子コア
衝撃波

中性子星



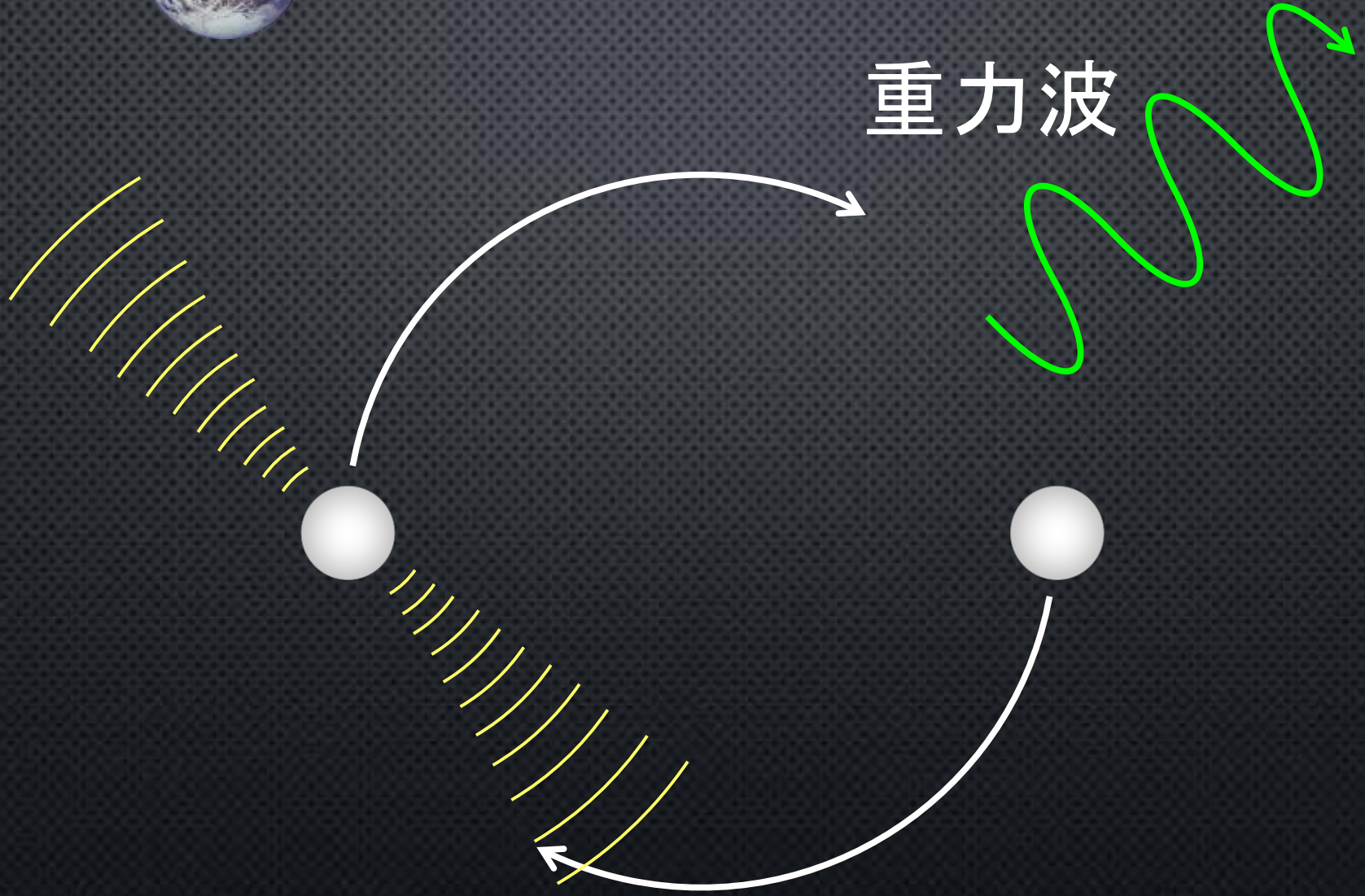
William Crochot - http://science.nasa.gov/media/medialibrary/1999/02/25/ast05mar99_1a_resources/N_sctn2.jpg, Public Domain, https://commons.wikimedia.org/w/index.php?curid=36335367

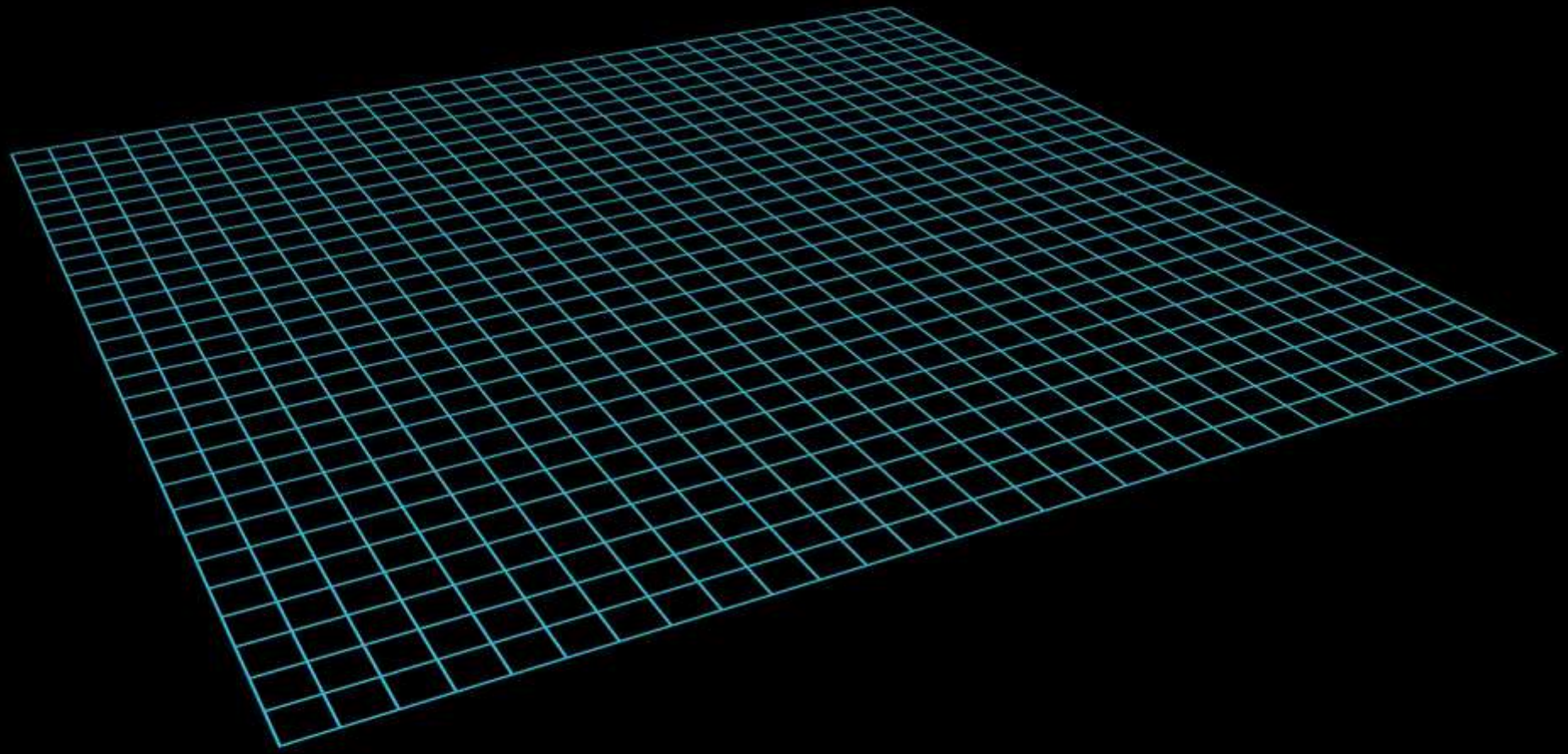

(C) KAGAYA

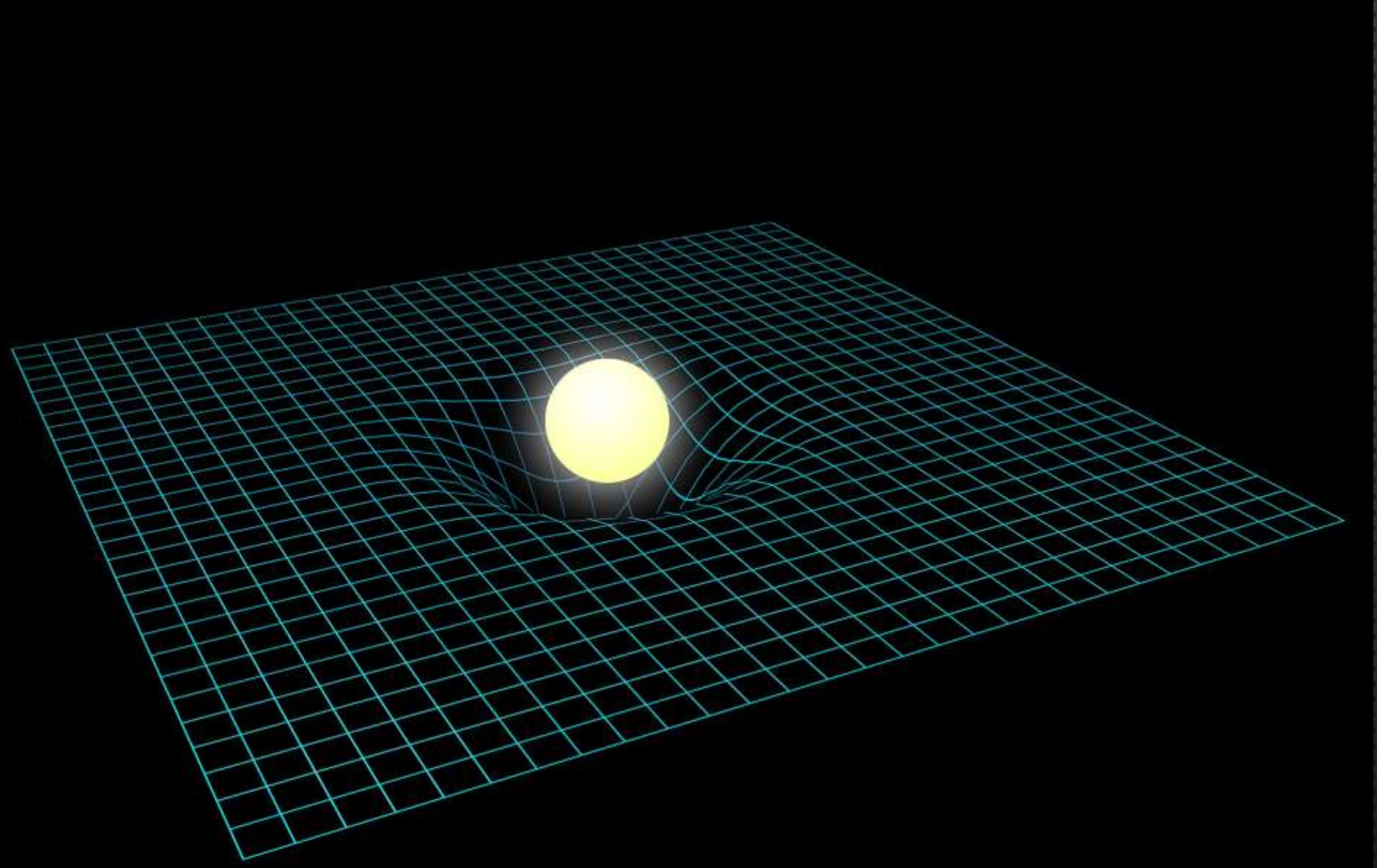


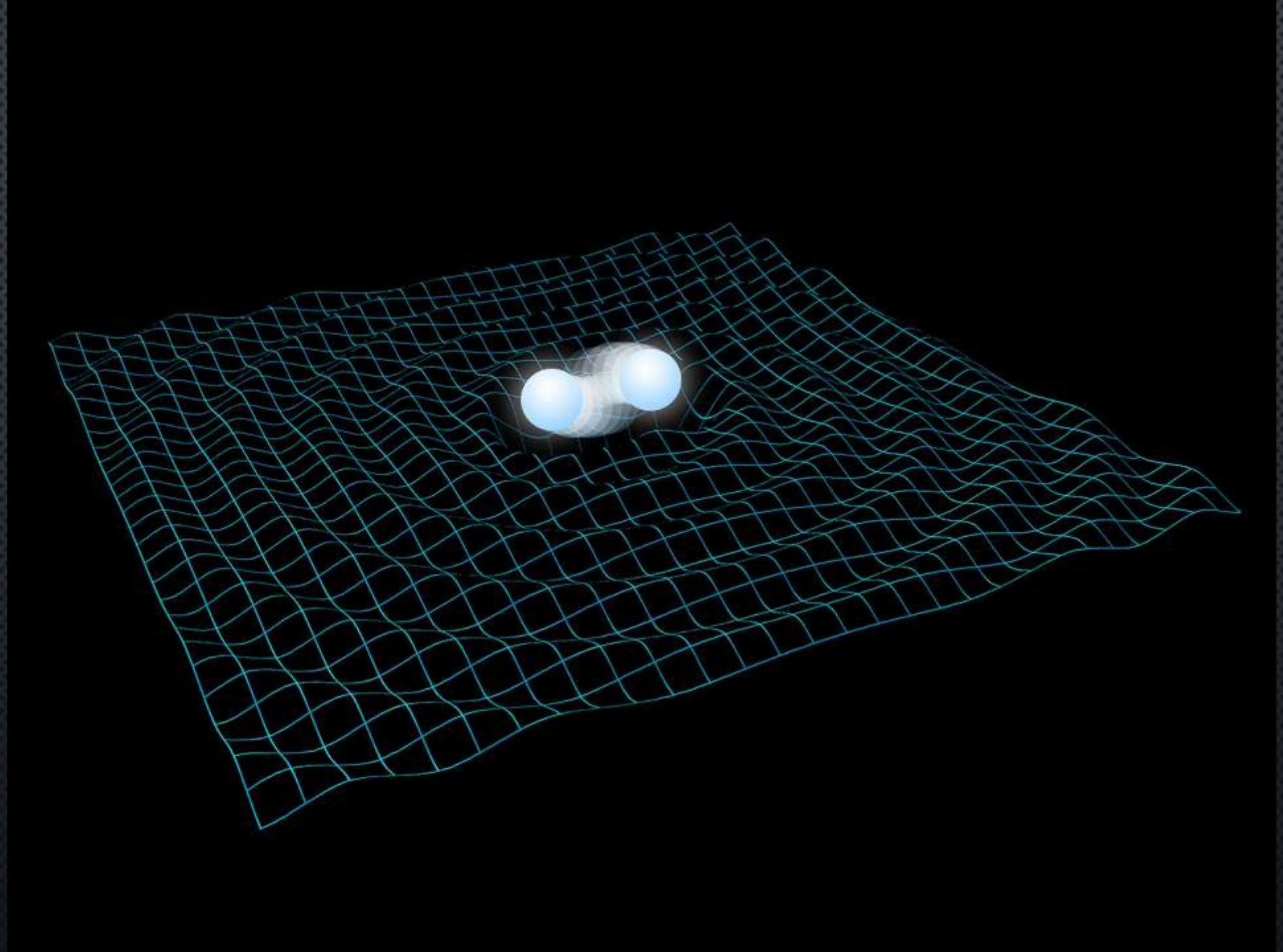
(C)NASA

重力波









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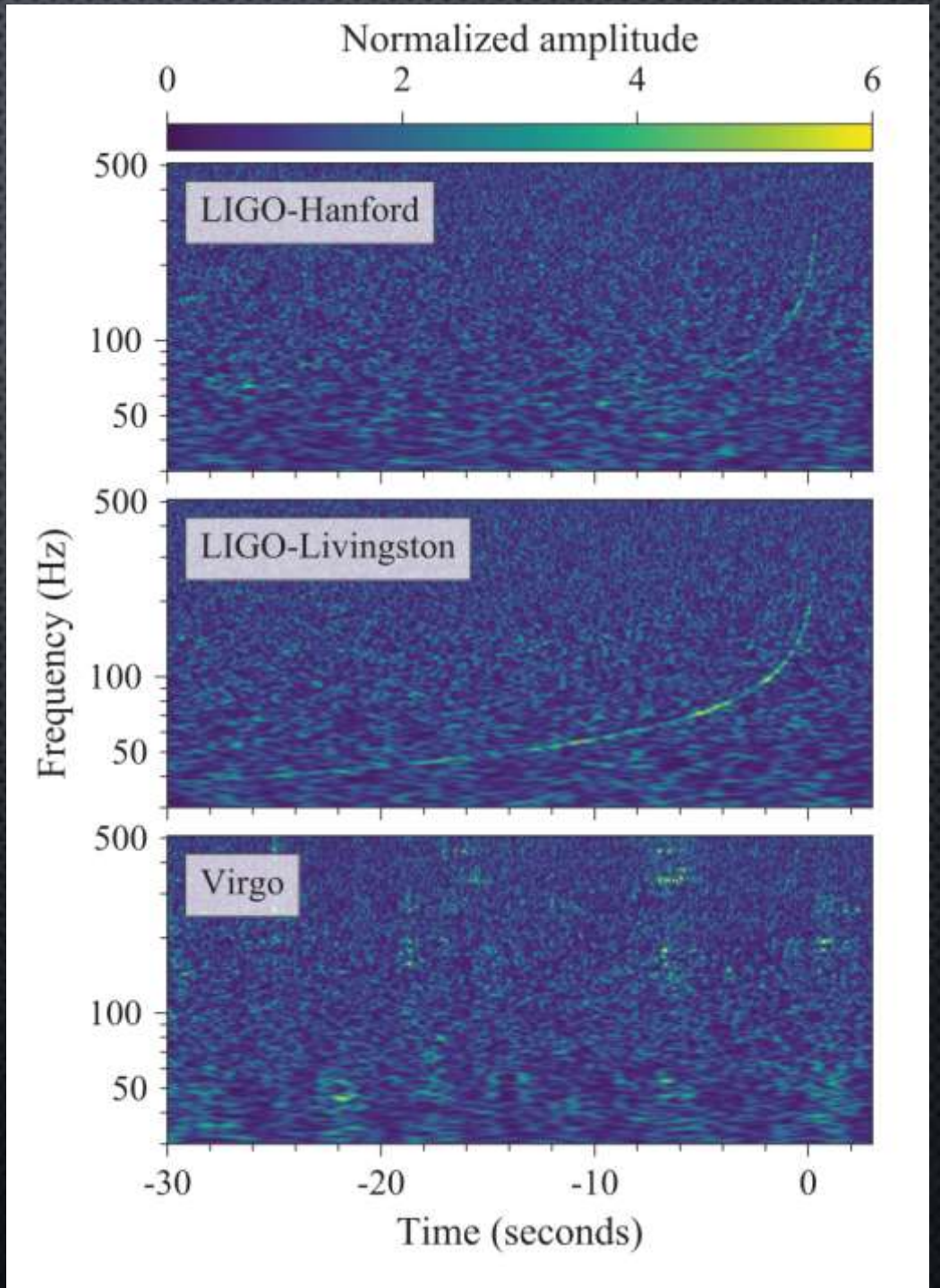
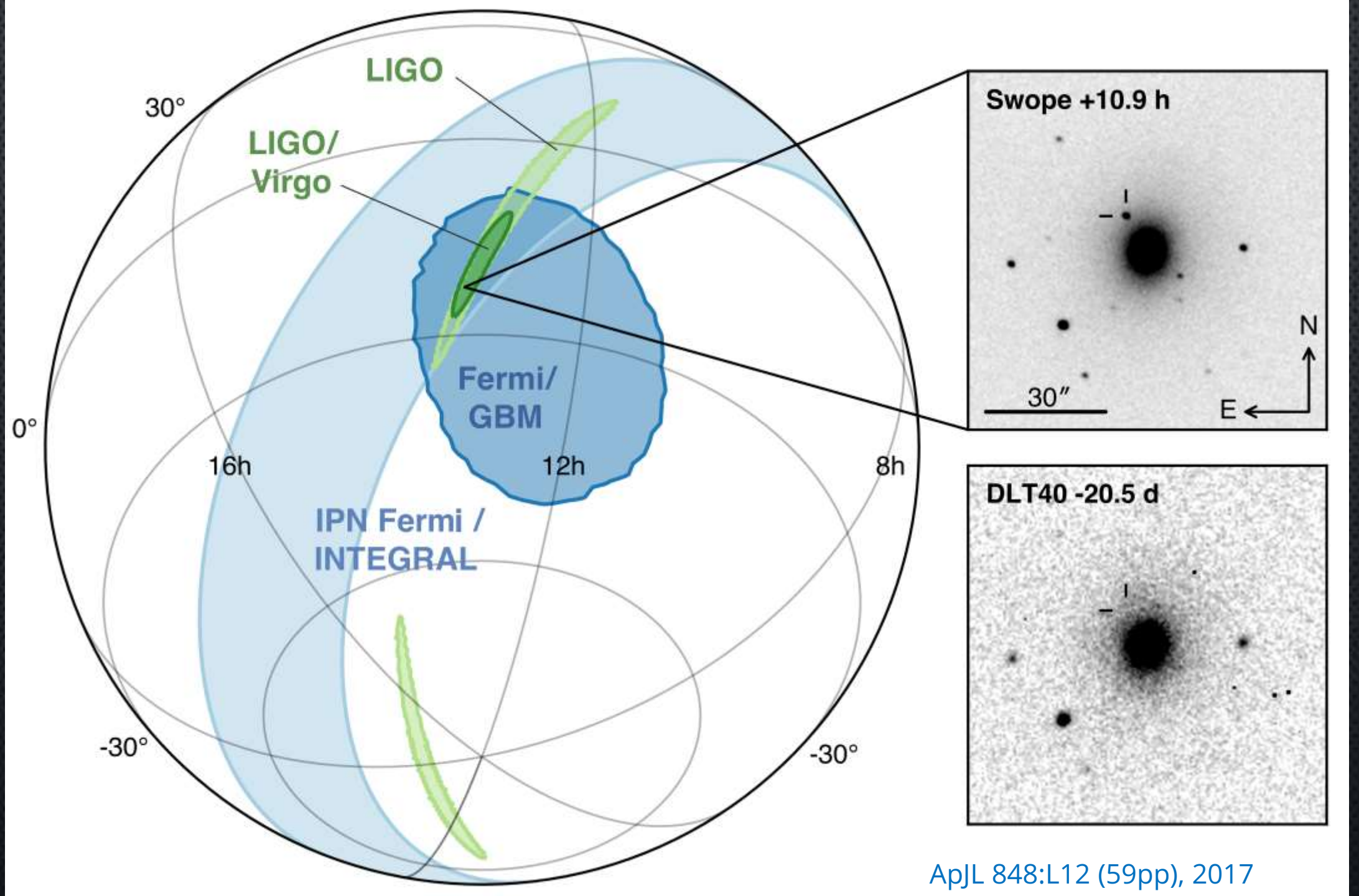
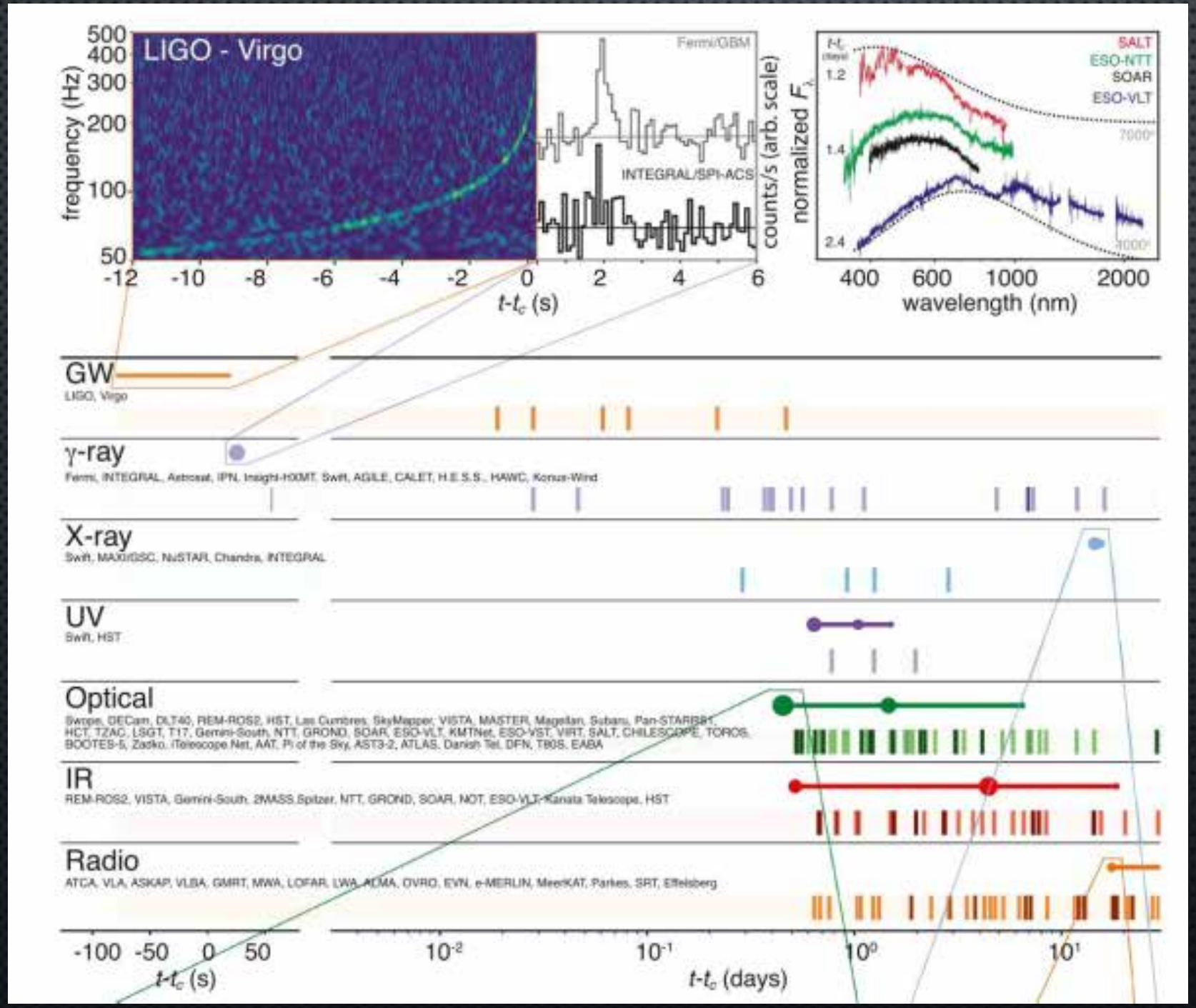


PRL 119, 161101(2017)



ApJL 848:L12 (59pp), 2017



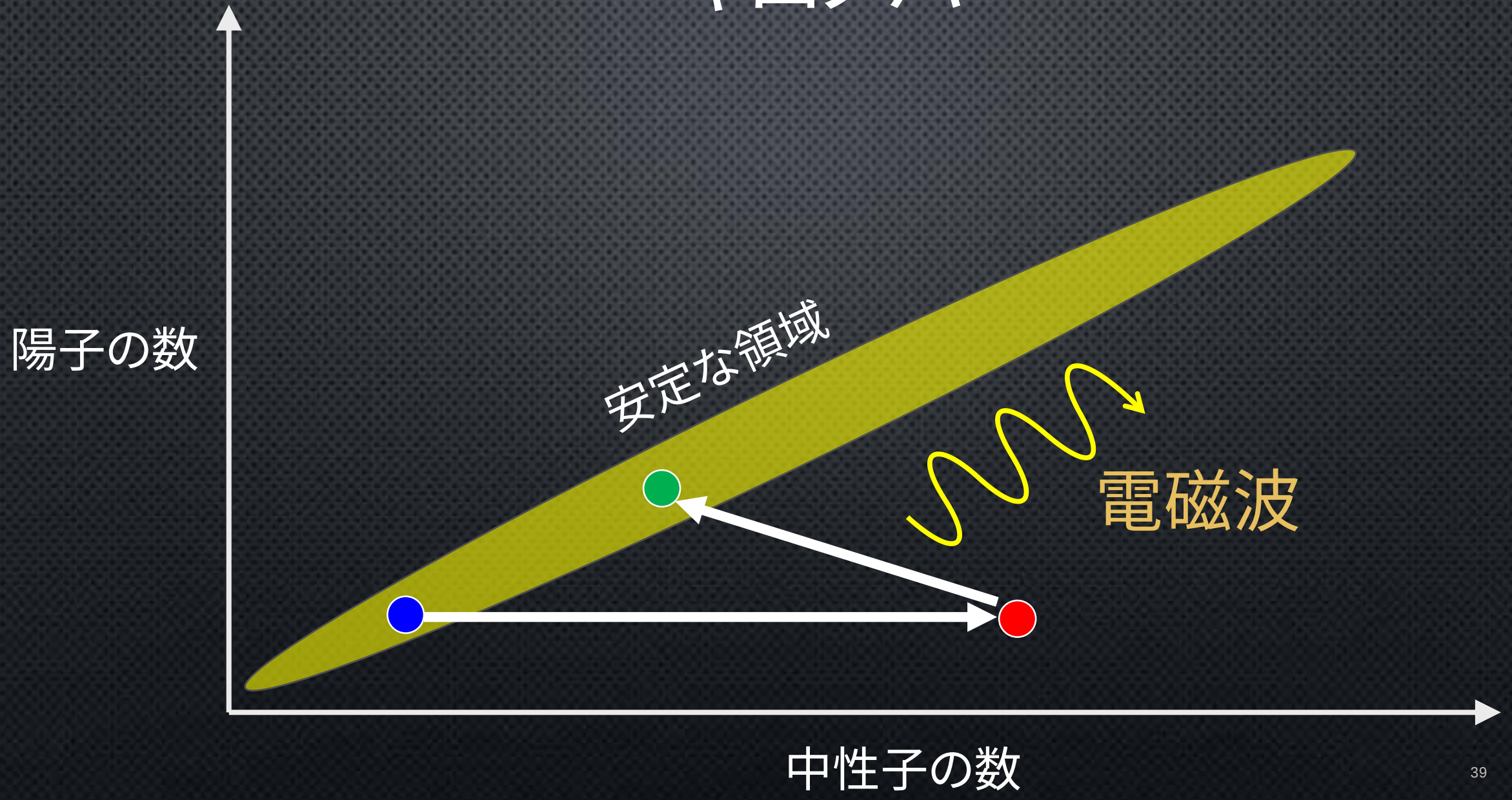
ApJL 848:L12 (59pp), 2017

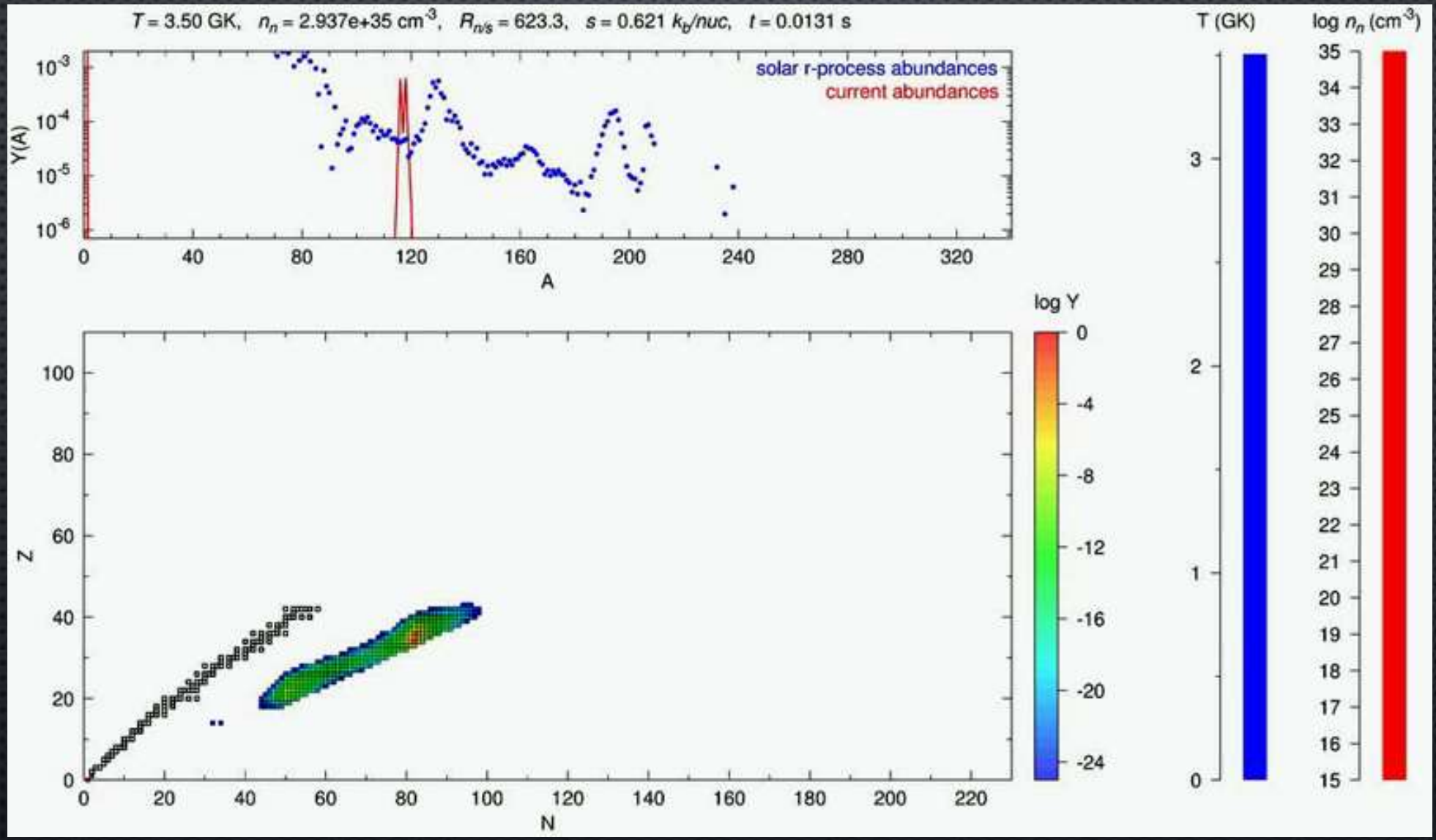
2017/8/18-19

2017/8/24-25

NGC 4993

キロノバ

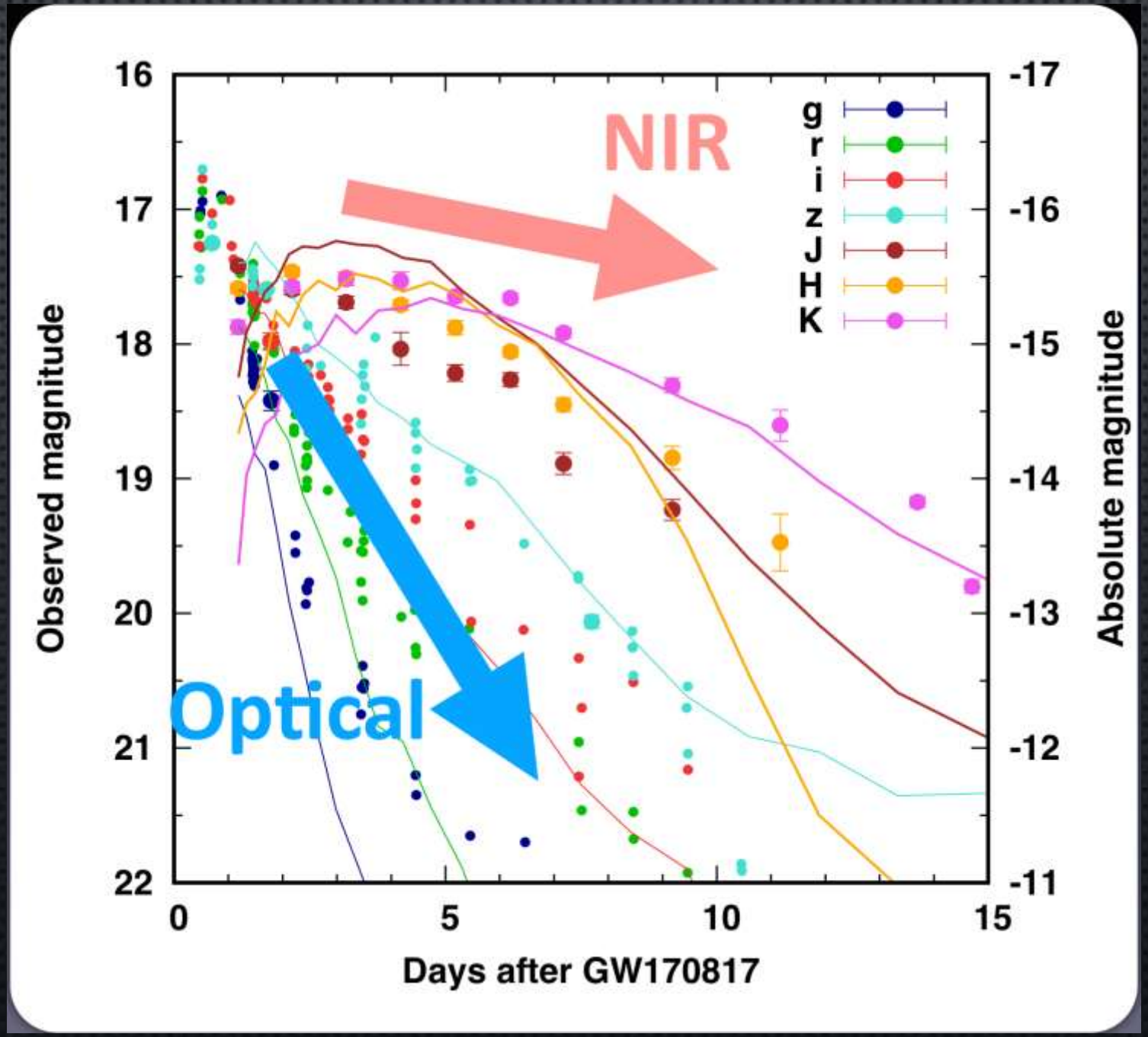




原子番号

中性子数

Joel de Jesus Mendoza Temis arXiv:1409.6135


NIR
Optical
g
r
i
z
J
H
K
Observed magnitude
Absolute magnitude
Days after GW170817
16
17
18
19
20
21
22
-17
-16
-15
-14
-13
-12
-11
0
5
10
15

(C) M. Tanaka

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Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
Cs 55	Ba 56	La 57	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
Fr 87	Ra 88	Ac 89	Rf 104	Db 105	Sg 106	Bh 107	Hs 108	Mt 109	Ds 110	Rg 111	Cn 112	Nh 113	Fl 114	Mc 115	Lv 116	Ts 117	Og 118

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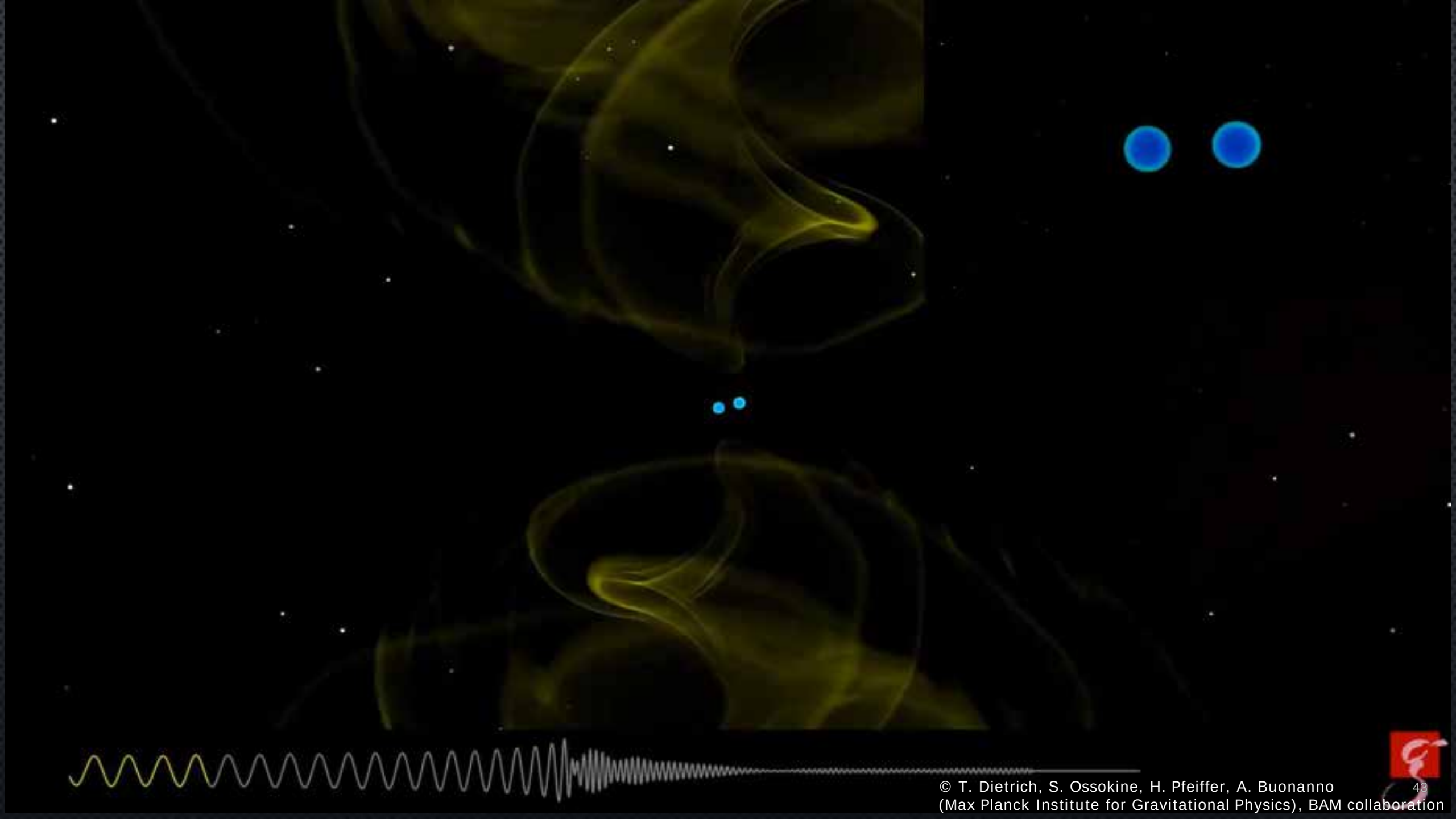
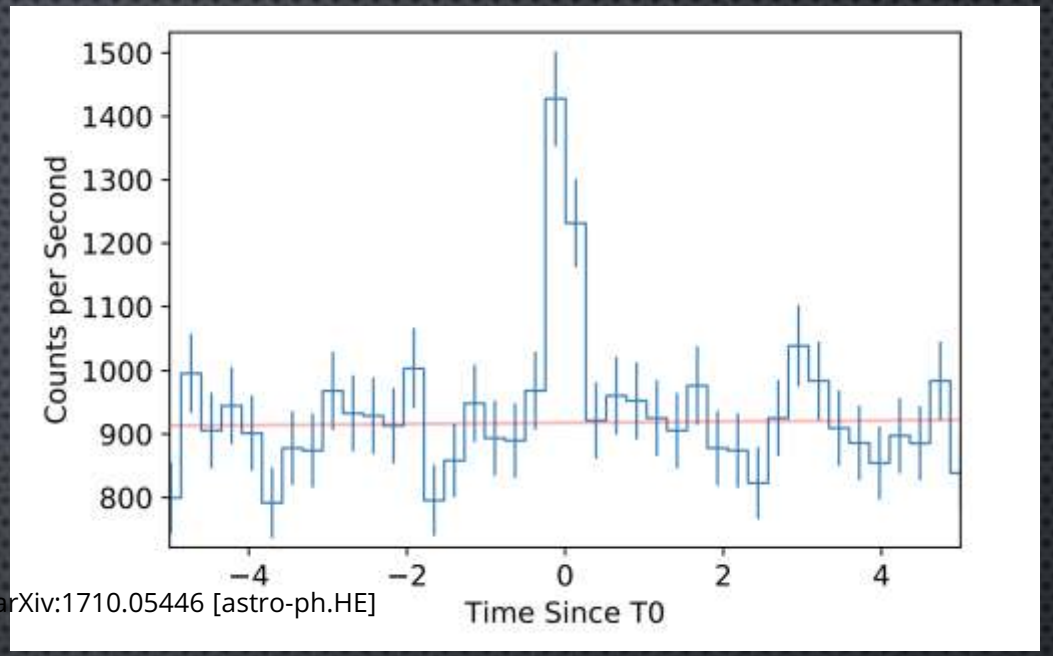
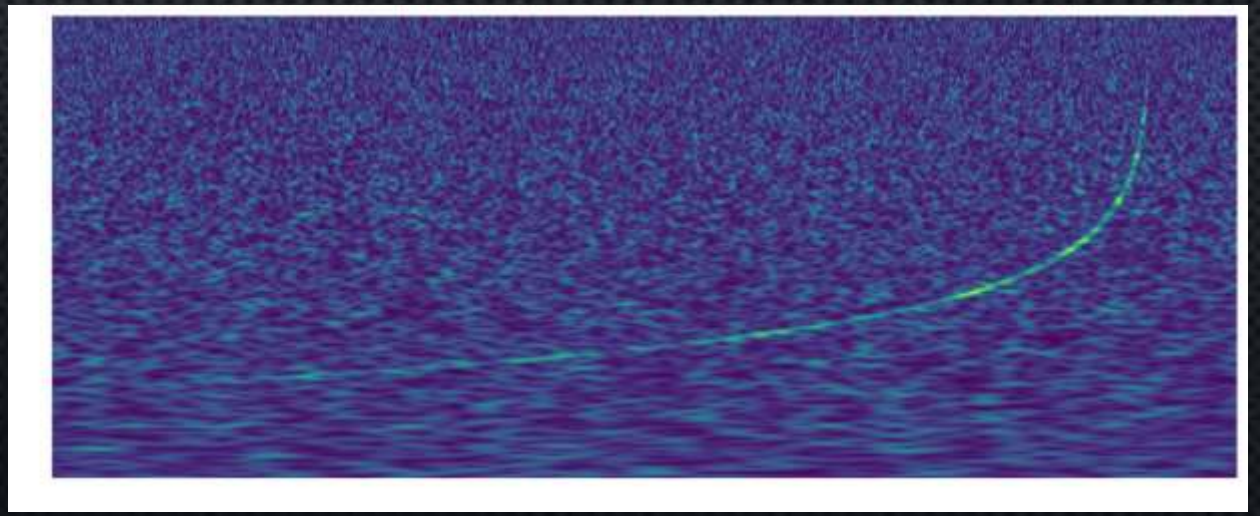


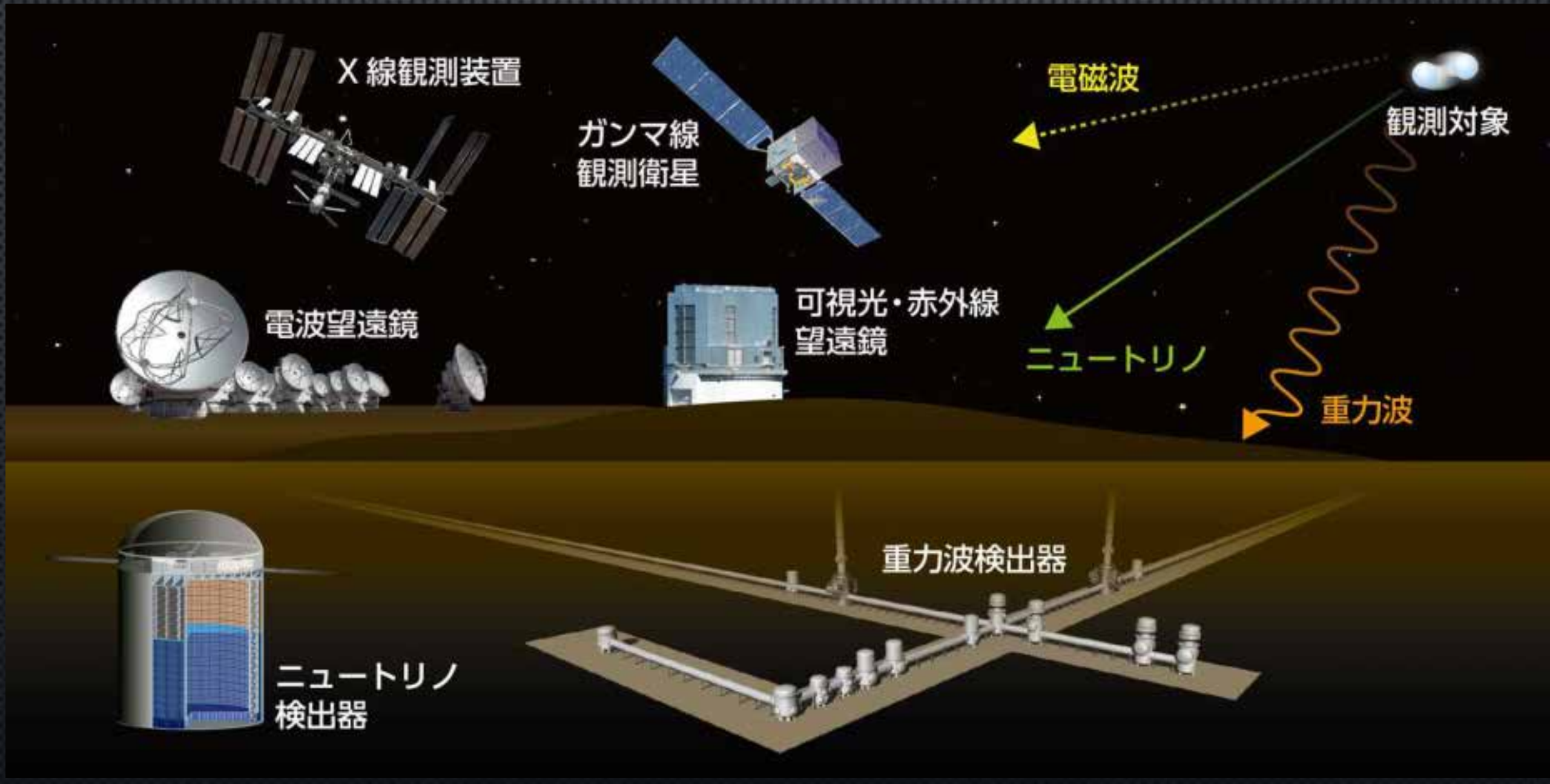


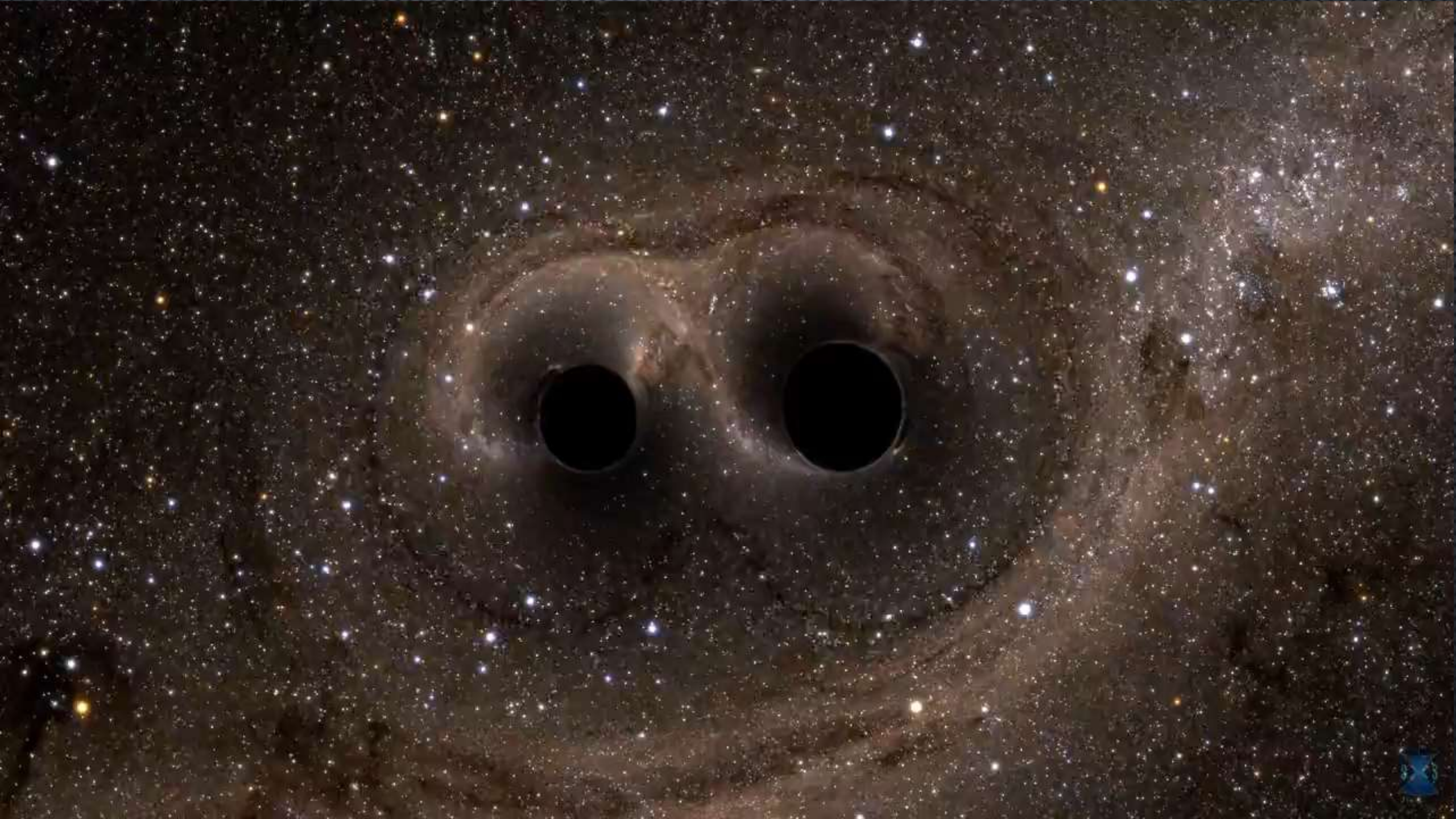
arXiv:1710.05446 [astro-ph.HE]

1.7秒差 → $|c_{GW} - 1| < 10^{-15}$

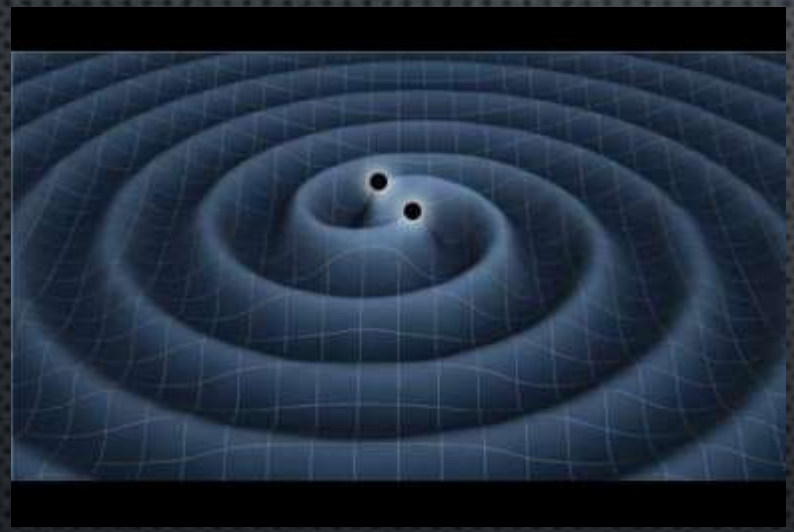


マルチメッセンジャー天文学





重力波の
エネルギー放出率



$3.6 \times 10^{49}\,\mathrm{J/s}$

$\geq$

全宇宙可視光
のエネルギー放出率

$1 \times 10^{49}\,\mathrm{J/s}$

観測運転(Observational run)

O1: 2015 Sept. 12 – 2016 Jan. 19

O2: 2016 Nov. 30 – 2017 Aug. 25
(Virgo joined on 2017 Aug. 1)

O3: 2019 Apr. 1 - on going (until 2020 Apr. 30)

観測運転(Observational run)

O1: 2015 Sept. 12 – 2016 Jan. 19

O2: 2016 Nov. 30 – 2017 Aug. 25
(Virgo joined on 2017 Aug. 1)

ブラックホール連星合体: 10件

中性子星連星合体: 1件

O3: 2019 Apr. 1 - on going (until 2020 Apr. 30)

観測運転(Observational run)

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中性子星連星合体: 1件

O3: 2019 Apr. 1 - on going (until 2020 Apr. 30)

ブラックホール連星合体: 23件
中性子星連星合体: 3+件
ブラックホール-中性子星連星: 3+件
マスギャップ: 2件

観測運転(Observational run)

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O2: 2016 Nov. 30 – 2017 Aug. 25
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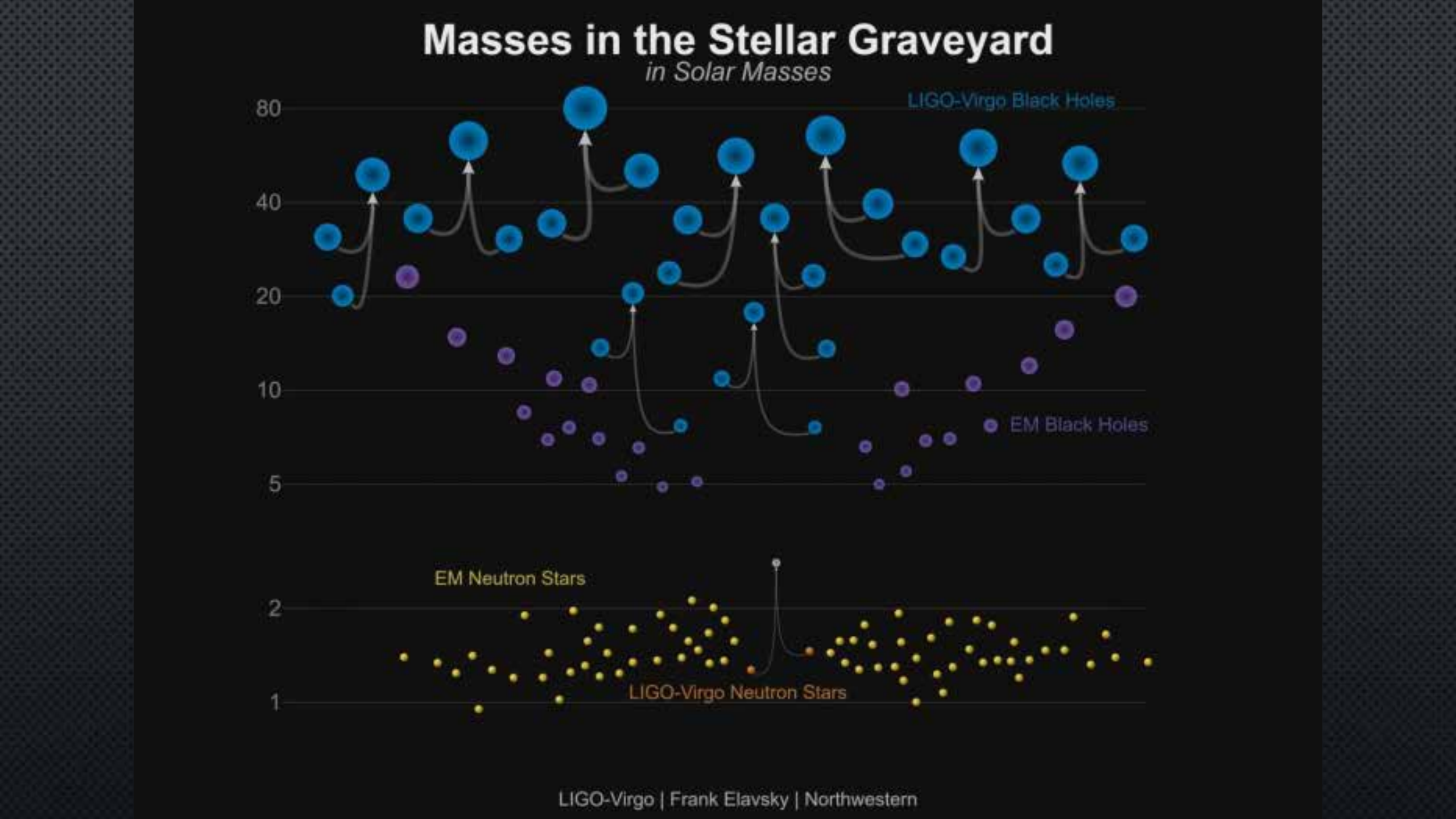
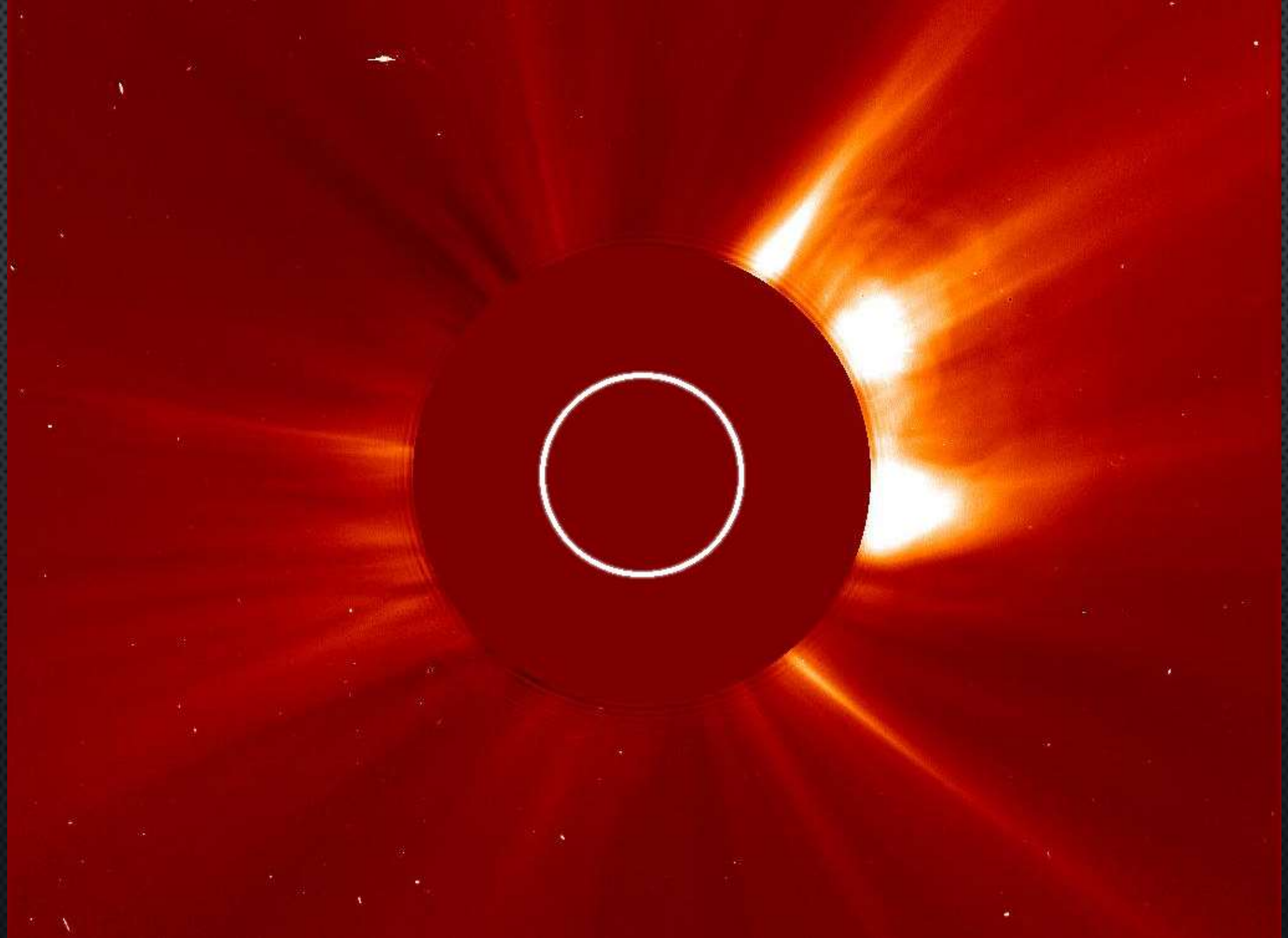
ブラックホール連星合体: 23件
中性子星連星合体: 3+件
ブラックホール-中性子星連星: 3+件
マスギャップ: 2件

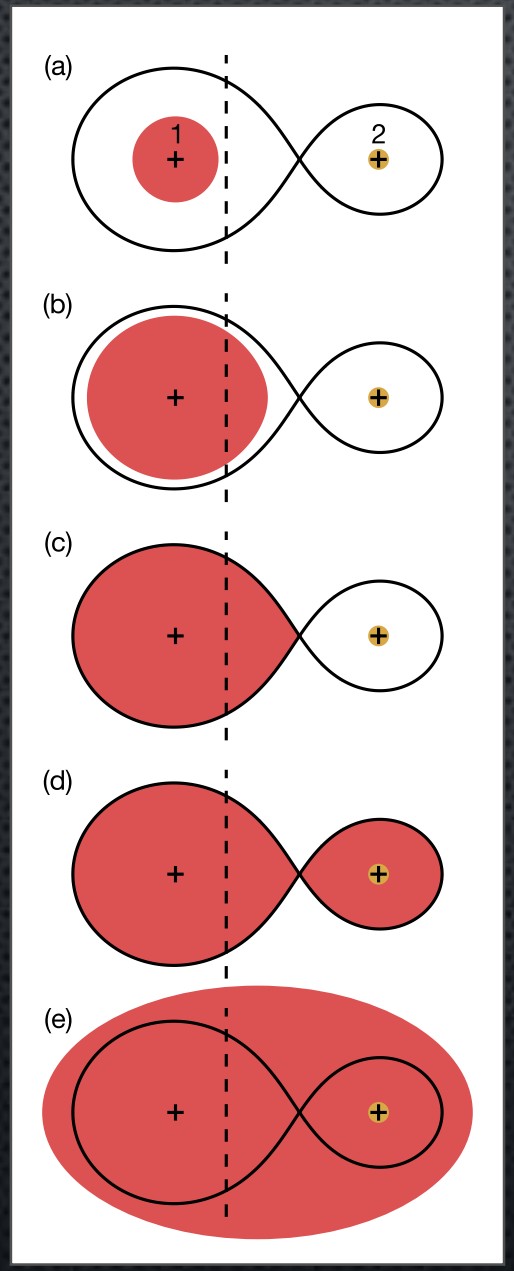
Open Public Alert
概要のみ公開

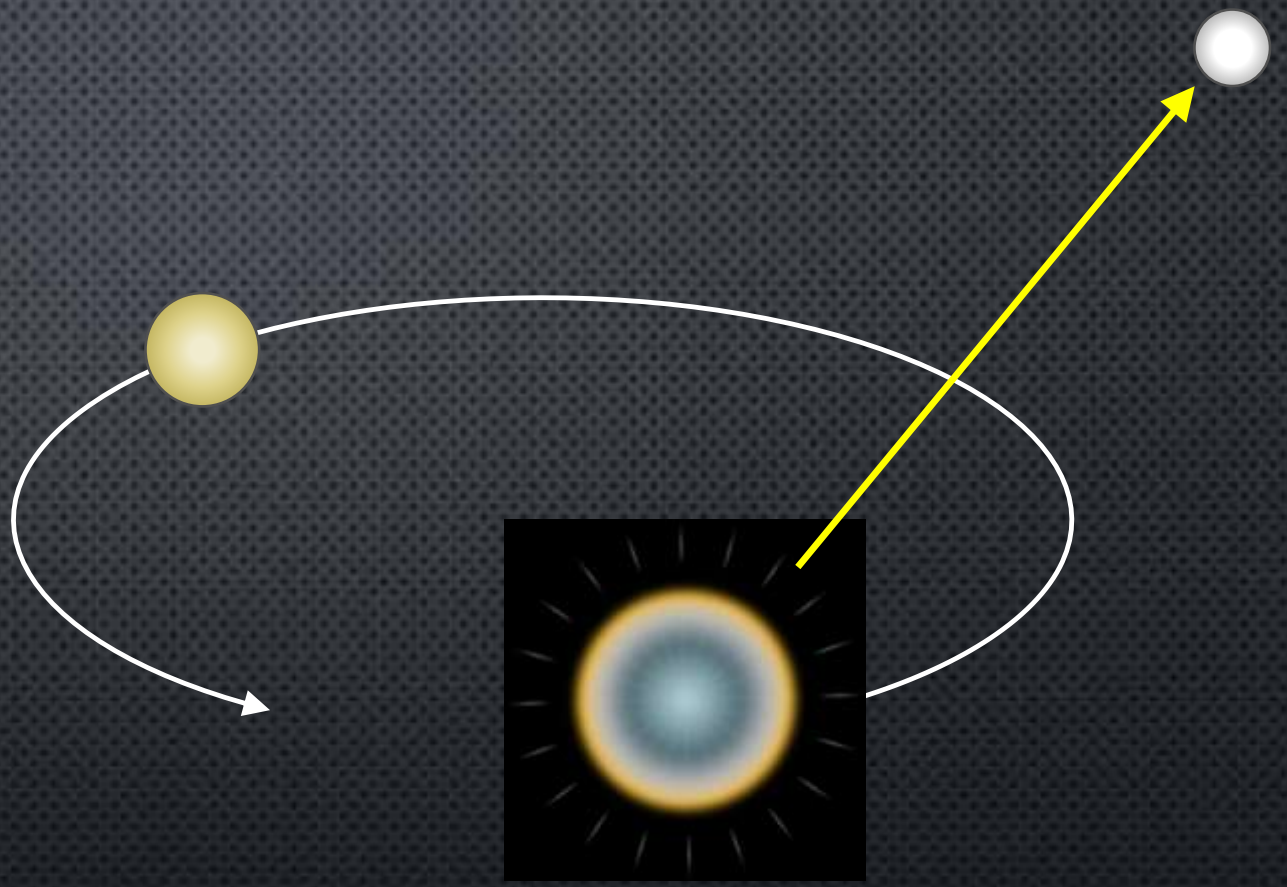

Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern



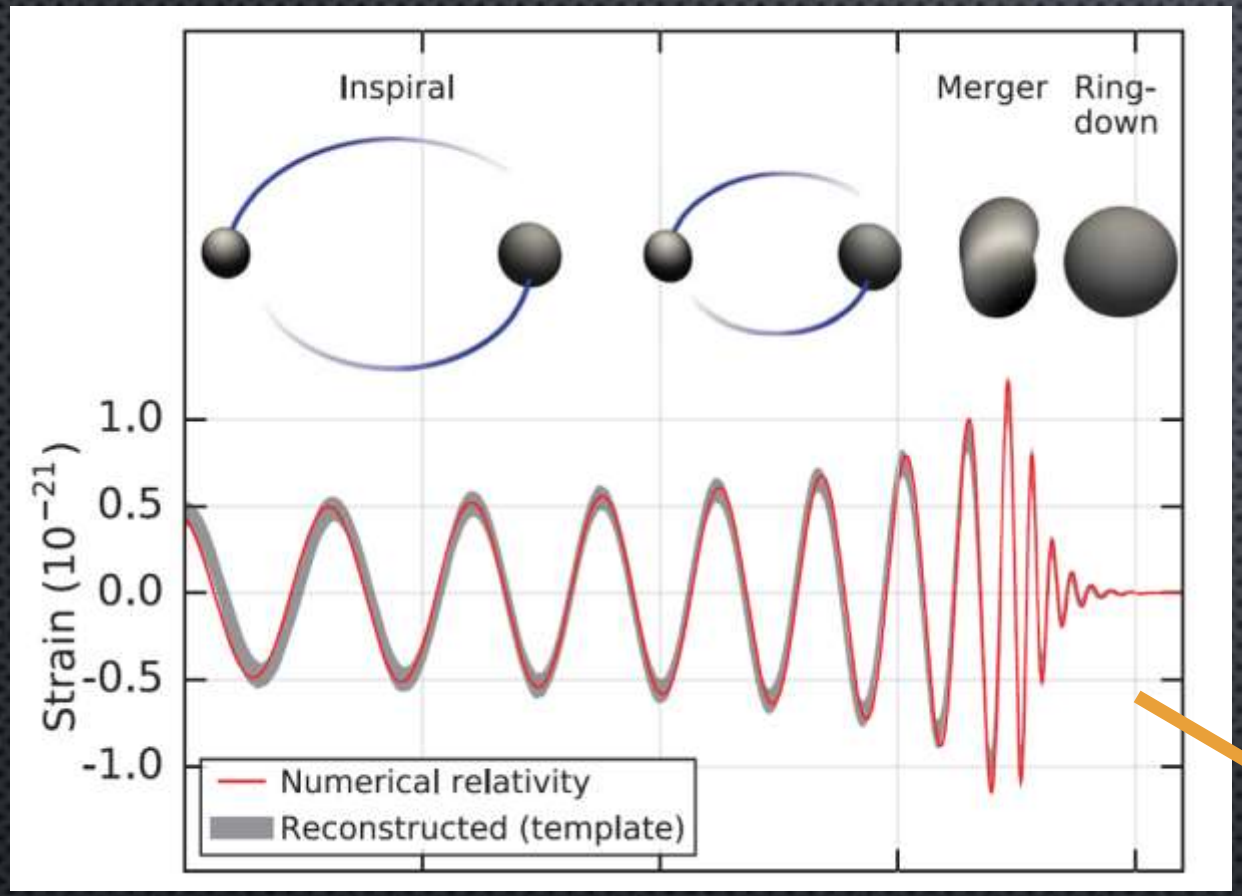
(C) NASA/SOHO


(C)NASA



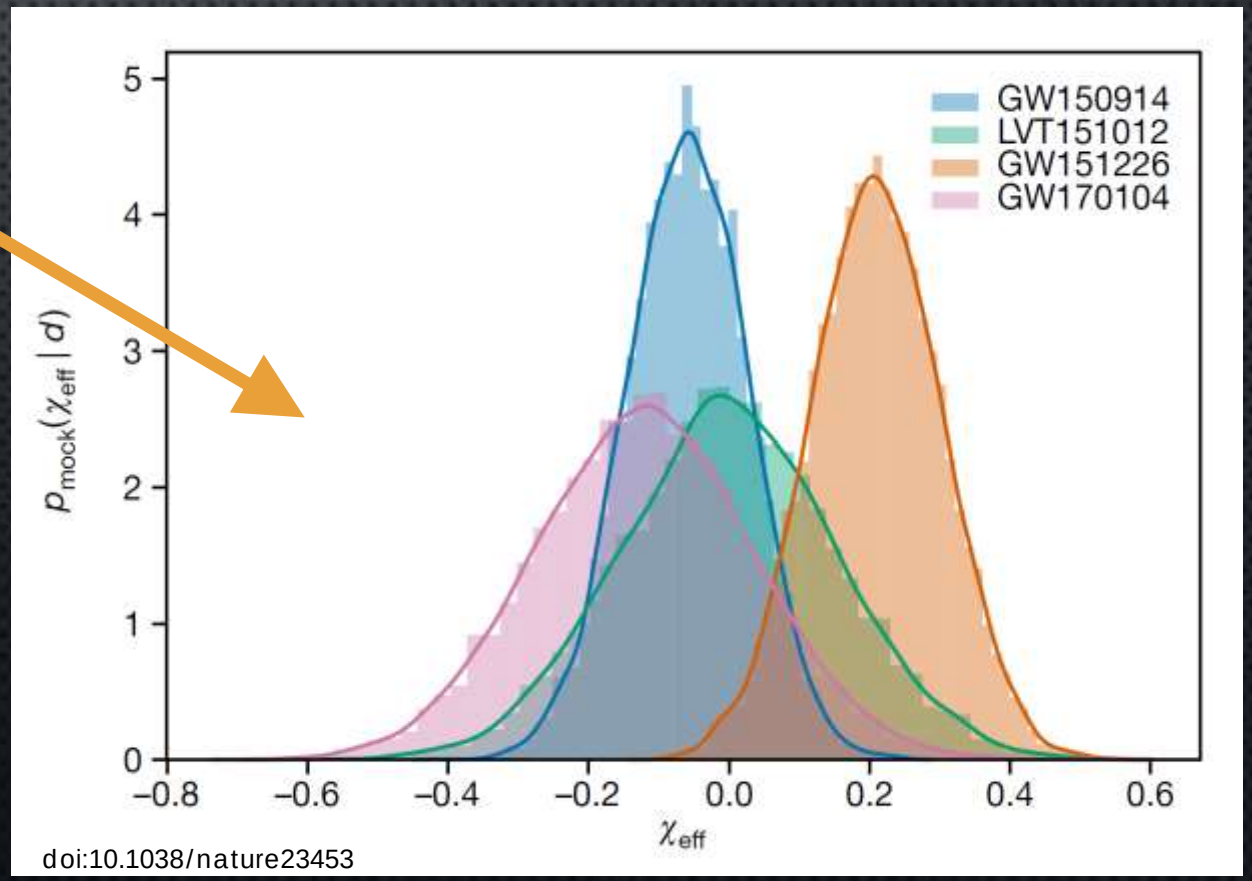


By NASA, The Hubble Heritage Team, STScI, AURA



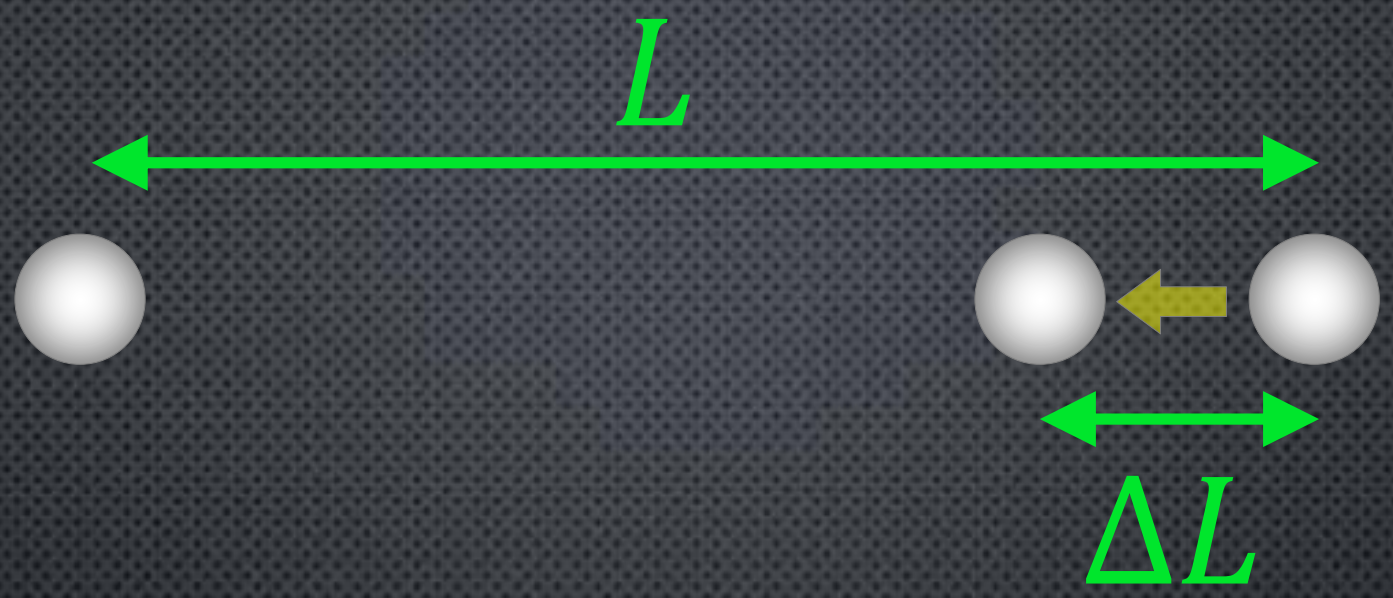
重力波波形

ブラックホールのスピン



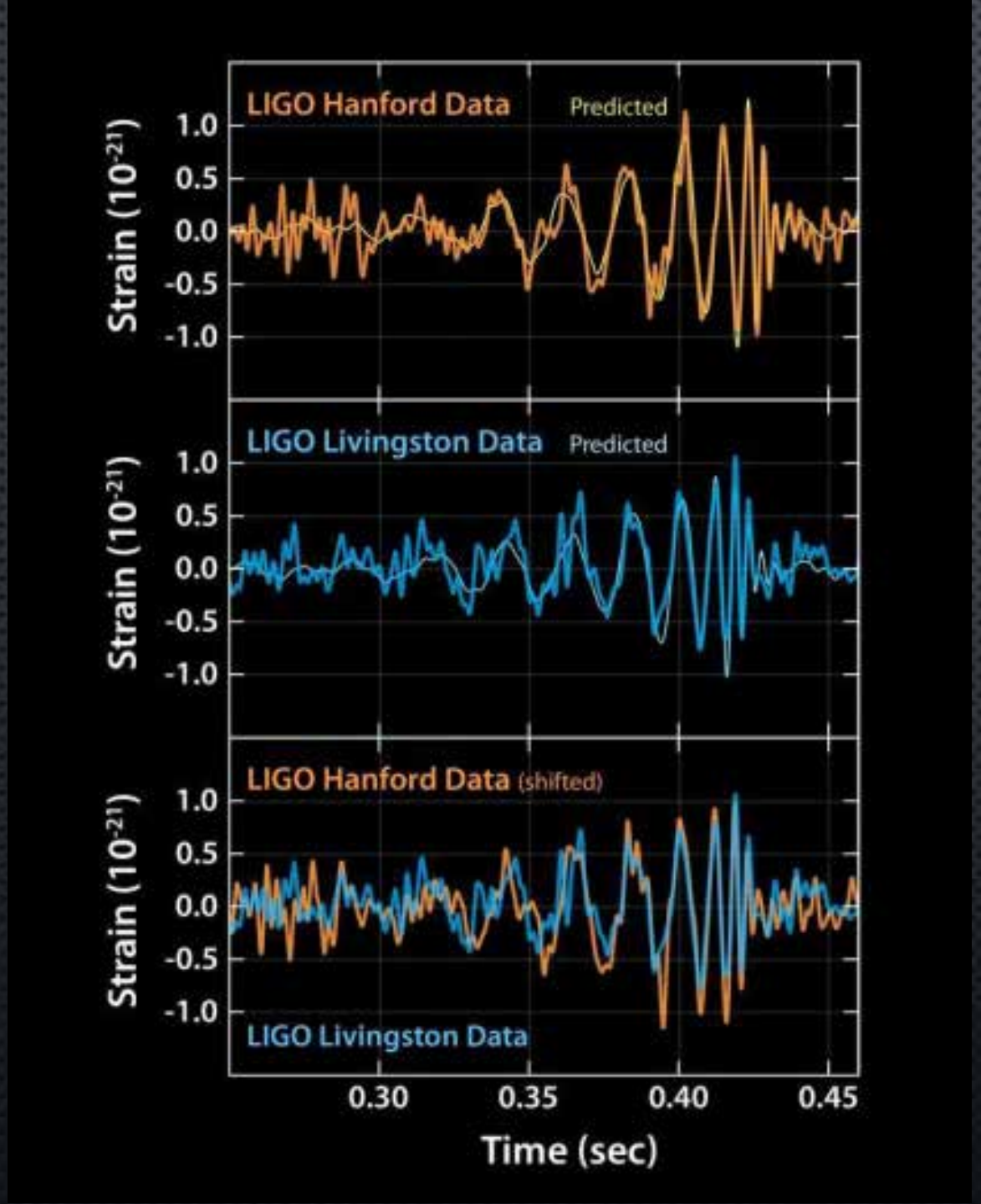
doi:10.1038/nature23453

どうやって重力波を検出するか?

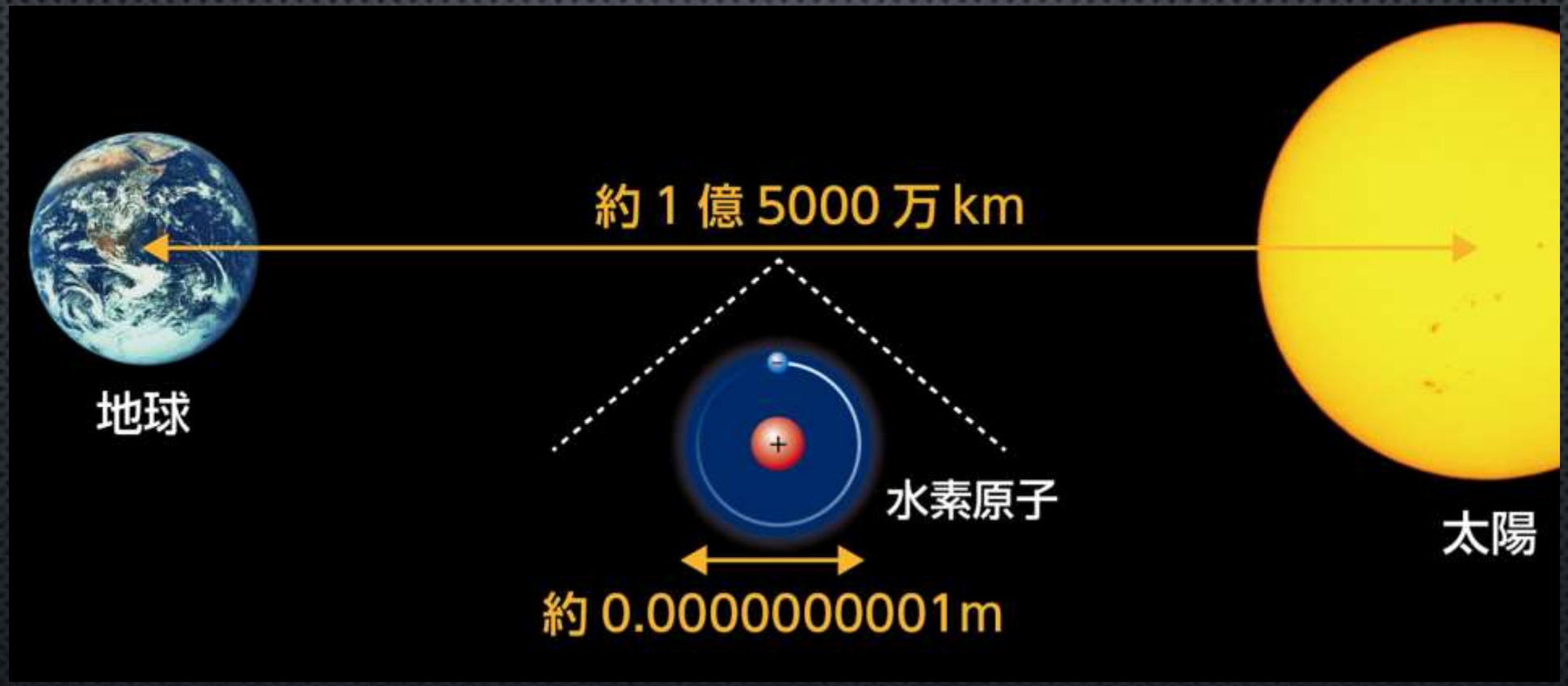


$$h \equiv \frac{\Delta L}{L}$$

重力波振幅



$$h \approx 10^{-21}$$

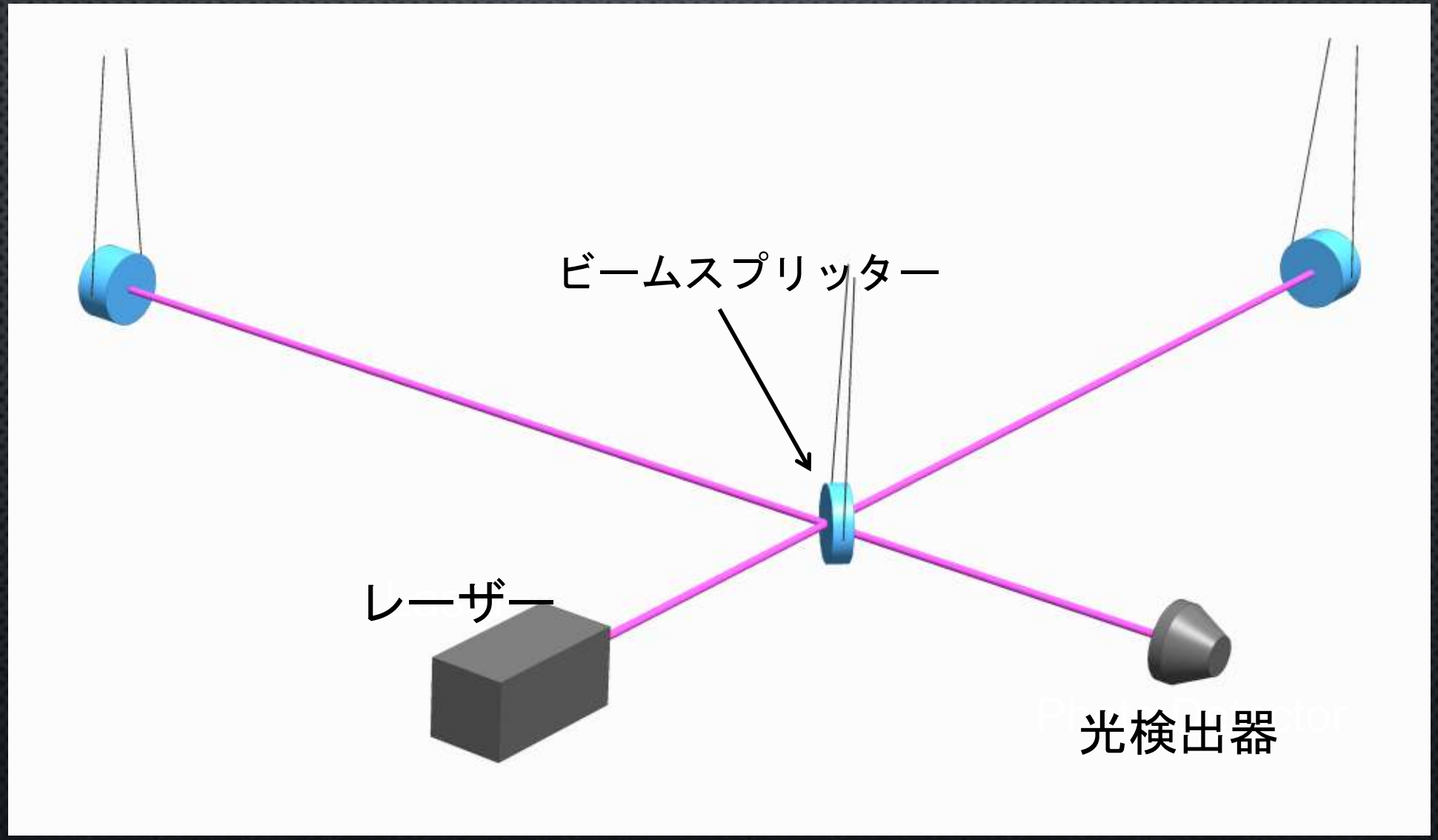


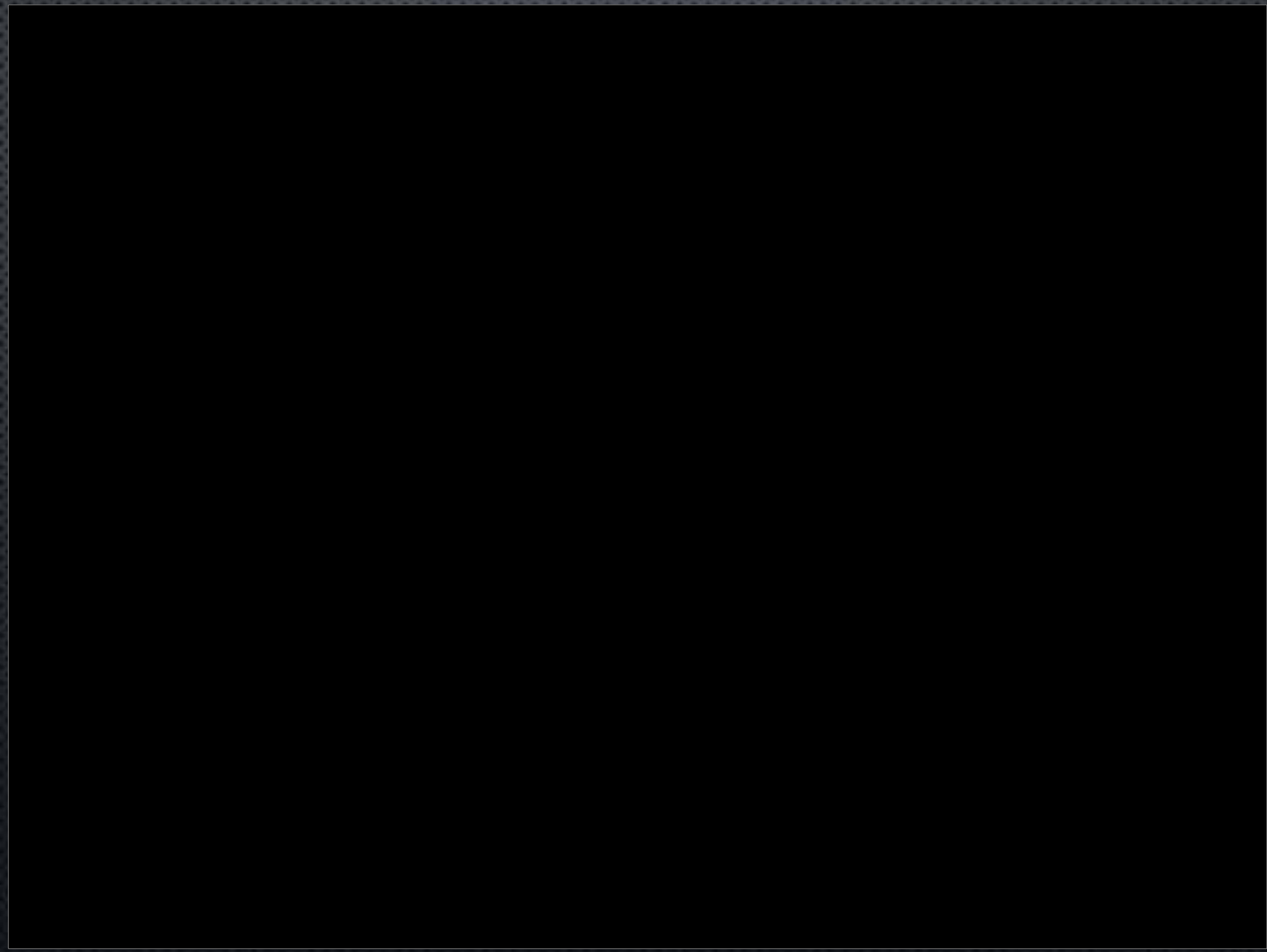
$$h = 10^{-21}$$

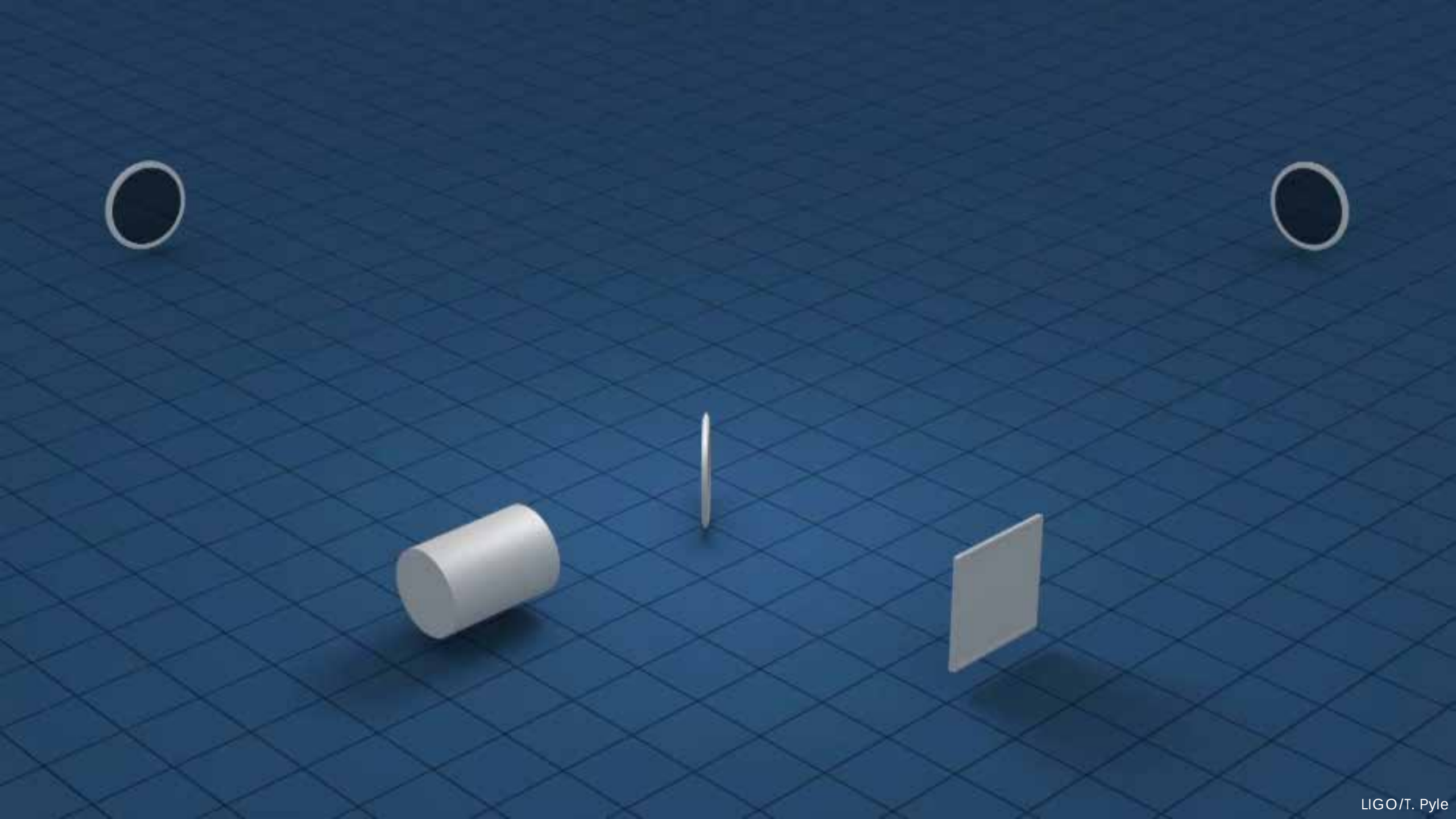
$$\times \frac{1}{1000}$$

$$h = 10^{-24}$$

マイケルソン干渉計



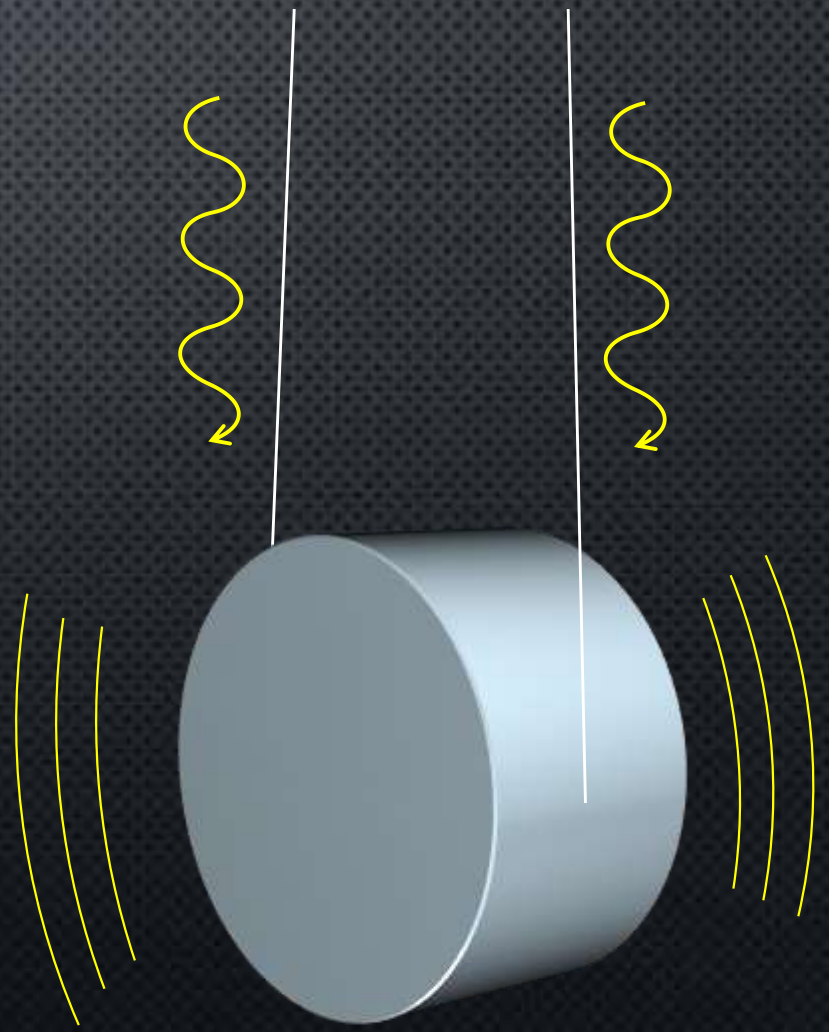



LIGO/T. Pyle

どこまで見えるのか?

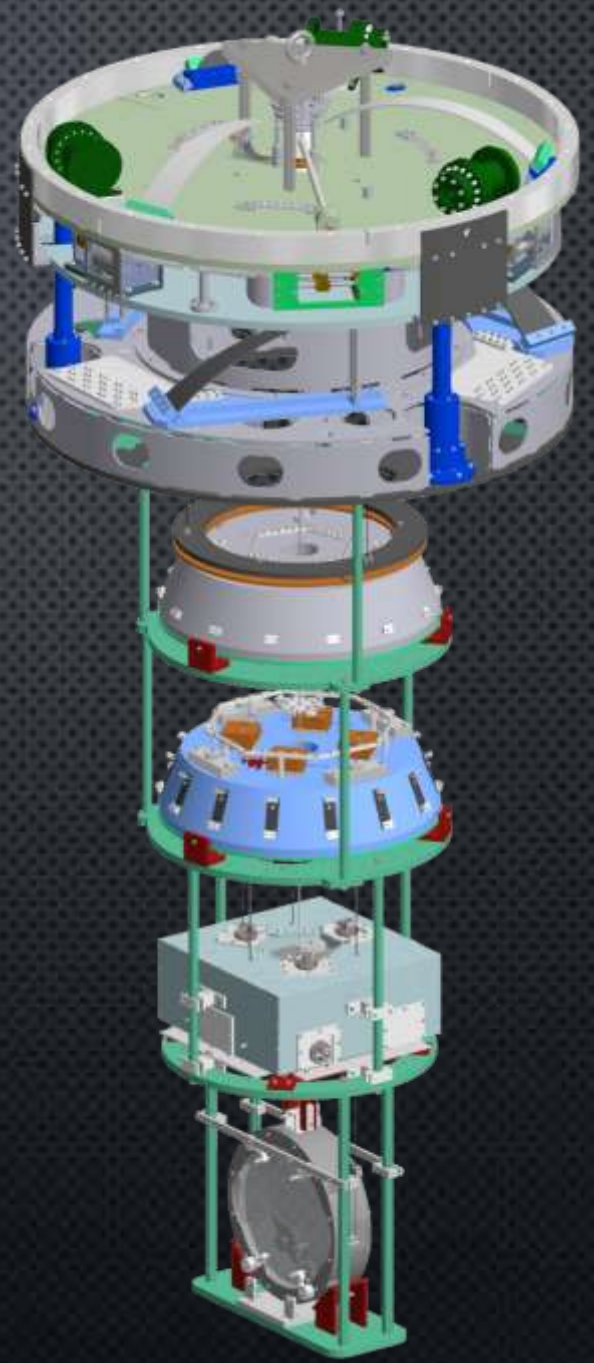
信号 > 雑音

地面振動

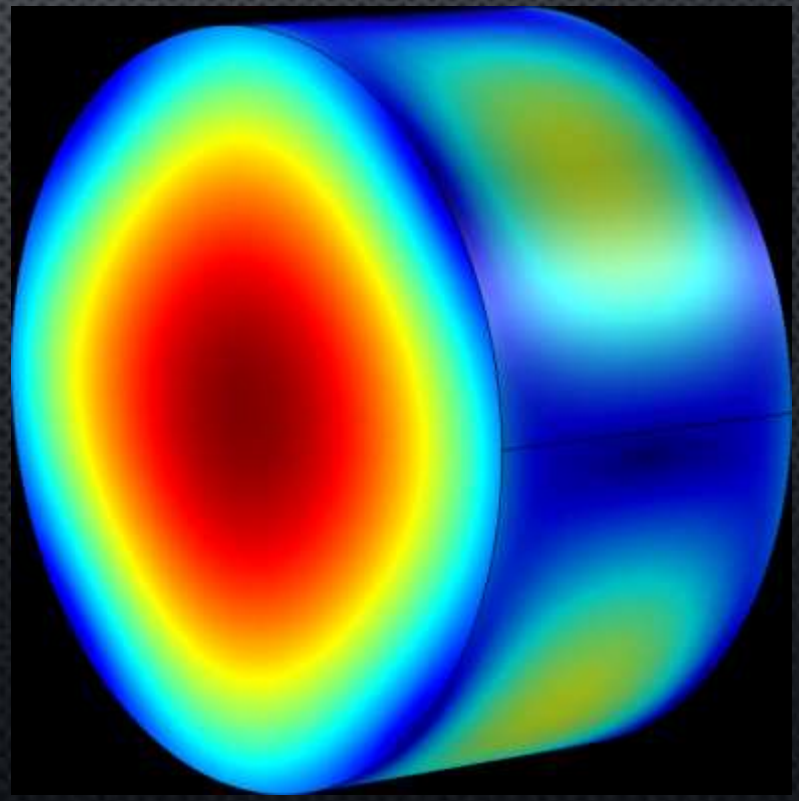


多段防振システム

$$\frac{1}{10000000000}$$

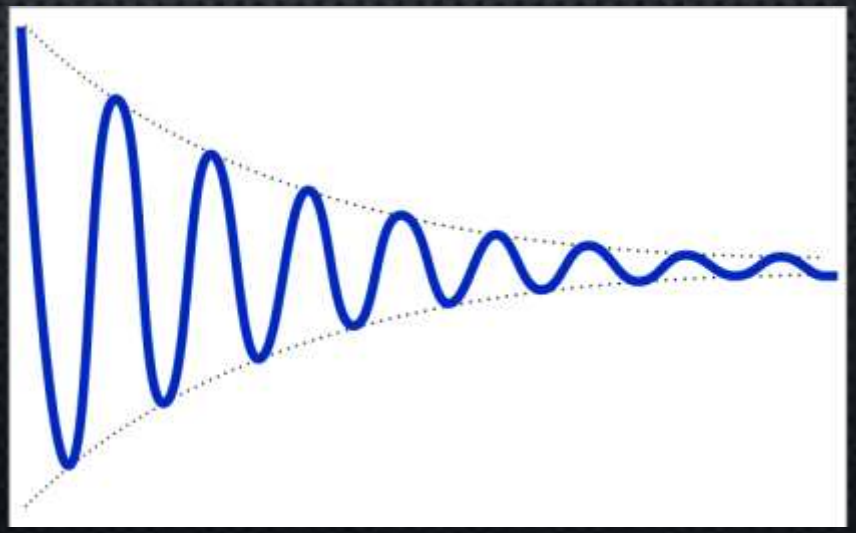


熱雑音



温度

機械的エネルギー損失



Fused Silica

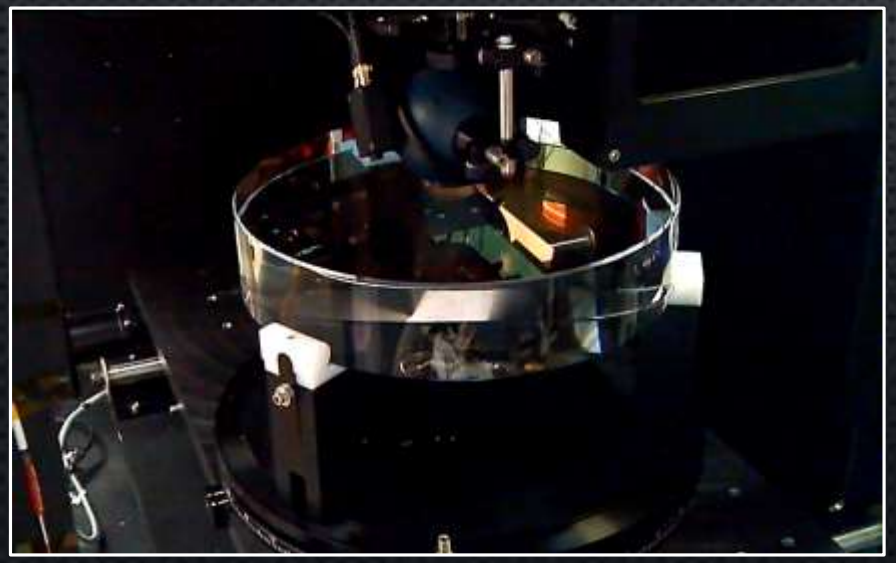
Sapphire

大型超低損失ミラー

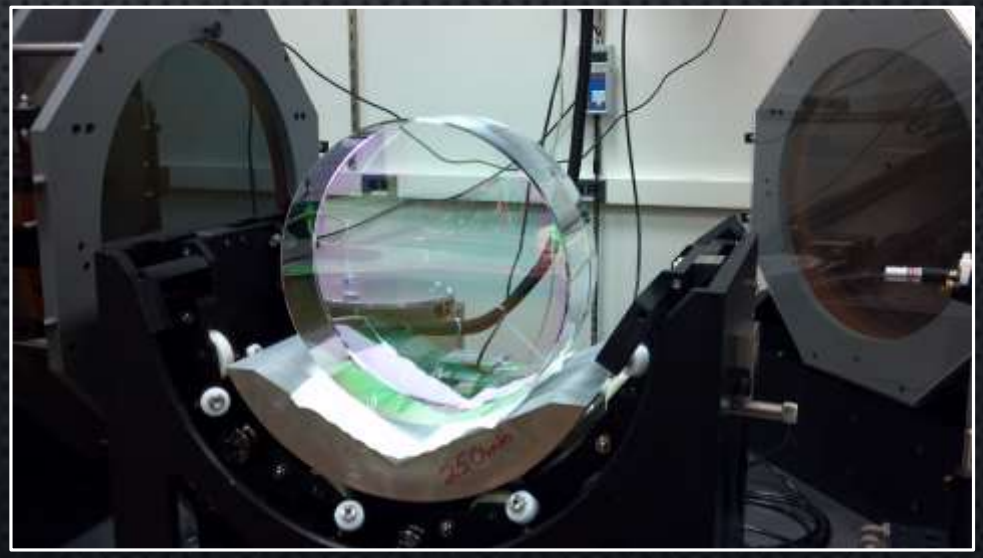
光学損失: 50ppm未満

面精度: λ/100

面粗さ: 10Å未満

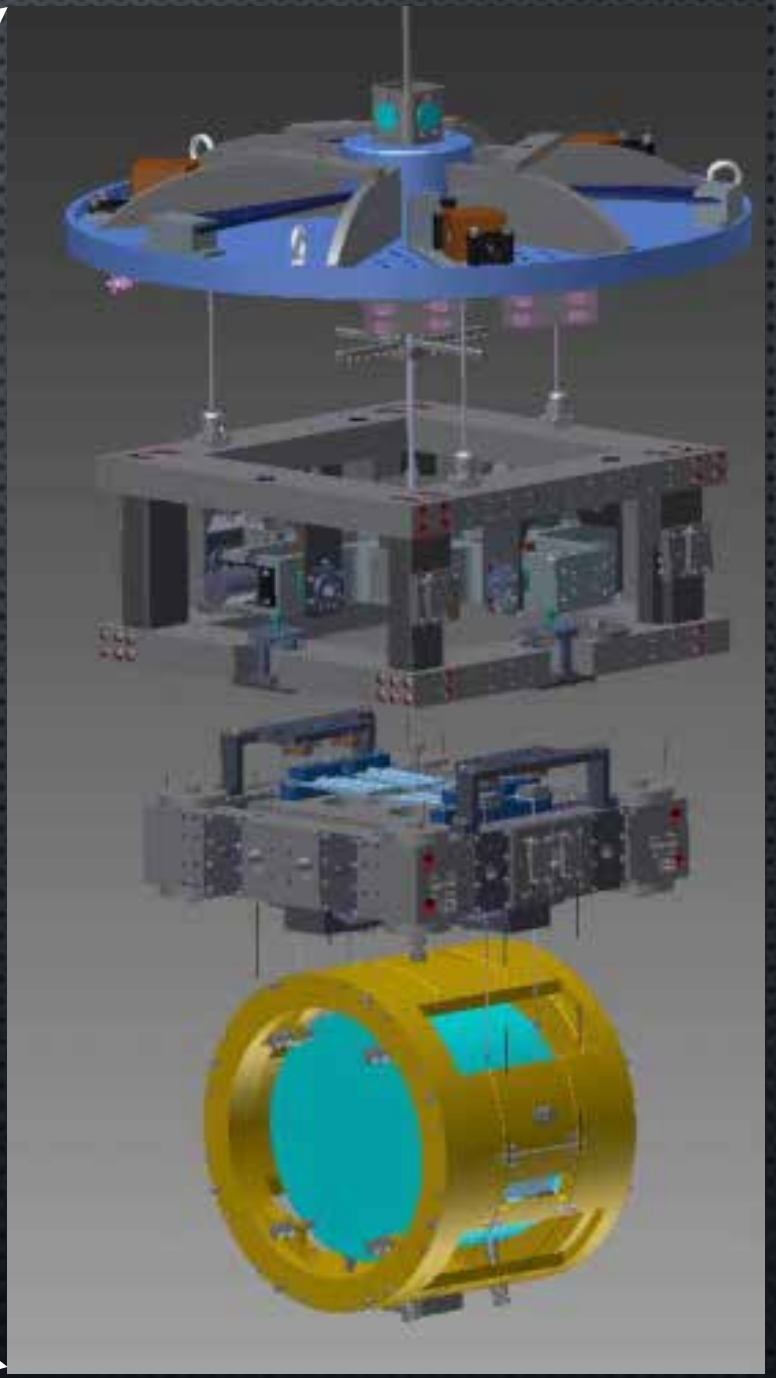


Beamsplitter(370mm dia) during coating characterization

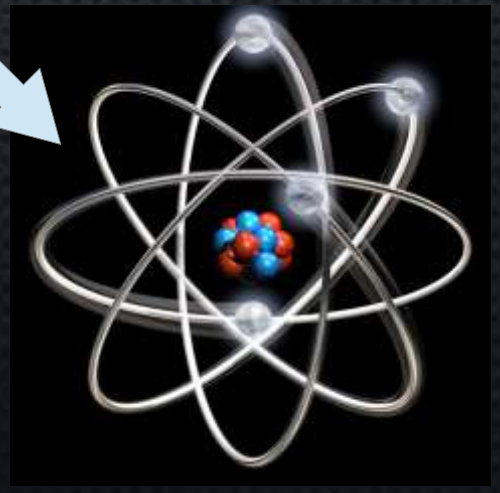


iKAGRA TM (250mm dia) during figure measurement

冷却(20K)

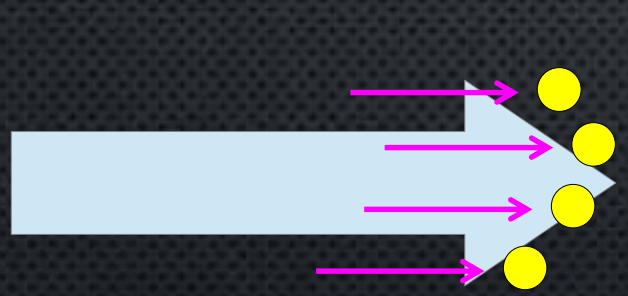


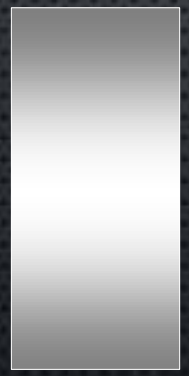
量子力学的不確定性原理



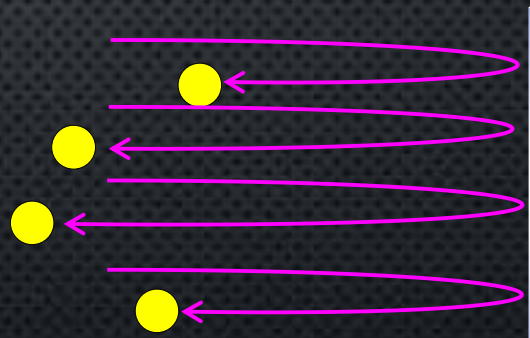
ショットノイズ

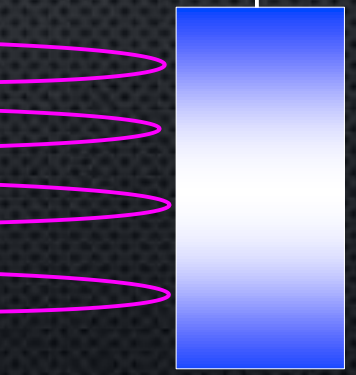
輻射圧雑音





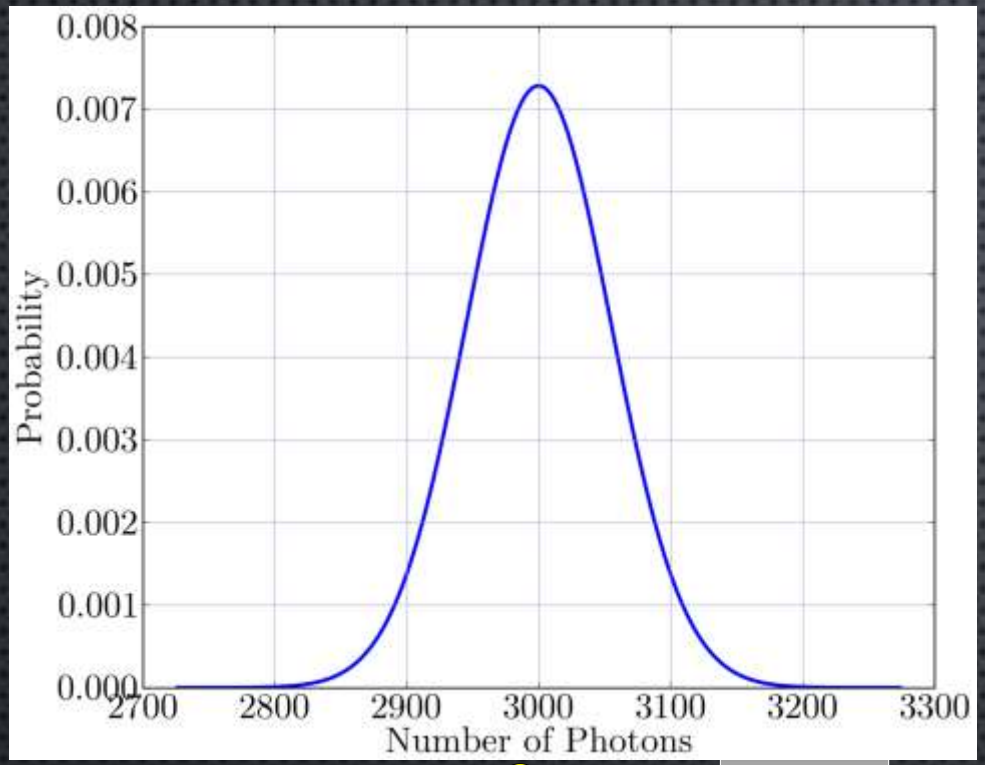
光検出器

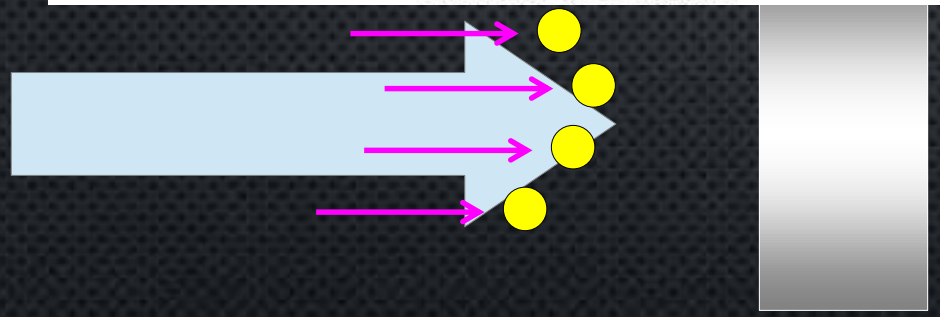




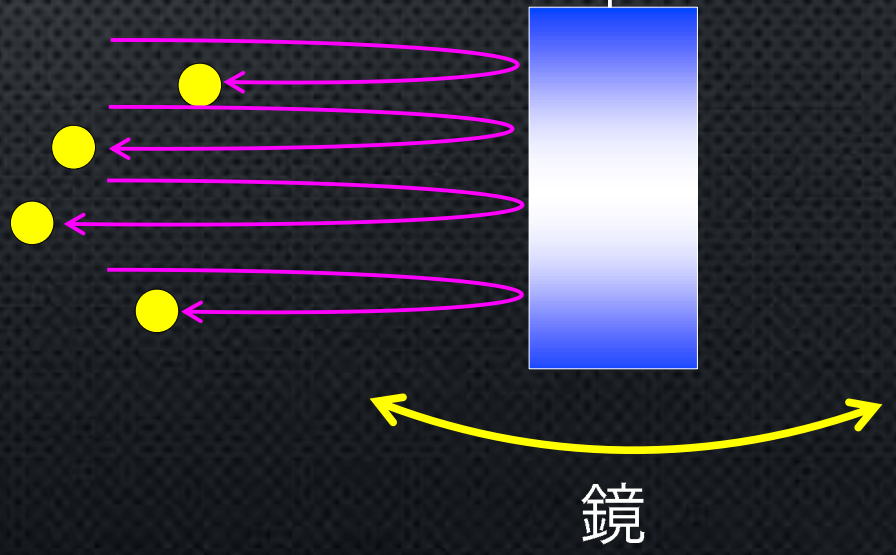
鏡

輻射圧雑音


0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0.000
Probability
2700
2800
2900
3000
3100
3200
3300
Number of Photons

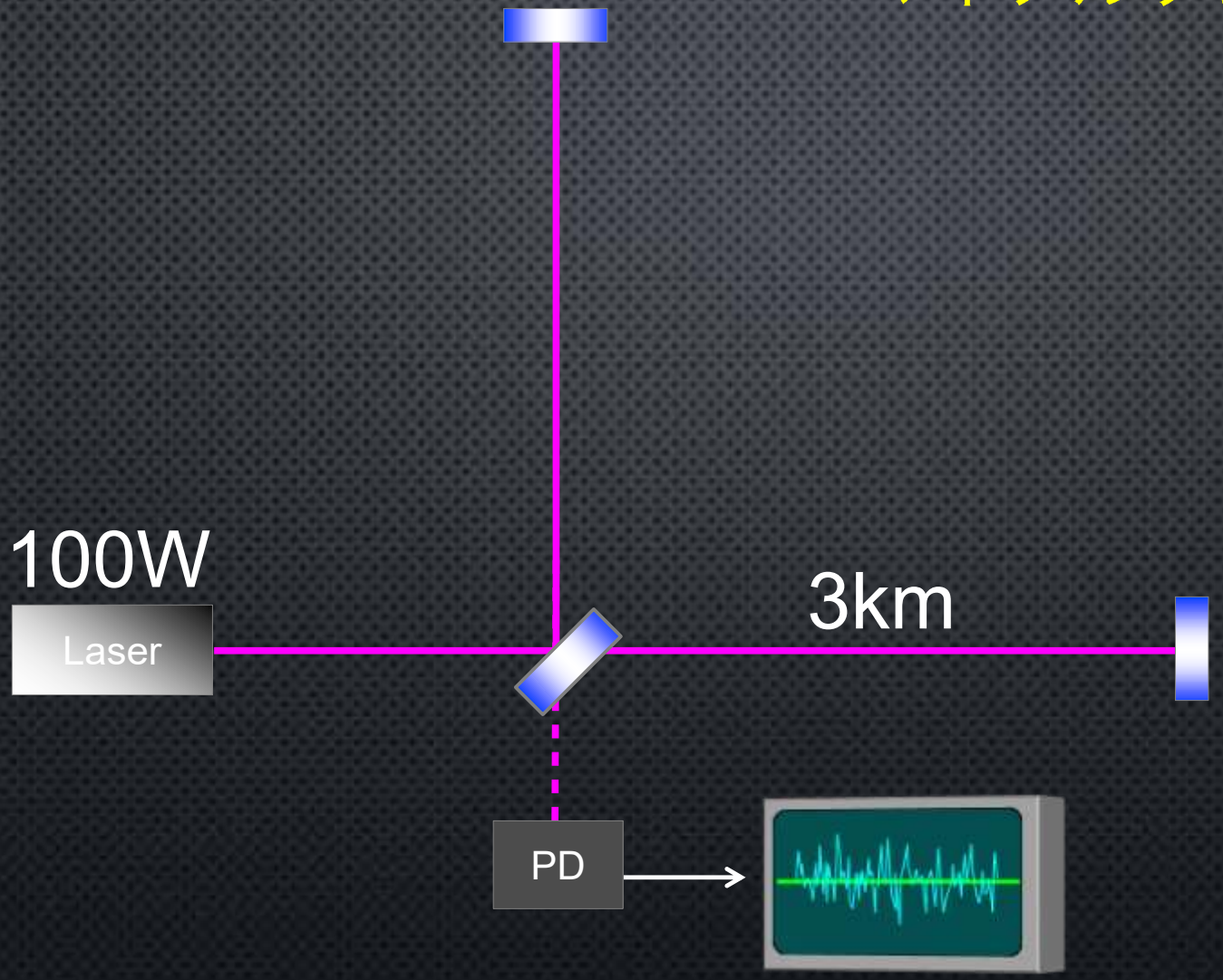


光検出器



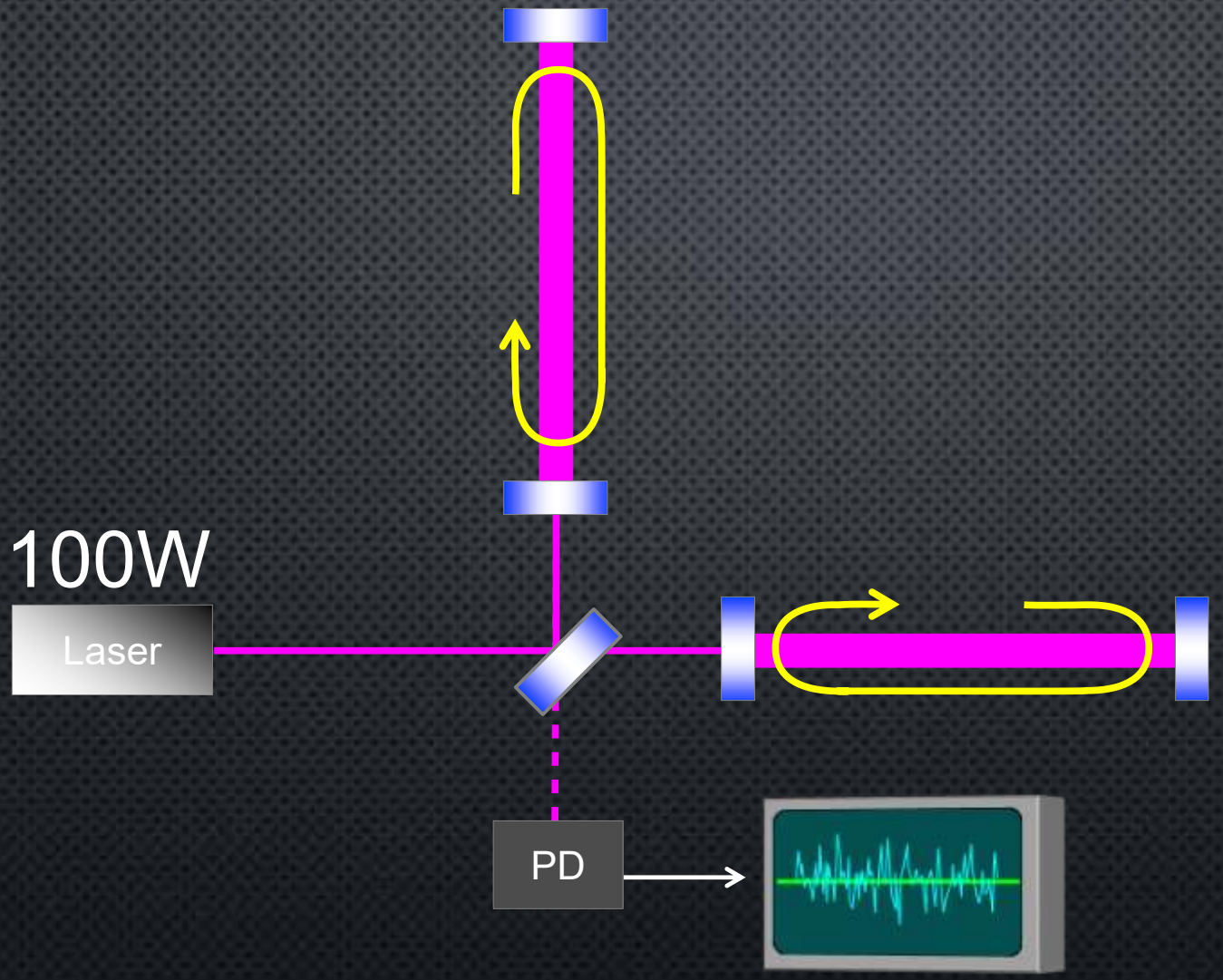
鏡

マイケルソン干渉計

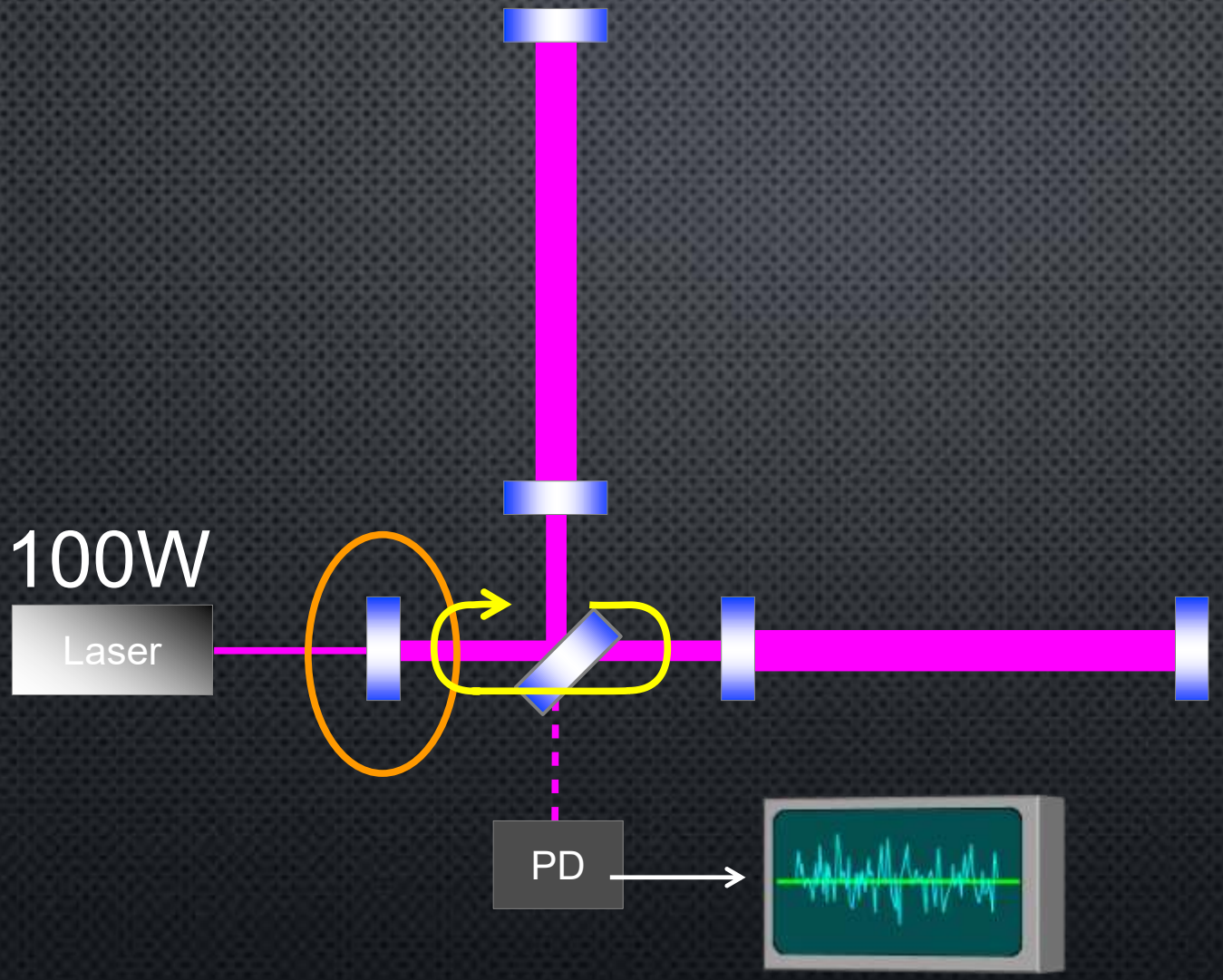


$$h = 2 \times 10^{-21}$$

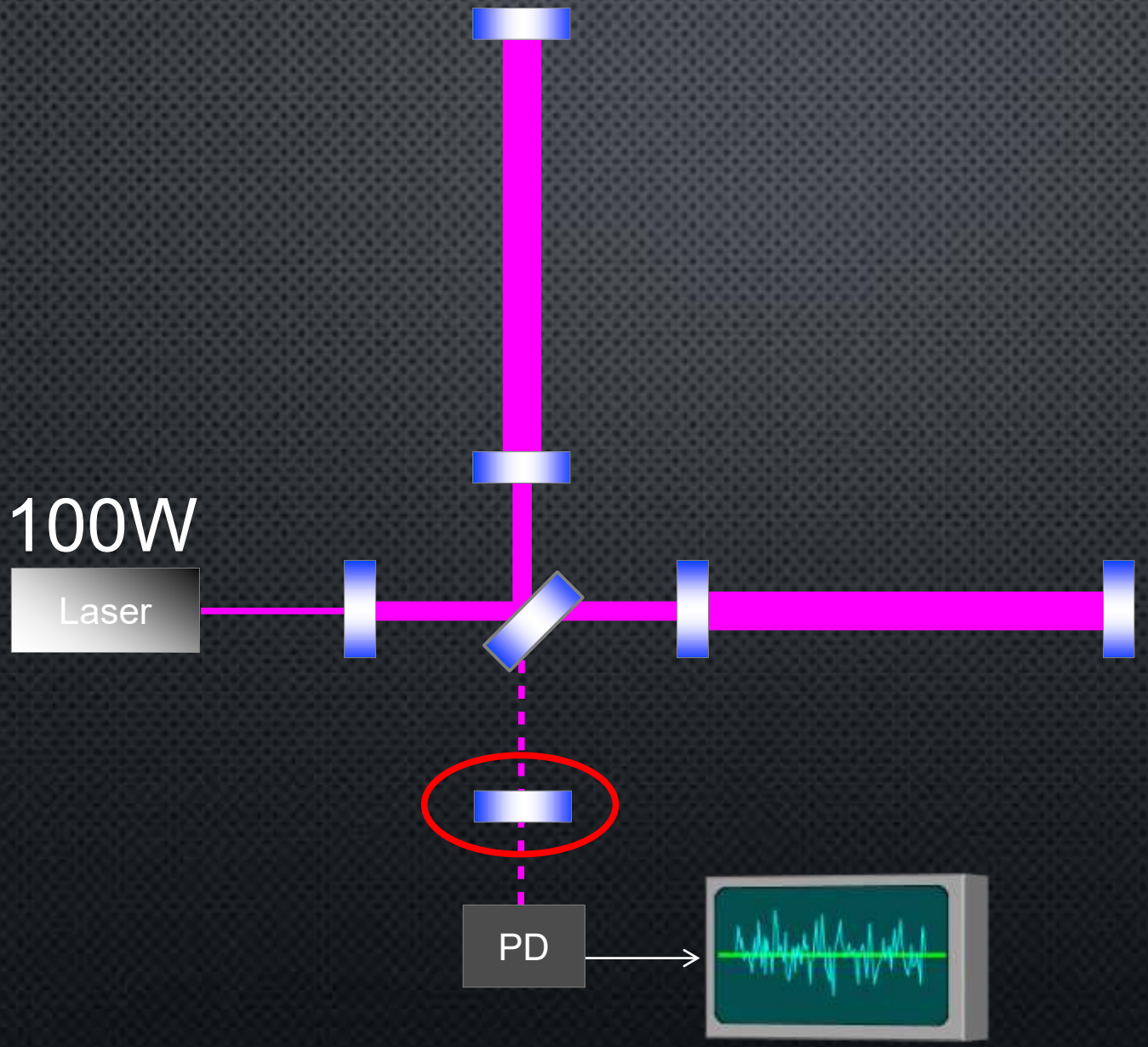
Fabry-Perot Michelson



Power Recycling

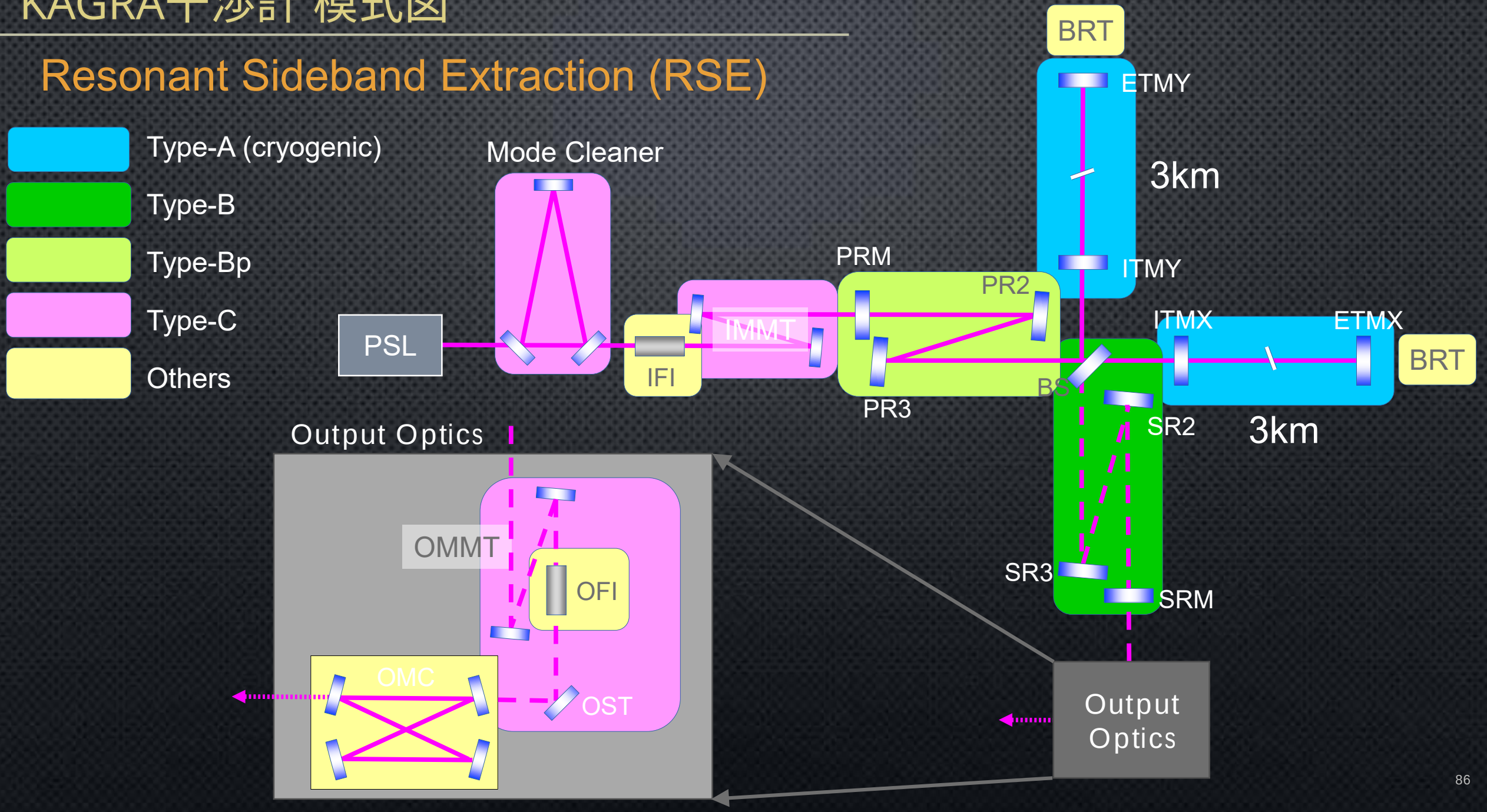


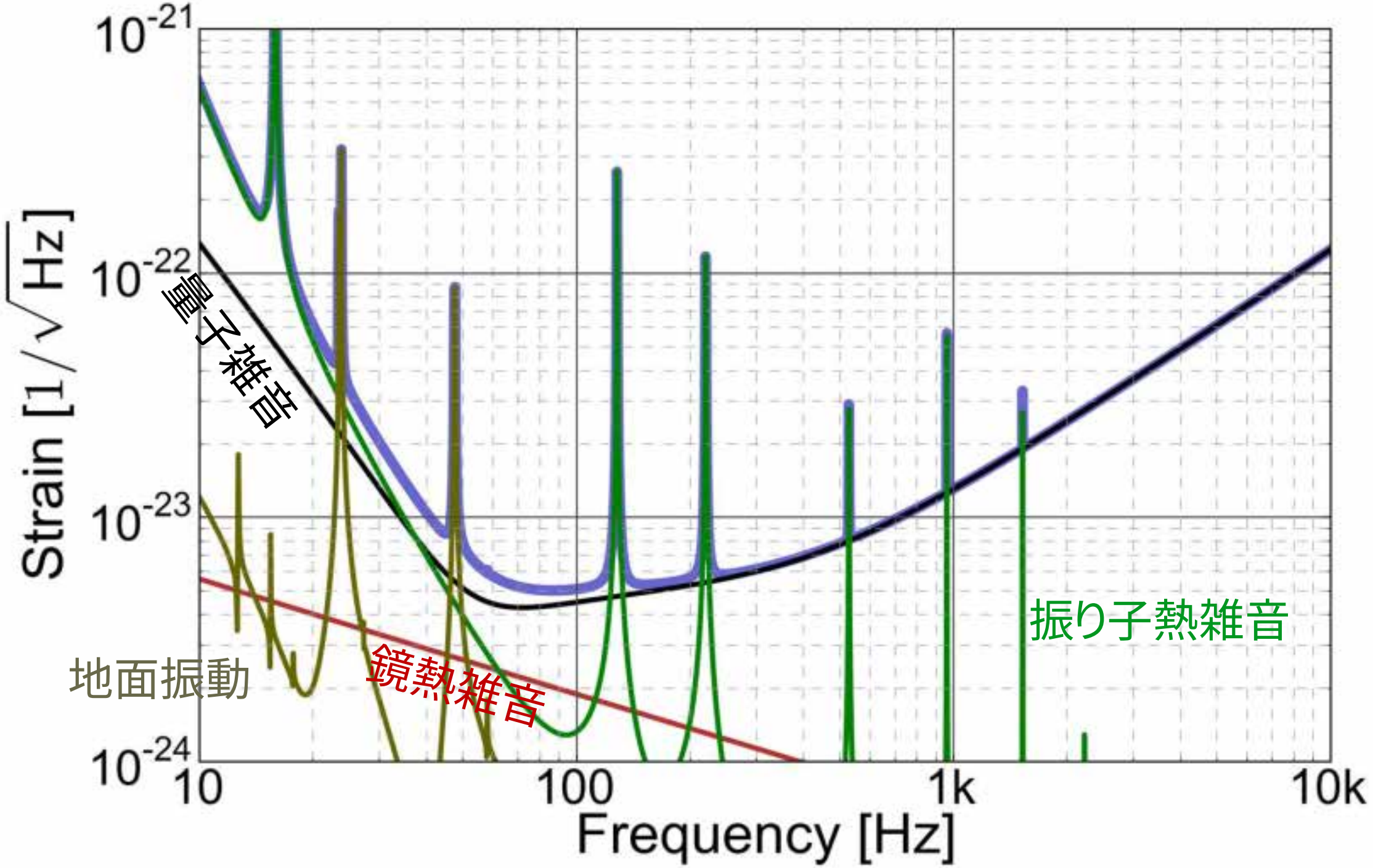
Resonant Sideband Extraction (RSE)



KAGRA干渉計 模式図

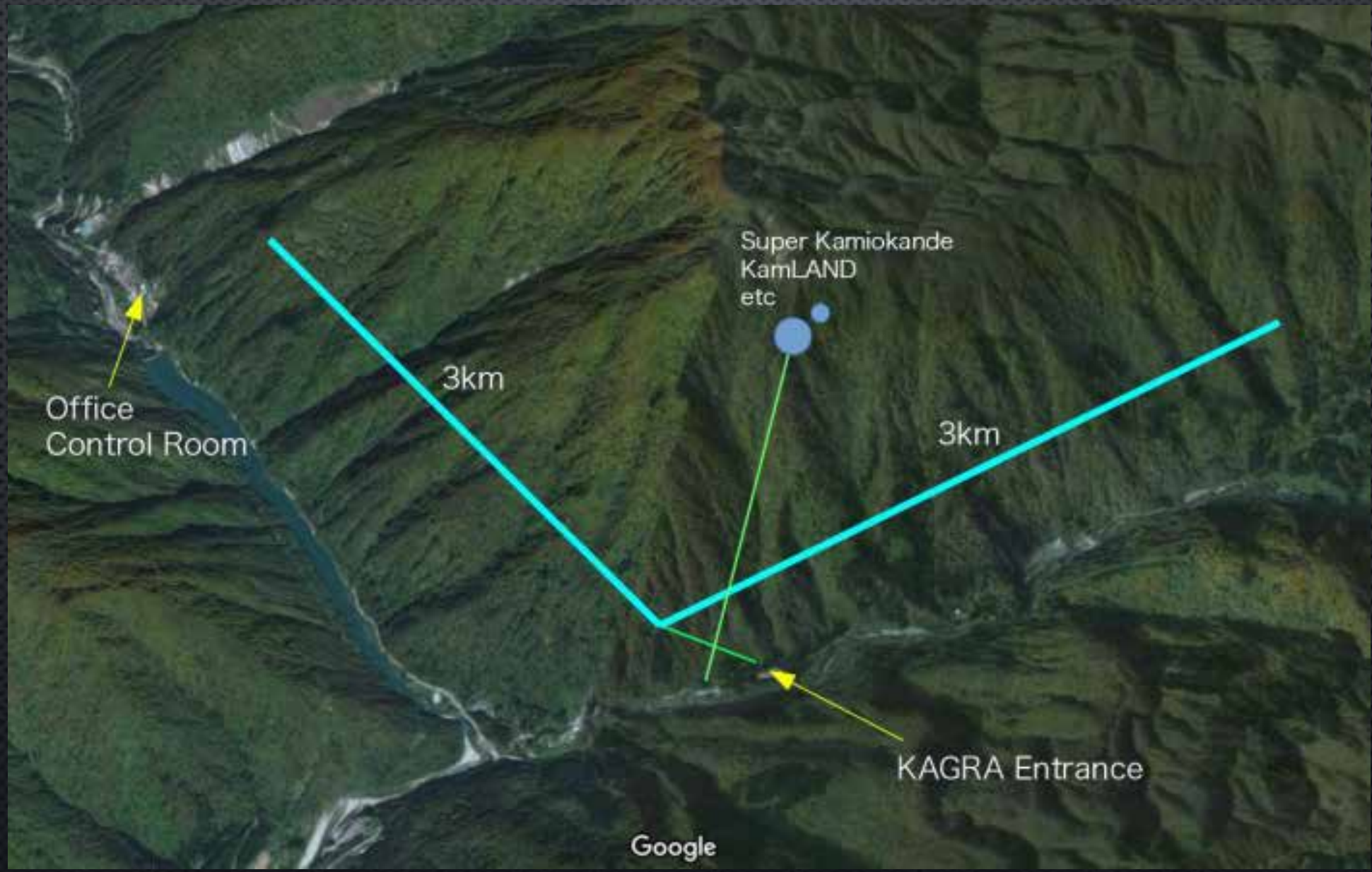
Resonant Sideband Extraction (RSE)

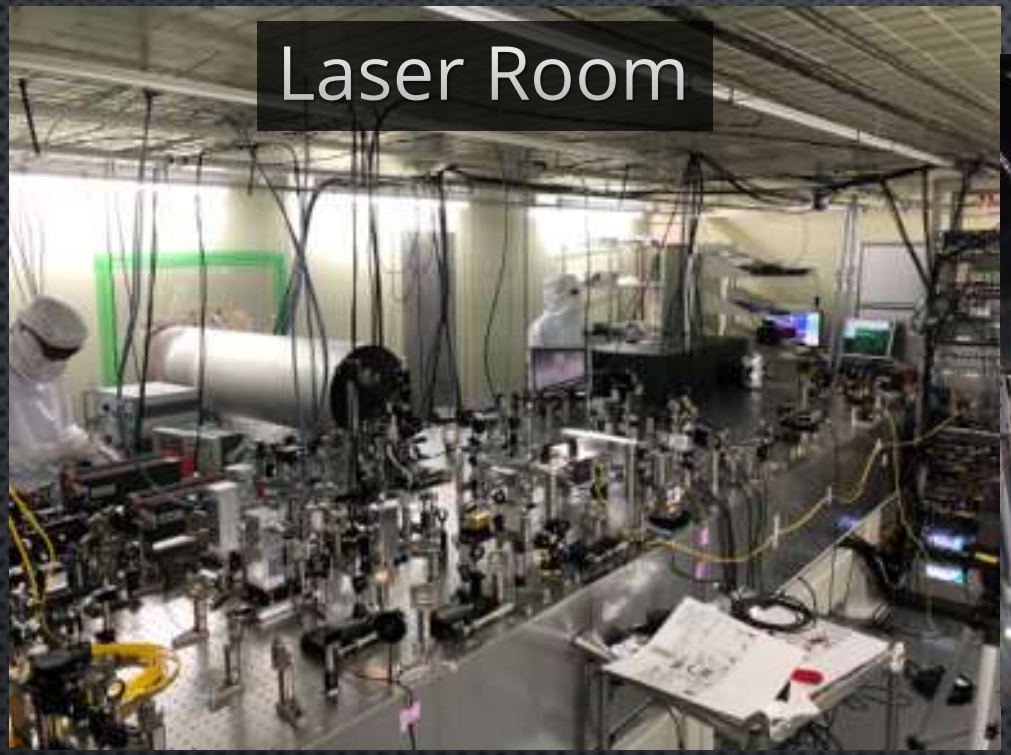



10^{-21}
10^{-22}
10^{-23}
10^{-24}
Strain [1/√Hz]
量子雑音
地面振動
鏡熱雑音
振り子熱雑音
10
100
1k
10k
Frequency [Hz]

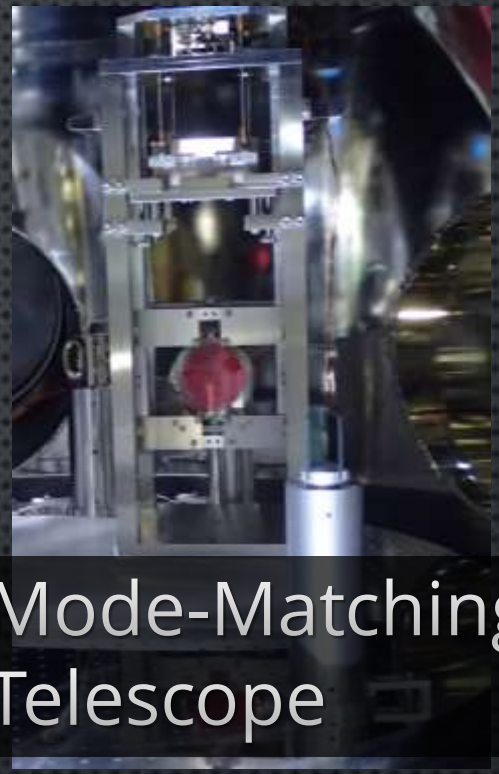
The KAGRA Project

- 約300人の共同研究者
- 国内30以上，海外40以上の研究機関

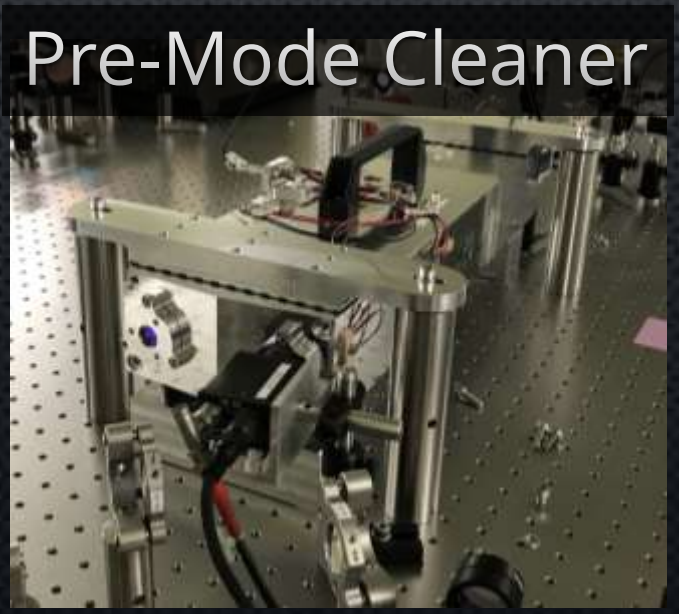

Super Kamiokande
KamLAND
etc
3km
3km
Office
Control Room
KAGRA Entrance
Google

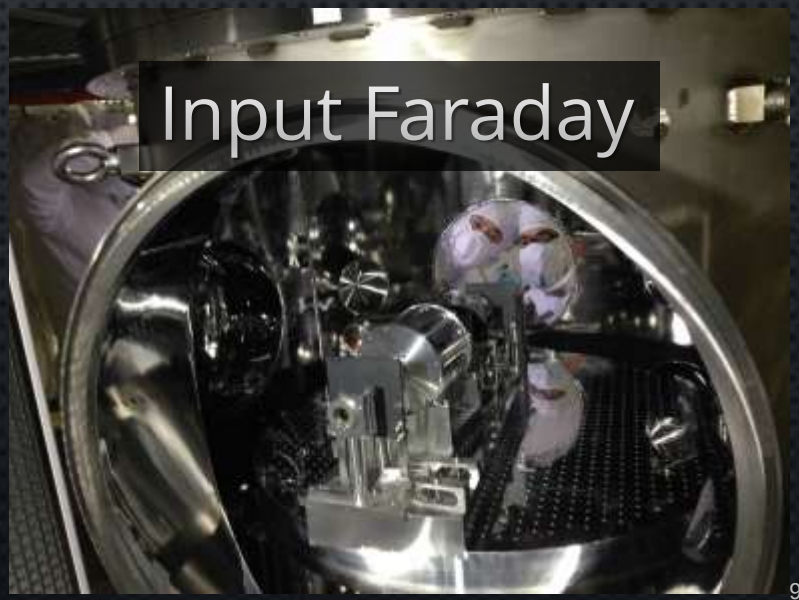

Laser Room

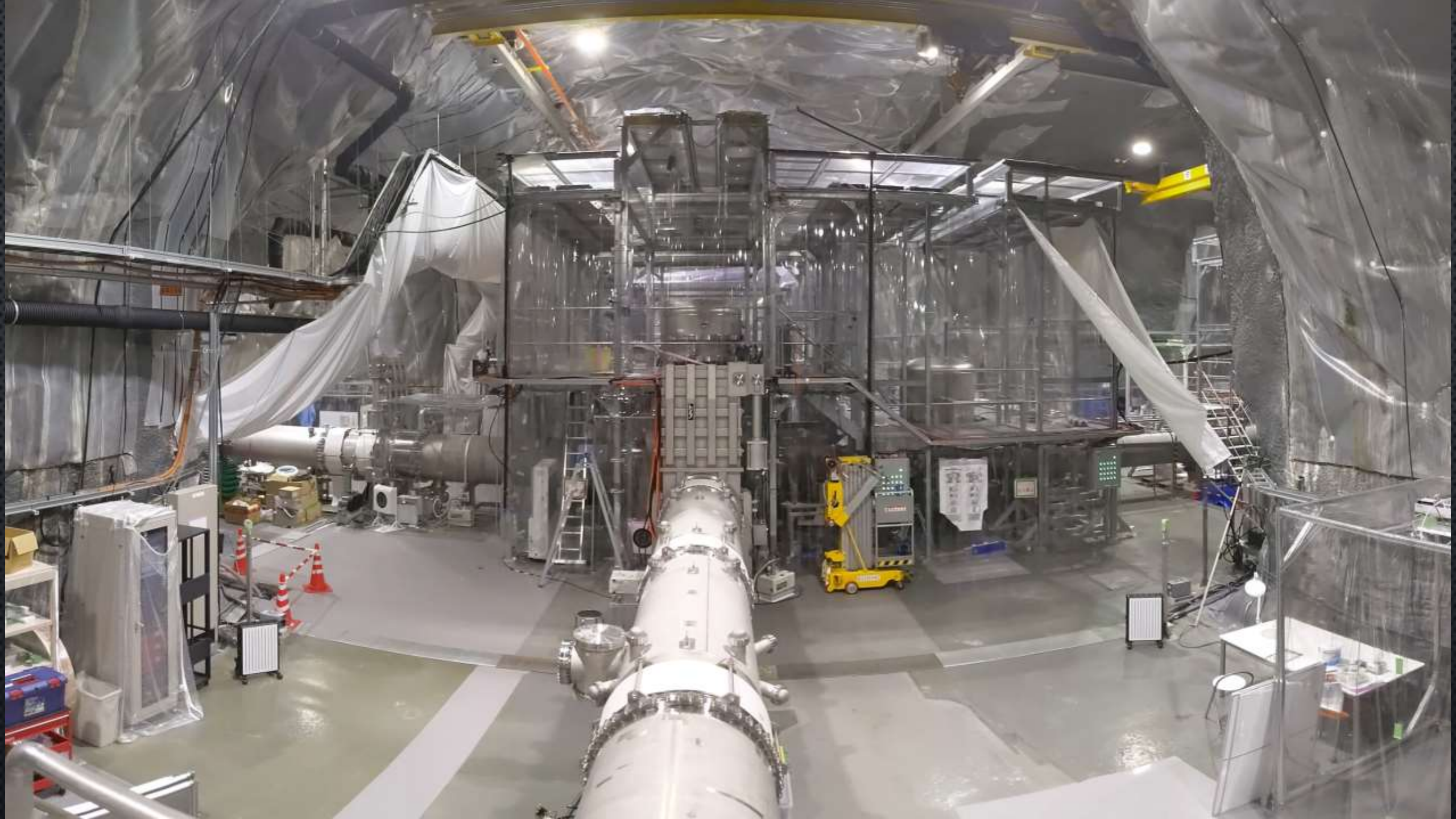

Mode Cleaner


Mode-Matching Telescope

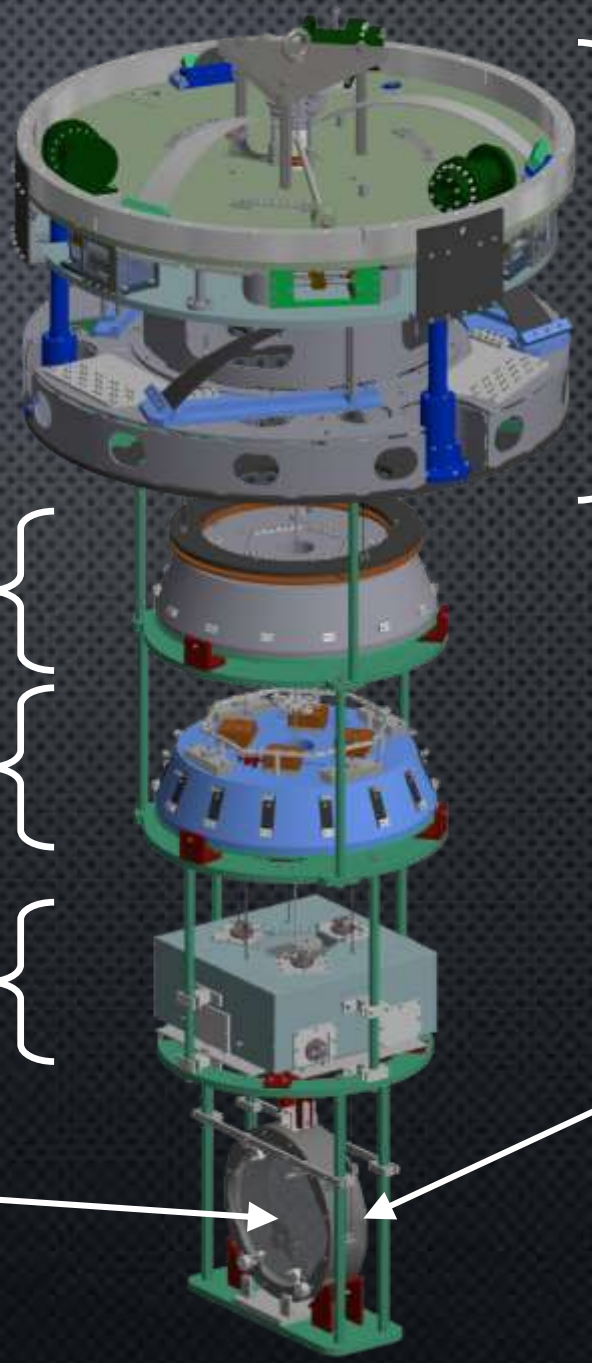

Reference Cavity

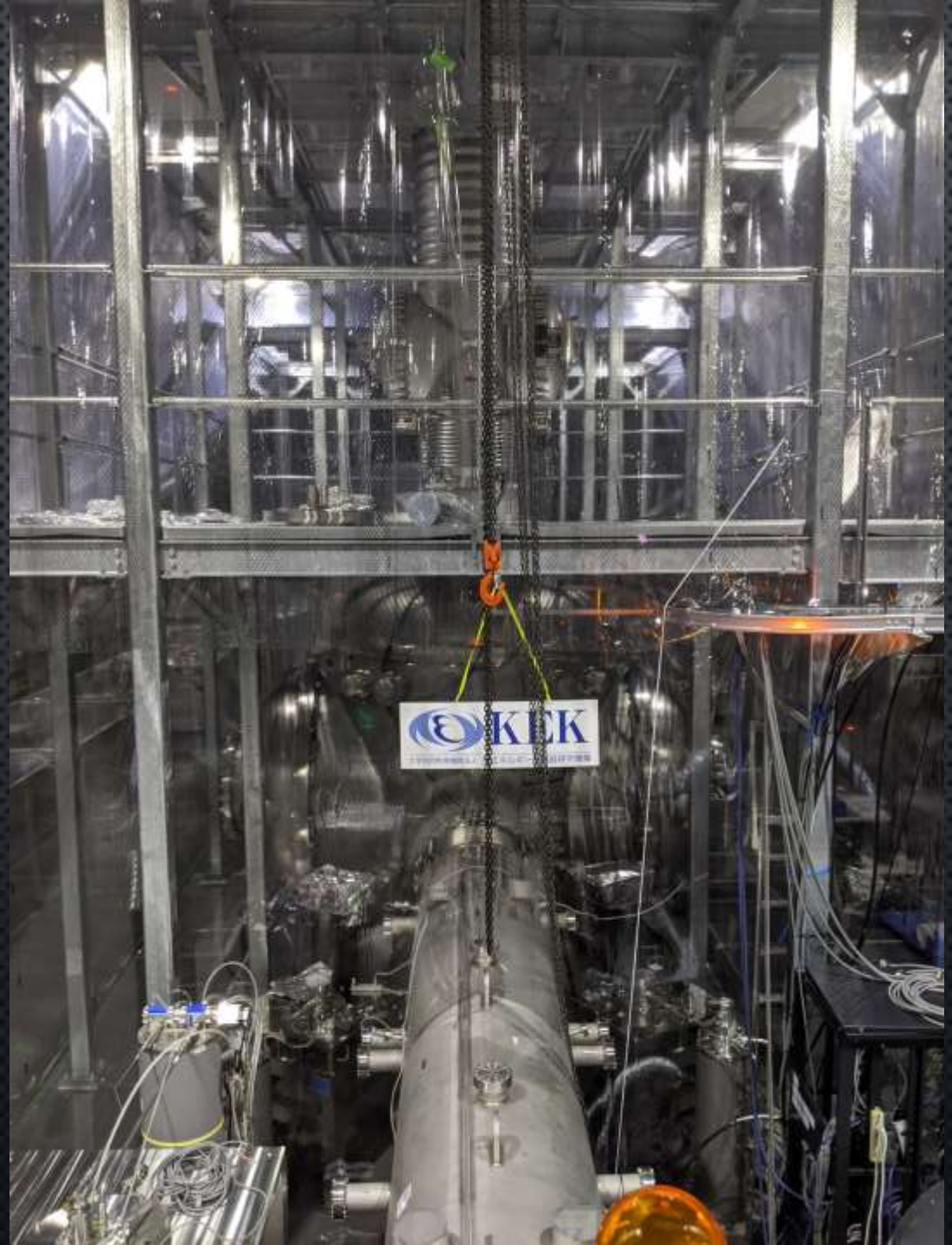

Pre-Mode Cleaner


Input Faraday



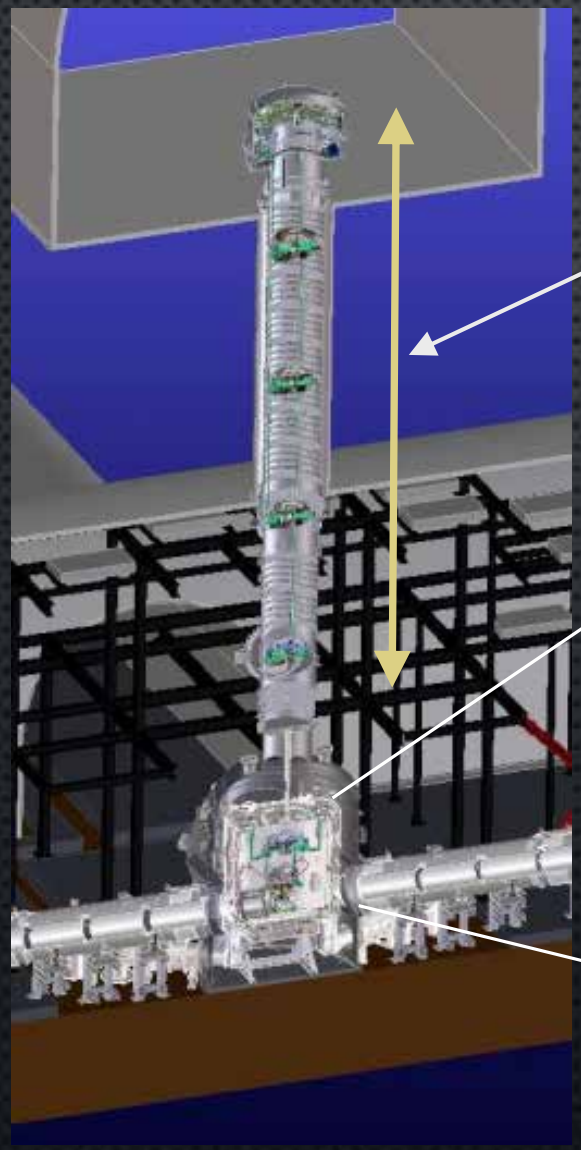
Beam Splitter Suspension




KEK

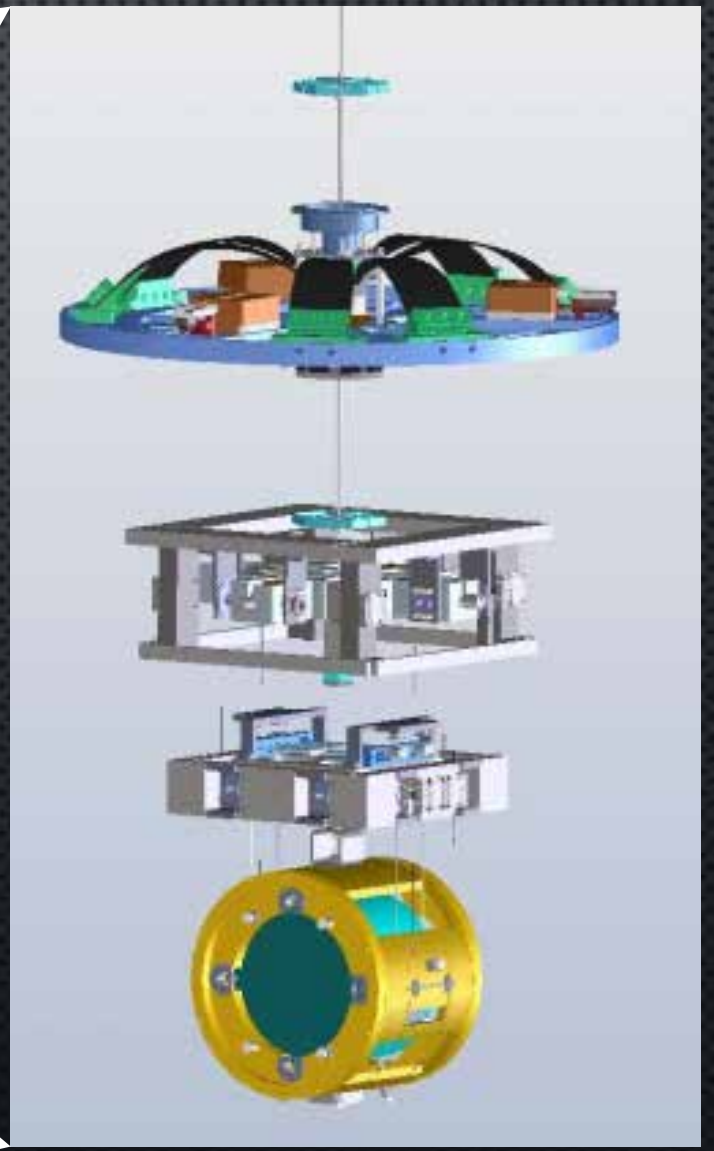
Type-A + Cryogenic Suspension

14m

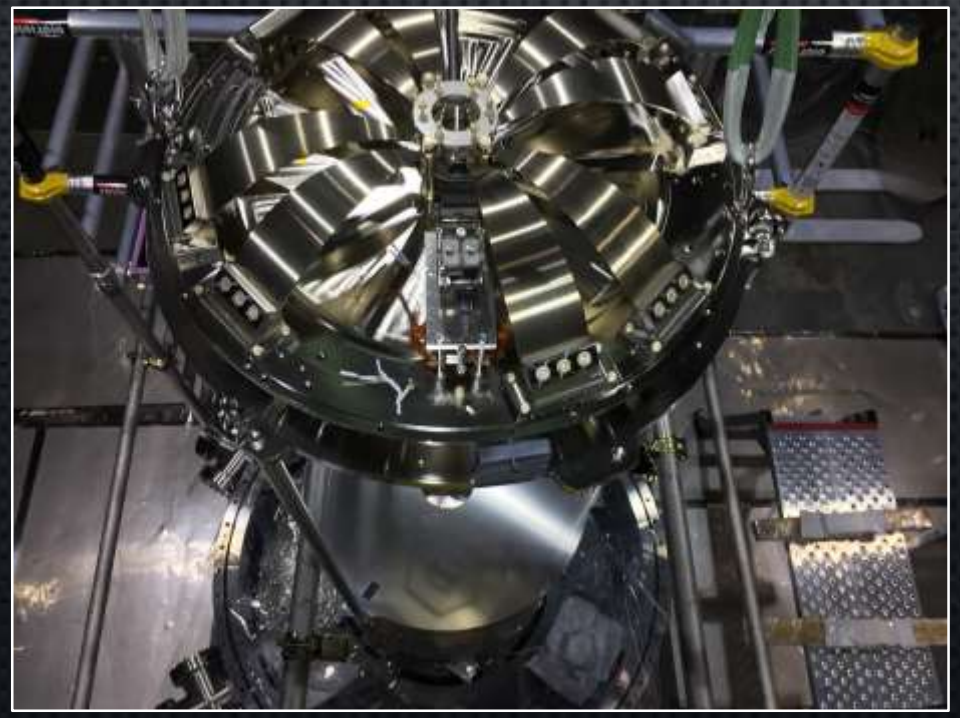


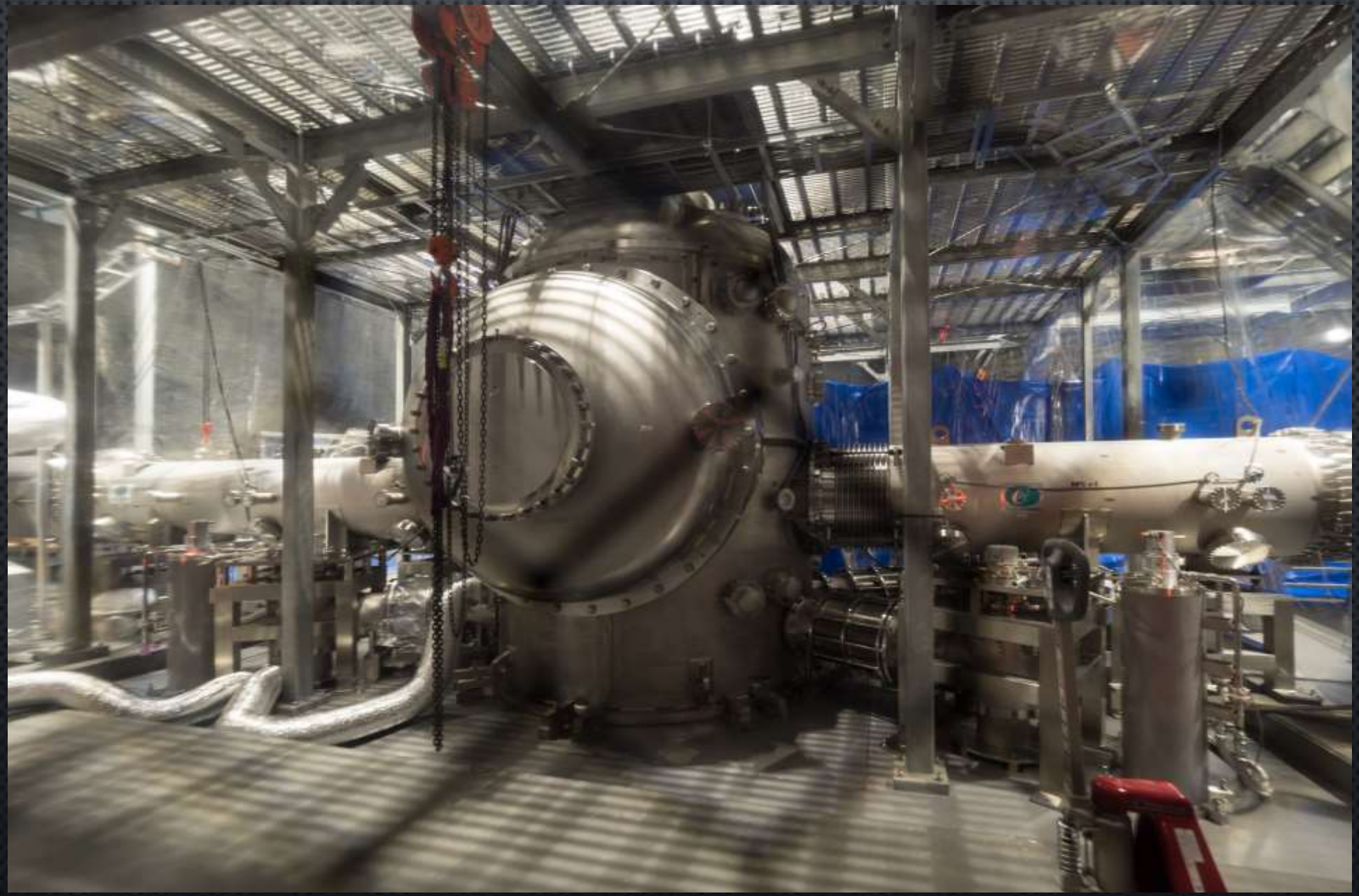
Type-A
(room temp.)

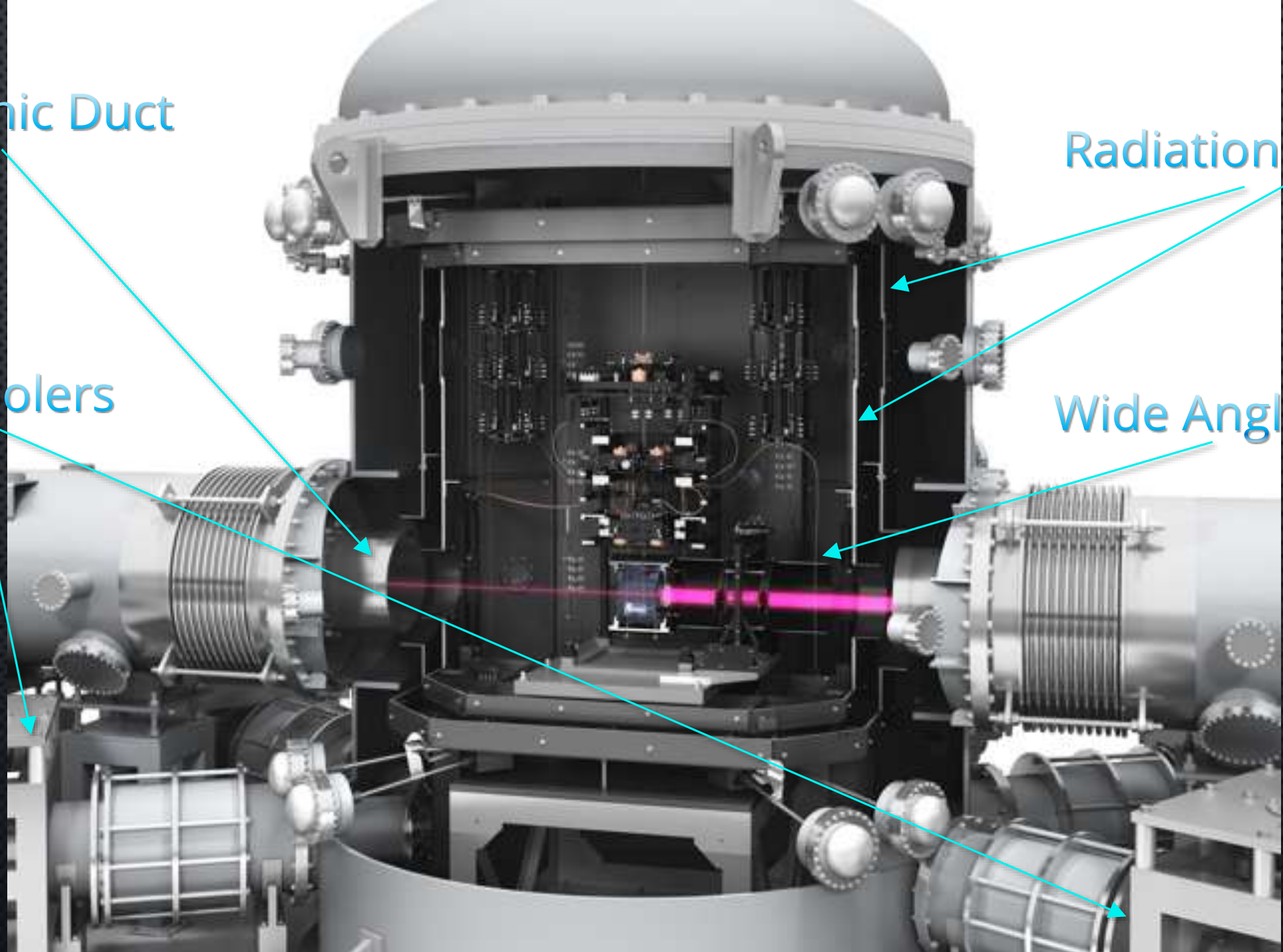
Cryo-Payload



Type-A Suspension Installation



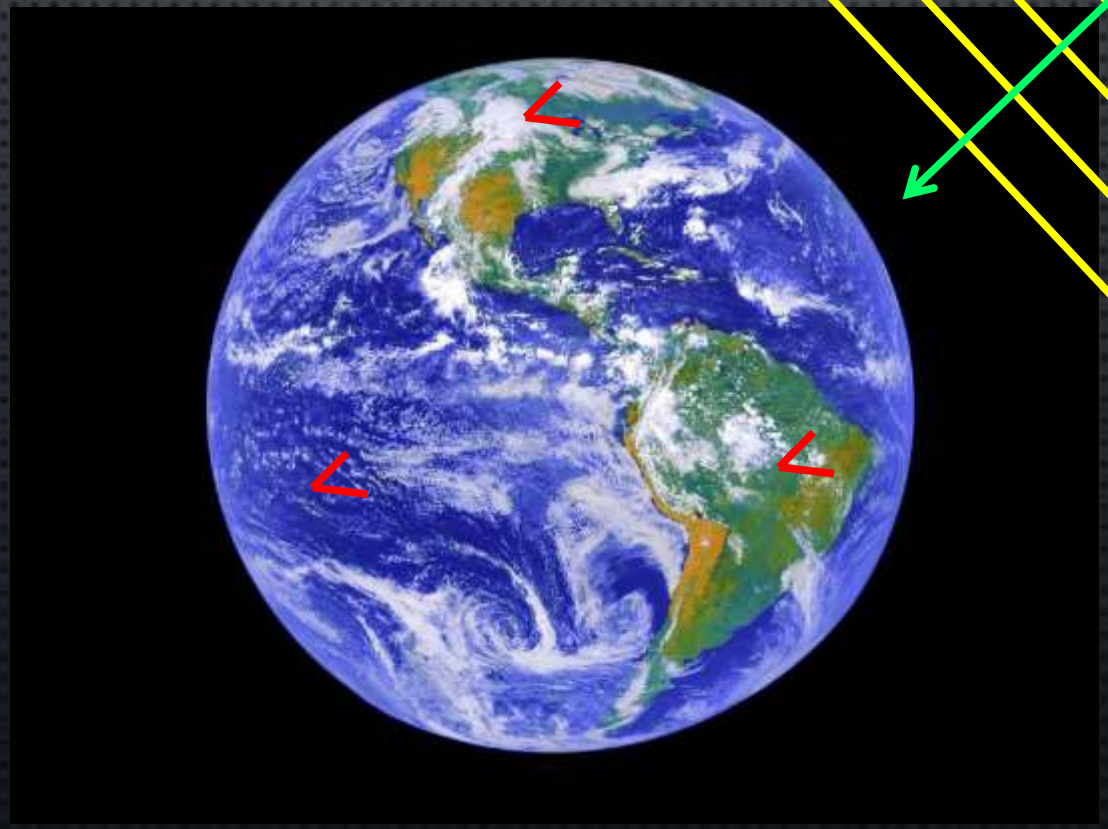


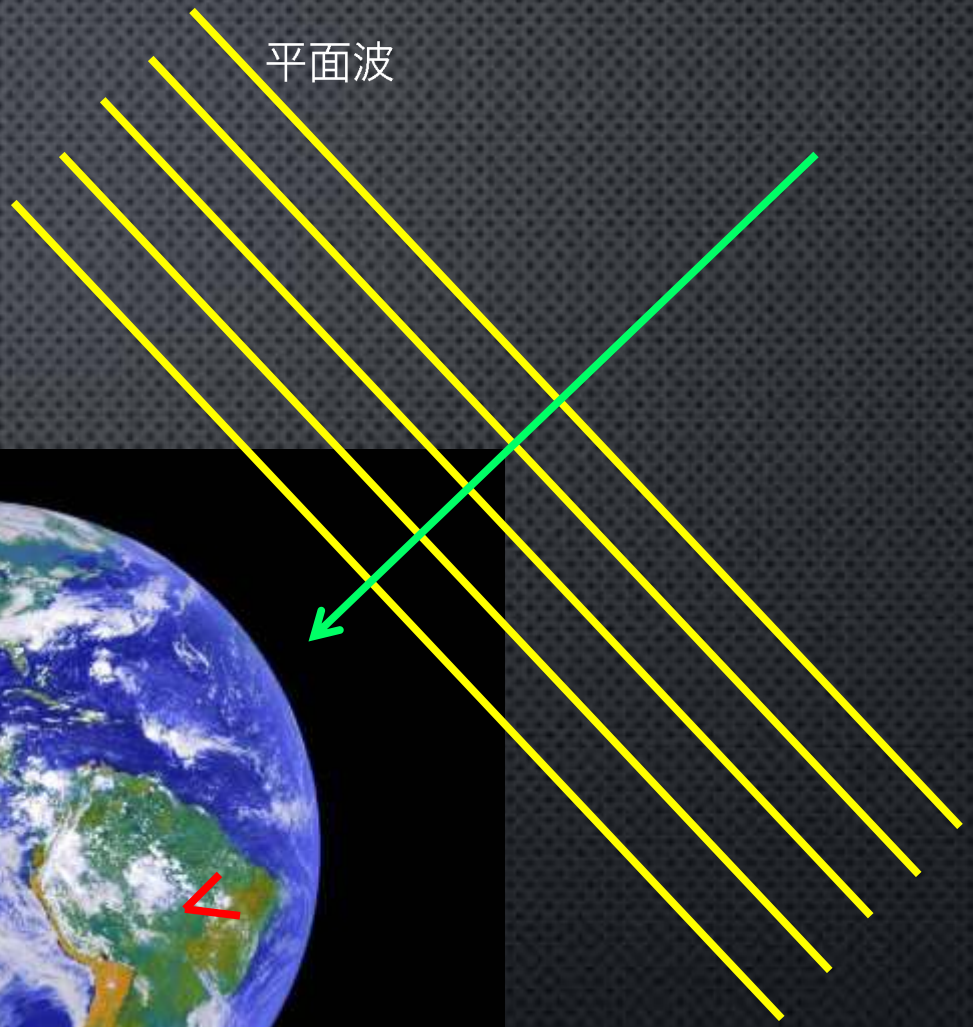

Cryogenic Duct
Radiation Shields
Cryo-Coolers
Wide Angle Baffle

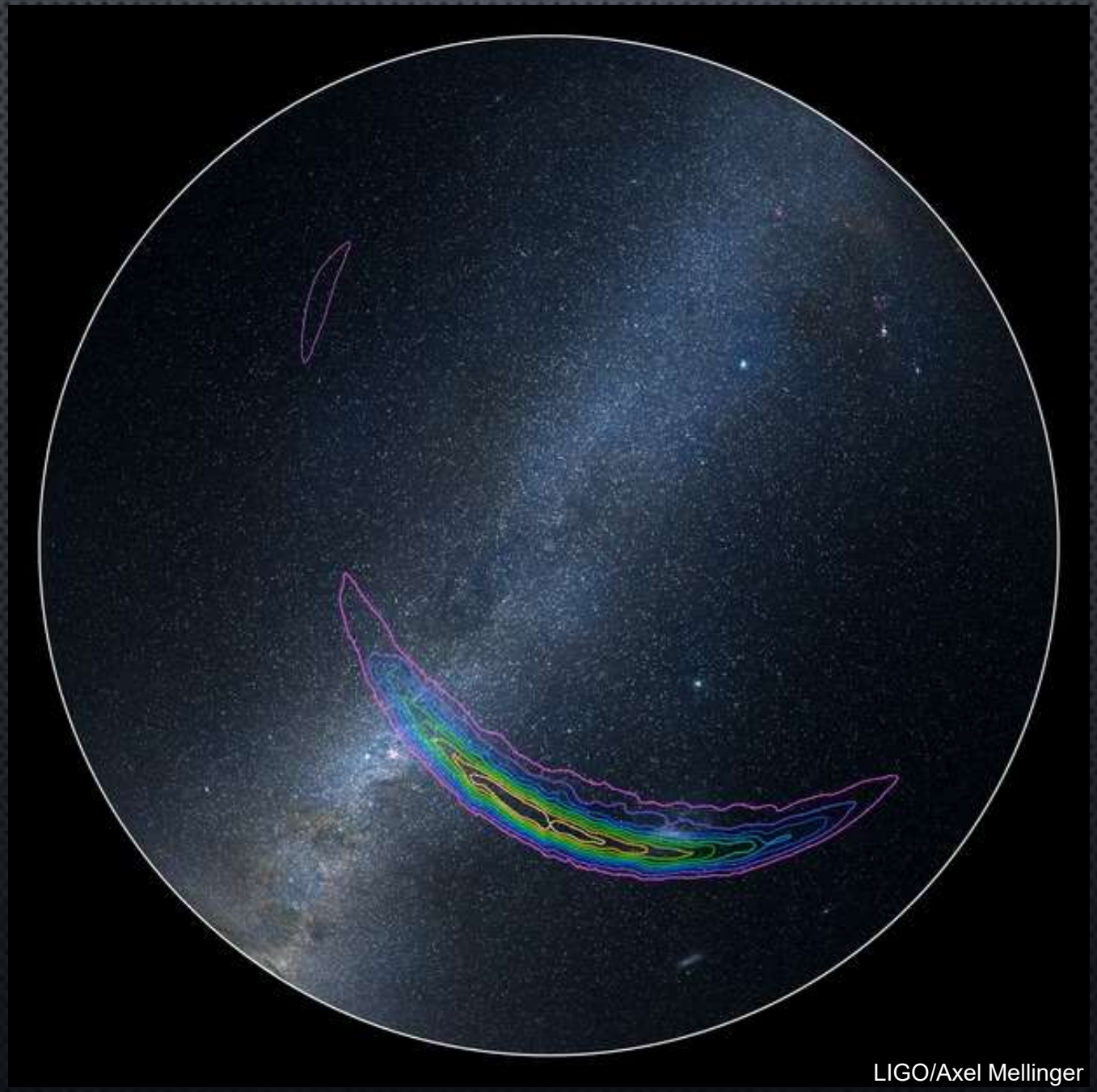
重力波源方向特定

到着時刻の違い

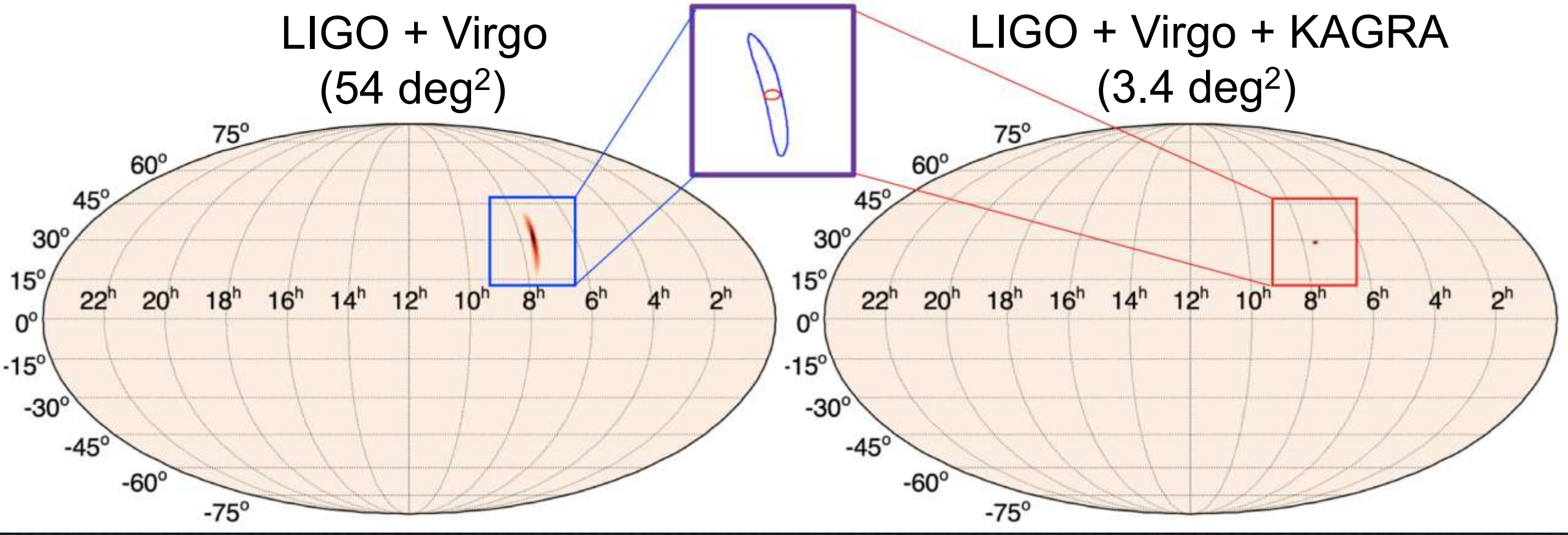
→ 三角測量



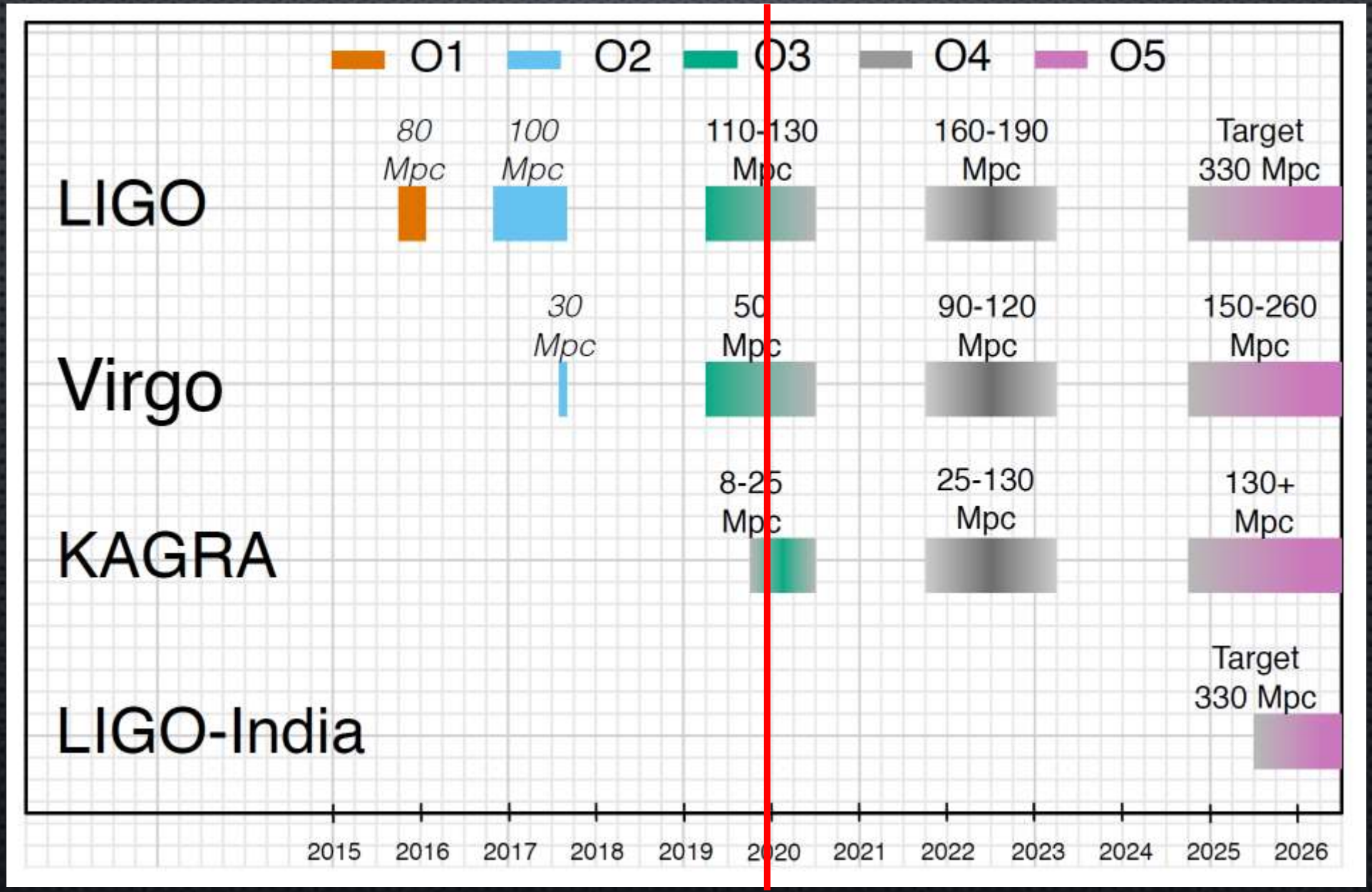



LIGO/Axel Mellinger

Improved event localization



世界の重力波検出器ネットワーク


O1
O2
O3
O4
O5
LIGO
80 Mpc
100 Mpc
110-130 Mpc
160-190 Mpc
Target 330 Mpc
Virgo
30 Mpc
50 Mpc
90-120 Mpc
150-260 Mpc
KAGRA
8-25 Mpc
25-130 Mpc
130+ Mpc
LIGO-India
Target 330 Mpc
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026

Now